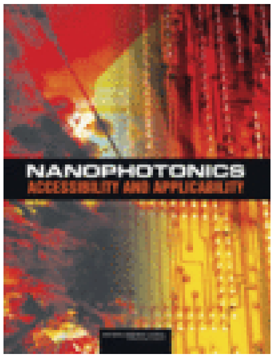
Nanophotonics: Accessibility and Applicability



Committee on Nanophotonics Accessibility and Applicability, National Research Council

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NANOPHOTONICS
ACCESSIBILITY AND APPLICABILITY

Committee on Nanophotonics Accessibility and Applicability

Division on Engineering and Physical Sciences

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[1]NAS, member of the National Academy of Sciences.
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Preface

The issues identified in the statement of task for this study[1] are part of a very broad and important set of issues for appropriate agencies of the intelligence community, the Department of Defense (DOD) research and development community, and other government entities. In addressing the statement of task, the National Research Council's (NRC's) Committee on Nanophotonics Accessibility and Applicability studied both the threats and the opportunities posed by emerging applications of nanophotonics. In this report, the committee presents recommendations regarding priorities for future action by the intelligence community and the DOD in the field of nanophotonics.

We wish to express our appreciation to the members of the committee for their contributions to the preparation of this report. The committee is also grateful to the staff of the Defense Intelligence Agency for its continuous sponsorship, and it is grateful for the active participation of the intelligence community throughout the study. The committee greatly appreciates the support and assistance of NRC staff members Michael Clarke, Daniel Talmage, Jr., Emily Ann Meyer, Carter Ford, Detra Bodrick-Shorter, Enita Williams, Lindsay Millard, Urrikka Woods, LaShawn Sidbury, and Dionna Ali in the production of this report.

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[1]The statement of task appears in Box 1-1 in Chapter 1.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Dan Gammon, U.S. Naval Research Laboratory,
Sharon Glotzer, University of Michigan,
Joseph Goodman (NAE), Stanford University,
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Alton D. Romig, Jr. (NAE), Sandia National Laboratories, and
Costas Soukoulis, Iowa State University and Ames Laboratory.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Elsa Garmire (NAE), Dartmouth University. Appointed by the NRC, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Acronyms and Abbreviations

ADDL	amyloid derived diffusible ligand
AFM	atomic force microscopy
Ag	silver
Al	aluminum
APTES	aminopropyltriethoxysilane
AR	antireflection
Au	gold
BB	blackbody
BCP	block copolymers
BEM	boundary element method
BOX	buried oxide
CDEW	composite diffracted evanescent wave
CdSe	cadmium selenide
CdTe	cadmium telluride
CHEM	chemical enhancement mechanism
CMOS	complementary metal oxide semiconductor
CMP	chip multiprocessor
CNT	carbon nanotube
CO_2	carbon dioxide
COTS	commercial off-the-shelf
CPP	channel plasmon polariton
CPU	central processing unit
CVD	chemical vapor deposition

DARPA	Defense Advanced Research Projects Agency
DDR&E	Director, Defense Research and Engineering
DFARS	Defense Federal Acquisition Regulations Supplement
DFB	distributed feedback lasers
DIA	Defense Intelligence Agency
DIBCS	Defense Industrial Base Capabilities Studies
DNA	deoxyribonucleic acid
DOD	Department of Defense
EAM	electro absorption modulators
EM	electromagnetic
EU	European Union
FDTD	finite-difference time-domain
FEM	finite element method
FET	field effect transistor
FMM	fast multipole method
FOM	figure of merit
FPA	focal plane array
Ga	gallium
GaAs	gallium arsenide
GaN	gallium nitride
Ge	germanium
HAMR	heat-assisted magnetic recording
HD	hard disk
HDD	hard disk drive
HgCdTe	mercury cadmium telluride
ICP	inductively coupled plasma
IEEE	Institute of Electrical and Electronics Engineers
IL	interferometric lithography
IMI	insulator-metal-insulator
InAs	indium arsenide
InGaN	indium gallium nitride
IR	infrared
IT	information technology
ITRS	*International Technology Roadmap for Semiconductors*
ITWC	intelligence technology warning community
JLIST	Joint Service Lightweight Integrated Suit Technology
JTEC	Japan Technology Evaluation Center
KAIST	Korean Advanced Institute of Science and Technology

L	slab thickness
LED	light-emitting diode
LSPR	localized surface plasmon resonance
LWIR	long-wave infrared
MBE	molecular-beam epitaxy
MEMS	microelectromechanical system
MIM	metal-insulator-metal
MIT	Massachusetts Institute of Technology
MM	multimode
MOCVD	metal-organic chemical vapor deposition
MOVPE	metal-organic vapor-phase epitaxy
MWIR	mid-wave infrared
NH_4OH	ammonium hydroxide
NIR	near infrared
NRC	National Research Council
NSF	National Science Foundation
NSL	nanosphere lithography
NSOM	near-field scanning optical microscope
OLED	organic light-emitting diode
PDMS	polydimethylsiloxane
PEEM	photoelectron emission microscopy
PIC	photonic-integrated circuit
PIPS	polymerization-induced phase separation
PSTM	photon scanning tunneling microscopy
PV	photovoltaic
QCL	quantum cascade laser
QCSE	quantum confined stark effect
QD	quantum dot
QDIP	quantum dot infrared photodetector
QKD	quantum key distribution
QW	quantum well
QWI	quantum well intermixing
QWIP	quantum well infrared photodetector
R&D	research and development
RC	resonant-cavity
RCWA	rigorous coupled wave analysis
RIE	reactive ion etching
S&T	science and technology
SEF	surface-enhanced fluorescence

SEIRA	surface-enhanced infrared absorption spectroscopy
SEM	scanning electron microscope
SEROA	surface-enhanced Raman optical activity
SERS	surface-enhanced Raman spectroscopy
SES	surface-enhanced spectroscopy
Si	silicon
SiC	silicon carbide
SiN	silicon nitride
SiP	system-in-package
SLS	strained layer superlattices
SM	single mode
SMS	spatial modulation spectroscopy
SoC	system-on-chip
SOI	silicon on insulator
SoP	system on a package
SP	surface plasmon
SPASER	surface-plasmon amplification by stimulated emission of radiation
SPM	scanning probe microscopy
SPP	surface plasmon propogation
SPR	surface plasmon resonance
s-SNOM	scattering-scanning near-field optical microscopy
STM	scanning tunneling microscope
TAR	thermally assisted recording
TEM	transmission electron microscope
TEOS	tetraethylorthosilicate
TERS	tip-enhanced Raman spectroscopy
THPC	tetrakis(hydroxymethyl)phosphonium chloride
TIGER	(standing committee on) Technology Insight—Gauge, Evaluate and Review
TiO_2	titanium dioxide
TPV	thermophotovoltaic
UAV	unmanned aerial vehicle
UV	ultraviolet
VLS	vapor-liquid-solid
VLWIR	very long wave infrared
WDM	wavelength division multiplexing
WR	waveguide ring
ZnS	zinc sulfide

Summary

The purpose of this study, carried out by the National Research Council's Committee on Nanophotonics Accessibility and Applicability, is to determine the accessibility of nanophotonics technology in a 10-to-15-year time frame, to identify the nations that control these technologies, and to review the scale and scope of offshore investments and interests in nanophotonics. Further, this study identifies feasible nanophotonics applications; their potential relationship to military systems; associated vulnerabilities of, risks to, and impacts on critical defense capabilities; and other significant indicators and warnings that can help prevent and/or mitigate surprise related to technology application by those with hostile intent. Finally, this report recommends priorities for future action by appropriate departments of the intelligence technology warning community (ITWC), the Department of Defense (DOD) research community, and other government entities.

THE BOTTOM LINE

The domain of nanoscale science and technology lies between the familiar classical world of macroscopic objects and the quantum mechanical regime of atoms and molecules. Nanostructures can have unique, controllable, and tunable optical properties that arise from their nanoscale size and from the fact that they are smaller than the wavelength for which they are designed. Both the properties of the nanostructures and their organization into large-scale materials, which may be ordered on the scale of the wavelength, are important for determining the optical response. Indeed, the optical properties of nanomaterials can be tailored for important commercial and defense applications, such as compact photoelectric power sources; efficient and tunable light sources, detectors, filters, waveguides, and modulators; high-speed all-optical switches; environmental (both chemical and biological) sensors; next-generation classical and quantum computation; and biophotonic medical diagnostics and therapeutics. This area of nanoscience, called *nanophotonics*, is defined as "the science and engineering of light-matter interactions that take place on wavelength and subwavelength scales where the physical, chemical or structural nature of natural or artificial nanostructured matter controls the interactions."[1]

[1]See http://www.phoremost.org/about.cfm. Last accessed April 9, 2007.

One-dimensional nanoscale structures, such as multilayer optical coatings and distributed Bragg reflectors, have long been staples of optical design and engineering. This report is restricted to the new developments that arise from the ability to control structures at the nanoscale in multiple dimensions (two-dimensional and three-dimensional photonic crystals, reduced dimensionality, and quantum confinement), to control both the magnetic and the electrical response of materials (metamaterials), or to manipulate nanoscale structures for enhanced field concentration (plasmonics). The areas of nanophotonics discussed in this report are characterized by their different physical nanoscale phenomena and the scale (relative to a wavelength) of the modulation of the index of refraction in the nanoscale material or system. Following are the four areas of nanophotonics selected by the committee as most relevant to cover in this report:

- *Photonic crystals*—in which the spatial index modulation is on the order of a wavelength;
- *Metamaterials*—in which the structural elements are much smaller than the wavelength, permitting an effective medium approach to the optical properties;
- *Plasmonics*—in which manipulation of light at the nanoscale is based on the properties of surface plasmons arising from metal free-electron response (negative permeability); and
- *Confined semiconductor structures*—whose physics is driven by reduced dimensionality and quantum confinement.

ACCESSIBILITY

The committee identified several overarching themes regarding the accessibility of nanophotonics technology in a 10-to-15-year time frame. First, nanophotonics will provide foundational building blocks for military capabilities, as discussed by the committee in addressing nanophotonics in relation to major strategic/critical military technologies. Second, advances in nanophotonics will enable new systems. A third theme noted by the committee is that of commercial markets pushing advances in nanophotonics to an increasingly greater degree while DOD and intelligence community agencies concurrently play lesser roles as drivers of this field.

Specific technological advances in nanophotonics are expected to contribute to major scientific and applications developments. The following list of such innovations is representative, not exhaustive:

- The surmounting of optical wavelength limitations in electronic devices, allowing unprecedented resolution in imaging applications, as well as the true integration of photonic and electronic functionalities. Implications include the ability to truly realize "optics on a chip" through the combination of nanoelectronics and nanophotonics, enhancing a range of capabilities from information technologies and advanced computing to advanced sensing. Success in this area would also enable breakthroughs in imaging systems and microscopies where the diffraction limit to resolution will be overcome in many important cases.
- The confinement of optical-matter interactions to the nanoscale, where the quantum mechanical regime dominates interactions and yields size-dependent, novel electronic and optical properties. Progress in this area would enable a wide range of "quantum technologies" such as quantum computing, quantum cryptography for secure communications, and advanced sensing capabilities. Other applications include tunable and efficient light sources, detectors, and other optical elements with enhanced and reconfigurable functionality.

- The ability to dramatically alter the optical properties of virtually any material by suitable combinations of "top-down" and "bottom-up" fabrication technologies, enhancing the capabilities for signaling, switching, detection, and concealment.

Profound advances in the control of single photons, the increased efficiency of photonic devices, and the interaction of photons with matter have been realized over the past 15 to 20 years. The committee expects that the pace of innovation and implementation will only increase with the availability of novel nanophotonics building blocks, the development of enabling technologies, and the insights gained by characterizing nanophotonics devices and phenomena.

APPLICATIONS

Nanophotonics-based systems are expected to have far-reaching applications in both military and commercial markets, including the following:

- Power, weight, and volume savings with higher speed and functionality on all military systems, including but not limited to (1) uncooled, infrared sensors and night vision; (2) ultrasecure communications and quantum information processing; and (3) photovoltaic power sources;
- External photonic communications between nanophotonic-enabled silicon chips, with widespread application likely within a few years, particularly for computers and microprocessors;
- Internal photonic communication within chips, enabling militarily significant functions, such as (1) potentially significant power savings within computing systems and (2) multicore processor interconnects leading to advanced computational applications such as image recognition;
- Heat-assisted magnetic recording using plasmonic focusing, which is part of the roadmap of the hard-disk drive industry; and
- Biosensing systems based on fluorescent molecules and/or quantum dots and on plasmonic effects—for example, surface-enhanced Raman scattering—for use in medical in-field diagnostics, bioagent detection, and bioremediation.

FOREIGN CAPABILITIES AND INVESTMENTS

Very large, focused, and growing foreign investments are enabling significant research programs in nanophotonics overseas. These programs highlight the international scope and inherent complexities of nanophotonics research and development (R&D). They include the following:

- In *Europe:* Large, multicountry collaborations in plasmonics, metamaterials, and nanocavity quantum electrodynamics are being sponsored by the European Union.
- In *Japan:* Japan funds nanotechnology research primarily through its Ministry of Technology and its Ministry of Education. Researchers in Japan have made seminal contributions in the achievement of high-quality photonic crystal devices for low-threshold lasing, low-loss waveguiding, high-speed switching, all-optical circuit switching, and other applications. There is also forefront R&D in the areas of efficient optical sources, including quantum dot lasers and prototype nanophotonic devices. Finally, research on the theory of optical near-field interactions with nanomaterials is underway, and work is progressing toward the fabrication of prototype nanophotonic devices.

- In *China:* China continues to make huge investments in education and research infrastructure. In the past 5 years (through 2006), the Chinese publication rate in areas related to nanophotonics has increased enormously. A closer inspection of the publication topics indicates a large proportion of research related to the simulation and modeling of nanophotonic structures and devices rather than to demonstrations of fabricated devices and systems. However, as the required experimental infrastructure is further developed and employed, advanced technological demonstrations of nanophotonic systems can be expected. A critical precursor technology, silicon integrated circuit planar fabrication, is already gaining a large foothold in China (JTEC, 1996).

KEY FINDINGS

In reviewing the global state of nanophotonics R&D, with a particular emphasis on military applications, the committee identified several key findings that have broad and critical implications regarding the accessibility and applicability of nanophotonics, as well as the importance of potential nanophotonics technologies to national economic and military security. These key findings, which are the basis of the committee's recommendations, are presented below (with their position in the main text noted in parentheses) in the context of a necessarily abbreviated discussion reflecting the committee's deliberations. More detailed justification of these findings and additional, more specific findings are contained in the body of the report.

Because of its unique scale length at the interface between the quantum and the classical descriptions of matter, and because of the exceptionally wide range of materials and fabrication processes that have applicability, nanophotonics necessarily draws on a broad range of scientific disciplines. The uses of nanophotonics require additional expertise in devices and systems. Finally, manufacturing at the nanoscale is an emerging discipline that draws on many different fields. While there are many similarities with manufacturing for the electronics industry, nanophotonics involves a much wider range of materials, offering unique manufacturing challenges. Progress in nanophotonics, which is characterized by its interdisciplinary nature, requires significant teaming across many fields.

Nanophotonics is a highly interdisciplinary field requiring expertise in many areas of materials science, chemistry, applied physics, optics, electrical engineering, systems engineering, and modeling and simulation, among other disciplines. **(Finding 6-1)**

Traditionally, synthesis, growth, and fabrication have been separately identified stages in the development of functional devices. Thus, for example, in today's electronics and photonics manufacturing, the preparation and growth of full-wafer epitaxial layers are performed before fabrication processes are used to define selected lateral areas for devices and related circuit elements. In the nanoscale era, these distinctions among synthesis, growth, and fabrication are blurring, and the steps are implemented in mix-and-match ways to produce novel functional nanostructured materials and to arrange them with the necessary hierarchical organization to produce new functionalities. Many researchers are investigating epitaxial growth on nanoscale areas, defined by some transverse fabrication before the growth process is initiated.

Traditional electronic-device fabrication employs well-defined and largely separate stages of synthesis, growth, and fabrication. In contrast, the generation of nanophotonic materials and devices blurs these distinctions, and certainly the order of these stages, interleaving them in new and novel ways. **(Finding 3-2)**

Because of the evolving, interdisciplinary, and complex nature of nanosynthesis, growth, and fabrication, state-of-the-art capabilities to perform this R&D are becoming increasingly expensive, even prohibitively so. The wide range of materials involved in today's nanoscience research and the need to avoid cross-contamination require multiple copies of expensive equipment, further compounding the cost issue. For example, gold is frequently needed for nanophotonics research, but it is anathema in any silicon (Si) fabrication facility because the fast diffusion rates of gold in Si affect doping and electronic device performance. Research institutions ranging from universities to industrial research laboratories to national laboratories are finding that building such facilities is often unaffordable, and that even maintaining existing facilities at the state of the art is becoming increasingly difficult to sustain.

The necessary fabrication facilities are becoming increasingly expensive and difficult for U.S. research institutions to maintain. **(Finding 6-2)**

The development of enabling technologies, along with significant infrastructure, will be essential for the implementation of commercial and military applications of nanophotonics. The essential enabling elements for nanophotonics include (1) synthesis, growth, and fabrication of nanomaterials and nanostructures; (2) characterization techniques for nanophotonics; (3) modeling and simulation; and (4) packaging and integration of nanophotonic devices. The presence of these enabling technologies in a country is often an important indicator of the state of maturity of nanophotonics in that country. However, because the approach to nanophotonics R&D is significantly more interdisciplinary and revolutionary than the current approach to photonics or microelectronics, countries with significant infrastructure in these traditional application areas will not necessarily dominate nanophotonics R&D. Other countries may emerge as leaders in nanophotonics based on initiatives that enable breakthrough technologies. At the same time, the accelerating diffusion of advanced manufacturing technologies for traditional electronics and photonics is enabling new opportunities for countries that have not heretofore had strong national efforts to establish R&D programs that will compete for the new possibilities enabled by nanophotonics.

Developments in synthesis, growth, and fabrication for photonic nanostructures extend across a wide range of materials and techniques and follow nontraditional paths. While it is tempting to assume that those countries which today have an extensive infrastructure for traditional photonics and microelectronics will continue to be the dominant developers of this new technology, this infusion of new ideas and new technologies means that new players can emerge over the 10-to-15-year time frame covered by this report. **(Finding 3-1)**

The globalization of science and technology, along with the increase in the quality of scientific institutions and universities abroad, particularly in Asia, is likely to diminish and even eliminate the scientific edge that the United States enjoys, particularly in emerging technologies such as nanophotonics. The globalization of expertise in nanoscale science and technology, as shown in part by the growth in publications in nanophotonics by researchers in countries such as China, will become increasing evident over the next decade and beyond.

It is likely that certain foreign nations will have equal or superior technical capability in nanophotonics compared with that of the United States within the next 10 to 15 years. These capabilities include fabrication, design, and systems integration; fundamental research; and a trained and talented workforce and educators. **(Finding 6-3)**

The committee believes that there is clearly a potential for nanophotonics to have a significant impact on military systems for both symmetric and asymmetric warfare. It is also true that nanotechnology insertion into disruptive technologies that could pose threats is difficult to anticipate by the very nature of such threats and the sometimes embryonic state of research in nanophotonics relative to other technologies. Some applications may take substantial investments and time before they are realized. Moreover, the application of nanophotonics requires a fabric of supporting and enabling technologies. This technology environment (at least in part) does not exist today, which further complicates the outlook. Therefore, most applications of nanophotonics will yield evolutionary changes in the current state of military technology, both domestic and foreign. However, there is a small but finite chance of a possible "game changer" technology emerging from the realm of nanophotonics, particularly in the area of information technologies, where breakthroughs in nanophotonics R&D could potentially enable a much more ubiquitous and pervasive data processing (and sensing) capability than is currently available.

The committee believes that, because of the infancy of nanophotonics, the probability of near-term revolutionary changes using nanophotonics is small but not negligible, for both domestic and foreign entities. **(Finding 4-1)**

KEY RECOMMENDATIONS

As a result of its study, the committee developed several key recommendations based on the key findings summarized in the previous section. These recommendations address the broad and critical implications regarding the accessibility and applicability of nanophotonics, as well as the importance of potential nanophotonics technologies to national economic and military security. These key recommendations are presented here, along with a necessarily abbreviated discussion of the committee deliberations. More detailed justification of these recommendations and additional, more specific recommendations are contained in the body of the report.

In the context of globalization, it is folly to assume that the United States will lead in all technologies relevant to military applications. The trend toward globalization is believed by the committee to also hold true for nanophotonics. Nanophotonics components, modules, and subsystems will play a large role in future U.S. weapons systems. In order to have the best and most affordable weapons systems, some of the nanophotonics items used in future U.S. weapons systems will probably not be produced within the United States, as is now the case for increasing numbers of other technologies' components, modules, and subsystems. This situation requires careful oversight and monitoring on the part of the ITWC.

The committee recommends that the intelligence technology warning community establish, maintain, and systematically update and analyze a comprehensive array of indicators pertaining to the globalization and commercialization of nanophotonics technologies that would complement and focus intelligence collection on and analysis of the topic. This effort should have a strong focus on monitoring the developments of the technology in countries not predisposed to selling such technology for use in U.S. military systems. The intelligence technology warning community is advised to monitor those countries that have strong backgrounds in related technologies, integrated optics, semiconductor lasers, compound semiconductors, microelectronics, and nanoscale photolithography. **(Recommendation 5-1)**

Consistent with current policies and practices, the United States has retained the domestic industrial capacity for specific strategic and critical military capabilities, including mid- and long-wavelength in infrared imaging; chemical and biological threat detection; secure communications (encryption, decoding, electromagnetic eavesdropping); situational awareness; secure computing; electronics systems on weapons platforms; battlefield control; stealth; countermeasures—infrared and visible; weapons platforms; and nuclear weapons. The committee thus assumes that filling the need for these critical capabilities is not likely to be left to foreign industries. However, an up-to-date understanding of the evolving global situation in this arena is essential and requires constant, systematic monitoring.

The committee recommends that the intelligence technology warning community monitor the worldwide development of nanophotonics technologies that have a high probability of impacting U.S. strategic and critical military capabilities, such as in mid- and long-wavelength infrared imaging systems, chemical and biological threat detection with compact and rugged instruments, secure communications, situational awareness, secure computing, enhancement of the electronics systems capabilities on U.S. weapons platforms, and enhancement of U.S. battlefield control capabilities. **(Recommendation 6-1)**

Due to the highly interdisciplinary nature of nanophotonics R&D and the potential for new and unexpected developments, effective monitoring of advances in nanophotonics is expected to be difficult and complex. Therefore, comprehensive and systematic monitoring is required in order to avoid surprise from advances in the field or at least to become aware of such developments as soon as they occur. The committee found that the methodology proposed in the National Research Council report *Avoiding Surprise in an Era of Global Technology Advances* (NRC, 2005) for categorizing and identifying current and potential future threat environments provided a good framework for this task.

To enable a more efficient technology watch and warning process for the U.S. intelligence community, the committee recommends that a data-mining tool be developed to uncover "triggers" and "observables" that will enable the U.S. national security establishment to preserve the dominance of the nation's warfighting capability. In order to uncover pertinent information, the U.S. government could provide a mechanism to leverage critical information from the nanophotonics community. Such a secure and structured database could reveal (across all of the military services) technologies that can support multiple service needs, while also stimulating domestic nanophotonics developments. **(Recommendation 4-1)**

The extensive investment in nanotechnology R&D by industry and academia suggests the need for the intelligence technology warning community to establish a sustained relationship with the non-governmental nanophotonics scientific, technical, and industrial communities—that is, universities, professional societies, and trade organizations—in order to bolster its understanding and anticipation of nanophotonics technology trends. The intelligence technology warning community needs to have access to experts as nanophotonics breakthroughs occur throughout the world, particularly in countries that do not have a strong coupling to the U.S. defense community.

The intelligence technology warning community should develop a sustained relationship with nanophotonics scientific and technical communities, not only within government agencies, but also in industry, academia, and technical societies, to bolster its understanding and anticipation of nanophotonics technology trends. **(Recommendation 6-3)**

In this present early development stage of nanophotonics technology, the U.S. R&D funding agencies can accelerate the development of nanophotonics technology by funding relevant R&D as they have repeatedly done in the past for other technologies. Two past examples are Si-based microelectronics and lasers. Such R&D funding action matures the technology faster so that it becomes clearer at an earlier stage how the technology can uniquely contribute to military applications, and the probability is increased that the U.S. military will be first to deploy the technology. As was the case with microelectronics and lasers, the commercial applications of nanophotonics are likely to overwhelm the military uses, requiring a healthy nanophotonics industry. Government R&D investment in nanophotonics is equally important for the emergence of this nascent industry.

For the United States to maintain a leading role in the development of the interdisciplinary field of nanophotonics, a stable funding profile must be maintained. For the Department of Defense to have assured access to nanophotonics capabilities, a healthy commercial nanophotonics sector with the ability to conduct pioneering R&D is essential. Historically, feedback from basic research to applications and back to basic research has been a major factor in U.S. technological success; in an interdisciplinary field this cycle is even more vital.

The committee recommends that the U.S. government funding agencies continue to support the research and development of nanophotonics technology in the United States across all phases from basic research to applications development. **(Recommendation 6-2)**

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1

Introduction

SCOPE OF THE STUDY

The purpose of this study is to determine the accessibility of nanophotonics technology in a 10-to-15-year time frame and to identify the nations that control these technologies, both currently and throughout the time frame of the study, reviewing the scale and scope of offshore investments and interests in nanophotonics. Further, this study aims to identify feasible nanophotonics applications; their potential relationship to military systems; associated vulnerabilities of, risks to, and impacts on critical defense capabilities; and other significant indicators and warnings that can help avoid and/or mitigate surprise related to technology application. Finally, this study recommends priorities for future action by appropriate departments of the intelligence community (IC), the Department of Defense (DOD) research and development (R&D) community, and other government entities.

In this study, the National Research Council's Committee on Nanophotonics Accessibility and Applicability (see Appendix A for biographical information) addresses the following questions (see Box 1-1 for committee's statement of task):

- Can emerging nanophotonics technology lead to disruptive capabilities that could threaten U.S. national security? Will nanophotonics introduce a paradigm shift that could potentially alter the balance of power?
- Can a country accomplish meaningful results that would enable significant applications in nanophotonics with a modest effort? If so, what indicators exist to gauge milestones on the way to the achievement of such results?
- By adopting nanophotonics as a technology, is the United States unknowingly leaving itself vulnerable from a national security perspective?

In answering these questions, the committee examines the threats, opportunities, and vulnerabilities posed by emerging applications of nanophotonics. It also examines the underlying capabilities required to develop a strong nanophotonics technology base. Although the focus of this study is defense applica-

BOX 1-1
Statement of Task

The NRC will:

Study the accessibility and potential applicability of nanophotonics in the 10-15 year timeframe and identify who controls these technologies in the areas of photonic crystals, plasmonics, metamaterials, and negative index materials.[a]

Review the scale and scope of off-shore investments and interest in nanophotonics.

Identify feasible nanophotonic applications, their potential relationship to military systems, associated vulnerabilities, risks, impacts to critical defense capabilities, potential alternate technologies that could compete with nanophotonics, and other significant indicators and warnings to help avoid and/or mitigate technology application surprise.[b]

Suggest priorities for future action by appropriate departments of the Intelligence Community, Department of Defense R&D community, and other Government entities.

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[a]"The charge to determine 'who' controls nanophotonics is interpreted as 'which nations' control nanophotonics. This precludes the notion that specific research institutions or industries, smaller in scale than a nation, may control facets of nanophotonics. These entities may possess fundamental knowledge, trade secrets, or capacities for innovation that may be hidden from the academic community or that may be so broadly networked (even across international boundaries) that their latent ability for break through discovery may not be obvious. However, because global multi-institution and multi-national research collaborations are abundant the bias to categorize the threat of technological surprise by nation may be limiting."

[b]By the definition of basic research, nanophotonics is still at an early stage with many possibilities and ultimate applications are still undefined. Discussing alternatives to as yet undeveloped technologies is clearly folly. The committee did identify underlying themes that characterize nanophotonics (see summary). Most of these have to do with surmounting wavelength limitations and enabling optical functionality at sub-wavelength scales. This by definition is "nanophotonics" and anything that allows it will be called "nanophotonics," whether it is one of the classes of objects we have identified or an as yet undiscovered direction. In this sense the question is moot. Manifestly there are advantages of optical functionality at sub-wavelength scales, and just as manifestly the enabling technology will be called nanophotonics. It is not as if we are considering a single system such as a biosensor and trying to decide between an optical (nanophotonic) approach and, for example, gas chromatography coupled with mass spectroscopy. In this specific case the question is well posed. In a global sense, however, it is not.

tions, commercial applications are also described and discussed, since much of the infrastructure and many of the capabilities required for defense applications will be commercially driven.

BACKGROUND

The domain of nanoscale science and technology lies between the familiar classical world of macroscopic objects and the quantum mechanical regime of atoms and molecules. Nanostructures can have unique, controllable, and tunable optical properties that arise from their nanoscale size and from the fact that they are smaller than the wavelength of light used to observe them. Both the properties of the nanostructures and their organization into large-scale materials, which may be ordered on the scale of the wavelength, are important for determining the optical response. Indeed, the optical properties of nanomaterials can be tailored for important commercial and defense applications, such as compact photoelectric power sources; efficient and tunable light sources, detectors, filters, waveguides, and modulators; high-speed all-optical switches; environmental (both chemical and biological) sensors; next-generation classical and quantum computation; and biophotonic medical diagnostics and therapeutics. This area of nanoscience, called *nanophotonics*, is defined as "the science and engineering of light-matter interactions that take place on wavelength and subwavelength scales where the physical, chemical or structural nature of natural or artificial nanostructured matter controls the interactions."[1]

One-dimensional nanoscale structures, such as multilayer optical coatings and distributed Bragg reflectors, have long been staples of optical design and engineering. Form-birefringence is an example of a well-known two-dimensional structural optical functionality with pattern scales below the wavelength. This report is restricted to the new developments that arise from the ability to control structures at the nanoscale in multiple dimensions (two- and three-dimensional photonic crystals, reduced dimensionality, and quantum confinement), to control both the magnetic and the electrical response of materials (metamaterials), or to manipulate nanoscale structures for enhanced field concentration (plasmonics).

For purposes of this study, the committee divided the areas of nanophotonics to be discussed in terms of the different physical nanoscale phenomena, driven by physics that is determined by the size scale (relative to a wavelength) of the modulation of the index of refraction in the nanoscale material or system. The resultant four areas of nanophotonics discussed in this report are as follows:

- *Photonic crystals*—in which the spatial index modulation is on the order of a wavelength;
- *Metamaterials*—in which the structural elements are much smaller than the wavelength, permitting an effective medium approach to the optical properties;
- *Plasmonics*—in which manipulation of light at the nanoscale is based on the properties of surface plasmons arising from metal free-electron response (negative permeability); and
- *Confined semiconductor structures*—whose physics is driven by reduced dimensionality and quantum confinement.

Photonic crystals are optical materials engineered using periodic dielectric structure with spatial periodicity of the order of the wavelength of the light that enables the tailoring of the propagation of light through the control of the photonic crystal structure (John, 1987; Yablonovitch, 1987). A key idea for photonic crystal structures is the periodicity of the structure giving rise to dramatic changes in the optical properties and possibly to the formation of a forbidden gap in the electromagnetic spectrum, a "photonic" band gap, thus altering the properties of the light passing through the structure (Ho et al., 1990, 1991).

The photonic band gap defines a set of frequencies for which light cannot propagate in the crystal: the tunability of the band gap, through control of the dimensions and symmetry of the photonic structure, provides exquisite frequency control of the propagation properties through the crystal. Alternatively, the perfect translational symmetry of the photonic crystal can be disrupted in a controlled manner, providing a localized photonic state within the photonic band gap, making possible the localization of photons (Yablonovitch et al., 1991). As with surface plasmons, extremely high field densities can be achieved within these photonic crystal "defects" or resonators, leading to a wide range of opportunities for nonlinear operation and highly sensitive detection. Another consequence of the structure of the photonic band

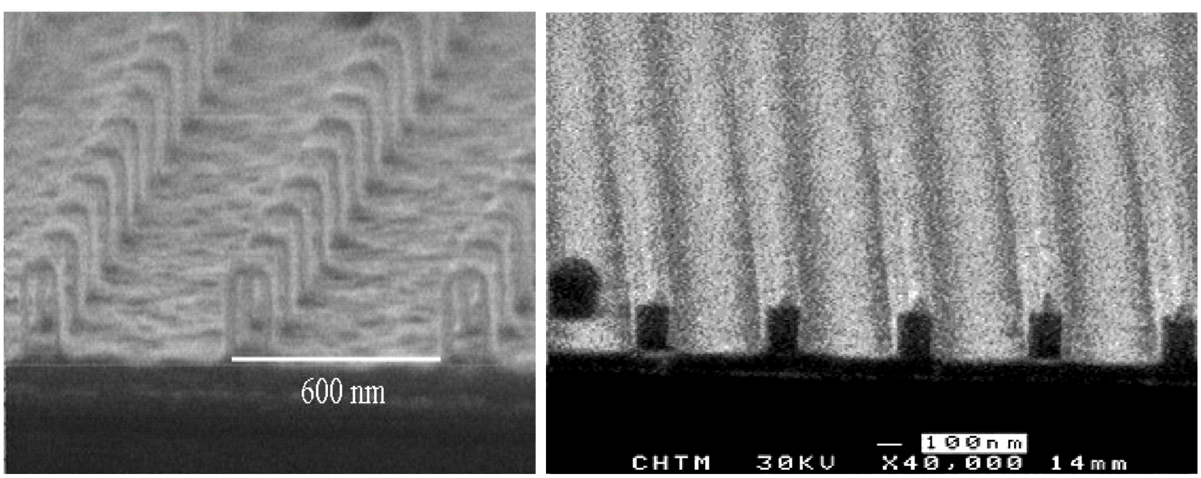
[1]See http://www.phoremost.org/about.cfm. Last accessed April 9, 2007.

gap is the dispersion behavior near the band edge, and the possibility of group velocities approaching zero, thus "slowing" light in the photonic crystal, or the velocity can be negative as in opposed phase and group velocities (Notomi et al., 2001; Vlasov et al., 2005).

Electromagnetic metamaterials are created from individual nanostructures that are fabricated on a scale much less than a wavelength and that respond resonantly to either electric or magnetic fields (Pendry et al., 1999, 2004), as shown in Figure 1-1.

To first order, the subwavelength dimensions of such resonant structures allow for treating the composite structures in the effective medium limit, enabling the construction of materials composed of arrays of these particles with specifically designed electromagnetic properties. Such composite materials can be described in terms of the constitutive relations appearing in Maxwell's equations, meaning that the electrically resonant response is characterized by the electrical permittivity $\varepsilon(\omega)$ and the magnetically resonant response is characterized by the magnetic permeability $\mu(\omega)$. This new ability to design metamaterials with tunable ε and μ enables many applications hitherto unattainable. In particular, it is possible to design metamaterials with a magnetic response at optical frequencies that no known natural material exhibits.

To date, the primary goals of metamaterials research have been the extension of the wavelength range to the near infrared and visible regions; increasingly, attention is turning to the novel optical properties that can be achieved with spatial control of the refractive index over wide, and including negative, ranges. Although most of the metamaterials community has focused on the demonstration of a negative index at optical frequencies, a host of other exciting and relevant possibilities exist, including high-sensitivity detection as well as switching and modulation. The frequency of the response of metamaterials can be scaled from the microwave to the near infrared by decreasing the dimensions of the nanostructures (Dolling et al., 2006; Shelby et al., 2001; Yen et al., 2004; Zhang et al., 2005b). There



a b

FIGURE 1-1 (a) Array of nanoscale resonators (gold loops, inductors, atop a dielectric/metal film stack, capacitors). The resulting structure has a resonance evident in the normal incidence reflection spectrum in the mid-infrared at approximately 5 μm and exhibits a negative permeability; (b) staple-shaped nanostructures. SOURCE: Reprinted with permission from Zhang et al. (2005a). Copyright 2005 by the American Physical Society.

are well-established fields using subwavelength structures for antireflection coatings, form-birefringent polarization manipulation, and other optical elements. This report is restricted to the new developments arising from the ability to control *both* the magnetic and the electric response of materials.

Reduced dimensionality and quantum confinement occur when a structure's extent in one or more dimensions becomes comparable to the Fermi wavelength of the charge carrier (i.e., electron or hole). See Figure 1-2 for a visual depiction of the latest developments in increasing the resonance frequency in metamaterials. Very recently, these results have been extended throughout the visible spectrum using wire pairs (vertically stacked metal-dielectric-metal structures similar to the structure at the top right in Figure 1-2) (Cai et al., 2007).

In this case, the allowed energy levels of the charge carriers become significantly modified, increasing in energy as the structure dimensions are decreased and the confinement becomes more severe. The double heterostructure—which eventually came to be called a quantum well—enabled the charge carriers to be concentrated into a thin layer of material having a smaller band gap than the material surrounding it (Ho et al., 1994). This suppressed electron-hole recombination outside the active region, and increased optical confinement owing to the higher index of refraction in the quantum well. In such two-dimensional semiconductor structures, the fundamental concept of quantum confinement uses quantum wells to localize excitons, increase oscillator strengths, enhance radiative recombination efficiencies, and control charge-carrier transport. One-dimensional quantum confined structures, quantum wires, and zero-dimensional quantum structures—quantum dots or nanocrystals—also yield size-controlled optical and electronic properties of importance to nanophotonics. Indeed, quantum dots can be considered tunable "artificial atoms" whose optical properties can be engineered for a particular application.

Based on the properties of surface plasmons, *plasmonics* is a subfield of nanophotonics concerned primarily with the manipulation of light at the nanoscale. Plasmons are the collective oscillations of

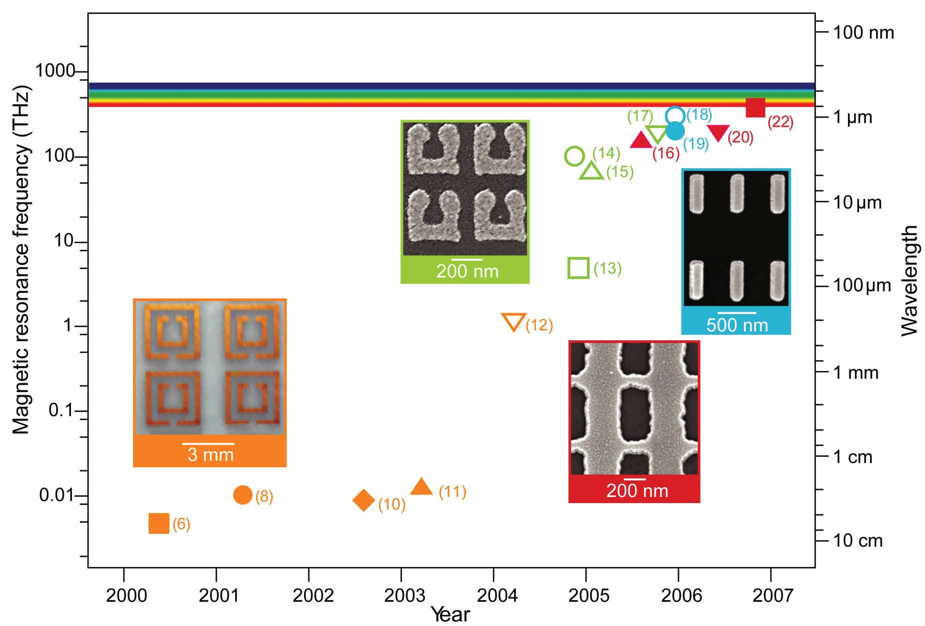


FIGURE 1-2 Latest developments in increasing the resonance frequency of metamaterials. The four insets show fabricated structures in different frequency regions. SOURCE: Soukoulis et al. (2007). Reprinted with permission from AAAS.

the electron gas in a metal or semiconductor. The bulk plasmon is a strictly longitudinal excitation that does not couple to transverse field photons. The coupling to photons is possible only in the presence of a surface or a boundary. There are both longitudinal and transverse parts to the surface plasma wave fields on both sides of the interface. Surface plasmon polaritons, also called surface plasmons, represent an electromagnetic wave bound to the surface of a metal film surrounded by a dielectric. This excitation can be considered as a charge density wave combined with an electromagnetic field. The surface plasmon has a propagation vector parallel to the interface, while its amplitude decays exponentially in the direction orthogonal to the surface (see Figure 1-3) (Barnes et al., 2003).

Unlike pure electromagnetic (optical) waves, surface plasmons can be localized to subwavelength dimensions in the plane perpendicular to the propagation direction, providing a viable route to nanoscale optics. Much of today's research is aimed at structures that provide additional localization in multiple dimensions; examples are surface plasmons localized to single metal particles and to the interstices between metal particles. Localization of the electromagnetic fields at the nanoscale also yields a dramatic increase in the field intensity, thus suggesting the use of surface plasmons in nonlinear applications, such as optical switching, Raman spectroscopy of single molecules and atomic clusters, and even coherent control of a single molecule's quantum dynamics. Surface plasmons are supported by structures at all length scales and largely determine the optical properties of metal-based nanostructures. The field of plasmonics is based on the use of surface plasmons for a large variety of tasks, through the design and manipulation of the geometry of metallic structures, and consequently their specific plasmon-resonant or plasmon-propagating properties.

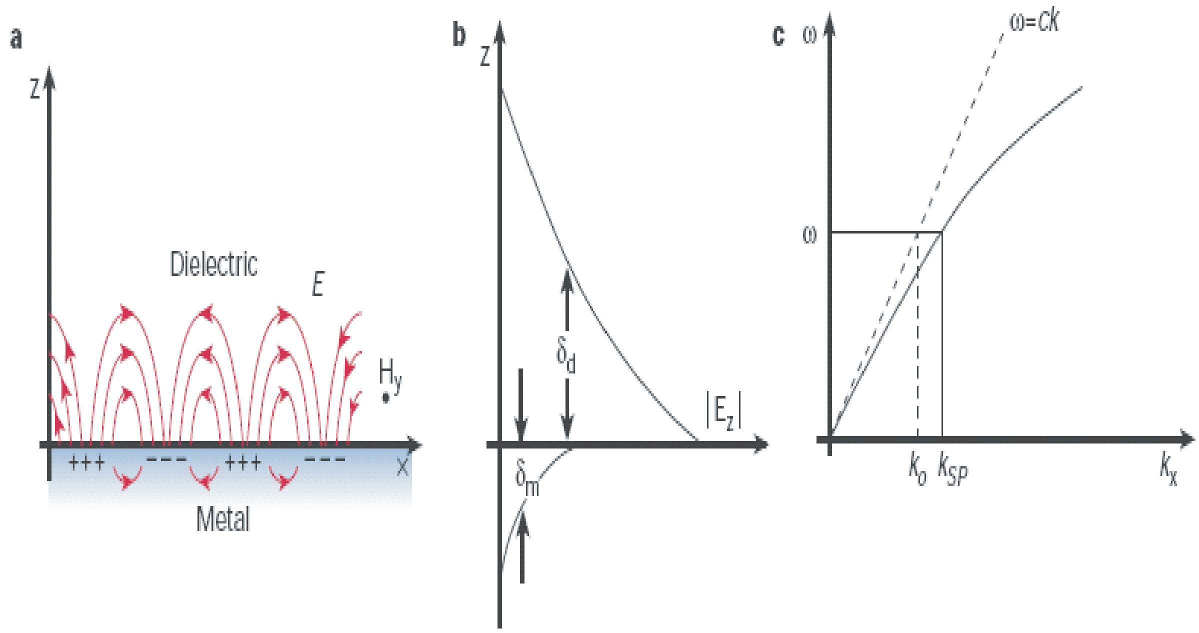


FIGURE 1-3 Surface plasmons (SPs) at a metal-dielectric interface: (a) electromagnetic field vector and charge distribution diagram, (b) field amplitude dependence orthogonal to the interface, and (c) dispersion curve for SPs (solid line) and photons (dashed line) showing the momentum mismatch. SOURCE: Reprinted by permission from Macmillan Publisher's Ltd: Barnes et al. (2003). Copyright 2003, Macmillan Publisher's Ltd.

METHODOLOGY

The scope of interest of this study is global in terms of developments in nanophotonics technology, but it *emphasizes* the following:

- Speculation on future advances in nanophotonics *relevant to U.S. military applications;*
- Identification of vulnerabilities of, risks to, and impacts on critical defense capabilities from feasible nanophotonics applications and alternatives; and
- Assessment of *offshore* research and development in nanophotonics.

Data and other information for the study included the following:

- Relevant prior studies (see Appendix C for excerpts from selected studies),
- State-of-the-art reviews,
- Current research and development reviews, and
- Presentations to the committee (see Appendix B for the list of presentations).

The committee's review considered historical trends, notable domestic centers of excellence, offshore competition, and related enabling technology developments. The report includes projections of future developments and the identification of plausible applications and threats related to such developments. The scope of coverage of technological developments also includes nonoptical frequencies (as exemplified by terahertz phenomenology and technology, where the concepts are similar but the size scale is appropriately extended).

Anticipating Threats and Projecting Threat Levels

In a generic sense, a difficulty with anticipating threats is the latency between innovation, application, and emerging threat. This latency makes translating nanophotonics technology innovations into specific long-term military spin-offs problematic. An additional challenge is that the assessment also depends on the state of the industrial and enabling technology base. Commercial trends in this report are increasingly important and are further enabled by globalization trends, which can be become somewhat convoluted. Potential threats to U.S. military systems from outside the United States may be leveraged or reverse-engineered from U.S. technology and may even be a driver for subsequent U.S. technological developments.

While the danger of threats could be prioritized, for example, in terms of possible geographic extent (city to nation) and impact (nature of disruption, monetary losses, and fatalities), this study attempts to assess nanophotonics-related threats in terms of the IC's technology watch and warning framework, which correlates projected threat levels with technology development phases or milestones over a progressive time line, as illustrated in Figure 1-4. But this is not the only paradigm, since it can be short-circuited—that is, competitors may enter the development chain at any point.

Ideally an assessment should identify the utility or observables to monitor, track, and quantify in terms of the expected benefits—for example, gains in performance (decibels). Type I and Type II errors (false positives and false negatives) will be unavoidable. In addition to projecting threats, results of this will help ensure technological superiority and influence investment strategies for U.S. programs, especially within the context of globalization and a perceived decline in a U.S. science and engineering advantage.

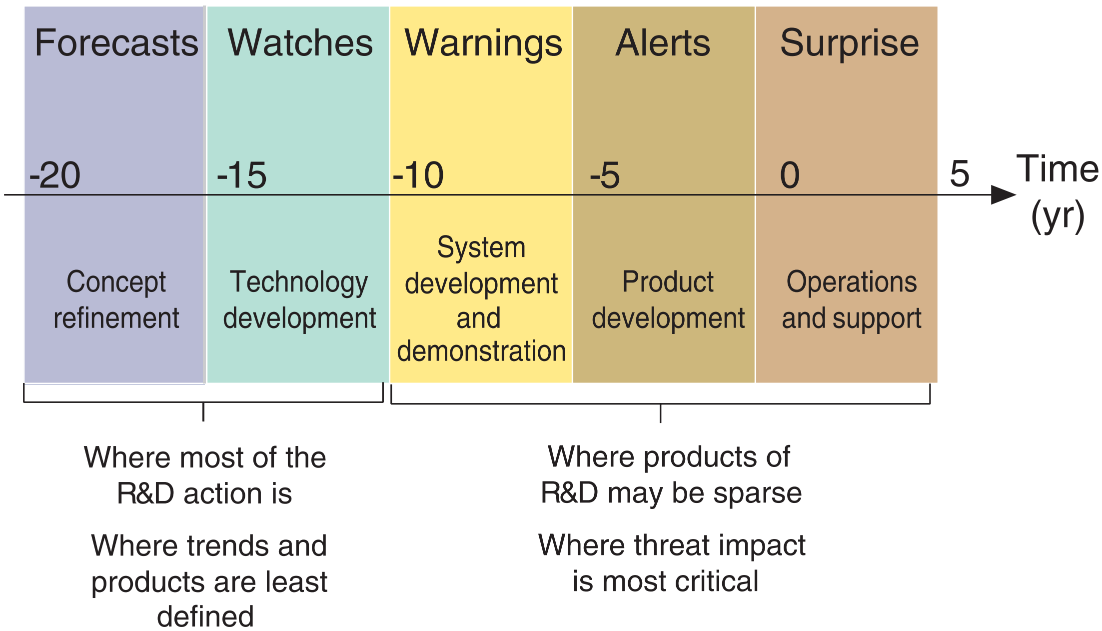


FIGURE 1-4 Time line for technology development common in commercial, defense, and space sectors of the "blue world" (domestic and other Western countries).

Two related "landscapes" exist: one delineated by threat and one by the technology. In general, threats can be broken down by the scope of their geographic coverage and their credibility. Supporting evidence must eventually be weighted by the possible strategies for conflict resolution: direct military conflict, economic competition, or terrorism.

Technology can be broken down by technology subareas directly (e.g., metamaterials, photonic crystals, and so on.), by enabling technologies (fabrication versus modeling and simulation), and by physics constraints (fundamental limits). The evidence supporting the committee's findings could conceivably just include weighting the findings by analogy with common practices ("blue world" R&D methodologies) and in terms of the credibility of a competing (foreign) R&D technology base. But not all such threats follow this model. Important exceptions include leveraging or reverse-engineering of commercial-off-the-shelf technology and their implementation as so-called asymmetric threats.

Matrix of Critical Technologies

The committee formulated a matrix of critical technologies to "roll up" more detailed deliberations into a top-level assessment: the matrix shows the major areas of nanophotonics (photonics, metamaterials, negative index materials, and plasmonics) versus a notional critical technologies list, as shown in Figure 1-5. This assessment is described in more detail in Chapter 6.

The committee considered four levels of probability in estimating the likelihood of a technology's impacting U.S. strategic and critical capabilities (extremely high, high, medium, and low) and the case of not applicable (none). In arriving at these probabilities, the committee implicitly took into account several levels of maturity:

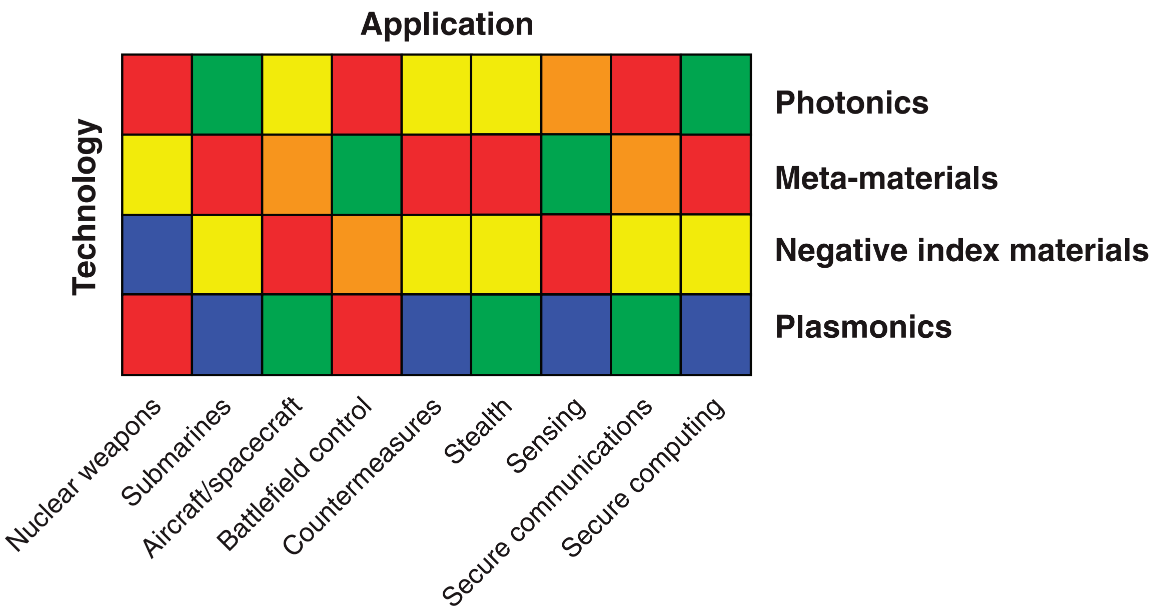


FIGURE 1-5 Matrix of critical technologies developed by the committee for the top-level assessment of nanophotonics.

- Is the technology in a conceptual feasibility phase?
- Is it in hardware development?
- Is it ready to embed in a system?
- Is it in product development?
- Is deployment imminent?

Technological applications were also assessed by the committee in terms of their perceived potential for immediate application. The two distinctive domains of this aspect of the assessment are (1) envisioned or pending applications, and (2) enabling technology, as delineated below. Examples of applications of the first domain include the following:

- Embedded sensors fabricated by replication or self-assembly and scalable to large areas;
- Stealthy nanoscale taggants for warning or for the tracking of security perimeter incursions;
- Metamaterials enabling enhanced antennas for sensing, and for communications with covertness and/or stealth at selected frequencies;
- Reverse-engineered, remotely activated nanoparticles; and
- Micro- and nano-optical elements for ultraminiature hybrid optoelectronic processors.

Examples of applications of the second domain, enabling technology, include the following:

- Fabrication, both top down (classic semiconductor techniques) and bottom up (self-assembly, growth, and synthesis);

- Characterization of nanophotonic materials and devices;
- Modeling and simulation; and
- Packaging and integration.

STRUCTURE OF THE REPORT

Following this introductory chapter, the four areas that comprise nanophotonics are described in more depth in Chapter 2; supporting material in Appendix D describes a representative sampling of research efforts in the area of plasmonics. The enabling technologies for nanophotonics, including nanomaterials growth, synthesis and fabrication, characterization of nanophotonic materials and devices, nanoscale device integration, nanophotonic packaging, and modeling and simulation, are discussed in Chapter 3. Chapter 4 presents potential applications of nanophotonics, emphasizing those of interest to the defense and intelligence communities. The focus of Chapter 5 is international capabilities and investments in nanophotonics. Finally, Chapter 6 discusses the relevance of nanophotonics to major strategic and critical military technologies and summarizes the committee's conclusions and recommendations.

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2

Nanoscale Phenomena Underpinning Nanophotonics

This chapter explores the physical phenomena that distinguish nanophotonics from photonics. The chapter is organized in sections on photonic crystals (structures on the scale of the optical wavelength), metamaterials (structures much less than the optical wavelength), plasmonics (structures using the large, negative permittivity of metals to manipulate optical fields), and reduced dimensionality and quantum confinement (semiconductor nanostructures on the scale of electronic wave functions). Because many of the phenomena of nanophotonics are largely electromagnetic in origin, the discussion also includes applications to longer wavelengths (terahertz) to which the appellation "nano" no longer strictly applies. A very important caveat: the research areas discussed here are very active, with new developments being announced at a breakneck pace; the report provides a snapshot, frozen in time in the spring of 2007, of things that will inevitably have changed by the time the report is being circulated. Nonetheless, it is important to elucidate the fundamental concepts and to establish the vector along which the field of nanophotonics is progressing.

SPATIAL MODULATION AT FRACTIONS OF A WAVELENGTH—PHOTONIC CRYSTALS

Introduction

In a paper published in 1987, Yablonovitch anticipated the possibility of inhibited spontaneous emission in solid-state materials through the formation of a three-dimensionally periodic dielectric structure with spatial periodicity on the order of the wavelength of the light considered (Yablonovitch, 1987). Such periodic structures can be formed from two materials that have different indices of refraction—for example, air and SiO_2. In the same time frame, S. John published a similarly visionary paper that speculated on strong localization of photons in "certain disordered superlattice microstructures of sufficiently high dielectric constant" (John, 1987). These papers formed the foundations of the tremendously fertile and productive research field of *photonic crystals:* this field involves engineered optical materials providing a multitude of ways to tailor the propagation of light through the control of the photonic crystal structure. While the first demonstrations of photonic crystal behavior were carried out at microwave frequencies in scaled structures of 6 millimeter (mm) Al_2O_3 spheres (Yablonovitch and Gmitter, 1989) or drill/etched Stycast 12 (Yablonovitch et al., 1991), current research on photonic crystals truly embodies the concepts of "nanophotonics," with spatial index modulation (etched holes or solid rods) at the 100 nanometer (nm) scale, allowing compact, highly integrable waveguides, filters, resonators, and high-efficiency lasers. The original predictions of Yablonovitch and John have been realized: first reports of photonic crystal lasers were made in 1999 (Painter et al., 1999), and localization of photons within photonic crystal "defects" was first observed in 1991 in the microwave regime (Yablonovitch et al., 1991a).

Photonic Band Gap

A key idea for photonic crystal structures is the periodicity of the structure giving rise to the formation of a forbidden gap in the electromagnetic spectrum, thus altering the properties of the light passing through the structure. One-, two-, and three-dimensional photonic crystals, as well as a photonic band structure are described in Figure 2-1.

The *photonic band gap* defines a set of frequencies for which light *cannot* propagate in the crystal: the tunability of the band gap, through control of the dimensions and symmetry of the photonic structure, provides exquisite frequency control for multiple wavelength information processing (or wavelength division multiplexing, WDM). Various photonic crystal waveguides have been formed with deliberately engineered stop bands (e.g., Davanco et al., 2006; Fleming and Lin, 1999). Equally interesting, or perhaps more so, is the case in which the perfect translational symmetry of the photonic crystal is disrupted in a controlled manner. John (1987) alluded to these "certain disordered dielectric superlattices" in his 1987 paper, and Yablonovitch et al. (1991b) used the analogy of donor and acceptor modes in semiconductor crystals in defining these "defect" states: the disruption from symmetry providing a photonic state within the photonic band gap, making possible the localization of photons.

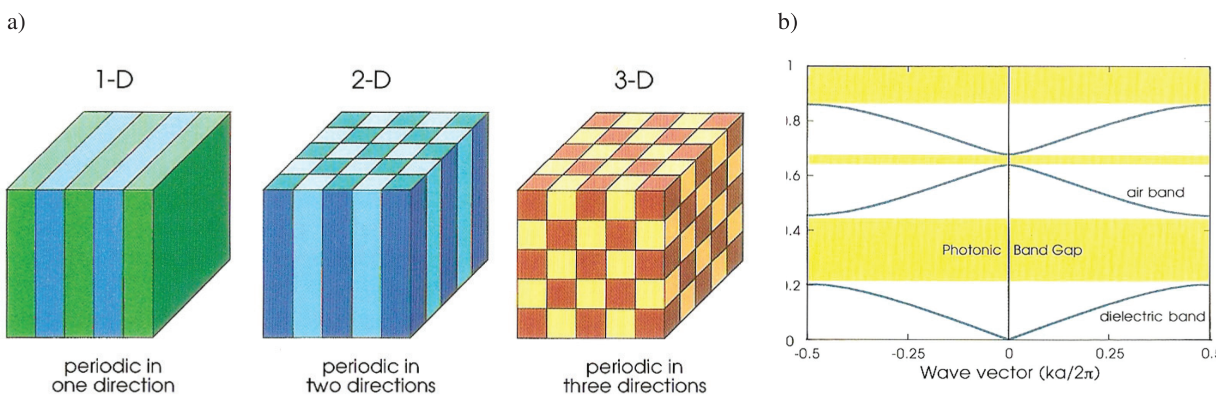

FIGURE 2-1 (a) Simple examples of one-, two-, and three-dimensional photonic crystals. The different colors represent materials with different dielectric constants. (b) A notional dispersion diagram for a photonic crystal showing a band gap and regions of anomalous dispersion. SOURCE: Joannopoulos et al. (1995). Reprinted by permission of Princeton University Press.

Defects in Photonic Crystals: Localization of Light

A linear defect, in which the field propagates along the direction of the defect and decays exponentially in the transverse direction, can serve as an on-chip optical waveguide with some exceptional properties. More-typically-fabricated on-chip optical waveguides confine optical modes through differential indices of refraction and can display radiation losses—for example, at the bends of curved waveguides. Appropriately designed photonic crystal waveguides are prohibited from radiating into the surrounding bulk material, even for a 90° bend in the waveguide (Meade et al., 1994) (see Figure 2-2).

The first experimental demonstration was carried out for a photonic crystal comprising alumina rods with a lattice constant of 1.27 mm, evidencing 80 percent transmission around a 90° bend (Faraon et al., 2007; Lin et al., 1998; Scherer et al., 2005). Various photonic crystal waveguides have since been fabricated with much smaller lattice constants (<0.4 micrometer [μm]) (e.g., Chutinan et al., 2002), and controlled interactions and light exchange between two or more waveguides are possible (Chong and Rue, 2004; Fan et al., 1998).

The Control of Dispersion and the Slowing and Storage of Light

An interesting and powerful consequence of the structure of the photonic band gap is the dispersion behavior near the band edge and the possibility of group velocities approaching zero. Such slowing of light has been observed in photonic crystal slab waveguides, etched into semiconductor materials (Notomi et al., 2001; Vlasov et al., 2005). The slowing of light and the control of the dispersion properties of the material hold important implications for compact, on-chip processing systems in which controlled delay and storage of optical signals would form important components of any optical-information-processing strategy.

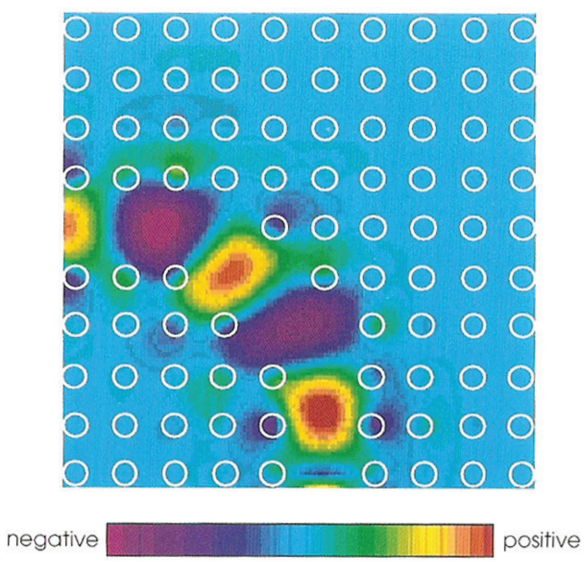

FIGURE 2-2 The field of a transverse-magnetic mode traveling around a sharp bend in a waveguide carved out of a photonic crystal square lattice. SOURCE: Joannopoulos et al. (1995). Reprinted by permission of Princeton University Press.

High-Efficiency Optical Sources

A "point defect" can localize photons, and the early predictions of possible high Q (low optical loss) have proven to be true (Meade et al., 1994). The combination of high Q and low modal volume possible with photonic crystal "defects" or cavities proves an extremely powerful one in producing ultralow-threshold lasers.

Lasing was demonstrated in a quantum well (QW) gain medium in a photonic crystal structure (Painter et al., 1999) at low temperature, and subsequently in a dense quantum dot (QD) medium at room temperature (Yoshie et al., 2002). With lower density, QD and strategic matching of QD emission to photonic crystal cavity modal pattern, lasing has been observed at optical pump powers as low as 10s of nanowatts (nW), coupling to only 2 to 4 QDs (Strauf et al., 2006) (see Figure 2-3). Achieving lasing at such low thresholds is testimony to the control over spontaneous emission that formed the original vision for photonic crystals; numerous recent efforts have separately addressed these issues (Fujita et al., 2005; Lodahl et al., 2004; Ogawa et al., 2004).

By changing the photon states accessible in the material, photonic crystal patterning of optical structures has also been shown to be an effective way of increasing the extraction efficiency of light-emitting diodes (LEDs), ideally converting optical guided modes within the device to extracted modes, with minimal loss. By designing the appropriate photonic crystal pattern for an LED structure, one can achieve efficient optical emission at particular wavelengths and angular directions (David et al., 2006; Oder et al., 2004; Orita et al., 2004; Wierer et al., 2004).

The combination of high Q and low modal volume also makes photonic crystal cavities excellent testbeds for the validation of quantum computation schemes. Quantum dots or other emitters incorporated into the photonic crystal can be weakly or strongly coupled to the cavity: thus, control of the cavity (environment) can result in direct control of the emitters (qubits) within the environment (Badolato et al., 2005; Hennessy et al., 2007).

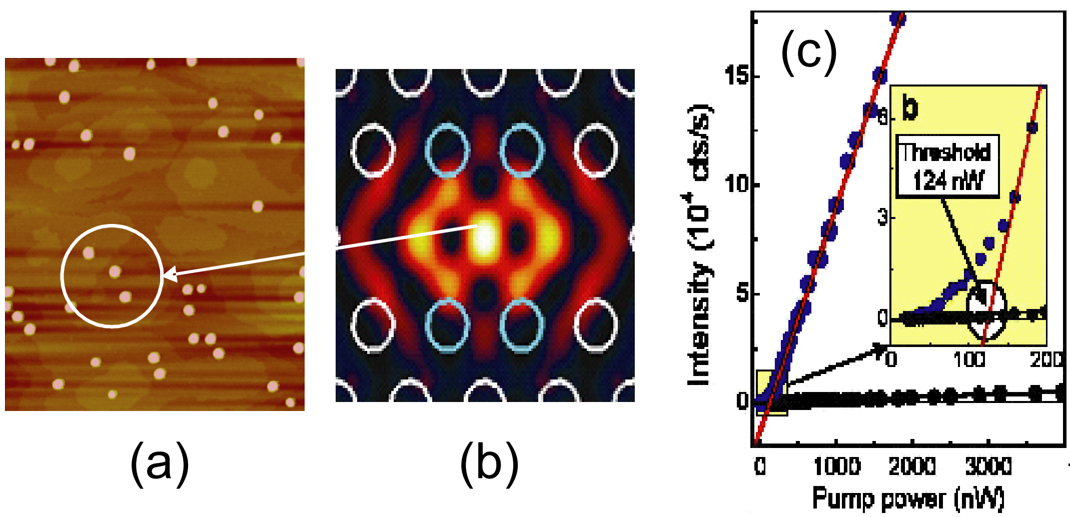

FIGURE 2-3 (a) Atomic force microscope showing ~5 quantum dots/μm$_2$, mapped onto (b) simulation of mode strength in photonic crystal cavity, giving rise to (c) lasing characteristics with ultralow threshold. SOURCES: (a) Evelyn Hu, University of California at Santa Barbara; (b&c) Reprinted with permission from Strauf et al. (2006). Copyright 2006 by the American Physical Society.

Photonic Crystal Waveguides and Fibers

A number of powerful photonic crystal elements currently will allow on-chip, fairly dense integration of optical processing components: waveguides and filters of exceptionally high frequency resolution, the possibility of optical storage and delay through photon localization and control of group velocity, and extremely low threshold optical sources, with narrow spectral outputs that can be sensitively directed in-plane or out of plane. Tuning the band structure of these photonic crystal elements allows photon generation, transmission, and coupling with minimal loss. The majority of the applications described above have been fabricated in a planar geometry, forming two- or three-dimensional photonic crystal device elements on a planar substrate. *Photonic crystal fibers* represent a very powerful technology that applies many of the advantages previously described to the transmission and modulation of light propagating through optical fibers. These structures show a lateral periodic variation in the index of refraction (e.g., inclusion of air holes) along the entire length of the fiber. Examples of the cross sections of photonic crystal fibers are shown in Figure 2-4.

From the initial demonstrations in the 1970s of low-loss (<20 decibels per kilometer [dB/km]) single-mode transmission, optical fiber technology has rapidly developed to become the predominant means of rapid, long-distance, low-loss transmission of optical signals. Conventional optical fibers employ stepped changes in the index of refraction to confine and guide light; the application of photonic crystal concepts allows the following: the engineering of index differences, beyond the choice of the fiber material alone; selective transmission of particular wavelengths; control of the dispersion properties of the

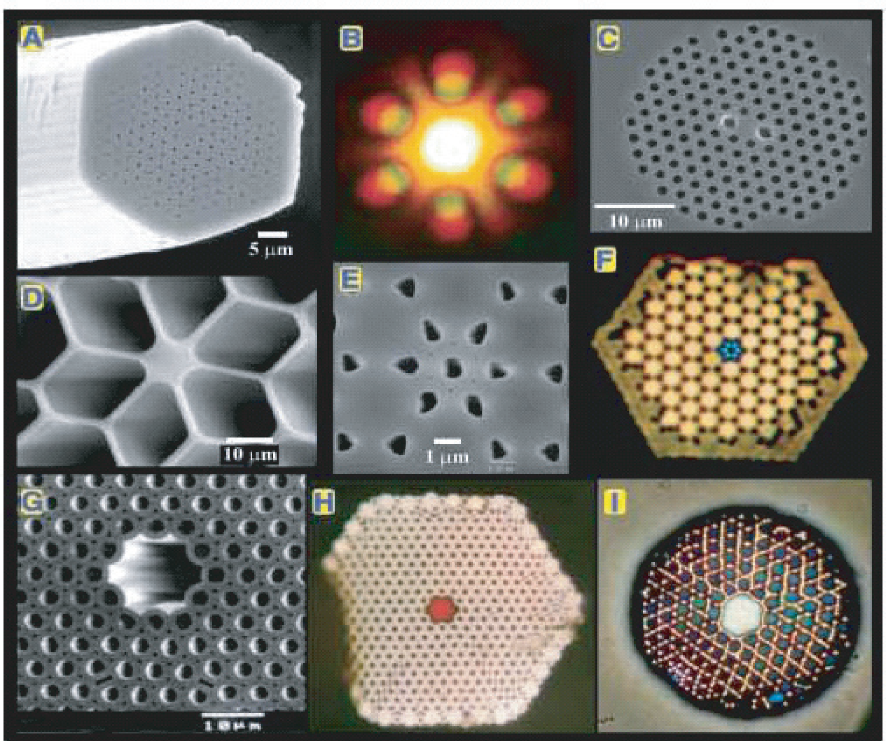

FIGURE 2-4 Various photonic crystal fiber cross sections. SOURCE: Russell (2003). Reprinted with permission of AAAS.

fiber; lower propagation loss; and lower loss from bending of the fiber. Additional optical properties, such as birefringence, can be engineered into the fiber, allowing the preservation of optical polarization information.

Photonic crystal fibers can be formed with "hollow cores," making possible a number of new applications: very high power, ultrashort pulse propagation (Ouzounov et al. 2003), and nonlinear optical processes in gases that fill the hollow core (Knight, 2003; Russell, 2003). The relative ease of formation of photonic crystal fibers, its compatibility with existing optical fiber manufacturing techniques, and a natural scalability to the appropriate nanoscale modulation no doubt have all contributed to the rapid development of photonic crystal fibers between the time that the initial ideas were put forward in the 1990s and the current availability of commercial suppliers of such specialty fibers—for example, Crystal Fibres, Newport Corporation, and Corning International Corporation.

Feasibility and Impact

In a scant 20 years, the visionary predictions of the power of photonic crystal structures to modulate and control light have been dramatically proven to be accurate. Overcoming challenges of high-resolution fabrication, process imperfections, and materials loss, photonic crystal structures have shown the ability to filter and slow light, control spontaneous emission, and enhance optical efficiency. The impact of these structures is profound and wide-ranging, allowing top-down alteration of the fundamental optical properties of the materials that are used as platforms for optical devices and systems. The challenges ahead with respect to photonic crystals lie in the achievement of superior performance of individual devices at reduced or equivalent cost and the ability to realize a major benefit of photonic crystal elements in the integration of multiple devices into high-performance, lightweight, compact systems. Further work will be required to achieve active electrical control and modulation of photonic crystal devices without loss. Much work needs to be done to improve understanding of long-term reliability and packaging issues associated with this technology.

The link between potential benefits, feasibility, and impact of the photonic crystal technology can be demonstrated in the progress of photonic crystal fibers. With photonic crystals as vehicles for light transmission, the incorporation of photonic crystal modulation serves to make an inexpensive, outstanding technology even better, promising lower loss, control over dispersion, the possibility of optimization of transmission and various wavelengths (not just the wavelength determined by the core properties of the fiber), and the implementation of highly sensitive sensing and signal amplification. The benefits of the technology in this case are amplified and catalyzed by the existence of a manufacturable fabrication strategy. Once similar technological challenges are met for planar dielectric photonic crystals, it is expected that their impact on optical information sensing and processing will be further realized.

International Perspective

The field of research in photonic structures has been an international endeavor from its very inception, with substantial efforts taking place within the United States, Europe, Japan, and most recently China and Taiwan. Figure 2-5 illustrates some of the general trends in research as measured by publications. Using the ISI Web of Knowledge and the Science Citation Index, all publications with any of the following topics: photonic band structure, or photonic crystal, or inhibited spontaneous emission, or localization of photons, were identified and separated into the time intervals 1986-1996, 1996-2001, and 2001-2007. The number of publications is plotted according to country or region and by time interval. "Europe" as used here refers to England, Germany, France, and Italy, which are generally the most prolific European countries working in this area of research. The data in Figure 2-5 are intended simply to provide a general picture of the activity in the area of photonic crystal research by country or region and over time. Obvious trends are the accelerating activity in this area (comparing the number of publications in the 10-year period from 1986 through 1995 to the number in the roughly 6-year period from 2001 to the present) and the recent dramatic rise in publication activity in the People's Republic of China.

It would be interesting (but probably more difficult) to similarly monitor the changing patent portfolios in this area.

At present, there are few examples of commercial products based on photonic crystal technology, with the exception of photonic crystal fibers, which are produced by companies in Europe and in the United States (Crystal Fibre in Denmark and Newport in the United States). Commercial opportunities may give rise to photonic crystal technology for enhanced light extraction in LEDs in the nearer term, although increased manufacturing costs and as-yet not fully proven enhancements will prove to be formidable barriers.

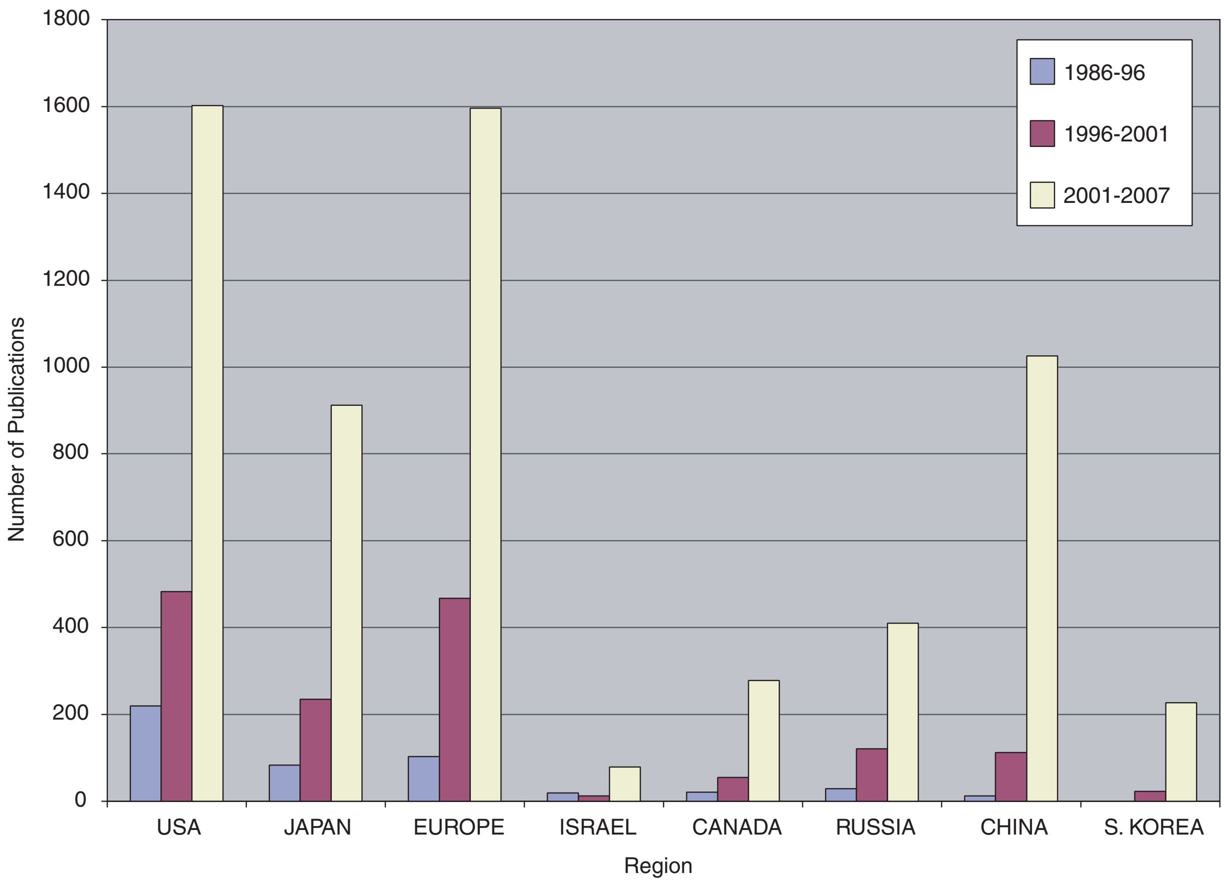

FIGURE 2-5 Analysis of photonic crystal research by country or region between 1986 and 2007, from the ISI Web of Knowledge and the Science Citation Index. NOTE: "Europe" as used here refers to England, Germany, France, and Italy.

METAMATERIALS—SPATIAL INDEX MODULATION AT A SCALE LESS THAN A WAVELENGTH

Electromagnetic radiation exists from below the radio frequency (rf) to x-rays and above. However, this committee takes the field of nanophotonics to apply to the much more restricted range of frequencies spanning the infrared (IR) (~20 terahertz [THz] to 350 THz), the visible, and the ultraviolet (UV) spectral regions. In these regions the scale of the wavelength ranges from tens of micrometers to hundreds of nanometers, and consequently the size of the structures devised to manipulate this radiation is commensurate with developing nanoscale fabrication and integration technologies.

Background

We are accustomed to describing electromagnetic interactions with materials in terms of continuum constitutive relations (electric permittivity, ε; magnetic permeability, μ). Materials, of course, consist of atoms and molecules with a spatial scale much less than the optical wavelength, so these continuum approximations are appropriate. With some important exceptions, the permittivity and permeability are related primarily to the density of the material constituents and are relatively independent of their organization. The emerging field of metamaterials is largely concerned with the fabrication of individual structures, on a scale much less than the wavelength, with localized electromagnetic resonances and their combination into macroscopic materials with novel electromagnetic responses, for which an effective permittivity and permeability are appropriate descriptors.

Nature provides a wealth of materials with a wide range of electromagnetic properties. Dielectric (nonconducting) materials such as oxides exhibit dielectric permittivities (over their respective transparency ranges) from about 2 up to about 3. Semiconductors typically have larger permittivities; from approximately 5 up to about 20. Metals have by far the largest available permittivities, because the free electrons in metals respond to screen an applied electric field; the metal permittivity is negative below the plasma frequency (which is in the UV for most metals) and can be quite large. For example, for gold (Au) at 5 µm, $\varepsilon = -433 + i37$, where the imaginary part is a result of electron-scattering processes in the metal. The metal ε is also quite dispersive, following a Drude model $1/\omega$ dependence across the infrared, with a complex behavior, with more losses, in the visible and ultraviolet as a result of contributions from bound transitions in addition to the free-electron contribution (Shelby et al., 2001).

In contrast to the wide diversity of electrical permittivity, there is no magnetic response (i.e., $\mu = 1$) for all known materials. At lower radio frequncy and microwave frequencies, magnetic materials (ferrites) are available, but they involve collective excitations and therefore have limited frequency response. Over the wavelength range being considered here, there are no naturally occurring magnetic materials.

Therefore, the emphasis of the effort in metamaterials has been to construct materials with a magnetic response. Since there are no magnetic monopoles, the building blocks of magnetic materials are magnetic dipoles (subwavelength current loops). In order to get a large magnetic response at specific frequencies, it is often necessary to provide resonant structures (inductor-capacitor tank circuits). The first of these structures was the split-ring resonator (Pendry et al., 1999). The current state of this research is reviewed in the next subsection.

Status

The field of spatial index modulation began in the late 1990s with the theoretical prediction and the first demonstration of split-ring resonators with a negative permeability in the rf (Pendry et al., 1999; Shelby et al., 2001). The frequency of operation has been steadily increased, first to 1.2 THz and then to the IR (Linden et al., 2004; Yen et al., 2004; Yen et al., 2005). Initially, there was some skepticism that continued scaling from the lower frequencies would be possible because of the extremely small dimensions involved. At higher frequencies, the inductance is dominated by the inertia (mass) of the free electrons, and the geometric loop structure is no longer needed. This advance has led to a dramatic increase in the ability to fabricate metamaterials; a simple metal-dielectric-metal structure with transverse dimensions less than the relevant wavelength provides a simple, manufacturable route to negative-permeability metamaterials. As an aside, this structure is closely related to a gap-mode surface plasma wave, and there is a strong connection between metamaterials and plasmonics (see the section on "Plasmonics" in this chapter).

A major driver of this technology has been the development of negative-index materials (materials with both a negative permittivity and a negative permeability). The negative permittivity is easy to accomplish with metals; the negative permeability is the difficult part. Recently, three experimental groups (two in the United States and one in Germany) have demonstrated negative-index materials using negative-permeability metamaterials (Dolling et al., 2006; Shalaev et al., 2005; Zhang et al., 2005b). The wavelength has rapidly advanced from near infrared (2 μm) to visible (800 nm). At present, the best results have been obtained with a "fishnet" structure in a stacked metal-dielectric-metal film (Chettiar et al., 2006; Ku and Brueck, 2007).

Spatial Index Modulation

Metamaterials: Anisotropy

The classical prescription of Pendry to realize negative-index metamaterials is to construct resonant elements with negative electric susceptibilities ($\chi_E < 0$) and magnetic susceptibilities ($\chi_M < 0$). If the magnitudes of the susceptibilities and the number densities ρ of the elements are sufficiently large, then the electric permittivity $\varepsilon = \varepsilon_0 (1 + \rho_E \chi_E)$ and the magnetic permeability $\mu = \mu_0 (1 + \rho_M \chi_M)$ will both be negative, and a negative refactive index $n = \sqrt{\varepsilon\mu}$ can be realized.

To avoid scattering of radiation, the resonant elements must be much smaller than the wavelength at which the metamaterial is to operate.

Since metals have negative dielectric permittivity at frequencies below the plasma frequency, metallic nanowires can provide negative susceptibility. The depolarizing factors arising from their shape introduce resonances in their response, with the result that their susceptibility is very different—possibly even in sign—for electric fields parallel and perpendicular to their length.

Since all known natural materials have positive magnetic permeabilities, negative magnetic susceptibility can only be realized through a resonant response. Metallic split-ring resonators and similar structures, which function like LC circuits, can give rise to large negative magnetic susceptibility, but only near resonance and only when the magnetic field is perpendicular to the plane of the ring or ring-like planar structure.

Both types of elements are inherently anisotropic; that is, their susceptibility depends on the orientation of the applied fields relative to the elements. Metamaterials consisting of regular lattices of such elements tend to be anisotropic. Anisotropy, which implies polarization dependence, is not desirable, but may be acceptable for some applications. It may be eliminated by incorporating elements with different orientation in the metamaterial, but the orientationally averaged susceptibilities of the elements may be far from ideal, and significant loss in performance may result.

An alternate strategy for high-definition imaging has been proposed; it relies on anisotropy and may overcome the problem of losses (Jacob et al., 2006; Liu et al., 2007). The basic idea is to abandon negative magnetic permeability, with its requirement of operating very near resonance and the high attendant losses. Instead, it is noted that evanescent waves occur when the magnitude of the wave vector carrying image information is greater than $2\pi n / \lambda_O$. If the refractive index n could be made sufficiently large, then arbitrarily high resolution image information could be carried by the wave without the wave vector exceeding the limit of $2\pi n / \lambda_O$ and thus without evanescent decay.

In uniaxial anisotropic media, there are two modes of propagation, with the dispersion relation for the extraordinary mode being

$$\frac{k_\perp^2}{\varepsilon_\parallel} + \frac{k_\parallel^2}{\varepsilon_\perp} = \frac{\omega^2}{c^2}$$

where $k_\perp$and $k_\perp$are components of the wave vector perpendicular and parallel to the optic axis. If one of the principal values of the dielectric tensor is negative, then the magnitude of k, that is, the refractive index n, may be arbitrarily large. Thus, anisotropic metamaterials, consisting of positive and negative dielectric components, such as oriented metallic nanowires in a dielectric host, should be capable of subwavelength imaging with modest losses.

Issues

To date, experimental metamaterials rely predominantly on metallic structures and current flow to produce the negative permeability, and the associated losses are too large to allow many applications. A figure of merit, –Re(n)/Im(n), has been introduced to capture the loss information. Table 2-1 presents the reported results.

Fabrication is another major issue. To date, the demonstrations have all been in thin-film materials with a total thickness (for all three layers) of much less than a wavelength. Recently, a theoretical prediction suggested that a thicker stack of material (up to 10 layers) would have a lower loss and a dramatically improved figure of merit (Zhang et al., 2005c). No experiments have yet been reported. This is still a thin film, and it does not seem likely that the current approach will yield bulk materials, both because of the excessive losses and because of the difficulty of extending thin-film approaches to macroscopic scales. Two different fabrication techniques have been used to date: electronic-beam direct write and interferometric lithography (Dolling et al., 2006; Shalaev et al., 2005; Zhang et al., 2005a; 2005b). Direct write is a serial technology that is not scalable to large volumes of material. Interferometric lithography, as a simpler version of traditional optical lithography, is a large-area technique that is directly scalable to manufacturing volumes. Additional discussion of fabrication approaches is presented in Chapter 3.

TABLE 2-1 Reported Metamaterials Experiments in the Near Infrared Spectral Region

Material	Structure	λ (μm)	Figure of Merit [–Re(n)/Im(n)]	Reference
Au/Al_2O_3/Au	Two-dimensional perforated films (symmetric)	2.0	0.5	Zhang et al. (2005b)
Au	Metal line pairs	1.5	0.1	Shalaev et al. (2005)
Au/Al_2O_3/Au	Two-dimensional perforated films (asymmetric)	2.0	1.0	Zhang et al. (2006a)
Ag/MgF_2/Ag	Two-dimensional perforated films (asymmetric fishnet)	1.4	3.0	Dolling et al. (2006)

An exciting new direction is the introduction of active materials (gain) and the integration of these negative-index materials with semiconductor and other gain media. The challenges are large as a result of the short range of the interactions and the nonradiative losses introduced by the close proximity of the gain media to the metal films.

Impact

New and improved optical materials have always led to advances in optical systems. Currently, the first tentative steps at realizing these materials are under way. As always, the materials are too difficult to work with and too lossy to realize the benefits. However, these are very early days in this process, and it is clear on the basis of analogies with other major advances in optical characteristics that there will be many new capabilities associated with these hitherto-unavailable characteristics. Some promising directions include nonlinear optics, subwavelength cavities and field concentration for both sources and detectors, imaging at scales much less than a wavelength, negative dispersion and dispersion compensation, and many others. These are discussed at length in later chapters in this report.

To date, most of the work on metamaterials has focused on the fabrication and demonstration of homogeneous materials. Recently, the Duke group demonstrated an inhomogenous metamaterial lens by systematically varying the structure of the metamaterial elements (Driscoll et al., 2006). Because the lens is fabricated with only few metamaterial layers, it is much more lightweight than traditional approaches. In another set of experiments, the same group has demonstrated the "cloaking" of electromagnetic radiation by arranging an inhomogenous array of metamaterial elements in concentric rings around an object (Schurig et al., 2006). These experiments point to exciting new directions for metamaterials and confirm the hypothesis stated above—new materials lead to new functionality and to new applications.

The enhancement associated with subwavelength apertures will be of particular importance in mid- and long-wave infrared applications such as focal plane arrays. Room-temperature IR detectors are either very noisy as a result of large thermal dark currents in narrow band-gap semiconductor materials or very slow as in microelectromechanical systems (MEMS)-based microbolometers because of the thermal response of the isolated materials. In both cases, plasmonic antenna concepts offer revolutionary new capabilities. The dark current scales with the detector area and the noise scales as the square root of the area; thus, the figure of merit is the relative signal for a small detector versus a large-area detector divided by the square root of the area ratio. For microbolometers, the speed scales directly as the area (capacitance and thermal time constant) of the small elements. Box 2-1 and Box 2-2 provide examples of optical system advances made possible by improved optical materials.

PLASMONICS

Plasmonics is a subfield of nanophotonics concerned primarily with the manipulation of light at the nanoscale, based on the properties of surface plasmons. *Plasmons* are the collective oscillations of the electron gas in a metal or a semiconductor. Rigorously, the plasmon is the quasi-particle resulting from the quantization of plasma oscillations, a hybrid of the electron plasma and the photon. Although plasmons are quantum mechanical in nature, their properties, most specifically with respect to the coupling of light to plasmon oscillations, can be described rigorously by classical electrodynamics. *Surface plasmons* (SPs) are the electromagnetic waves that propagate along metallic/dielectric interfaces; they can exist at any interface, and for any frequency region, where the complex dielectric constants of the media constituting the interface are of opposite sign and the sum of the dielectric constants are negative. SPs are supported by structures at all length scales. They largely determine the optical proper-

BOX 2-1
Prospects of Far-Field Imaging with the Superlens

One of the most compelling aspects of nanophotonics is the possibility of high-resolution imaging, as illustrated in Figure 2-1-1.

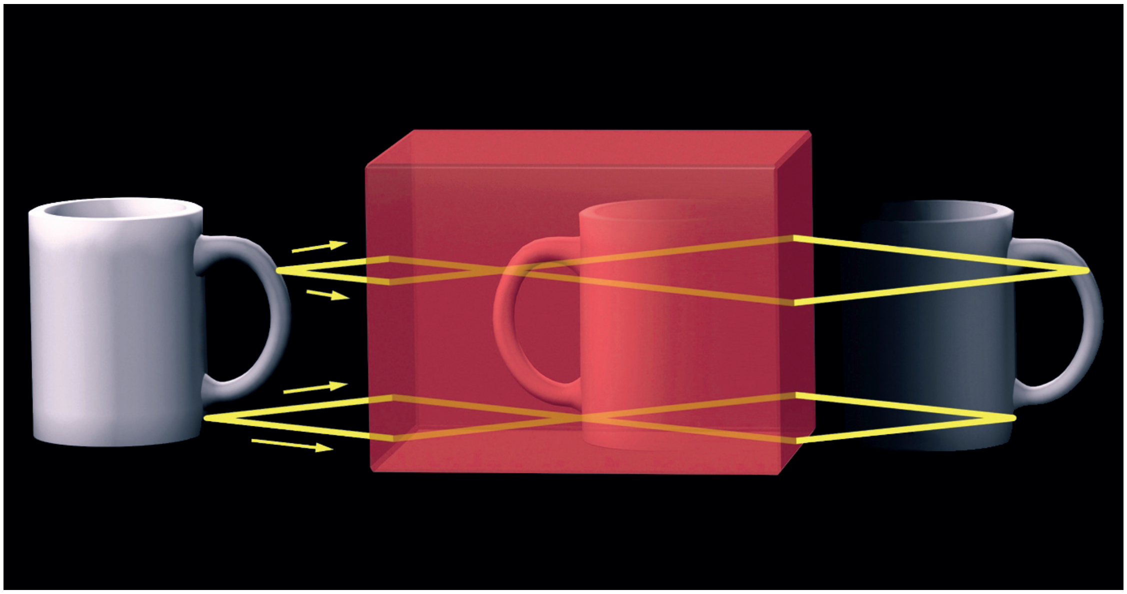

FIGURE 2-1-1 The superlens. SOURCE: Reproduced with permission of Melissa Thomas.

The superlens, proposed by Pendry, relies on the negative refractive index that can be realized using metamaterials. The possibility of subwavelength resolution has captured the popular imagination, as well as the attention of device developers. There are two fundamental challenges, how-

ties of metal-based nanostructures. In fact, the first quantitative theoretical success of electromagnetic theory was the explanation of the preferential absorbance of green light by gold nanoparticles, imparting an intense red color to the material (glass) in which they are embedded, known historically as ruby glass. The field of plasmonics is based on utilizing SPs for a large variety of tasks by designing and manipulating the geometry of metallic structures and consequently their specific plasmon-resonant or plasmon-propagating properties. While many metals support SPs, gold and silver have thus far dominated experimental work in this area.

Within this rapidly developing and highly multidisciplinary field, several key research directions have been established. These range from the propagation of signals and information on metal-based waveguides, to enhanced sensing and spectroscopies for the chemical identification and detection of ever, to realizing superlenses capable of high-resolution far-field imaging: loss and impedance matching. These challenges pose critical obstacles to practical device development.

For a metamaterial slab, imaging as shown in Figure 2-1-1, the image distance + object distance are equal to the slab thickness (L). The use of a macroscopic object in Figure 2-1-1, the coffee cup, suggests that this structure will work for $L >> \lambda$; as it turns out, this is a misperception. Losses in metamaterials are characterized by the figure of merit, $FOM \equiv -\text{Re}(n)/\text{Im}(n)$, and the attenuation factor for light traversing the slab is $e^{-4\pi L/\lambda FOM}$. The highest-performance optical metamaterials today are those with fishnet structure (Dolling et al., 2006) with FOM ~3; hence, even for a slab with a thickness equal to the wavelength, more than 98 percent of the light is absorbed. For imaging objects more than a few wavelengths away from the slab, the attenuation is absolutely prohibitive.

Another formidable problem is that of impedance matching. Any mismatch between the impedance of the host (usually air) and the impedance of the metamaterial (e.g., η and $\eta + \delta$) gives a limit on the spatial bandwidth (Smith et al., 2003). The maximum resolution enhancement $R = \lambda / \lambda_{min}$ of the lens is $R = -\frac{\lambda}{2\pi L}\ln\left(\frac{\delta}{\eta}\right)$, where L is the thickness of the slab. For a slab of thickness equal to the wavelength, a resolution enhancement of $R = 2$ requires that $\delta < 3.5 \times 10^{-6}$!—and since the scaling is exponential, for a slab of thickness 2λ, the requirement is that $\delta < 10^{-11}$!! Since negative-index materials are inherently dispersive, the range of frequencies for which this condition can be satisfied becomes vanishingly small, along with the prospects for transmitted information content. In contrast, for a slab of thickness $\lambda/10$, the constraint is only $\delta < 0.28$. The same constraints hold in the case of losses; that is, where δ is imaginary. This indicates that, with materials comparable to the best-performing materials achieved to date, subwavelength resolution is only possible for thin ($L < \lambda$) slabs and in the near field, at distances from the slab comparable to λ. For far-field imaging, which requires large phase shifts and large slab thicknesses of $L >> \lambda$, the constraints on impedance matching with practical finite bandwidth sources such as typical lasers are unachievable.

Finding 2-1. The committee finds that, in spite of their enormous appeal, beyond the diffraction limit, near-"perfect" slab lenses, which image in the far field, do not appear to be feasible, barring some unforeseen breakthrough.

biomolecules or biological agents, to near-field optics and scanning microscopies employing metallic probe tips, to enhanced absorption and fluorescence processes in solid-state detectors and devices, to molecular systems, active plasmonic devices, and biomedical applications. Fabrication methods in plasmonics include both top-down and bottom-up strategies using clean-room and chemical techniques, also spawning novel hybrid fabrication approaches that combine both wet and dry fabrication techniques. Quantitative and computationally intensive electromagnetic modeling has assumed a dominant and increasingly important role in this field, employing fully numerical methods such as finite element, boundary element, and finite difference-time domain approaches; analytical or semianalytical methods such as plasmon hybridization and discrete dipole approximation; and lumped circuit concepts for the design of complex plasmonic systems.

BOX 2-2
A Cloak of Invisibility

Metamaterials provide new ranges of optical properties, permittivity (ε) and permeability (μ), that can be combined in almost arbitrary configurations using emerging fabrication capabilities. Much attention has been paid to the negative refractive index ($n = \pm\sqrt{\varepsilon\mu}$) that arises when both ε and μ are negative, and to the consequences of this negative *n* for traditional optical elements such as prisms and lenses (see Box 2-1). Metamaterials offer degrees of freedom in optical design that are not possible with naturally occurring materials. Many of these are combined in the concept of optical cloaking, shown by a ray-tracing analysis in Figure 2-2-1, that was first introduced by Pendry et al. (2006).

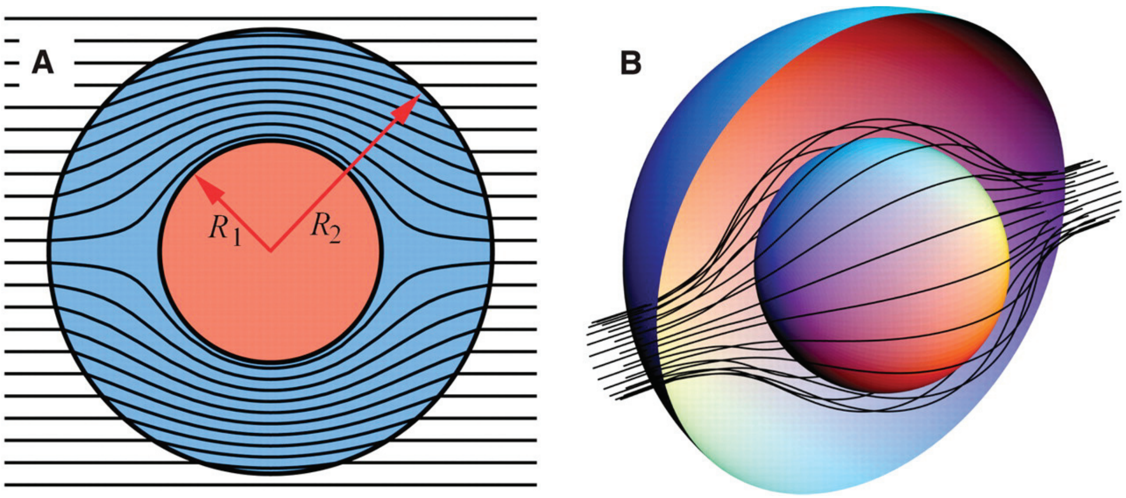

FIGURE 2-2-1 (A) Ray-tracing of a cloak extending from radius R_1 to radius R_2 around a spherical object, (B) showing the light bending around the cloaked region (radius $<R_1$) without penetration of the object and exiting from the cloak as if both the object and the cloak did not exist. SOURCE: Pendry et al. (2006). Reprinted with permission from AAAS.

Localized Surface Plasmon Resonance Sensing

The excitation of conduction electrons by light is denoted as a *surface plasmon resonance* (SPR) for planar surfaces or *localized surface plasmon resonance* (LSPR) for nanometer-sized metallic structures.[1] The plasmon-resonant frequency is determined by the dielectric properties of the metal, and specifically for nanoscale metallic structures by the size, shape, and local environment of the nanostructure.

[1]In Appendix D, "Selected Research Groups in Plasmonics," see the section entitled "Localized Surface Plasmon Resonance Sensing" for brief descriptions of the work of researchers in this field who have developed most of the concepts discussed in this section.

The cloak is based on a systematic variation of the optical properties (ε and μ) of the metamaterial in order to deflect the radiation around the object while at the same time eliminating reflections from the outer surface of the cloak. That is, at the outer edge of the cloak, the metamaterial impedance is matched to air; internal to the cloak, the electromagnetic waves are bent around the object. The spatial variation of the optical properties that gives rise to this functionality is (Pendry et al., 2006).

$$R_1 < r < R_2$$

$$\varepsilon_r = \mu_r = \frac{R_2}{R_2 - R_1}\frac{(r - R_1)^2}{r}$$

$$\varepsilon_\theta = \mu_\theta = \varepsilon_\phi = \mu_\phi = \frac{R_2}{R_2 - R_1}$$

$$r > R_2$$

$$\bar{\bar{\varepsilon}} = \bar{\bar{\mu}} = 1$$

Note that since $\bar{\bar{\varepsilon}}$ and $\bar{\bar{\mu}}$ are equal everywhere, the impedance is unity everywhere, and there are no reflections at any of the boundaries. At the inner boundary of the cloak, both ε_r and μ_r go to zero. This requirement of having components with the optical properties <1 is characteristic of the cloak, since the path length around the object is physically longer than the path length through the space occupied by the object, requiring a phase velocity greater than that in the space. Causality then requires that the cloak be dispersive, setting a bandwidth constraint on the cloaking that may pose an issue for practical applications.

In a first experiment, Schurig et al. (2006) demonstrated a cylindrical cloak using split-ring resonators with a somewhat modified variation of the optical parameters ($0.003 < \mu_r < 0.28$) and showed good agreement with the model. Since cloaking does not depend as critically on the resonant conditions as the perfect lens does, it appears to be more tolerant of small deviations from the ideal conditions (Cummer et al., 2006).

Metamaterials offer a much wider range of optical properties than those available from natural materials. Scientists have always been able to exploit new materials to provide new functionality. It would seem that the present case is no exception and that many exciting applications of metamaterials have yet to emerge.

Plasmon-resonance-based chemical sensing can be accomplished in a variety of ways. Historically, surface plasmon propagation (SPP) on functionalized continuous metal films was exploited. Modifications in the chemical environment due to the binding of molecules to the functionalized film can be monitored as changes in the angle of incidence required for SP excitation in an evanescent coupling geometry. More recently, metal nanostructures and nanopatterned surfaces have also been used as nanoscale SPR sensors, both in solution and immobilized on surfaces. In SPR spectroscopy, the wavelength shift of the plasmon resonance is monitored while the refractive index of the medium surrounding the metal is changed. These LSPR shifts, usually reported in eV/RIU (shift in photon energy per change in refractive index unit), help quantify their applicability as biological and chemical LSPR sensors. Another

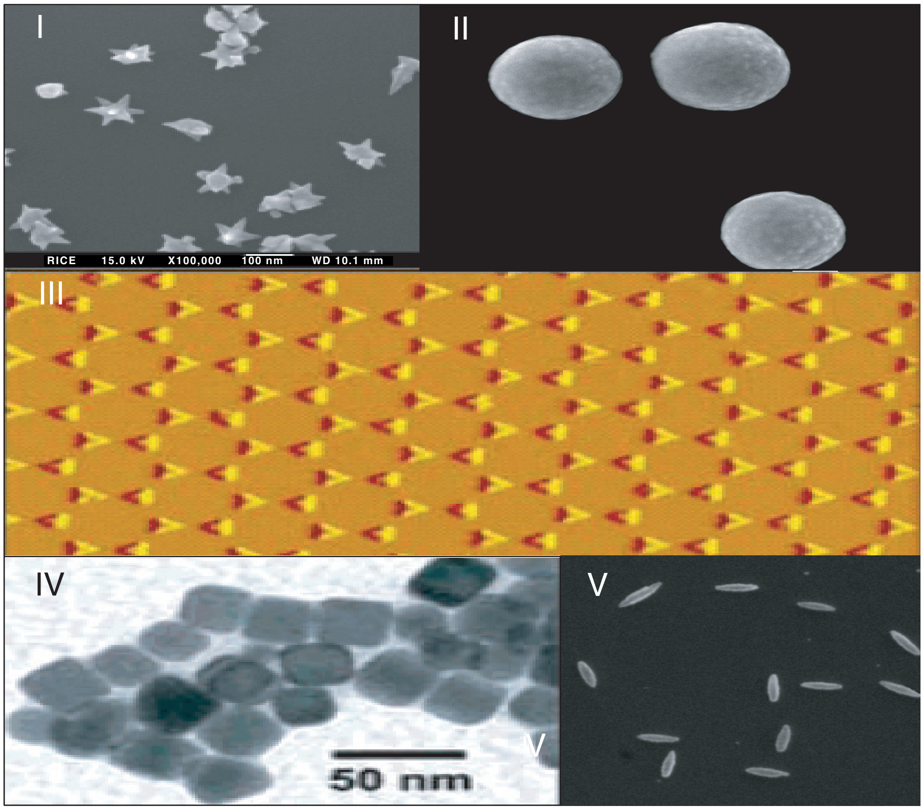

FIGURE 2-6 Various nanoparticles used in localized surface plasmon resonance sensing applications: (I) Gold nanostars (Hafner group, Rice University), Copyright 2006 American Chemical Society; (II) Silica-gold nanoshells (Halas group, Rice University) Permission from Rice University; (III) Atomic force microscopy image of silver triangles using nanosphere lithography (Van Duyne group, Northwestern University)reprinted with permission from the *Annual Review of Physical Chemistry*, Copyright 2007; (IV) Nanocube particles (Xia group, University of Washington, and Van Duyne group, Northwestern University) Copyright 2006 American Chemical Society; (V) Nanorice nanoparticles (Halas group, Rice University) Copyright 2006 American Chemical Society. In Appendix D, see the section "Localized Surface Plasmon Resonance" for information on the research groups named. SOURCES: Reprinted with permission from Nehl et al. (2006); Willets and Van Duyne (2007); Sherry et al. (2005); Wang et al. (2006b).

dimensionless figure-of-merit criterion for this sensing application is the ratio of the LSPR shift to the linewidth of the plasmon resonance (see Figure 2-6).[2]

The recent interest in the field can be attributed to large LSPR shifts reported for a variety of nanostructures such as silver and gold colloid, silver triangles deposited using nanosphere lithography (patterning using self-assembled arrays of microparticles as a shadow mask for metal deposition), (Hulteen and Van Duyne, 1995) gold nanoshells, (Tam et al., 2004) nanostars, (Nehl et al., 2006) nanorice, (Wang et al., 2006b), and so on. The high sensitivity has also led to real-time sensitive detection of binding

[2]Ibid.

TABLE 2-2 Various Nanoparticles Used for Localized Surface Plasmon Resonance Sensing

Table 1. LSPR properties reported for several gold and silver nanostructures.

Author	Particle	Single/ ensemble	Resonance		Linewidth		Shift/RIU		FOM
			nm	eV	nm	meV	nm	meV	
Tam (2004)	Au/SiO_2 shell	Ensemble	770	1.61	350	732	314	657	0.9
Sun (2002)	Au/AuS shell	Ensemble	700	1.77	400	1012	409	1035	1.0
Wang (2006)	Au nanorice	Ensemble	1600	0.775	600	291	801	388	1.3
Underwood (1994)	Au sphere	Ensemble	530	2.34	060	265	090	397	1.5
Raschke (2004)	Au/AuS shell	Single	660	1.88	077	220	117	333	1.5
Sherry (2005)	Ag cube	Single	510	2.43	091	433	146	695	1.6
Malinsky (2001)	Ag triangle	Ensemble	564	2.20	104	405	191	745	1.8
Nehl (2006)	Au star	Single	675	1.84	125	340	238	649	1.9
Mock (2003)	Ag sphere	Single	520	2.38	073	335	160	734	2.2
MacFarland (2003)	Ag particle	Single	585	2.12	49	178	203	736	4.1
Mock (2003)	Ag triangle	Single	760	1.63	080	172	350	751	4.4
Nehl (2006)	Au star	Single	770	1.61	124	260	665	1410	5.4
Sherry (2005)	Ag cube-sub	Single	430	2.88	022	146	118	792	5.4

To compare the figures of merit, results are only shown for reports that provide either the resonance linewidth or LSPR spectrum.
FOM: Figure of merit; LSPR: Localized surface plasmon resonance; meV: Millielectron volt; RIU: Refractive index unit.

SOURCE: Reproduced, with permission from Future Medicine Ltd., from Liao et al. (2006).

events studied using LSPR spectroscopy. LSPR spectroscopy is used for biological and chemical sensing by transducing changes in the local refractive index via a wavelength-shift measurement. Table 2-2 (Liao et al., 2006) lists various nanoparticles used for LSPR sensing.

Surface-Enhanced Spectroscopy

When an electromagnetic wave interacts with a roughened metallic surface or a metallic nanoparticle film, the electromagnetic (EM) fields in the vicinity of the surface or nanoparticle are greatly enhanced as compared to the incident EM field. This phenomenon has been attributed to the excitation of SPs at the metallic interface. This enhanced field has been exploited to enhance various vibrational and electronic spectroscopic signatures of molecules adsorbed onto the metallic surfaces or that are in close proximity to the surface, and is collectively known as *surface-enhanced spectroscopy* (SES).[3] The best studied of these is surface-enhanced Raman spectroscopy (SERS). Surface-enhanced spectroscopy also includes surface-enhanced fluorescence (SEF), surface-enhanced infrared absorption spectroscopy (SEIRA), and other surface-enhanced nonlinear optical spectroscopies such as surface-enhanced second harmonic generation and surface-enhanced sum frequency generation (see Figure 2-7).

[3]In Appendix D, "Selected Research Groups in Plasmonics," see the section entitled "Surface-Enhanced Spectroscopy."

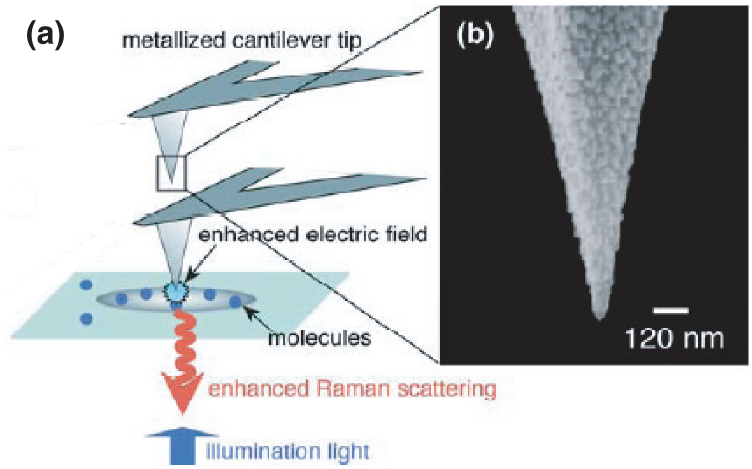

FIGURE 2-7 (a) Schematic representation of tip-enhanced Raman spectroscopy (TERS). (b) A silicon cantilever is coated with a 40 nm layer of silver and used for TERS. SOURCE: Adapted with permission from Hayazawa et al. (2003). Copyright Elsevier, Chemical Physics Letters, 2003.

Surface-Enhanced Raman Spectroscopy (SERS)

The field of surface-enhanced Raman spectroscopy was pioneered by the Van Duyne group at Northwestern University (Jeanmaire and Duyne, 1977) and Creighton at the University of Kent (Albrecht and Creighton, 1977) when they discovered that the Raman signal from molecules attached to roughened silver electrodes demonstrates a large enhancement of the Raman scattered intensity. Enhancement factors of 10^6-fold intensity have been observed over normal Raman scattering. This large enhancement is understood to be the product of two major contributions: (1) an EM enhancement mechanism and (2) a chemical enhancement mechanism (CHEM).

Since the original discovery, aggregated gold and silver nanoparticles have been used as efficient nanoantennas to focus the incident light and enhance the EM fields in the vicinity of the nanoparticles. Enhancement factors of up to 10^{14} in SERS signal of dye molecules, attained using aggregated metal nanoparticles, have led to single-molecule detection using SERS (Kneipp et al., 1997; Nie and Emory, 1997).

For the observation of SERS, a strong correlation has been observed between the SERS excitation and the SPR maximum (Jackson and Halas, 2004; McFarland et al., 2005). Individual silver and gold colloid particles exhibit strong plasmon resonances in the visible parts of the spectrum. Aggregated colloid particles have been shown to have plasmon resonances that are redshifted and lead to localized areas of intense local fields, or "hot spots." These localized hot spots give rise to the high enhancement factors that make single-molecule detection possible. In addition to aggregated colloid, many groups have developed robust substrates for SERS. A variety of shapes and geometries have been explored as SERS substrates, including metal island films (Jennings et al., 1984), large silver and gold colloid (Michaels et al., 2000), silver triangle arrays (Haynes and Van Duyne, 2003), silver and gold nanoshells (Jackson and Halas, 2004), and fractal silver films (Drachev et al., 2004). In addition to the experimental development of optimal SERS substrate, there has been a parallel effort to understand the physical mechanism behind SERS.

The SERS substrates made with gold and silver colloid produced large enhancement factors in small localized areas, but the heterogeneity of the hot spots makes quantitative measurements unreliable. For the past few years there has been great emphasis on rationally designing substrate geometries to achieve large enhancement factors. In many applications, where single-molecule detection is not required, substrates are being designed to optimize between the enhancement factors and are achieving a dense coverage of the adsorbate molecules to be detected. Simultaneously, the development of scanning spectroscopic techniques with subwavelength resolution allows a very small area to be imaged on any substrate.

SERS is rapidly maturing as a spectroscopic tool. This has led to application of SERS in many directions, most notably for the detection of chemical and biological molecules. Some of these applications are discussed in greater detail in later sections in this chapter.

Surface-Enhanced Infrared Absorption (SEIRA)

Molecules adsorbed on metal island films or metallic nanoparticles exhibit 10 to 1,000 times more intense infrared absorption than would be expected from conventional measurements without the metal. This effect is referred to as surface-enhanced infrared absorption. The enhanced field due to the SPRs supported by the metal plays predominant roles in enhancing the absorption of light by the attached molecules (Chang et al., 2006). The chemical interactions of the molecules with the surface can give additional enhancement (Huo et al., 2005). SEIRA is a complementary spectroscopic technique to SERS. SEIRA is being used as a molecule-specific technique for qualitative and quantitative chemical sensing and catalysis research (Ayato et al., 2006).

Surface-Enhanced Fluorescence (SEF)

Fluorescence is the emission of photons as a molecule relaxes from an excited electronic state to the ground state. The presence of a vicinal metallic nanostructure to a fluorophore strongly influences both the radiative and nonradiative decay of the fluorophore and its lifetime. The influence on the radiative rate, nonradiative decay rate, and lifetime of the fluorophore also depends on the distance between the metallic surface and the fluorophore. This discovery has led to the radiative decay engineering of SEF (Lakowicz et al. 2002), which offers new ways to increase the intensity of low-quantum-yield fluorophores and to improve the stability of fluorophores that can easily photobleach. Most of the applications of SEF have been in improving the fluorescence intensity of amino acids, oligonucleotides, and dye molecules used in imaging biological samples.

Techniques for Imaging and Spectroscopy of Plasmonic Structures

The development of advanced plasmonic devices is inseparable from the development of techniques to probe the properties of such devices. Applications of plasmonics range from macroscopic applications in thermal signature management and SPR sensing of biological and chemical agents; to microscopic studies of SERS, surface-enhanced fluorescence, and far-field microspectroscopy of isolated single nanostructures; to nanoscale probing of the detailed propagation of plasmons on micro- and nanostructures using near-field optical microscopy. Major techniques for the imaging and spectroscopy of plasmonic structures,[4] in order from macro to nano, include macroscopic absorbance spectroscopy, dark-field

[4]In Appendix D, “Selected Research Groups in Plasmonics,” see the section entitled “Techniques for Imaging and Spectroscopy of Plasmonic Structures.”

microcroscopy and microspectroscopy, confocal microscopy, photothermal microspectroscopy, near-field optical microscopy, two-photon induced photoemission microscopy, and cathodoluminescence, as shown in Figures 2-8 through 2-10. The development of imaging and spectroscopy techniques is also critical for the development of sensors based on SPs, as some method of reading out the information from the sensor is required.

Macroscopic absorbance spectroscopy employs a grating monochromator and an incoherent light source (quartz-tungsten-halogen, deuterium, and arc lamps are typically used) to measure the transmission of structures containing plasmon-resonant nanostructures. This technique is applied to studying the properties of nanoparticles produced in bulk (i.e., with wet chemistry), large-area substrates for surface-enhanced spectroscopy, and as readout in LSPR sensing (see Figure 2-11).

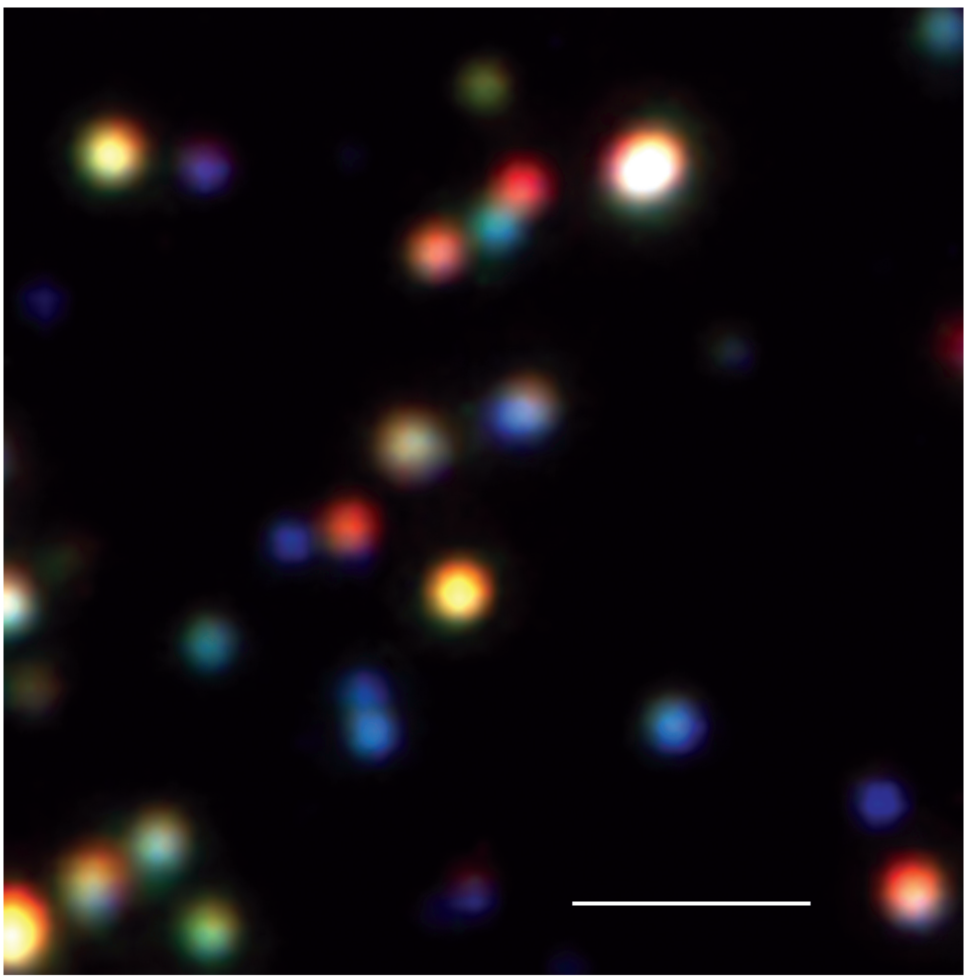

FIGURE 2-8 Dark-field microscopic image of a mixture of silver particles with a variety of shapes. NOTE: The particles appear to be different colors due to the dependence of the plasmon resonance wavelength on particle geometry. SOURCE: Orendorff et al. (2006). Copyright 2006 Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

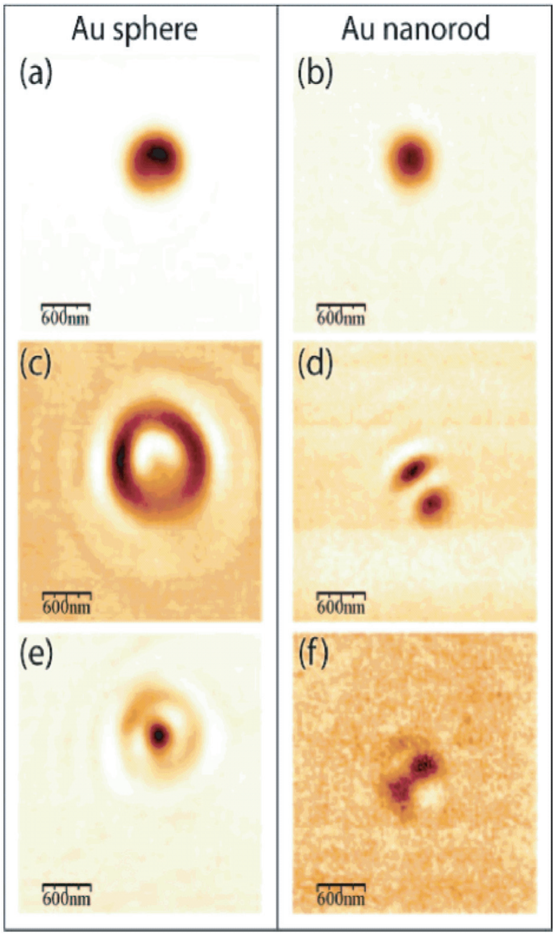

FIGURE 2-9 Illustration of the scattered light from gold nanoparticles using different Gaussian modes for excitation to determine particle orientation. Images on the left show scattering from a spherical Au nanoparticle and on the right, an Au nanorod. Three different types of excitation beam are employed: (a) and (b) use a linearly polarized Gaussian beam; (c) and (d) use an azimuthally polarized doughnut mode; (e) and (f) employ a radially polarized doughnut mode. The nonspherical nature of the nanorod can clearly be seen in (d) and (f). SOURCE: Reprinted with permission from Failla et al. (2006). Copyright 2006 American Chemical Society.

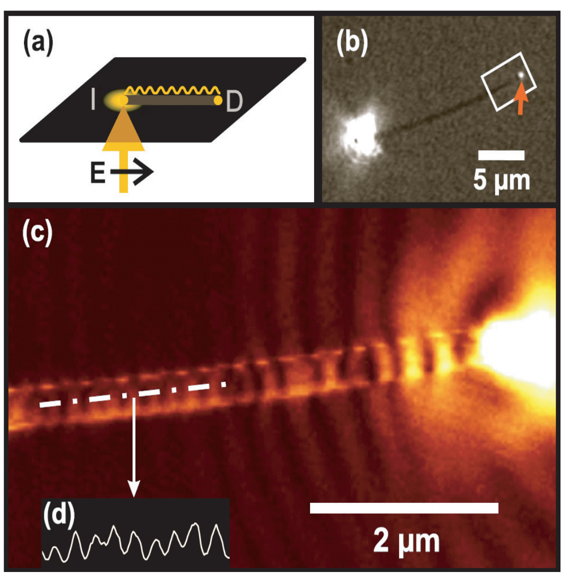

FIGURE 2-10 Photon scanning tunneling microscope (PSTM) image showing the propagation of light along a metal nanowire. The wire acts as a resonant cavity, and the resulting nodes are visible in the PSTM image. (a) Illustration of the scheme employed to excite the wire, (b) far-field microscopic image of the wire—the right spot on the left is the excitation light and the emitted light from the end of the wire is indicated with an arrow; (c) PSTM image of the end portion of the wire; (d) the standing wave pattern seen along the length of the wire. SOURCE: Reprinted with permission from Ditlbacher et al. (2005). Copyright 2005 by the American Physical Society.

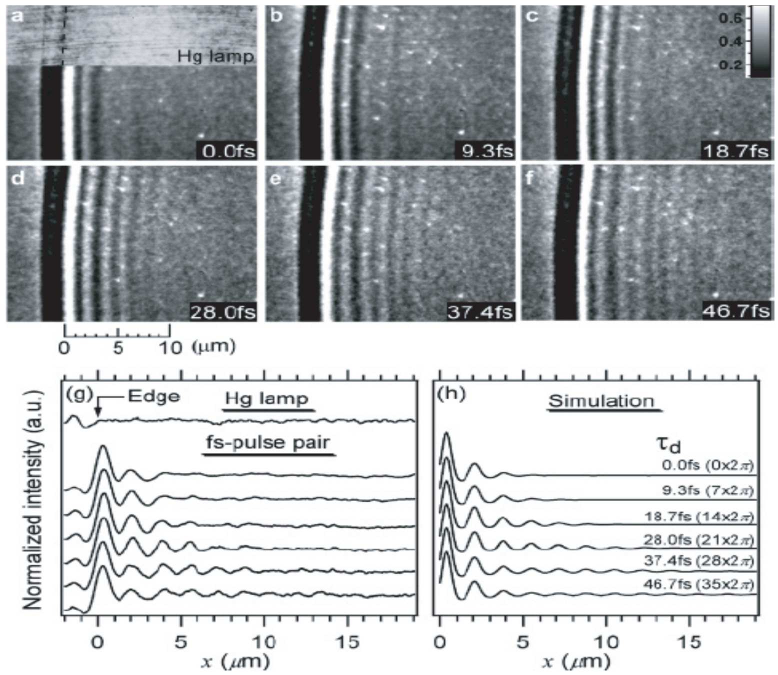

FIGURE 2-11 Plasmon propagation on a silver film measured using time-resolved photoelectron emission microscopy (PEEM). Upper portion of (a): Topography of the sample where the groove used to excite surface plasmons is clearly visible; (a) through (f): Images of the plasmon propagation at increasing delay times: (g): Experimental propagation of the plasmon wave measured from the images in (a) through (f); (h): Results from a simulation of the plasmon propagation. SOURCE: Reprinted with permission from Kubo et al. (2007). Copyright 2007 American Chemical Society.

Dark-field microscopy allows the background-free observation of scattering from plasmon-resonant nanoparticles or nanoholes. The sample is illuminated with light at high numerical aperture (large angles), and only the light scattered at smaller angles is collected. Direct reflection off the surface will occur at equal angles to the incident light and therefore will not be collected. Only light that is scattered by the particles into the objective will be captured. The scattered light can then be coupled into a spectrometer, allowing the scattering spectra of single nanostructures to be measured. The downside to this technique is that, unlike the case with near-field approaches, the diffraction limit applies, and therefore objects must be spaced at least on the order of a micron apart. Determining the geometry of the particles measured on subwavelength scale can still be achieved by using an indexed substrate and another microscopy technique such as scanning electron micrographs (SEMs) to image the nanostructure. Despite its downside, this technique has been quite successfully employed to study the scattering properties of the plasmon resonance of small Au and silver (Ag) nanospheres, nanorods, holes in thin metallic films, and Au nanoshells. Further, this technique has been applied to study SPR shifts of single nanostructures and may ultimately allow the observation of single-molecule binding events (Ditlbacher et al., 2005; Nehl et al., 2004; Sönnichsen et al., 2002).

Confocal microscopy has recently been demonstrated in the Meixner group at Eberhard-Karls-Universitat Tubingen, Germany, to be usable for determining the orientation of nonspherical metallic nanoparticles. This is of importance, as previously either electron microscopy or topographic imaging with an atomic force microscope or near-field scanning optical microscope (NSOM) tip was required to determine the orientation (Failla et al., 2006). In a related technique called spatial modulation spectroscopy (SMS), by dithering the sample position and employing a coherent supercontinuum source for illumination, it is also possible to obtain directly the absorbance spectrum of small nanoparticles (Muskens et al., 2006). Confocal microscopy is also frequently employed for surface-enhanced Raman spectroscopy (see the subsection above entitled "Surface-Enhanced Spectroscopy").

Photothermal heterodyne imaging allows for the measurement of the absorbance spectrum of very small particles using far-field excitation. In this technique, a laser resonant with the plasmon resonance of the nanoparticle is used to heat the particle, which in turn heats up the surrounding medium. Due to the temperature dependence of the index of refraction of the medium, a process called thermal lensing, a second laser beam is scattered off of the larger "particle" formed by the changed refractive index. Essentially, this process results in converting the problem of measuring the absorbance of a very tiny particle to one of measuring the scattering of a much larger particle. This process has been used to measure the size-dependent plasmon resonance of Au nanospheres as small as 1.5 nm in diameter (Berciaud et al., 2004, 2005). Using this technique, the plasmon resonance of these tiny particles can be clearly seen in biological samples, enabling their use as a contrast agent free of blinking of photobleaching effects that plague fluorescence from molecules or quantum dots (Lasne et al., 2006).

SPs on smooth films cannot be excited directly with light, owing to the mismatch in momentum. One classic solution to this problem is to use a prism on the bottom side of the film to excite a plasmon on the top surface of a film (the Kretschmann geometry). In this way the photon wave vector can be increased by a factor of the index of refraction of the prism material and thereby matched to a propagating SP polariton mode of the metal film-air interface. This same effect occurs in reverse when metal films on a dielectric substrate are used as a SP waveguide. While usually this would be a detrimental effect to the performance of the waveguide, it can also be used to observe the propagation of SPs in a technique called surface leakage radiation microscopy (Drezet et al., 2007).

Due to its recent commercialization, NSOM is rapidly becoming the tool of choice for the routine study of the optical properties of nanoplasmonic structures and devices such as plasmonic waveguides. Currently the two main vendors of near-field optical microscopes are Nanonics Imaging, Ltd., in Israel (bent tapered fiber tip) and the German firm WITec (microfabricated cantilever probes).

The basic point of near-field imaging is to create or capture light with larger wave vectors than are allowed to propagate in free space. The resolution that can be obtained in optical imaging is essentially limited by the range of wave vectors that can be employed in the measurement of an image. This measurement can be accomplished by using a small aperture or scattering particles either to confine light to a small spatial volume or to collect light from a small region.

NSOM can be broadly separated into two main categories: apertured and apertureless techniques. The latter technique relies on scanning a nanoscale scattering object, usually a metalized atomic force microscope tip or small metal particle, over a surface illuminated from the far field with a highly focused laser beam. The scattered light is then collected and analyzed. This technique is used for tip-enhanced spectroscopy, such as TERS, because the plasmon excited in the tip creates a large, highly localized near field at the end of the tip. Such a tip can also be used to scatter evanescent waves, such as those from propagating plasmons on surfaces or waveguides, into the far field to be detected (Huber et al., 2005).

Apertured NSOM relies on the confinement of light by a small hole in a metalized tip. Tips can either be made by tapering a standard optical fiber to a fine point and metallizing the outside to define an aperture or by microfabrication of a cantilever with a triangular point that is metallized on the outside to form an aperture. While the resolution obtained with apertured NSOM can approach 10 nm, typically 100 nm apertures are employed as a reasonable trade-off between decreased spatial resolution and increased signal relative to smaller tips (Hecht et al., 2000). Owing to relative experimental ease, the illumination mode is the more common variation of apertured NSOM. For experiments involving waveguides or active structures, collection-mode NSOM or photon scanning tunneling microscopy (PSTM) is the technique of choice, as either of these allows the field extending from the plasmon propagating along a waveguide or device to be imaged directly.

Two-photon photoelectron emission microscopy (PEEM) imaging can be used for ultrafast-phase resolved imaging of surface plasmon propagation. This recently developed technique is very promising for the study of SPP, as it can directly resolve the propagation of plasmons in time and space to extract not only the decay length, but also the relative phase of the plasmon mode. By using phase-locked pairs of 10 femtosecond (fs) ultrafast pulses in a pump-probe experiment with +/– 25 as delay resolution, and collecting the resulting two-photon photoemission, the propagation of surface plasmon polariton wave packets can be measured with 60 nm spatial and 10 fs temporal resolution (Kubo et al., 2007). The experimental complexity of such an apparatus means that this will remain a specialized technique; it is nonetheless important, as it is currently the ultimate measuring tool for SPP.

In cathodoluminescence spectroscopy, an electron beam is used to directly excite plasmons in a metallic nanostructure. While light can only efficiently excite dipole-active plasmon modes, electrons are far less restricted. For example, an electron beam can directly excite plasmons in a metal film. Very high resolution can be obtained using this technique, because the electron beam creates a point source of SPs on the order of the beam diameter, potentially allowing structures to be studied on sub-10 nm scales. This technique was recently demonstrated by measuring the length of SPP on Au and Ag films (van Wijngaarden et al., 2006); it can potentially can be used to study plasmonic waveguides directly where direct excitation from the far field is cumbersome owing to the low resolution obtainable with such a technique.

Extraordinary Transmission, Subwavelength Holes

In 1998 Thomas W. Ebbesen and his colleagues published some remarkable results concerning how much light is transmitted through an array of holes having a diameter smaller than the wavelength of light (Ebbesen et al., 1998). They found that at certain wavelengths of incident light, such an array of holes is quite transparent, yet it had long been predicted by Hans Bethe that the light transmitted through a single subwavelength hole should be negligible (Bethe, 1944). However, not only was the transmission greater than the theoretical predictions, but in fact the amount of light transmitted was about twice as much as was incident on the total surface area occupied by the holes. Ebbesen et al. (1998) suggested that SP polaritons, or charge-density waves propagating on a metal surface, were responsible for the extraordinary transmission. See Figure 2-12, which shows various NSOM images. A laser illuminates the bottom side of the Au film while the NSOM tip is scanned over the top side. Interference between the light transmitted through the film and the surface plasmons generated on the top surface by the presence of the hole creates fringe patterns characteristic of the propagating surface plasmon wavelength. This experiment concentrated on the demonstration of the coupling between a normal-incident optical beam and surface plasmons provided by a subwavelength hole. Although the interhole spacing was deliberately too large for efficient coupling into a resonant surface plasmon mode, an eight-fold enhanced transmission compared to a bare film was observed, and the images provide direct evidence of the excitation of SPs in a nanohole array system (Gao et al., 2006). These images confirm the pres-

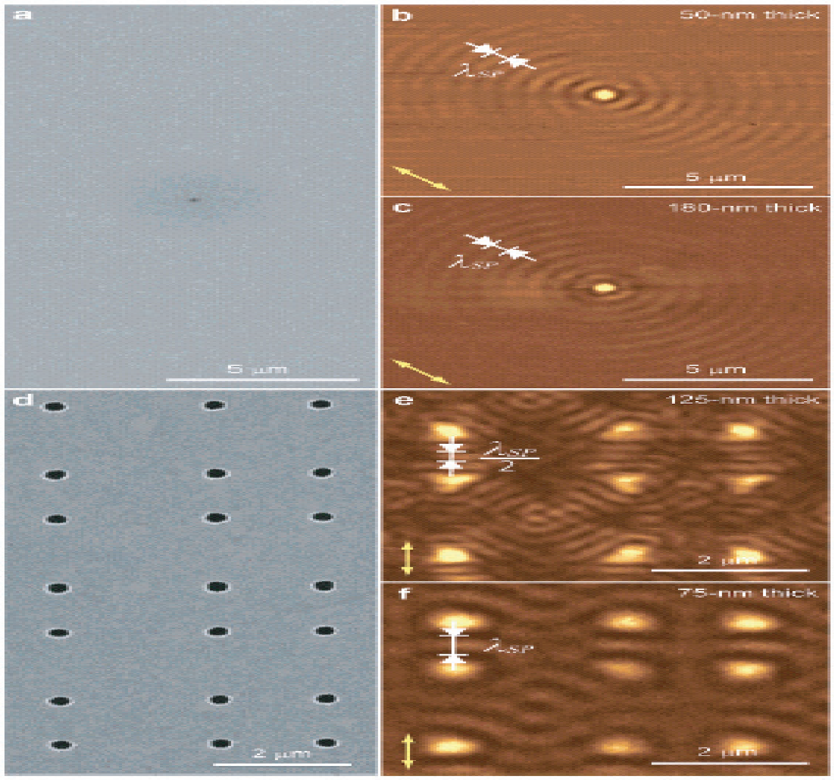

FIGURE 2-12 Scanning electron micrographs of a single nanometric hole in a gold film (a) and of a nanohole array (d), and near-field scanning optical micrographs of a single nanohole (b, c) and of nanohole arrays (e, f). SOURCE: Reprinted with permission from Gao et al. (2006). Copyright 2006 American Chemical Society.

ence of SPs in the nanohole array system and provide direct evidence for their role in the extraordinary transmission phenomenon.[5]

Some controversy has accompanied the assertion that surface plasmons are responsible for the extraordinary transmission effect. Papers published subsequent to Ebbesen (1998) presented results confirming the SP model (Ghaemi et al., 1998; Martín-Moreno et al., 2001). Some studies, however, countered this view. For example, Treacy (1999) suggested that ordinary diffraction effects might play a major role in the extraordinary transmission. Phillippe Lalanne's group then argued that their models indicated that SPs should actually suppress the extraordinary transmission effect and thus could not be the cause of it (Cao and Lalanne, 2002).

Despite these differences, the majority opinion was that SPs indeed were the dominant effect in the extraordinary transmission model. However, in a 2004 publication (Lezec and Thio, 2004), two of the authors of the original 1998 paper in *Nature* changed their stance on this issue. They showed experimental results of extraordinary transmission through nonmetallic films, and since only metals can support SPs, they argued that the SPs were not responsible for the extraordinary transmission. They further proposed a new

[5]In Appendix D, "Selected Research Groups in Plasmonics," see the section entitled "Extraordinary Transmission, Subwavelength Holes."

model based on what they called composite diffracted evanescent waves (CDEWs), and they showed that their model agrees with experimental data. This model has been received with skepticism, however, and Philippe Lalanne's group has offered results showing that the CDEW model may not be sufficient to explain extraordinary transmission, and that SPs are still the likely candidate (Lalanne and Hugonin, 2006).

Figure 2-13 shows a scanning electron micrograph of two regions of small dimples in a silver film arranged in square arrays. Some of the dimples were milled completely through the silver film to make holes in a pattern forming the letters "hν." Due to the extraordinary transmission phenomenon, the holes permit light of a color determined by the array's period (center-to-center hole or dimple spacing) to be transmitted through the silver film when white light is shone on the back of the film. The array containing the "h" has a period of 550 nm, allowing red light to be transmitted, while the array containing the "ν" has a spacing of 450 nm, allowing only green light to be transmitted (pictured in the inset). This demonstrates the ability to tune the wavelength of the transmitted light and suggests great potential for optical filtering applications.

Regardless of which theory best explains the extraordinary optical transmission phenomenon, subwavelength holes and subwavelength-hole arrays have many practical applications. First, because the wavelength of the transmitted light in a hole array is dependent on the period (or interhole spacing), hole arrays can serve as optical filters in which the allowed transmission can be tuned by changing the hole spacing (Genet and Ebbesen, 2007).

Arrays of holes also offer potential for display devices. In 1999, Tineke Thio's group (Arinna, LLC) showed that the wavelength and intensity of transmission through hole arrays could be changed electooptically by immersing the hole array in a liquid crystal matrix and varying the applied voltage (Kim et al., 1999). This structure simultaneously combines the functionality of the crossed polarizers, the

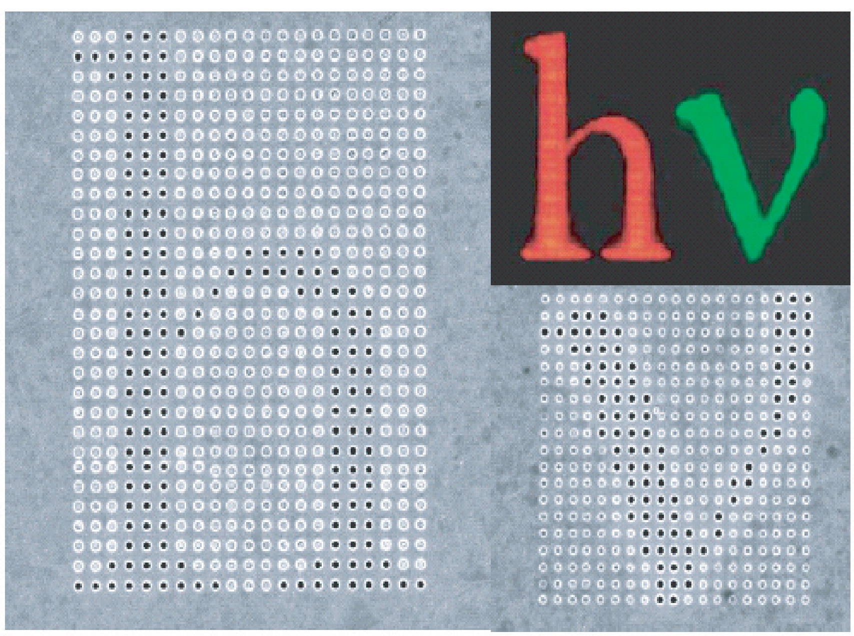

FIGURE 2-13 Scanning electron micrograph of two regions of small dimples in a silver film arranged in square arrays. SOURCE: Reprinted by permission from Genet and Ebbesen (2007). Copyright 2007 by Macmillan Publishers Ltd.

liquid-crystal modulator, and the color filters in traditional liquid-crystal displays, offering the potential of enhanced efficiency and simpler manufacturing.

Hole arrays also offer promise in the realization of all-optical switching components. Thomas W. Ebbesen's group (Institut de Science d'Ingeniere Supramoleculaire, Universite Louis Pasteur, Strasbourg, France) has recently performed experiments which show that putting molecules inside of the hole arrays allows for terahertz-speed all-optical switching of the refractive index (Dintinger et al., 2006). Optical components such as these are essential for the realization of useful optical circuits.

Recently, attention has turned to alternatives to simple hole arrays. C-apertures have been investigated by the Stanford University group of Hesselink, and annular (coaxial) apertures have been shown to provide significantly improved transmission, particularly on high-index substrates (Fan et al., 2005). Another exciting direction is the incorporation of nonlinear materials inside the aperture. Coupled with the large fields associated with the plasmonics, very large second-harmonic signals, comparable to those generated in much longer conventional nonlinear media such as lithium niobate, have been observed (Fan et al., 2006). Nonlinear plasmonics holds potential for dramatically extending the domain of optical nonlinearities and possibly eliminating the need for extended phase matching, making the equivalent of radio-frequency mixers available throughout the optical spectrum.

Plasmonic Waveguides and Other Electromagnetic Transport Geometries

On-chip optical data transfer could greatly enhance computation. However, in order for this technology to be feasible, light must be confined and routed in dimensions smaller than its own wavelength to allow for sufficient miniaturization of chips employing this technology. To date, SP waveguides exhibit relatively high losses, and these losses become worse as the wavelength is decreased to the near infrared (NIR) and visible—the important wavelengths for the application to on-chip communications. Nonetheless, this is a very active area of research because of the importance of the application, and innovations are being introduced at a rapid pace. Several geometries of plasmon waveguides exist, as discussed in the following subsections.[6]

Metal Stripe Waveguides

One possible geometry of plasmon waveguides is a long, thin metal stripe. In 2000, Pierre Berini's group (School of Information Technology and Engineering, University of Ottawa, Canada) first demonstrated long-distance plasmon propagation in such a geometry (Charbonneau et al., 2000). While a very large propagation length (3.5 mm) was achieved at a wavelength of 1.55 μm, the width of the metal stripe was 8 μm wide, which is not subwavelength confinement. However, early experiments indicated that subwavelength confinement and propagation on such structures may be possible. For example, Franz Aussenegg's group was able to get propagation over several micrometers in a wire that was 200 nm wide (Krenn et al., 2002). This group also showed that the propagation lengths depended heavily on the width of the metal stripes (Lamprecht et al., 2001), as demonstrated in Figure 2-14.

Mark Brongersma's group (Geballe Laboratory for Advanced Materials, Stanford University) constructed a model explaining the dependence of the propagation length on the width of the metal stripe (Zia et al., 2005) and pointing out the differences between leaky SP modes and bound guided modes as well as the difficulty involved in distinguishing between the two. In Zia et al. (2005), the group predicted

[6]In Appendix D, "Selected Research Groups in Plasmonics," see the section entitled "Plasmonic Waveguides and Other Electromagnetic Transport Geometrics."

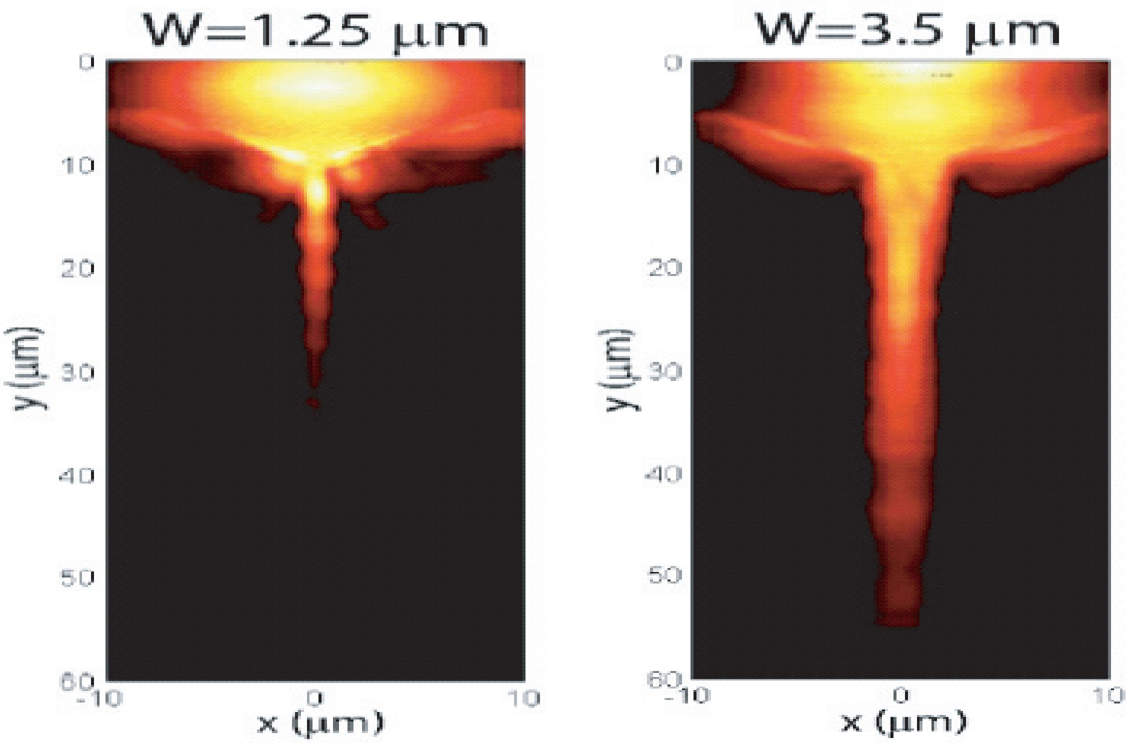

FIGURE 2-14 Near-field micrograph of plasmon propagation down a metallic stripe waveguide. (Left) Width of stripe: 1.25 µm. (Right) Width of stripe: 3.5 µm. Light is launched down the waveguide from an illumination source below the structure and photon scanning tunneling microscopy images the plasmon propagating down the stripe. These images demonstrate that the distance which the light propagates down the stripe is dependent on the stripe's width. For a wider stripe, a longer propagation length can be achieved. SOURCE: Reprinted with permission from Zia et al. (2006). Copyright 2006 by the American Physical Society.

that at a certain width of metal stripe, no guided wave modes can exist. In a subsequent, detailed experimental study (Zia et al., 2006), the group was able to show that indeed, as the metal stripe waveguide becomes narrower, one can predict the finite number of guided modes and the stripe width at which each mode will be cut off. Zia et al. (2006) found that at a certain stripe width, no more guided modes exist, and that propagation on the stripe is thus very limited. These findings suggest that while the metal stripe waveguide can support long propagation lengths for large stripe widths, it is not useful for the purpose of subwavelength confinement.

Metal Nanowire Waveguides

In 2000, Robert Dickson's group at the Georgia Institute of Technology reported observing plasmon propagation down very long, chemically prepared silver and gold nanorods where the transverse dimension of the rods is less than 100 nm and the longitudinal dimension is ~4 µm. The group was able to couple light in with a diffraction-limited laser spot on one end of the rod and to observe the other end of the rod light up, proving that plasmons were in fact propagated along the rod (Dickson and Lyon, 2000).

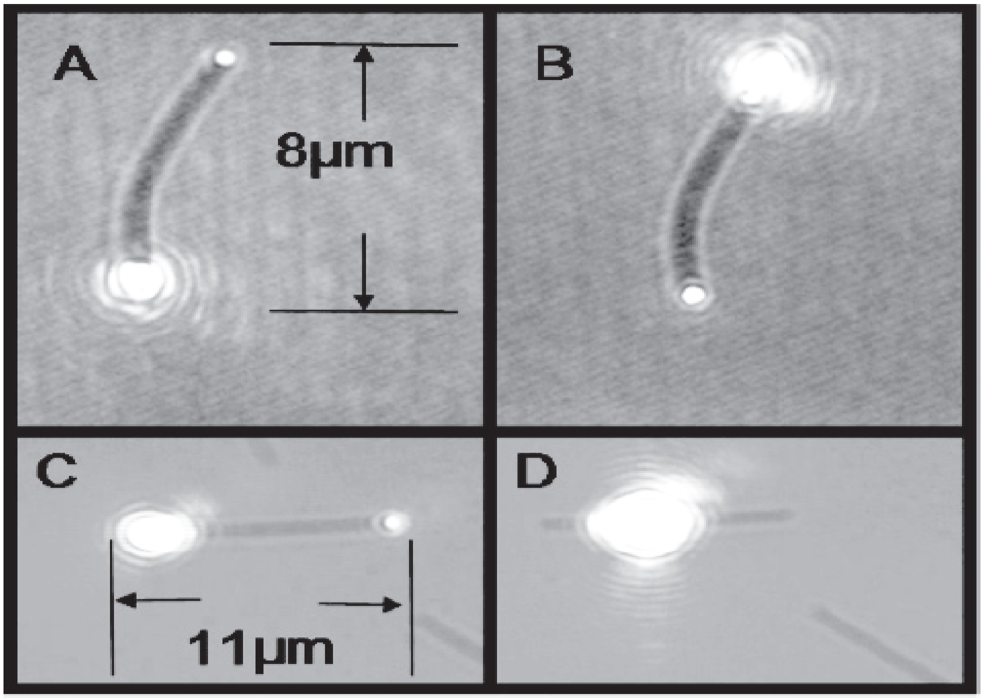

FIGURE 2-15 Micrographs showing propagation of light down silver nanowires. (A) A laser is focused to a diffraction-limited spot and positioned at the bottom of the end of a silver nanowire. Light is then propagated down the wire via the SP and coupled out of the nanowire at the top end. This demonstrates that a metal nanowire is an effective plasmonic waveguide. (B) The nanowire is the same as in A, but the light is coupled into the top end of the wire and out of the bottom end, illustrating that light can be propagated in either direction. (C) A silver wire is used; light is coupled into the left end. (D) The wire is the same as in (C), but now the laser is focused onto the center of the wire. Here, a plasmon is not excited, and thus light is not guided down the wire. SOURCE: Reprinted with permission from Sanders et al. (2006). Copyright 2006 American Chemical Society.

Graff et al. (2005) also saw this in 2005. This group had actual silver wires that were 25 nm wide and ~50 μm long. They used a similar method of coupling the light into the wire, but embedded the wire in a fluorescent matrix. Light propagated down the wire excited the fluorophore, allowing the researchers to observe that the plasmon was propagating for about 15 μm down the wire (see Figure 2-15).

Recently, Mark Reed's group also performed experiments showing the propagation of SPs down silver nanowires (Sanders et al., 2006). However, this group was also able to observe that plasmons are coupled back into free space at sharp bends in the wire and at places where the wire branches into multiple paths. They also observed that at such bends in the wire, the plasmon continues to propagate down both paths of the wire, suggesting an optical splitting component.

Nanoparticle Chain Waveguides

The idea of using chains of nanoparticles as plasmonic waveguides for optics was first proposed by Franz Aussenegg's group in 1998 (Quinten et al., 1998). Since then, Harry Atwater's research group

(Thomas J. Watson Laboratory of Applied Physics, California Institute of Technology) has extensively studied this system. This group has found that metal nanoparticles arranged in linear chains coupled to each another via the optical near field when light was incident on them (Maier et al., 2002a) and proceeded to characterize the utility of these structures as waveguides (Maier et al., 2002b). Because each of these studies relied on far-field techniques, the entire nanoparticle chain had to be illuminated at the same time, which disallowed the direct observation of optical energy transport from one end of the chain to the other (see Figure 2-16). However, in 2003, Atwater's group presented results that employed a near-field scanning optical microscope to excite plasmons on one end of the nanoparticle chain and observe that plasmons propagated down the chain transporting energy, thereby proving the waveguiding abilities of such structures (Maier et al., 2003).

Stephen Mann's group has demonstrated the capability of making highly anisotropic branched chains of nanoparticles via a wet chemistry technique and has observed plasmonic mode coupling in the chains (Lin et al., 2005). This technique of fabricating nanoparticle chains could be far surperior to conventional top-down approaches such as electron-beam lithography. The group of Marcus Dantus has done a similar study in which waveguiding via plasmons was observed in a dendritic silver nanoparticle mesh. The group was able to control the direction of the propagation using polarization and was able to observe propagation distances of up to 100 microns (Gunn et al., 2006).

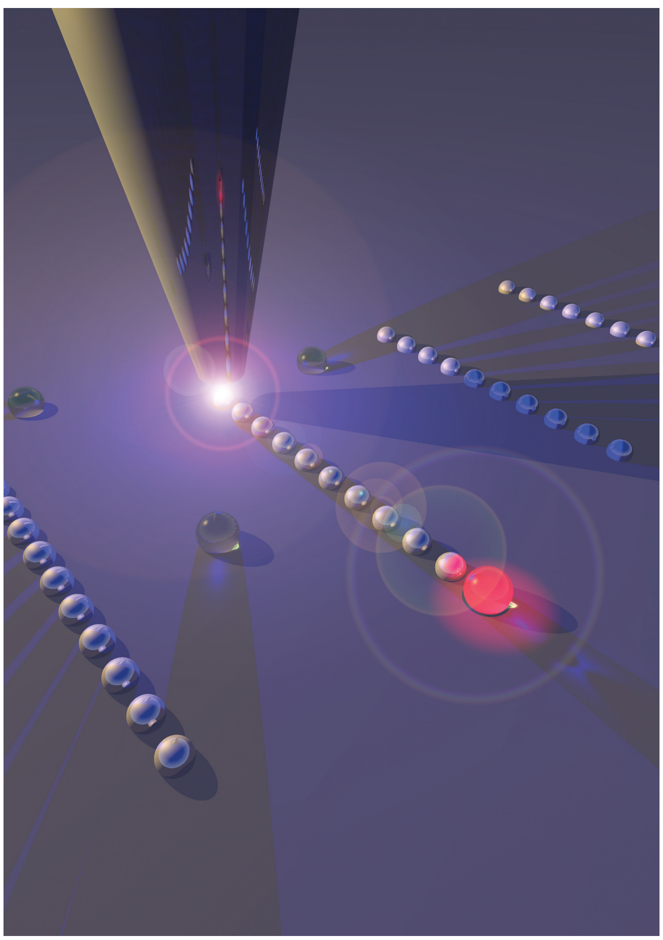

FIGURE 2-16 Schematic representation of a nanoparticle chain plasmonic waveguide. The schematic shows a tip of a near-field scanning optical microscope coupling light into a nanoparticle at the far end of a linear chain of nanoparticles. Light is then propagated down the nanoparticle waveguide via near-field coupling between plasmon resonances in each successive nanoparticle. Light is then coupled out of the waveguide by the last particle in the chain. SOURCE: Stefan Maier, 2008, with permission.

Metal-Insulator-Metal Waveguides

Recently, the waveguide geometry consisting of an insulator with a metal cladding has gained increased interest. Theoretical studies first suggested that these metal-insulator-metal (MIM) structures offer superior subwavelength confinement for plasmon waveguides. Mark Brongersma's group theoretically compared insulator-metal-insulator (IMI) and MIM waveguiding structures. The group concluded that by the MIM structures had far superior ability to confine the plasmon modes into subwavelength sizes (Zia et al., 2004). Harry Atwater's group then extended the study of MIMs by theoretically studying them using realistic optical properties of metals. This group focused specifically on planar-multilayered MIM systems and found that such structures could support both plasmonic modes and photonic modes (normal propagating electromagnetic modes) (Dionne et al., 2006a). The group then fabricated and studied these structures experimentally (Dionne et al., 2006b). In this study the researchers fabricated $Ag/Si_3N_4/Ag$ layered MIM structures and characterized their waveguiding properties. They were able to couple light into and out of these structures using slit openings in the metal. They were able to observe broadband propagation of electromagnetic energy over distances of several micrometers. They were also able to observe that these structures support both the plasmonic and photonic modes as they had previously predicted.

Channel Plasmon Polaritons

The history of channel plasmon polaritons (CPP) is briefly reviewed by Francisco J. García-Vidal (2006) in a *Nature* news brief. In 1990, the group of Alexei. A. Maradudin theoretically predicted that guided electrostatic modes would exist in a V-shaped groove in a metal film (Lu and Maradudin, 1990). In 2002, the group revisited the problem, extending Maradudin's theory past the electrostatic limit to include propagating electromagnetic modes bound inside such a groove, dubbing them "channel polaritons" (Novikov and Maradudin, 2002). Figure 2-17 demonstrates that channel plasmons can propagate effectively over long distances and can propagate around sharp bends. The waveguide-ring (WR) resonator structure can be used to control the wavelength that is allowed to propagate along the waveguide.

Soon after this work, D.K. Gramotnev and D.F.P. Pile began to study channel plasmon polaritons using the Finite-Difference-Time-Domain (FDTD) numerical method. In 2004, they modeled the propagating modes and discussed the properties of CPP and also suggested that CPP seems to experience less dissipation over long propagation distances than other plasmonic waveguide structures do (Pile and Gramotnev, 2004). Next, they predicted that CPP should undergo nearly no dissipation at sharp bends in the V-groove (Pile and Gramotnev, 2005).

In 2005, Sergey I. Bozhevolnyi's group (Aalborg University, Denmark) first demonstrated experimentally that the earlier theoretical studies were correct (Bozhevolnyi et al., 2005). This work involved measuring the propagation distance that could be achieved in such a waveguide structure by using an NSOM to image the electromagnetic near-field as it propagates down the channel groove. They observed propagation lengths of ~100 μm at wavelengths of 1,425 nm to 1,620 nm, similar to typical telecommunications wavelengths. While this study only included straight-line propagation, in 2006 this same group demonstrated that the V-groove waveguide could, as predicted, support remarkably low loss at sharp bends in the channel's path (Bozhevolnyi et al., 2006). The group also reported the achievement of making several on-chip optical components from this structure, such as a Y-splitter, an interferometer, and a ring resonator. The further characterization and optimization of this waveguiding system remain an active area of study.

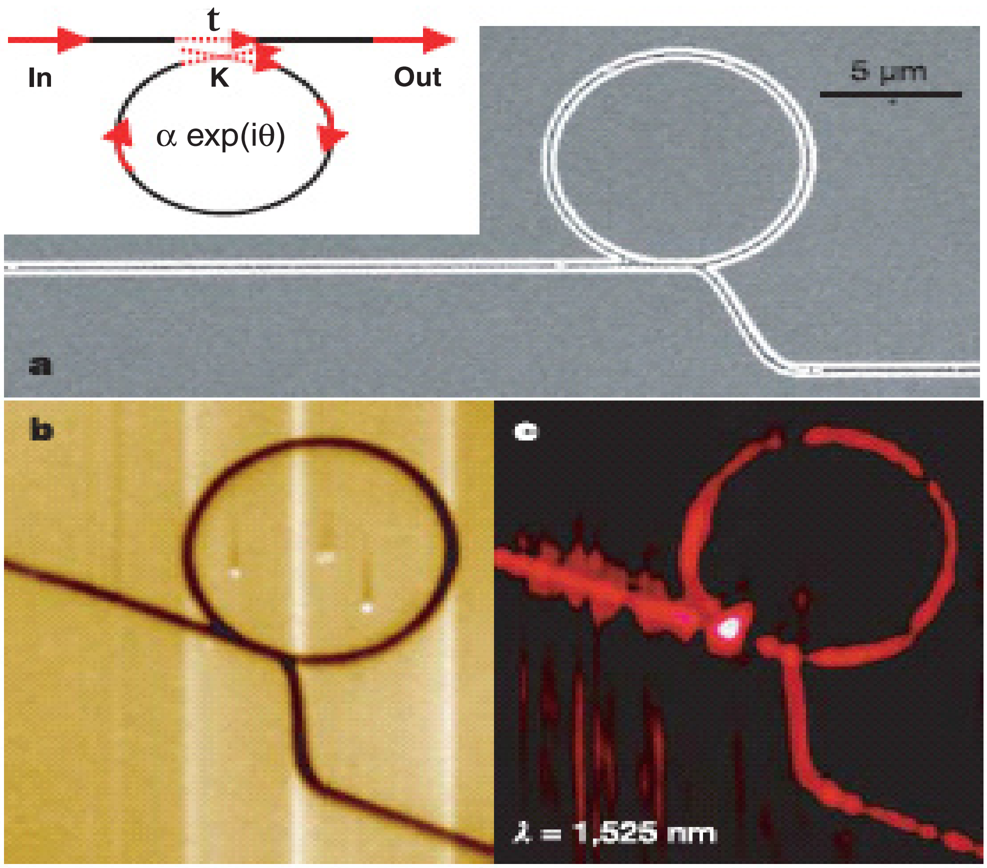

FIGURE 2-17 A plasmonic waveguide ring (WR) resonator. (a) Scanning electron micrograph of WR resonator structure. (b) Topographical image of the same structure. (c) Near-field scanning electron micrograph of the WR resonator showing light of wavelength 1,525 nm propagating through the structure. SOURCE: Reprinted by permission from Bozhevolnyi et al. (2006). Copyright 2006 by Macmillan Publishers Ltd.

Plasmon-Based Active Devices

Going beyond the passive on-chip information-transportation applications discussed above, active generation, amplification, and switching of plasmons will allow on-chip routing and integrated sensors.[7] In conjunction with the plasmonic detectors discussed in the next subsection and the passive on-chip transportation and filtering discussed above, active devices may allow the creation of highly integrated single-chip sensors for biological or chemical detection (see Figure 2-18).

Directly switching, routing, and modulating optical fields is an area of intense technological importance for optical networking and on-chip routing applications. Removing the need to convert optical signals into electronic signals to route information would allow significant improvements in bandwidth. The electrical modulation of surface plasmons is also important for interfacing electronics with plasmonics in on-chip applications.

[7]In Appendix D, "Selected Research Groups in Plasmonics," see the section entitled "Plasmon-Based Active Devices."

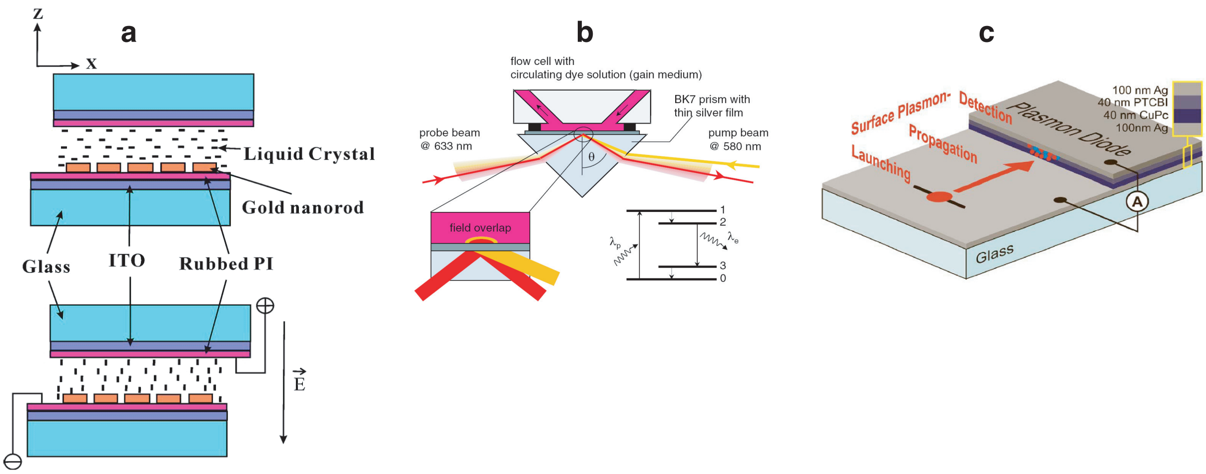

FIGURE 2-18 (a) Schematic of a device to electrically modulate the plasmon resonance of gold nanorods. The nanorods are deposited on one surface of a cell containing aligned liquid crystals. Applying a voltage across the cell causes the liquid crystals to change orientation, which in turns changes the dielectric environment to which the plasmon resonance in the nanorods responds. This change results in modulation of the spectral position of the plasmon resonance. (b) One technique employed to amplify surface plasmons propagating on a metal film. A laser at 580 nm excites a population inversion in the dye solution, which coherently delivers energy to the plasmon on the surface of the film by using a 633 nm laser by stimulated emission. The energy-level diagram for this process is illustrated in the bottom-left part of (b). (c) Integrated plasmon detector. Surface plasmons, launched on the film using a slit, propagate into the device where they generate carriers in the semiconductor layer giving rise to a detectable electric current. SOURCES: (a) Reprinted with permission from Chu et al. (2006), Copyright 2006, American Institute of Physics; (b) reprinted with permission from Seidel et al. (2005), Copyright 2005 by the American Physical Society; and (c) reprinted with permission from Ditlbacher et al. (2006), Copyright 2006, American Institute of Physics.

In the same fashion as for LSPR sensing, changing the refractive index of the medium surrounding a plasmonic nanostructure can be used to shift the plasmon resonance. This effect can be exploited to bring about modulation by using a material that changes the refractive index under either electrical or optical stimulation. One such technique is to electrically modulate the plasmon resonance of a nanostructure by exploiting the change in refractive index that a nematic liquid crystal undergoes when an electrostatic field is applied (Chu et al., 2006; Muller et al., 2002). Another proposed system that may allow for higher-speed modulation is the electrooptic effect in ferroelectric films (Liu and Xiao, 2006). Thermal modulation of the medium surrounding metal strip waveguides can also be exploited to modulate plasmons, in which case the metal strips supporting the plasmon propagation can themselves be used as ohmic heating elements to spatially localize the effect (Nikolajsen et al., 2004).

Rather than changing the dielectric constant of the surrounding medium, it is also possible to construct waveguides in which the optical properties of the waveguide material itself can be changed. Just as for gold or silver films, thin films of gallium (Ga) on dielectric substrates support surface plasmons. Unlike other materials used for plasmonics, the phase of Ga can be changed between metastable metallic phases (m-Ga) and a polymorphic phase (α-Ga) which exhibits strong absorption across the visible and NIR due to the presence of covalently bound Ga_2 molecules. In thin films, this phase change can be triggered either optically or thermally. Remarkably, this effect can happen on timescales as short as 4 picoseconds (ps), allowing for high-speed modulation of SPs (Krasavin et al., 2005).

In the visible spectrum, optical modulation of a 633 nm light by a continuous wave (CW) laser at 488 nm using $\chi^{(3)}$ nonlinearity of poly-3-butoxy-carbonyl-methyl-urethane deposited in nanohole arrays in a thin Au film has been demonstrated (Smolyaninov et al., 2002). This switching mechanism in principle can allow for very high speed switching. Due to the strong field enhancement arising from the surface modes of the hole array, this effect is strong enough to be observed with a CW control beam rather than requiring pulsed excitation.

Semiconductors exhibit a Drude response in the terahertz range similar to that of metals at optical frequencies. Unlike metals, in which the carrier concentration is essentially fixed, the permittivity of semiconductors can be easily modified by changing the free carrier concentration by, for example, changing the temperature or optically generating electron-hole pairs. This effect has been exploited to change the transmission of surface plasmons propagating on grating structures fabricated on the surface of an InSb wafer by optically creating electron-hole pairs. While this technique has only been demonstrated thus far with a CW modulation laser, potentially this switch mechanism can result in a transmission rise time on the picosecond timescale, enabling ultrafast all-optical switching of terahertz plasmons with low optical fluences on the order of $\mu J/cm^2$ (Gomez-Rivas et al., 2006).

As early as 1989, the use of amplification by creating a population inversion in a medium adjacent to a metallic film to increase the SPP propagation length was proposed. More recently, Mark I. Stockman has introduced the idea of SPASER (surface-plasmon amplification by stimulated emission of radiation) (Bergman and Stockman 2003), and several groups have experimentally demonstrated the amplification and generation of surface plasmons. Owing to the momentum mismatch between light and surface plasmons, efficient coupling between far-field excitation and propagating surface plasmons in waveguides is difficult to achieve. For on-chip transport applications or integrated sensors, an ideal solution to this problem is to create plasmons using, for example, a SPASER. In routing and long-distance applications, amplification of signals for off-chip communications without an optical-electronic-optical conversion is necessary in order to maintain signal levels. In addition, the high loss frequently encountered in SPP waveguides may be counteracted by the use of amplification. Surface plasmon lasers, or SPASERs, based on the coupling of a gain medium directly with surface plasmons, have been demonstrated in the mid-infrared (IR) spectral region using metallic structures on top of quantum cascade lasers (Bahriz et al., 2006; Moreau et al., 2006). The mid-IR is of particular interest, as plasmons propagate with far lower losses in this spectral region than in the visible. In addition, on-chip sensing applications can be imagined as well as traditional routing. In the visible, plasmon amplification by coupling to organic laser dyes has been demonstrated (Seidel et al., 2005). In solution, the effective negative imaginary part of the dielectric constant of excited rhodamine 6G dye was demonstrated to increase the Rayleigh scattering efficiency of aggregates of Ag nanoparticles by a factor of 6 due to partial cancellation of the imaginary part of the Ag dielectric function at the plasmon resonance (Noginov et al., 2006).

The final component necessary for active plasmonic devices to be used for on-chip communications or integrated sensor application is a surface plasmon detector. The next subsection discusses the concentration of light into small photodiodes, which is one way that surface plasmons could be detected on a small scale. Recently, however, a detector based on an organic photodiode constructed with an integrated surface plasmon waveguide to detect light propagating into the device from the waveguide directly has been demonstrated (Ditlbacher et al., 2006).

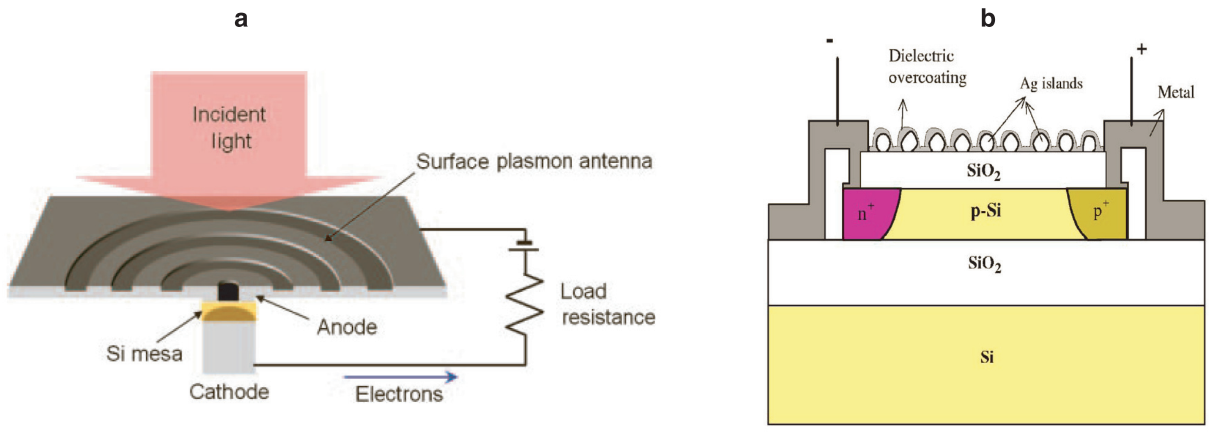

FIGURE 2-19 (a) Schematic illustration of a plasmonic focuser used to collect light from a large area and focus it into a high-speed nanophotodiode. (b) Silicon (Si) light-emitting diode employing the plasmon resonance of a silver island film to couple light trapped in the waveguide mode of the device to the far field. SOURCES: (a) Reprinted with permission from Ishi et al. (2005), Copyright 2005, Institute of Pure and Applied Physics; (b) reprinted with permission from Pillai et al. (2006). Copyright 2006, American Institute of Physics.

Plasmon-Enhanced Devices

Plasmon-enhanced devices generally fall into two categories: enhanced emission devices and enhanced detection devices.[8] In the former case, plasmons are used to increase the emission efficiency of LEDs and other light emitters by either improving the coupling of light out of the structure or changing the decay rates of the emitting material directly to enhance the emission of light. Enhanced detectors can fall into two categories as well: in one category plasmons are used to concentrate the light to smaller areas than could be achieved using conventional optics for ultrahigh speed photodiodes, and in the other category the coupling of light into a conventional device is enhanced by scattering off plasmonic nanoparticles into the device (see Figure 2-19). Further, because plasmonic enhancement is generally performed with metallic structures, one could also employ these structures as electrical contacts, thereby creating contacts that enhance the performance of a device rather than just having the detrimental effect of reducing the overall efficiency of a device by shadowing part of the active area.

Shrinking high-speed photodiodes enables higher speeds because the response time is limited by the junction capacitance and transit time of photogenerated carriers. Shrinking the devices reduces both effects. However, coupling light into nanoscale photodetectors with conventional optics is limited by the diffraction limit to devices with active areas of at least several hundred nanometers in diameter. Plasmonics allows the concentration of light into nanometer-scale volumes, thereby enabling ultrahigh-speed nanophotodiodes to be fabricated. Two structures have recently been demonstrated to collect and concentrate light into nanoscale volumes at the surface of photodiodes using surface plasmons: C-apertures in a metal film to enhance a germanium (Ge) photodiode operating at 1310 nm (Tang et al., 2006) and concentric metallic rings in a metallic film (Ishi et al., 2005) to enhance the performance of an Si nanophotodiode (see Figure 2-20). A similar idea can also be employed in on-chip interconnect

[8]In Appendix D, "Selected Research Groups in Plasmonics," see the section entitled "Plasmon-Enhanced Devices."

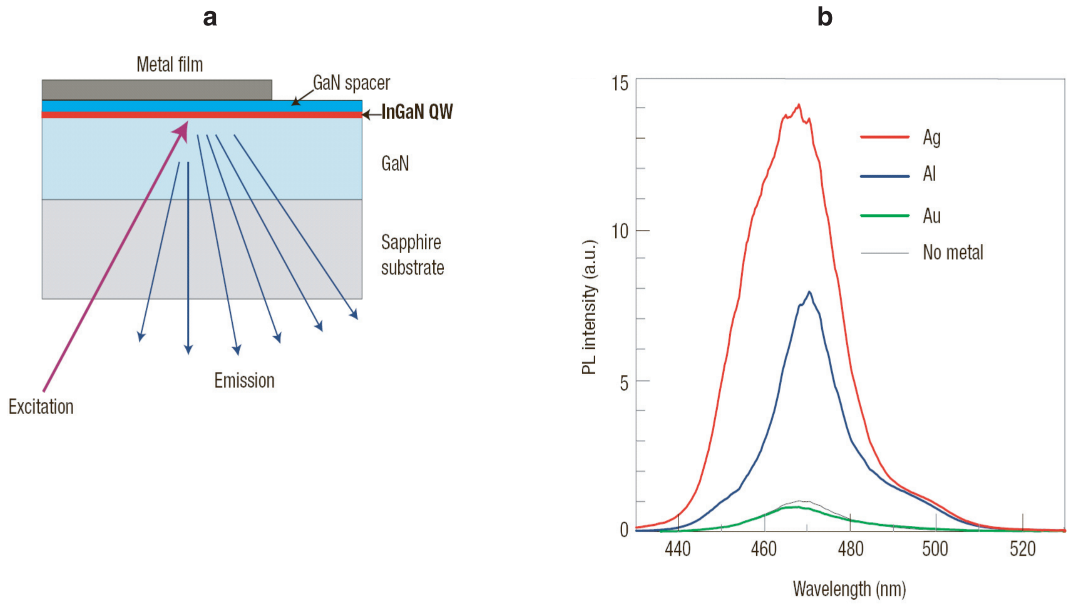

FIGURE 2-20 (a) Sample geometry for enhancing the radiative decay rate of indium gallium nitride (InGaN) quantum well (QW) emission. The metal film on the top surface supports a plasmon resonance that enhances the radiative decay rate of the InGaN QW. (b) Emission spectrum of the samples with metal films showing the enhancement in photoemission. The plasmon resonance of the Ag film is closest to the emission wavelength of the device and therefore causes maximum enhancement of the output. These devices have potential for improving white-light-emitting diodes. SOURCE: Reprinted by permission from Okamoto et al. (2004). Copyright 2004 by Macmillan Publishers Ltd.

systems to collect light from a larger waveguide structure and couple it to nanophotodiodes on size scales commensurate with the transistors making up the electronic part of the device.

For mid-IR detectors, reducing the volume of the semiconductor sensing element also has the important effect of reducing the thermal noise in the detector. Using the intensely concentrated near field of a plasmon, it is possible to concentrate light from a large area to enhance absorption by a small volume of material. It has recently been proposed that the enhanced near field caused by surface plasmons on metallo-dielectric diffraction gratings can be used to significantly increase the absorption of light by nanoscale mercury cadmium telluride (HgCdTe) (MCT) detectors. In this device, an Au film with 50 nm wide strips of MCT at regular spacing is shown to increase the amount of light absorbed in the MCT, owing to the intense near-field enhancement in the gaps, by as much as a factor of 250 at 9.8 μm compared to the same volume of MCT material as part of a thick slab with a conventional antireflection (AR) coating. In addition, the Au stripes could potentially be used for electrodes (Yu et al., 2006).

The performance of larger devices can also be enhanced in two ways: by increasing the coupling of light into devices through (1) far-field scattering of surface plasmons or (2) near-field enhanced absorption. Of particular importance is the development of inexpensive methods for enhancing the performance of solar cells. Recent theoretical work has developed techniques for determining the optimal nanoparticles for the collection of sunlight in such applications (Cole and Halas, 2006). One technique frequently used to enhance the performance of silicon devices, such as solar cells, is to texture the surface by etching depressions into the surface to trap light, allowing more efferent absorption of light by the device. Unfortunately, such texturing of the surface frequently results in degraded electrical performance, particularly in thin-film devices. The plasmon resonance of nanoparticles, metallo-dielectric diffraction gratings, or holes in a metal film could potentially all be used to scatter light into the device, enhancing the overall efficiency in a manner similar to that of conventional texturing techniques, without modifying the underlying device structure and thereby maintaining the electrical characteristics (Pillai et al., 2006). In addition, because metal structures are used for visible plasmonics, one could potentially devise structures in which the plasmonic structure acted as a front contact, eliminating the problems of "shadowing" part of the active area of the device by the front electrical contacts. Another technique is to use the enhanced near field directly to enhance the absorption of light by using the near field to concentrate light in a shallow active layer (Stuart and Hall, 1998).

The focusing effect of plasmons can also be used in the other direction; by depositing a plasmonic antenna on the surface of a conventional semiconductor diode, the light can be concentrated into a nanoscale volume of space directly above the surface of the laser. This is applicable as an active near-field optical microscope probe and to dramatically increase the density achievable with optical data-storage devices by replacing the conventional lens assembly in optical disk drives (Cubukcu et al., 2006).

Enhancing the performance of new solid-state lighting sources is of great current importance due to concerns over environmental conservation and energy security. In addition to the pressing need for improved illumination devices, other important applications include enhancing silicon light emission for integrated on-chip photonic devices and enhancing the performance of organic LEDs for display applications. For enhancing the light emission from devices composed of materials such as InGaN quantum wells (Okamoto et al., 2004), light-emitting polymers for organic LEDs (Neal et al., 2006), and Si nanocrystals (Biteen et al., 2006), enhancing the radiative decay rate of the light emission material allows a significant overall improvement in the device quantum efficiency. In the case of thin-film Si band-edge emission devices, coupling light out of the natural waveguide modes of the Si thin-film structure has traditionally been accomplished by surface texturing in the same fashion as for the solar cell applications discussed above (Pillai et al., 2006). As with detectors, nanoparticles on the surface can couple to these waveguide modes directly and efficiently, scattering light out to the far field, enhancing the overall external device efficiency.

Quantum cascade lasers (QCLs) for terahertz emission into the far field can also be enhanced by using surface plasmons. A plasmon waveguide constructed by applying gold films to both sides of the device, essentially a MIM waveguide, as discussed above, can confine light within the active region. Etching grooves in a gold film on the top of a QCL allows the creation of a second-order diffraction grating. The result is a plasmon band gap allowing feedback at only one laser mode. In addition, a second-order diffraction grating can be used to couple light out of the waveguide by scattering light into the far field in a direction normal to the top of the laser, enabling the creation of vertical emitting terahertz QCLs. Plasmonic waveguides are particularly advantageous for use with QCLs because the optical modes generated in the QCL are transverse-magnetic (TM) polarized, matching the TM polarization of surface plasmon waveguides. In addition, the gold used for the waveguides in these lasers also serves the dual purpose of acting as electrical contacts to the device (Fan et al., 2006; Tredicucci et al., 2000).

Plasmonics in Biotechnology and Biomedicine

As the field of plasmonics matures, there are many applications of plasmonic properties of nanoparticles in the field of biotechnology and medicine.[9] These applications can be broadly divided into the

[9]In Appendix D, "Selected Research Groups in Plasmonics," see the section entitled "Plasmonics in Biotechnology and Biomedicine."

subfields of chemical and biological sensing, plasmonic heating of nanoparticles, and optical imaging using nanoparticles.

The sensing applications include LSPR sensing and SERS of biomarkers of disease. Most notable in this regard is the optical biosensor for Alzheimer's disease that uses LSPR sensing to detect beta amyloid aggregation (Haes et al., 2005) and SERS sensors for in vivo blood glucose monitoring (Lyandres et al., 2005; Stuart et al., 2006b). Other SERS-based sensors for bioterrorist agents such as anthrax (Zhang et al., 2005c; Zhang et al., 2006b) and half-mustard gas (Stuart et al., 2006a) also demonstrate high sensitivity. SERS and surface-enhanced Raman optical activity (SEROA) (a vibrational spectroscopic technique that relies on the difference in the intensity of Raman-scattered right and left circularly polarized light due to molecular chirality) are also being investigated as highly molecular-specific techniques. LSPR sensing is also used to detect nanomolar quantities of antibodies in whole blood (Hirsch et al., 2003a).

Plasmonic heating of nanoparticles is being used to enhance laser tissue welding (Gobin et al., 2005) and photothermal cancer ablation therapies (Hirsch et al., 2003b; O'Neal et al., 2004). These have been demonstrated successfully in vivo in mice. Figure 2-21 shows a comparison of conventional sutures versus nanoshell-enhanced laser welding of incisions after surgery.

Plasmonic nanoparticles are being extensively used as optical contrast agents for imaging biological tissues (Stone et al., 2007). There are many groups using a variety of nanoparticles, from simple solid gold nanospheres to nanorods and antibody-targeted nanoshells for imaging applications, as shown in Figures 2-22 and 2-23. Figure 2-22 shows therapy of SKBr3 breast cancer cells using anti-HER2 nanoshells.

In Figure 2-23, as the collagen network is deformed by cell traction forces, the pattern of scattered light from the embedded nanorods also shifts and deforms. Digital image analysis can then be used to track the movement and deformation of the light pattern and to calculate local material deformations. Simultaneous fluorescence imaging can also be used to identify cell locations, in order to associate strain fields with the relevant cell spatial positions, morphologies, and orientations.

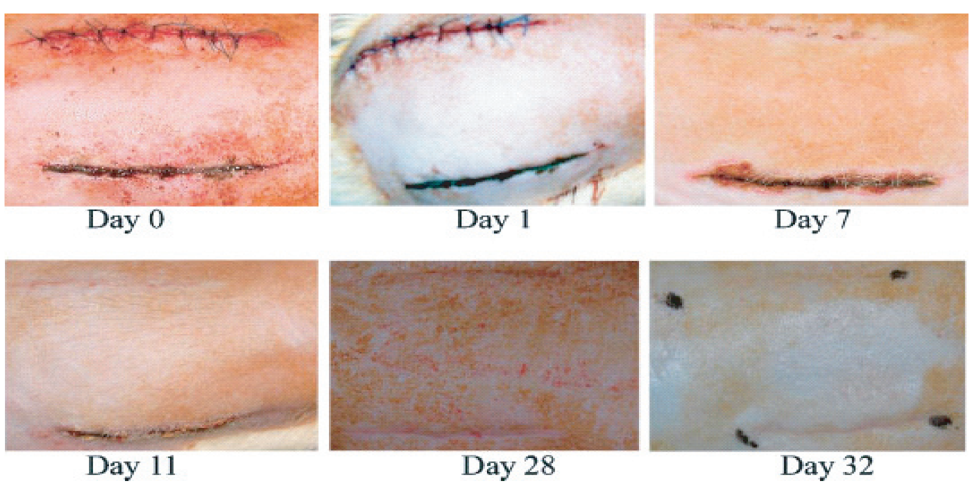

FIGURE 2-21 Comparison of conventional sutures (upper row of pictures) versus nanoshell-enhanced laser welding (lower row of pictures) of incisions after surgery. Photographs of an individual following surgery, day 0 to day 32. After 10 to 14 days, the scab on the soldered incisions fell off, leaving a fine scar where the animal is healing. The soldered row leaves a more defined scar compared to the sutured side but diminishes over time. SOURCE: Gobin et al. (2005). Copyright 2005. Reprinted with permission of Wiley-Liss, Inc., a subsidiary of John Wiley & Sons, Inc.

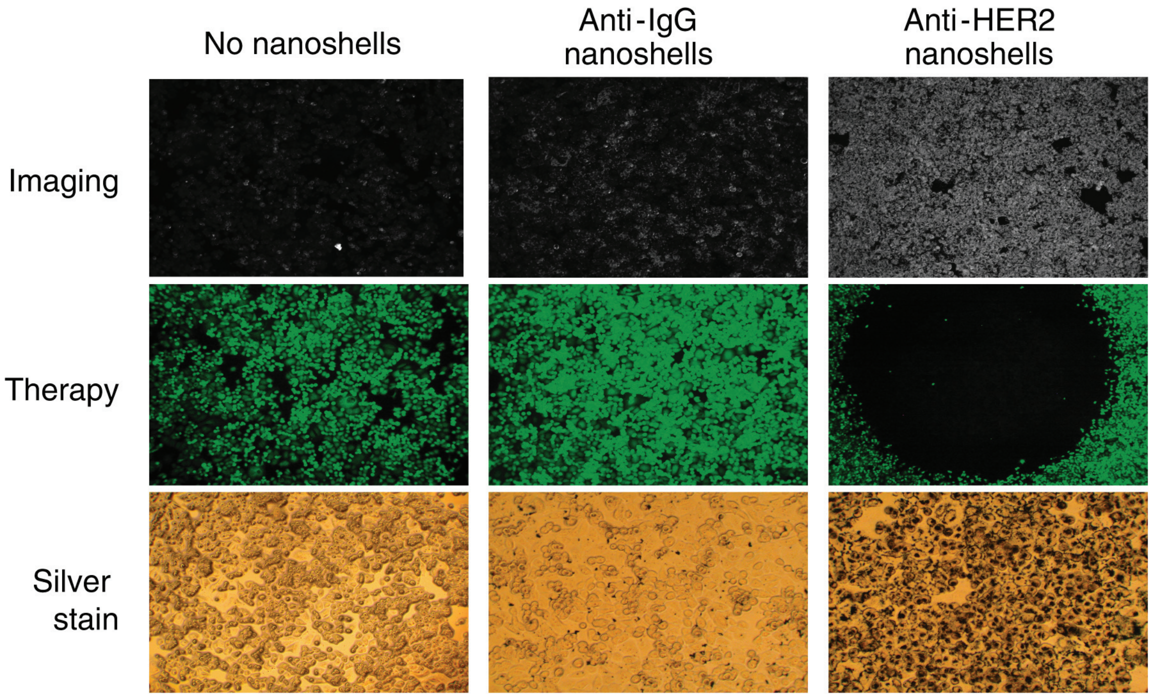

FIGURE 2-22 Therapy of SKBr3 breast cancer cells using anti-HER2 nanoshells. Cell viability assessed via calcein staining (top row), and silver stain assessment of nanoshell binding (bottom row). Cytotoxicity was observed in cells treated with a near-infrared (NIR) emitting laser following the exposure of cells targeted with anti-HER2 nanoshells only. Note the cytotoxicity (dark spot) in cells treated with an NIR emitting laser following nanoshell exposure (top row, right column) compared to the controls (left and middle columns). SOURCE: Reprinted with permission from Loo et al. (2005). Copyright 2005 American Chemical Society.

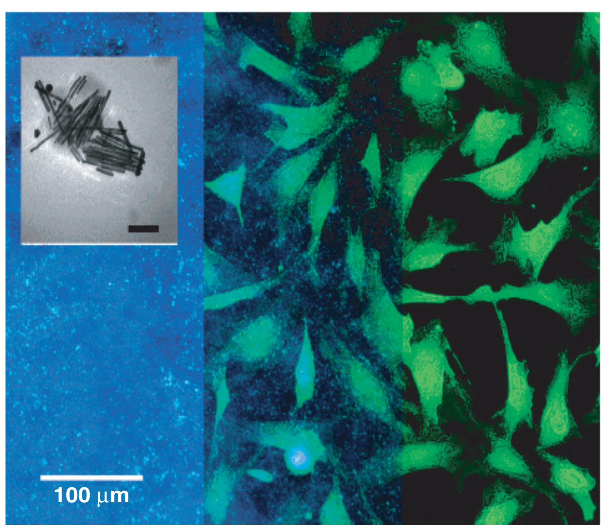

FIGURE 2-23 (Left) Dark-field optical micrograph of light scattered from gold nanorods embedded in cell-populated collagen layers. (Right) Simultaneous fluorescence image of cardiac fibroblast cells present on the collagen. The two images superimposed with some transparency (center panel). Scale bar = 100 μm. Inset: Transmission electron micrograph of the gold nanorods. Scale bar (inset) = 100 nm. SOURCE: Reprinted with permission from Stone et al. (2007). Copyright 2007 American Chemical Society

EMERGING TOPICS OF PHONON POLARITONS AND TERAHERTZ WAVEGUIDES

Phonon Polaritons

In 2002, Rainer Hillenbrand's group (Nano-Photonics Group, Max-Planck-Institute fur Biochemie and Center for Nanoscience, Germany) proposed that many of the subwavelength optics applications provided by surface plasmons in the visible/near-infrared spectral range had direct analogs in the mid-infrared range arising from surface phonon polaritons on polar crystalline dielectrics (Hillenbrand et al., 2002).[10] These phonon polaritons are propagating waves of lattice deformations of the polar crystal that can couple resonantly to electromagnetic radiation. The group studied this phenomenon at a silicon carbonide (SiC) surface using scattering-type apertureless scanning near-field optical microscopy (s-SNOM). The group demonstrated the ability to resonantly couple a subwavelength metal tip to a surface in the mid-infrared spectral region, which has opened the door to many potential applications. For example, this group demonstrated that because the phonon resonance depends greatly on the crystalline structure of the material, applications related to sensing the local crystal structure can be realized (Ocelic and Hillenbrand, 2004). The researchers demonstrated that they see a resonance for crystalline SiC but not for amorphous SiC. Using focused ion beam implantation to cause lattice defects in the SiC crystal, they wrote a subwavelength checkerboard pattern of intact crystalline SiC and damaged SiC (see Figure 2-24). Then, using their s-SNOM, they scanned the surface and found resonant coupling at the crystalline sites and little or no coupling at the damaged sites. They were able to resolve 200 nm (λ/50 resolution)-wide squares in the checker pattern and 100 nm (λ/100 resolution)-wide stripes in a stripe pattern. This work demonstrates a promising potentional for optical data-storage applications at subwavelength dimensions. The Hillenbrand group also has studied surface phonon polariton propagation (Huber et al., 2005) and has demonstrated that they can detect and image slight variations of structure in a crystal lattice (Huber et al., 2006).

Surface phonon polaritons on SiC have also been proposed to be useful for employment in particle acceleration. Gennady Shvets's group (Department of Physics and Institute for Fusion Studies, University of Texas at Austin) has proposed this application and is actively working toward its realization. The group has designed the structure, performed numerical simulations, and begun fabricating this structure (Shvets et al., 2004). The structure consists of an Si grating on one side of an Si wafer with an SiC layer grown on the other side. Two such structures are positioned together such that the SiC layers face each other and have a small vacuum gap between them. Carbon dioxide (CO_2) laser light (on resonance with SiC) is shone onto the Si grating and excites propagating phonons on the SiC surfaces, which produces an enhanced electric field directed down the vacuum cavity where particles can be accelerated. This group has recently performed additional tests to confirm and characterize the surface waves excited at the SiC surface (Kalmykov et al., 2006). The realization of such a device would offer an inexpensive desktop accelerator, making particle physics experiments much more accessible.

Terahertz Plasmonic Waveguides

Waveguides in the terahertz frequency range of the electromagnetic spectrum have proven to be a difficult technology to realize owing to high losses and group velocity dispersion.[11] In 2004, Daniel M. Mittleman's group (Rice University) reported the realization of a practical terahertz waveguide arising from surface plasmon polariton modes supported on bare metal wires (Wang and Mittleman, 2004).

[10]In Appendix D, "Selected Research Groups in Plasmonics," see the section entitled "Phonon Polaritons."
[11]In Appendix D, "Selected Research Groups in Plasmonics," see the section entitled "Emerging Topics in Plasmonics."

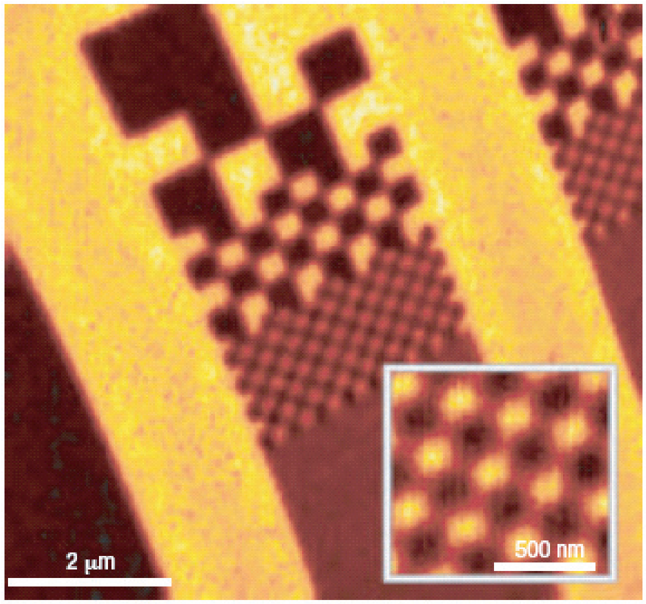

FIGURE 2-24 Near-field micrograph of a silicon carbonide (SiC) surface. A checkerboard pattern has been made on the SiC surface by using focused ion-beam implantation to effectively destroy the crystalline structure of SiC in the pattern. The near-field image was obtained using a scattering-type scanning near-field optical microscope (s-SNOM) with 11.22 μm wavelength light. Because only the crystalline sections of the SiC surface support phonon-polaritons, only those regions are bright in the s-SNOM image. The inset shows a near-field image of a checker pattern in which the squares are 200 nm wide, demonstrating a very fine spatial resolution, which suggests the potential for optical data storage applications. SOURCE: Reprinted by permission from Ocelic and Hillenbrand (2004). Copyright 2004 by Macmillan Publishers Ltd.

The group was able to couple terahertz radiation into the wire by placing another wire oriented perpendicular and proximal to the waveguide wire and focusing terahertz radiation at the place where the two wires cross. The researchers observed virtually dispersionless propagation along such a wire 24 cm long with a loss coefficient of 0.03 cm^{-1} carried by radially polarized SPP mode. This work represented the first viable waveguide for the terahertz frequencies. Daniel Grischkowsky's group (Oklahoma State University) then further characterized these wire waveguides and identified the propagating modes as Sommerfeld waves (Jeon et al., 2005). Mittleman's group then characterized the SPP dispersion, which, although small, was found to be nonlinear with wire thickness (Wang and Mittleman, 2006). Paul C.M. Plancken's group (Delft University of Technology, The Netherlands) showed that these wire waveguides become highly dispersive with even a thin coating of a dielectric material, suggesting the possibility of a sensor based on this change (van der Valk and Plancken, 2005).

Despite the promise of the bare metal wire waveguides, Stefan Maier (University of Bath, United Kingdom) has recently suggested that this geometry is not the best terahertz waveguide, because at terahertz frequencies, SPPs are not highly localized but instead extend out several wavelengths radially and suffer significant losses near bends and proximal objects. Thus, he has suggested alternative geometries for terahertz plasmon waveguiding based on structures containing periodic holes or grooves in a metal surface which support SPP-like modes that are highly confined similar to SPPs in the visible spectral region (Maier and Andrews, 2006). Subsequently, Maier has also proposed terahertz waveguides using cylindrical metal wires with periodic radial grooves. Such a structure is predicted to support highly confined SPP-like modes with dispersion relations similar in trend to SPPs in the visible spectral range (Maier et al., 2006).

REDUCED DIMENSIONALITY AND QUANTUM CONFINEMENT IN NANOPHOTONICS

Introduction and Background

This section addresses the ongoing and anticipated advances in photonics technology that are occurring as a result of emerging new ways of incorporating reduced-dimensionality structures, and the resulting quantum confinement of charge carriers, into optoelectronic devices. While quantum confinement has been used in optoelectronic devices for a few decades now, new approaches and new device concepts continue to be developed, producing dramatic new levels of capability and performance, over broad ranges of wavelength. It is anticipated that these advances will continue to occur at a rapid rate into the foreseeable future. These advances will benefit from and occur in parallel with ongoing advances in the sophistication and control of materials growth techniques and nanoscale fabrication and processing methods.

For the purposes of this report, the Committee on Nanophotonics Accessibility and Applicability takes its topic to include optoelectronic devices and device components that employ reduced dimensionality and quantum confinement to manipulate energy levels and tailor charge-carrier transport for improved performance. The committee provides a brief description of how some of these techniques have been used in the past. The majority of this section then describes emerging approaches in which quantum confinement is being used to develop entirely new approaches to photonic devices. Finally, a short speculative section discusses new types of device approaches, which at this stage are speculative and very long term, that might ultimately be developed.

Definition of Reduced Dimensionality and Quantum Confinement

Reduced dimensionality and quantum confinement occur when the structure extent in one or more dimensions becomes comparable to the Fermi wavelength of the charge carrier (i.e., the electron or hole). In this case, the allowed energy levels of the charge carriers become significantly modified, increasing in energy as the structure dimensions are decreased and the confinement becomes more severe. However, the committee takes the definition to be somewhat broader than the basic one provided above. The definition should include such techniques as the placement of thin barriers to manipulate the energy-dependent tunneling of carriers from one region to another, and the use of nanostructures to influence phonon transport independently from carrier transport—in which case the relevant length scale becomes the phonon mean free path rather than the electron Fermi wavelength.

The Double Heterostructure Laser: Earliest Use of Quantum Confinement in Photonics

The double heterostructure enabled the charge carriers to be concentrated into a thin layer of material having smaller band gap than the material surrounding it. This (1) suppressed electron-hole recombination outside the active region, (2) prohibited carriers from “overshooting” the active region by providing “blocking” layers of wider band gap, and (3) increased optical confinement owing to the higher index of refraction of the lower band gap material. Further increases in recombination efficiency and mode confinement were achieved by making the double heterostructure layer ever thinner, until eventually the electron energy levels became quantized and the structure became known as a quantum well. At present, the highest-efficiency semiconductor light emitters are QW-based lasers.

The ability to epitaxially grow heterostructure layers with low-defect densities was enabled by several atom-by-atom growth methods developed at around the same time, including molecular beam epitaxy (MBE), developed by A.Y. Cho and others, and metal organic chemical vapor deposition (MOCVD), with H. Manasevit, R. Dupuis, and P.D. Dapkus as major inventors. Several groups contributed to the development of this technology, including Alferov's group in Russia at the Ioffe Institute and groups at Bell Laboratories, Rockwell, IBM, and RCA in the United States. These groups rapidly advanced through a number of critical breakthroughs, including growth of lattice-matched structures, the use of band diagrams, and single heterostructure lasers. The first continuous-wave laser operation at room temperature was achieved in a double heterostructure independently by Alferov's group and M. Panish's group at Bell Laboratories in 1970. During this period, a group under M.G. Craford at Monsanto applied heterostructure concepts to new compound semiconductor alloys, achieving the first yellow LED and a 10-fold brightness increase in red and orange LEDs in the early 1970s. In the 1990s, efficient and durable blue LEDs and laser diodes were demonstrated by S. Nakamura at Nichia Chemical Industries, Ltd., using gallium nitride (GaN)-based heterostructures.

Thus, the fundamental solid-state physics concepts of quantum confinement and the use of quantum wells to localize excitons, increase oscillator strengths, enhance radiative recombination efficiencies, and control charge-carrier transport were largely developed in parallel with optoelectronics device research. This extremely close cycle between theory and experiment and between science and technology was unusually successful. (The basic science portion of this effort was recognized by a Nobel Prize in physics awarded to Alferov and Kroemer in 2000.) In the following subsections, the committee discusses how these concepts, and new ones as well, are being extended and combined in new configurations to create optoelectronic devices with novel properties and enhanced performance.

New Devices: Emitters

Following is a discussion of a number of optoelectronic emitters being developed that employ extended concepts of reduced dimensionality and/or quantum confinement.

Quantum Dot (QD) Lasers

Quantum dot lasers are conventional semiconductor lasers in which a layer of quantum dots is embedded within the active quantum wells of the laser structure. The quantum dots are typically formed by a spontaneous self-assembly process driven by strain. The canonical example is the formation of indium arsenide (InAs) QDs within a gallium arsenide (GaAs) quantum well. The QDs can be created by either MBE or MOCVD growth methods.

It has been known for a while that the incorporation of quantum dots in the active region of optoelectronic devices would drastically improve device performance, primarily owing to the enhanced Dirac-delta-like density of states function (Arakawa and Sakaki, 1982; Asada et al., 1986). The *density of states,* which is a measure of the total number of quantum mechanically allowed energy states per unit volume, is a very important parameter in solid-state physics, and a large density of states is highly desirable for optoelectronic devices such as lasers and detectors. As one goes from a bulk material in which there is no quantum confinement to a system in which the carriers are allowed to move in two dimensions (quantum well), one dimension (quantum wire), or in quasi-zero dimensions (quantum dots), the density-of-states function increases in magnitude and becomes discretized. The density of states in a semiconductor for various levels of confinement is shown in Figure 2-25. Some of the major advantages of lasers with quantum dots in the active region are as follows:

- A significant decrease in the threshold current and in the temperature dependence of the threshold current (Bimberg et al., 1997; Lester et al., 1999);
- A large increase in the differential gain and modulation bandwidth (Kamath et al., 1997); and
- A vastly reduced chirp and low linewidth-enhancement factor (Newell et al., 1999; Saito et al., 2000).

But the fabrication of these ultra-small (~10Å to 100Å) objects in the laboratory has been a major challenge. Even when these objects were formed, by using direct patterning or otherwise, they lacked not only the large areal density that was required to make them feasible for devices but also the high optical quality that was an essential prerequisite for optoelectronic devices such as lasers, modulators, and detectors (Prins et al., 1993).

It was only a decade ago that a novel technique, called *self-organization* or *self-assembly* (Stranski-Krastanov process), enabled the realization of coherently strained three-dimensional islands or "quantum dots" (Berger et al., 1988; Leonard et al., 1993; Tabuchi et al., 1991; Xie et al., 1995). It was observed that under certain conditions, during the heteroepitaxy of lattice-mismatched systems, either by MBE or by MOCVD, these dots were formed. Soon after, various electronic and optoelectronic devices such

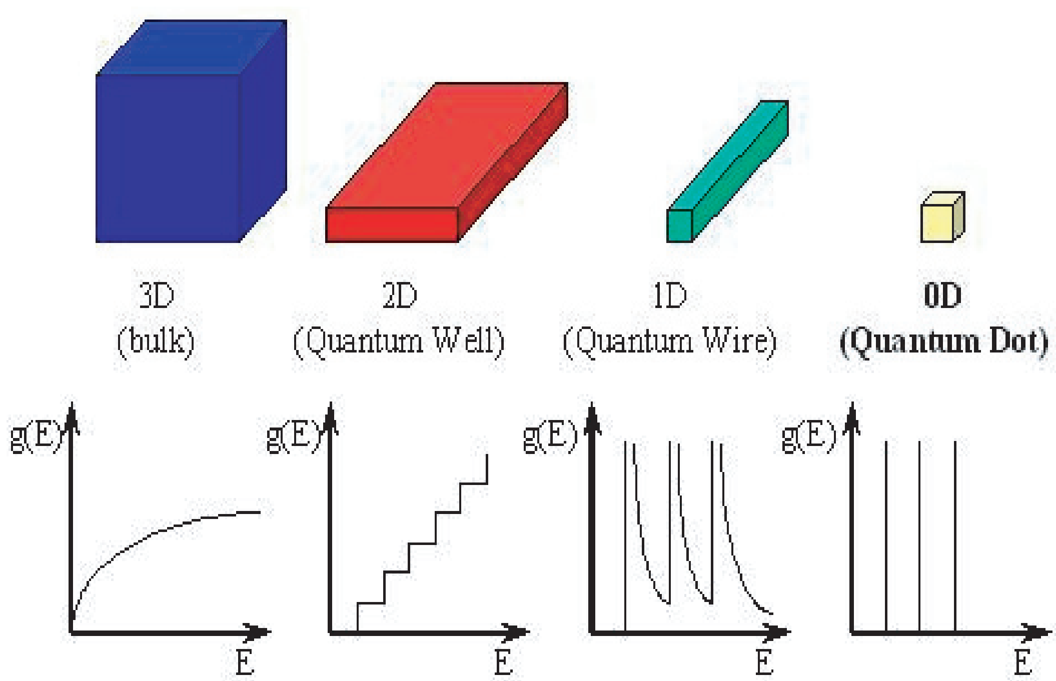

FIGURE 2-25 Plot of the electronic density of states g(E) as a function of energy E for structures of different dimensionality. SOURCE: Image provided by Paul Alivisatos, University of California at Berkeley. Reprinted with permission.

as lasers, mid-infrared detectors, emitters, single-electron transistors, and electrooptic devices were reported using quantum dot active regions (Grundmann et al., 2000; Kamath et al., 1996; Kastner, 1992; Kirstaedter et al., 1994; Krishna et al., 2000a; 2000b; 2001; 2002; Pan et al., 1998; Phillips et al., 1998a, 1998b; Raghavan et al., 2002; Ye et al., 2002). By embedding InAs dots in a conventional 980 nm quantum well pump laser structure, 1.3 micron lasing is achievable. Similarly, 1.48 micron to 1.6 micron emission is accessible by embedding the dots in a typical AlGaInAs quantum well laser design manufactured on an InP substrate. Threshold current densities in QD lasers have been demonstrated as low as 16 A/cm^2 (Liu et al., 1999).

In particular, mid-infrared detectors based on QDs have demonstrated very good performance. Recently, the first two-color camera was demonstrated using quantum dots in the active region (Krishna, 2005). Such cameras would be invaluable for a variety of applications ranging from night-vision equipment to chemical agent and pollutant monitoring.

The main advantage envisioned by using QDs in the laser active region is that (1) quantum confinement is greatly increased owing to the QDs' dimensionality being restricted in all three dimensions rather than only one, as is the case for a quantum well. This leads to the benefits of exciton localization, enhanced oscillator strength, and increased radiative recombination efficiency, but in greater degree than can be achieved in a single quantum well. In addition, because of the reduced electronic densities of states occurring in a QD, it is in principle easer to achieve population inversion. As a result, QD lasers can be engineered to be highly temperature-insensitive and have a very low linewidth-enhancement factor. For instance, the GaAs-based QD laser offers higher, more stable, better-uncooled performance over broader temperatures compared to QW designs. QD distributed feedback lasers (DFBLs) show a less than +/– 5 percent slope efficiency variation over a temperature range of 10ºC to 85ºC, which is approximately five times better than typical InGaAsP/InP QW DFBLs. For fixed-wavelength applications, the QD laser eliminates the need for a thermoelectric cooler and thermistor. In the case of Fabry-Perot lasers, T_0's, or characteristic temperatures, range from 50 K to 80 K for undoped dots and 160 K to infinity for p-type doped QD (Shchekin and Deppe, 2002). The trade-off with doped dots is an increase in internal loss from a typical 1.5-2 cm^{-1} to 4-5 cm^{-1}, which compromises the slope efficiency of the laser somewhat.

For both fixed-wavelength and external cavity laser applications, QD lasers offer extremely small linewidth enhancement factor, α (<0.1), not achievable with QW lasers. This result leads to the additional benefits of low chirp under direct modulation, insensitivity of the laser operation to optical feedback or back-reflections, and filamentation suppression.

III-N Lasers and LEDs

Lasers and LEDs fabricated from the aluminum indium gallium nitride ((Al)(In)(Ga)N) system (often called the III-N system, referring to column III of the periodic table) are relatively recent arrivals on the optoelectronics scene, having only been demonstrated in the early 1990s. (Prior to this, there were no bright LEDs available in the ultraniolet (UV), blue, and green regions of the spectrum.) However, the advances that have occurred since then have been astonishing: bright, high efficiency III nitride (III-N) LEDs are now seeing wide commercial use in signaling applications, and a nascent solid-state lighting industry is emerging. This development promises highly efficient, long-lived, environmentally benign, and mechanically robust lighting sources for residential and commercial lighting, aviation, and military applications. III-N lasers in the UV have applications to the sensing of chemical, biological, and nuclear agents. In the visible spectral region, III-N lasers have important military uses for image projection. Blue lasers are already being developed for information storage (the widely heralded "Blue Ray" and High Density Digital Versatile Disc [HD-DVD] standards). Because of the immense market potential of III-N emitters, many of the innovative nanophotonics approaches being explored today are using this system as a platform—including such approaches as using QDs as wavelength conversion materials, photonic lattices for achieving improved light extraction, directionality of emission, and internal quantum efficiency. Coupling of internal excitonic states to surface plasmons is also being explored as a means of improving quantum efficiency.

While the use of photonic lattices and surface plasmons is discussed in further detail in Chapter 3 of this report, the role of quantum confinement in III-N emitters is discussed here. Two major challenges currently face the further development of III-N emitters. First, because no native substrate exists in GaN or AlN (beyond small experimental efforts producing pieces on the order of 1 cm^2 in area), epitaxially grown material suffers from defect densities as high as 10^{11} cm^{-2}. These defects provide sites at which electrons and holes can recombine nonradiatively—that is, without producing a photon but instead producing waste heat. It is thus highly desirable to reduce the density of dislocations in order to improve efficiency and performance. The use of reduced-dimensionality nucleation layers—that is, initial growth layers composed of dense arrays of one-dimensional wires—offers a pathway toward lowering the defect densities. The one-dimensional wires act as a kind of suspension network, supporting a subsequent planar growth layer with a greatly reduced density of dislocations. The dislocations are effectively turned sideways during this growth process, annihilating each other. Initial research in this area is being sponsored by the Department of Energy.[12] For earlier related work, albeit not in the nanoscale regime, see Follstaedt et al. (2002).

Role of V-Defects Interacting with Dislocations

The second challenge concerns the difficulty in achieving high-efficiency green LEDs. In order to achieve green, the semiconductor quantum wells need to have high-In-content InGaN. However, as increasing amounts of In are added to the quantum well, the efficiency of the LED drops dramatically, tailing off around 550 nm, which is right at the center of the eye response curve. The origin of this effect is the subject of some controversy. However, one belief is that the In may spontaneously segregate at the nanoscale, forming QD-like regions of high-In content within the quantum wells. Initially these QDs may help to capture excitons and increase oscillator strengths. However, because most GaN-based emitters are grown on polar crystal faces, as the QDs become larger—as would be expected with increasing In content—they may actually lower the oscillator strengths. This is because the polar electric field will cause the electron and hole to become localized at opposite sides of the QD. It is believed that a deeper understanding of how In-rich QDs form and how they interact with dislocations may lead to methods of controlling their size and position so as to form ordered arrays with narrow size distributions. This could lead to the engineering of the nanoscale atomic structure of the active layers so as to achieve great improvements in efficiency and could ultimately lead to the development of III-N lasers spanning the range from pure InN (700 nm) to pure AlN (~200 nm).

Type II "W" Lasers for Infrared (InAs/GaSb)

Mid-infrared detectors based on InAs/indium (In), gallium (Ga) antimony (Sb) strained layer superlattices (SLSs) have been investigated for the past 15 years, ever since they were first proposed by Smith and Mailhiot (1987). The main advantage of this system lies in the fact that the band gap of

[12]See, for example, the Nanowire Templated Lateral Epitaxial Growth of Low Dislocation Density GaN, described at http://www.netl.doe.gov/ssl/portfolio-07/current-light/NanowireTemplatedLateral.htm. Accessed July 18, 2007.

the superlattice can be tailored over a wide range of wavelengths (2 μm < λ_c < 30 μm) by varying the thickness of the constituent materials. Thus, using two "mid" band gap semiconductors, devices can be fabricated with an operating wavelength spanning the entire regime—mid-wave infrared (MWIR), 3 μm < λ < 5 μm; long-wave infrared (LWIR), 8 μm < λ < 14 μm; and very long wave infrared (VLWIR), λ > 14 μm (Aifer et al., 2003; Fuchs et al., 1997; Johnson et al., 1996; Miles et al., 1990; Plis et al., 2006; Wei et al., 2005). Kaspi et al. (2002) have demonstrated high-power mid-infrared lasers using this technology.

Quantum Wire Heterojunctions and Carbon Nanotube Emitters

One-dimensional nanostructures, including semiconductor nanowires and carbon nanotubes (CNTs), have recently been investigated by a number of groups as potential nanoscale optoelectronic and photonic building blocks. In particular, GaN-based nanowires have shown promise as nanoscale light emitters and lasers in the UV to visible light range. Compared to conventional, planar GaN technologies that form the basis for current solid-state light emitters (LEDs) and lasers in the UV-to-green spectrum, GaN-based nanowires offer several potential advantages. One inherent advantage of nanowires, which can be considered one-dimensional systems, over planar systems is the ability to relieve strain energy by means of lateral relaxation. This quality has enabled the growth of high-quality, dislocation-free nanowires directly on lattice mismatched substrates, and it raises interesting possibilities for achieving highly efficient LEDs based on nanowire heterostructures. Because mismatch strain inhibits indium incorporation in InGaN on GaN, which is necessary for green emission, InGaN/GaN heterostructure nanowires may provide a route for achieving higher indium mole fractions due to strain relaxation. Reduced strain may also result in reduced piezoelectric fields in the active region, which may result in higher radiative recombination efficiency due to the increased hole and electron wavefunction overlap. The ability to grow nanowires free of dislocations is a further advantage that would result in additional improvements in the efficiency and lifetimes of nanowire-based emitters versus planar-based devices.

Another factor limiting the performance of conventional, planar LEDs is poor light-extraction efficiency due to internal reflection, which effectively traps the light within the device. Light-emitting nanowires may provide a solution to this issue, as they may have inherently high extraction efficiencies owing to their high number of facets, high aspect ratios, and subwavelength dimensions. Enhanced extraction efficiency has been observed in LEDs that have undergone "chip-shaping" to create beneficially angled facets (Krames et al., 1999), as well as in LEDs with reduced die areas, and so it is anticipated that quantum wires, with their large number of facets and high surface-to-volume ratio, will exhibit very high extraction efficiencies. Further, quantum wires of subwavelength dimension are expected to exhibit little internal reflection, if any.

Recently, Lieber and coworkers have demonstrated intense, color-tunable, and efficient light emission from individual core-multishell GaN/InGaN nanowires, as described in Figure 2-26. Recent advances have also demonstrated the growth of dense, vertical arrays of dislocation-free GaN nanowires (Wang et al., 2006a). The absence of dislocations arises due to the efficient strain relaxation enabled by the nanoscale sizes of the wires, and it is speculated that their absence could result in drastically reduced nonradiative exciton recombination rates. Dense, ordered arrays of heterostructure GaN-based nanowires could form the basis for highly efficient LEDs and lasers that address many of the issues afflicting current, planar-based technologies.

In addition, electroluminescence in CNT devices has been demonstrated, by taking advantage of the presence of Schottky barriers at the contacts. This allows the nanotube transistor to be biased such that holes are injected at one contact while electrons are injected at the other contact. The recombination of

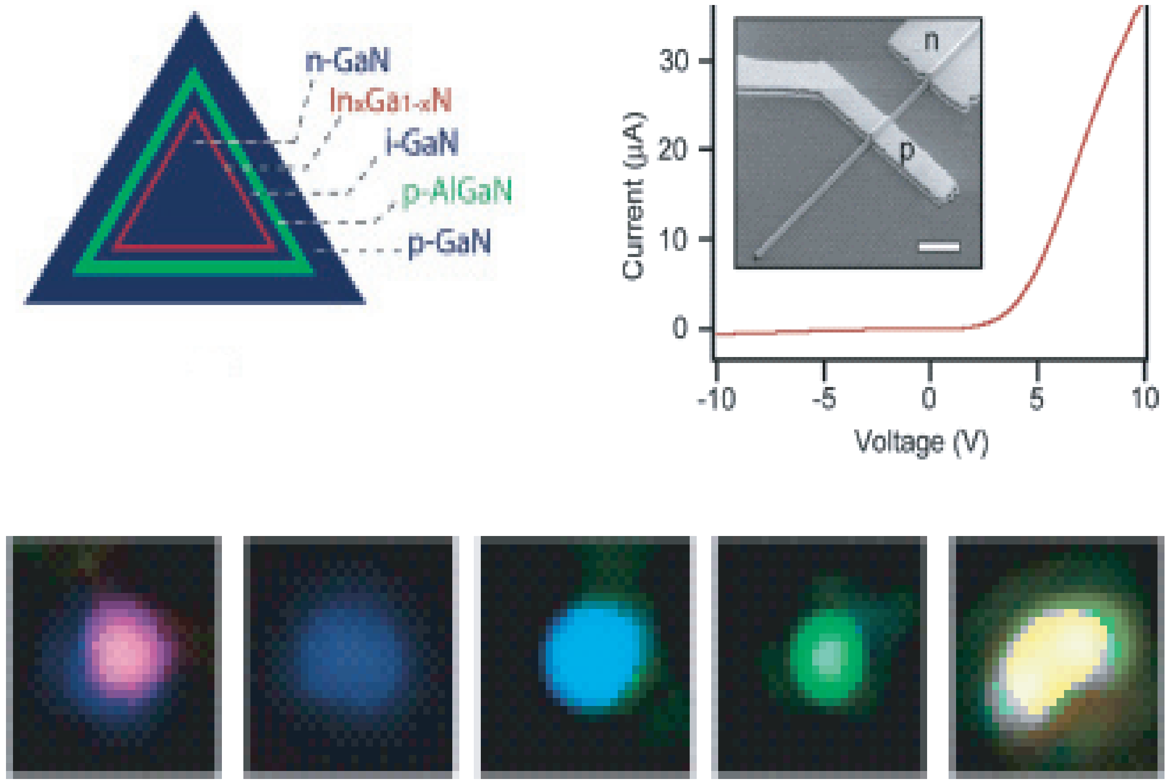

FIGURE 2-26 Core/shell nanowires allow the formation of color-tunable light emitters by changing the shell composition. (Top left) Sketch of the cross-section of a core/shell nanowire and (top right) a scanning electron microscope image of a single nanowire light-emitting diode and its current-voltage behavior. (Bottom) Light spots from nanowires of different shell composition. SOURCE: Reprinted with permission from Qian et al. (2005). Copyright 2005 American Chemical Society.

the electrons and the holes in the nanotube leads to light emission, with a wavelength that can be tuned by changing the diameter of the nanotube (Misewich et al., 2003). A variation of this approach uses very sharp band bending along the length of the nanotube to give very bright light emission from nanometer scale regions (Chen et al., 2005).

New Devices: Detectors and Modulators

Plasmonic Detectors

As discussed in earlier sections of this chapter, plasmons are the collective oscillations of the electron gas in a metal or a semiconductor. Plasmons naturally oscillate at very high frequencies, typically in the infrared region for metallic nanoparticles. However, the previous sections of this chapter have primarily dealt with plasmons in metallic nanostructures. In metallic nanostructures, the electron densities of the metals are essentially fixed, and the primary method of changing plasmon resonances is by changing the dielectric constant of the surrounding matrix material. Recently, however, it has been shown that the plasmon oscillations occurring in laterally confined quantum well structures can be used as resonant detectors of electromagnetic radiation. This opens up the possibility of an entire new class of *active plasmonic semiconductor devices*. These devices may enable revolutionary new capabilities based on two distinct advantages that they have over metallic plasmonic structures:

1. Because the charge layer is in a semiconductor QW, the charge-carrier density can easily be tuned with an electrostatic gate, as in a typical metal-oxide semiconductor field-effect transistor (MOSFET). This enables tuning of the plasmon oscillation frequency over an extremely wide range.
2. The QW in which the plasmon oscillation occurs can simultaneously be used as an electrical sensing channel in a MOSFET configuration.

The plasmon frequency easily extends into the terahertz in standard semiconductor materials, which opens up the possibility of creating a variety of devices, with new capabilities that are unattainable using conventional electronics and device concepts. It also turns out that the wavelength of plasmons is typically hundreds of times smaller than the wavelength of light, opening up the possibility for sub-wavelength detectors and nanoscale high-speed devices.

Tunable narrowband detectors of terahertz radiation, called plasmonic grating-gate detectors, which take advantage of the unique properties of plasmons, have recently been demonstrated. Essentially, these devices are field-effect transistors (FETs), except that the gate is fashioned into a grating to define distinct plasmon oscillations in the FET channel. The grating serves the additional function of coupling radiation into the plasmon channel. The detector sensitivity does not yet compete with broadband Schottky diode detectors, but using tunable plasmon excitations for the absorption mechanism provides unique "spectrometer-on-a-chip" functionality. The frequency response of the detectors is determined by the period of the grating the voltage bias on the gate (variable). To date, detection of radiation has been demonstrated from 100 gigahertz (GHz) (16 micron grating period) to 1 THz (4 micron grating period), although higher frequencies are easily attainable (see Figure 2-27).

Since the grating-gate detectors operate at normal incidence, they naturally lend themselves to focal plane arrays (FPAs) for terahertz imaging. Additionally, the subwavelength nature of semiconductor plasmons opens up the exciting possibility of multispectral FPAs. The useful pixel size, or system spot-size, of an imaging system is limited by the wavelength that one is looking at. Grating-gate detectors can easily operate at sizes significantly below these limits; this enables the placement of detectors within what would normally be considered the size of a single pixel (see Figure 2-27). Since these detectors have spectral analysis capability, each pixel could look at a different frequency range, or each pixel could look at the same frequency, but have a different plasmon harmonic in order to increase noise immunity.

Nanoschottky Diodes

The rectifying electrical contact between a metal and a semiconductor is called a *Schottky diode* and is a well-established and widely used radio-frequency and microwave signal detector. Schottky diodes are particularly valued as heterodyne mixer detectors, which generate a difference frequency between an unknown signal to be detected and a known frequency from a local oscillator. The ability to determine an unknown signal's frequency relative to the known local oscillator and the very high sensitivity possible using heterodyne mixing detection make Schottky diode-based receivers the technology of choice in many radio and microwave communications and radar applications.

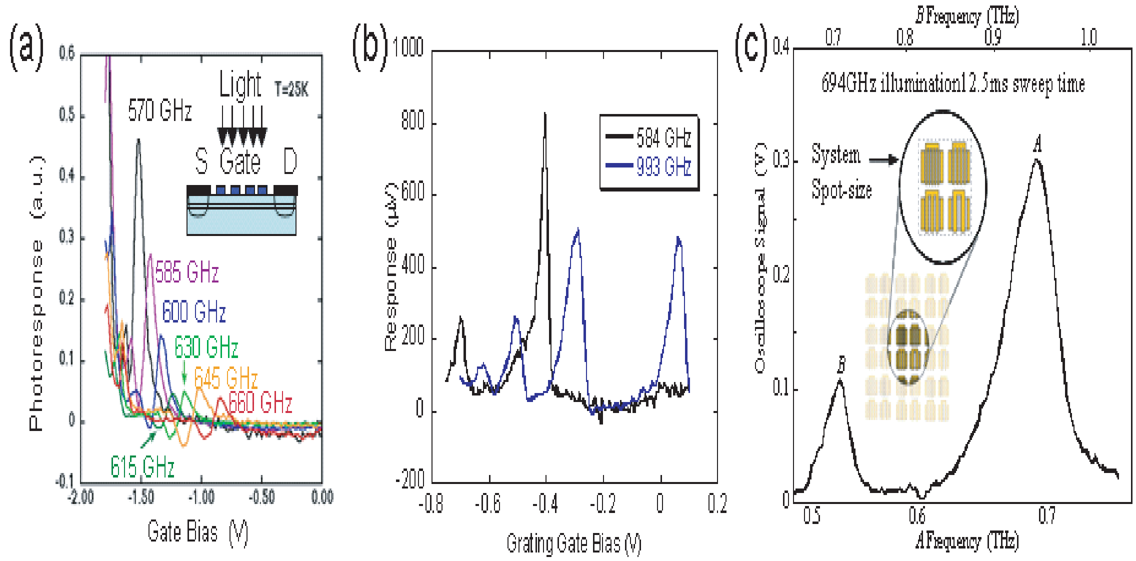

FIGURE 2-27 (a) Photoresponse of a plasmonic grating-gate detector as a function of gate bias for many different radiation frequencies. Clearly, each frequency produces a peak at a different gate voltage, demonstrating that the device can function as a "spectrometer-on-a-chip." Inset shows the normal incidence detection geometry. (b) Response of a single detector to two vastly different frequencies, 584 GHz and 993 GHz, covering 400 GHz bandwidth. Higher harmonic plasmon oscillations are clearly present. (c) Demonstration of true spectrometer-on-a-chip functionality with a 12.5 ms duration full spectral sweep. The multiple plasmon peaks in the detector response, while understood and predictable, tune in slightly different ways. The gate bias has been calibrated in units of frequency, with the lower axis corresponding to peak *A*, and the upper axis to peak *B*. Inset: illustration of how the subwavelength nature of the detectors enables multifunctional single pixels that operate within the diffraction-limited spot-size of an imaging system. SOURCE: Provided by committee member, Jerry Simmons.

Extending heterodyne mixing methods to higher frequencies, namely, as high as the near-infrared, presents a significant technological challenge. To function at higher frequencies, the parasitic capacitance of a diode mixer must be minimized so that high- frequency signals are not inadvertently shunted around the detector. For a Schottky diode, reducing capacitance requires making the contact area between metal and semiconductor extremely small. Using sophisticated nanofabrication methods, Schottky diodes with contact diameters of about 250 nm have been made with electron-beam lithography and carefully controlled etching. Such a contact area allows Schottky diodes to function as mixers up to far-infrared frequencies around 3 THz (Siegel et al., 1999).

Such electron-beam nanofabrication methods are very expensive, slow, and may not be able to produce Schottky mixers that work above 10 THz. However, recent research in semiconductor nanowires and carbon nanotubes may provide a "bottom-up" alternative route to fabricating Schottky mixers en masse at much lower cost and usable to much higher frequency, possibly to the mid- or near-infrared region. This possibility derives from the fact that such nanowires and nanotubes can be easily, controllably, and reproducibly synthesized with intrinsic diameters of 5 nm to 100 nm, eliminating the need for lithographic definition and precision etching down to nanometer length scales. Such nanomaterials are also amenable to inexpensive and fast self-assembly methods, such as dielectrophoresis, to place nanomaterials at specific points in a circuit. Most importantly, it has been shown that the contact between a semiconductor nanowire or semiconducting CNT and a good metal, such as gold, forms a Schottky diode contact with good electrical characteristics. If the nanotube/wire-to-metal contact area can be reliably limited to the diameter of the nanomaterial, area scaling arguments imply that the parasitic capacitance can potentially be reduced enough to enable mixer operation as high as near-infrared frequencies around 100 THz (Manohara et al., 2005). Such nano-Schottkys would bring to the near-infrared the benefits of heterodyne detection that are used so extensively in the microwave (Highstrete et al., 2006).

Detectors Based on Quantum Wires and Carbon Nanotubes

Devices that convert photons into electrical signals typically fall in two categories: those used simply to detect an optical signal (photodetectors) and those used to convert optical energy into electrical energy (photovoltaic devices or "solar cells"). In the photodetector area, one of the challenges is to detect low light intensities. Nanowires and carbon nanotubes offer potential because of their small size and ballistic electron transport. For example, a recent approach has used carbon nanotubes functionalized with chromophores to optically switch transistors with low-intensity UV light (Simmons et al., 2007). In the photovoltaic area, current approaches use either inorganic or organic materials. For maximum efficiency, inorganic solar cells require a semiconductor with a direct band gap such as GaAs. However, the cost per watt of such solar cells exceeds economic practicality because of the high cost of fabrication with such materials. On the other hand, silicon solar cells can be fabricated at much lower cost, but because Si has an indirect band gap, the efficiency is not as high. A similar situation arises with organic solar cells, which are inexpensive but have low efficiencies.

Nanowires and nanotubes may provide solutions to these problems. For example, not only are all the band gaps in all carbon nanotubes direct, but each carbon nanotube possesses a series of direct band gaps that span the infrared, the visible, and the ultraviolet. Furthermore, because the transport in nanowires and carbon nanotubes may be made ballistic, energy loss to scattering is reduced, giving additional improvements in efficiency. Recent calculations for carbon nanotube p-n junction devices have indicated that relatively high energy conversion efficiencies can be achieved (Stewart and Leonard, 2005; Stewart and Léonard, 2004); experimental realizations (Lee, 2005) of such devices show that they behave as near-ideal diodes with high conversion efficiencies (Lee, 2005; Stewart and Leonard, 2005; Stewart and Léonard, 2004).

Quantum-Confined Stark Effect Electro-Absorption Modulators

Early in the development of single- and multi-quantum well lasers, workers observed that the excitonic absorption edge of quantum wells red-shifts (moves to longer wavelength or lower energy) under the influence of an applied field (Yuh and Wang, 1988). This characteristic was quickly exploited to create external optical modulators for high-speed telecommunications over optical fiber. By placing several quantum wells in the center of a reverse-biased p-n junction and engineering the band gap to sweep through the transmitted photon energy under the applied voltage, quantum-confined stark effect (QCSE) electro-absorption modulators (EAM) can be made to reduce optical transmission by 35 decibels (dB) or more (Kawano et al., 1997; Takeuchi et al., 1997). These EAMs quickly replaced direct modulation of laser diodes for long-haul telecommunications because of their superior modulation speed and low residual wavelength modulation, or chirp. Today, QCSE EAMs have shown direct electrical modulation bandwidths in excess of 60 GHz, with some highly specialized structures exceeding 150 GHz (Kodama et al., 2004).

With the development of quantum well intermixing (QWI), these QCSE EAMs can be monolithically integrated with QW diode lasers and other optical devices such as photodiodes. QWI is an extremely powerful post-growth nanoengineering technique by which the width of a QW can be reduced with sub-nanometer precision causing the zero-field absorption edge to blue-shift as much as 120 nm (Skogen et al., 2002). Intermixing of quantum wells is achieved by artificially lowering the thermodynamic barrier to diffusion of individual atoms within the crystal lattice, having the effect of locally grading the as-grown abrupt heterojunction. Grading the band gap of the heterojunction alters the shape of the quantum well potential, giving the desired blue-shift. One method used to initiate intermixing is to implant phosphorus (P) atoms into InP. Under thermal treatment these excess P atoms and In vacancies diffuse through the crystal causing local intermixing. Together the development of QW lasers and QCSE EAMs with QWI have played a major role in the development of modern photonic integrated circuits (PICs).

New Class of Optoelectronic Devices Based on Intraband Transitions

Band Structure Engineering: Overthrowing Nature's Band Gap Tyranny

Up until now, this section of the report has discussed a number of new types of optoelectronic devices enabled by the introduction of nanophotonic structures. Thus, for instance, the QD laser promises great enhancements in performance owing to the confined density of states of the QD. The basic operating principle, however, remains similar to that of conventional semiconductor lasers.

At this point, however, let us turn to a set of completely novel nanophotonic device operating principles enabled by quantum confined structures: those based on *intraband transitions*. These devices employ energy-level control and population through band structure engineering, modulation doping, and electron tunneling. The canonical examples include quantum well infrared photodetectors (QWIPs) (Levine et al., 1987) and quantum cascade lasers (Faist et al., 1996). Unlike their conventional predecessors, these devices depend on using the physical concepts of tunneling, superlattice energy bands, and quantum confinement to create new optical devices whose properties depend only secondarily on the intrinsic characteristics of the semiconductor materials from which they are made. Rather, their properties are primarily determined by the thickness of the few-nanometer-thick layers that compose them—that is, the quantum confinement effects of the quantum wells and the tunneling characteristics of the barriers between them. Indeed, these devices are enabling a revolutionary new generation of optoelectronic devices operating in wavelength regions previously inaccessible to solid-state technology. Their revolutionary character arises in their use of engineered electron transitions *solely in a single-electron band*. Indeed, many of these devices are actually *unipolar optoelectronics*, since they involve carriers of only one charge polarity, either electrons or holes. By contrast, most optoelectronic devices heretofore employed electronic transitions between the conduction and valence bands, involving both electrons and holes. This meant that device characteristics were almost entirely determined by the band gap of the material. Hence, by incorporating new physical concepts and approaches, scientists have been able to overthrow nature's band gap tyranny and access new spectral regions.

QWIP Detectors

One of the first engineered unipolar optoelectronic devices was the quantum well infrared photodetector, or QWIP (Levine, 1993). The QWIP uses a series of quantum wells with typically n-type doping to populate the ground state of the QW. Under bias in the dark, the structure draws little current since all the electrons are trapped in the ground-state level of the QWs. However, when exposed to light, the electrons are excited out of the QWs and into continuum energy levels, where they are free to carry current to the device contacts. Conceptually, the QWIP can be thought of as an engineered photoconductor, where instead of electrons being excited out of defect levels determined by nature, they come from QW subband energy levels engineered by the magnitude of the QW potential and the width of the QW.

The QWIP is one of the most successful optoelectronic devices based on quantum confinement reduced-dimensionality effects. Large-imaging focal plane arrays (FPAs), 2,000 x 2,000 pixels, are now manufactured. At operating temperatures above 70 K, the detectivity of the QWIP is considerably lower than that of HgCdTe photodiodes; however, they have the advantage of not being subject to the high degree of defect problems that HgCdTe exhibit. Additional innovations being explored in QWIP-type structures include, for instance, voltage-tunable two-color QWIPs, which could allow increased levels of target discrimination (Majumdar et al., 2003).

One extension of QWIPs that holds promise for matching and exceeding the performance of HgCdTe photodiodes is QDIPs, or quantum dot infrared photodetectors. The quantum dots are formed through the strain-energy-driven two-dimensional to three-dimensional morphology transition when compressively strained films (InAs or InGaAs) are grown on larger band gap matrices (GaAs, AlGaAs, or InGaP). The QD ground state is populated with electrons by intentional n-type doping. Historically, efforts on QDIPs looked at quantum dot inclusion in a GaAs matrix (Chakrabarti et al., 2004; Pal et al., 2003). This approach requires tuning of the QD electronic levels to change the wavelength response and makes any device extremely sensitive to process changes. Also the wavefunction overlap between the occupied QD ground state and the continuum of states in the GaAs matrix is predicted to be low. An improved approach is to utilize a dot-in-a-well (DWELL) structure that couples the ground state of the QD to the unoccupied state that is determined by the QW width (Raghavan et al., 2004). Changing the QW width can vary the transition energy between the QD to QW. This design also results in a larger wavefunction overlap between bound states in the QD and the QW. QDIP devices have been the subject of intense interest as a possible replacement for HgCdTe and as a possible route to VLWIR radiation sensors (Krishna et al., 2003). The development of QDIP sensors could then leverage the developed FPA technology for QWIP FPAs to provide a higher-yield, lower-cost MWIR and LWIR imaging solution.

QDIPs have several potential advantages over QWIPs: sensitivity to normal incidence radiation, increased responsivity due to increased excited carrier lifetime, and higher-temperature operation due to reduced overlap of the QD density of states with the three-dimensional carrier distribution. The three-dimensional structure of the quantum dot allows it to couple to normal incidence radiation. This eliminates the need for surface patterning, such as gratings to couple only a fraction of the normal incidence radiation into the QWIP. The increased carrier lifetimes in quantum dots, tens of nanoseconds compared with tens of picoseconds for quantum wells, is attributed to reduced carrier-phonon coupling and results in higher detectivity. Higher-temperature operation is a result of reduced overlap of the quantum dot density of states with the distribution of states in the matrix. If these advantages can be realized, QDIPs should represent a superior alternative to QWIPs for infrared sensing. Displacing HgCdTe photodiodes is more difficult for middle-wavelength-infrared (3 μm to 7 μm) imaging. QDIPs represent at best an alternative technology in this part of the spectrum. At longer wavelengths, QDIPs should be competitive with HgCdTe photodiodes, and for VLWIR (>15 μm) QDIPs represent an opportunity to obtain radiation sensors operating at 70 K. State-of-the-art QDIPs are at best equal to QWIPs in performance. Most of this development has targeted the LWIR atmospheric window (8 μm to 12 μm). The development of QDIP sensors could easily leverage the development of QWIP FPA technology to provide a higher-yield, lower-cost LWIR imaging solution.

Quantum Cascade Lasers

Quantum cascade lasers are one of the most dramatic examples of a completely new device operating principle emerging from the ability to confine electron levels in reduced-dimensionality structures. The first QCL was demonstrated in 1994, at a wavelength of 4.2 μm (Faist et al., 1994).

QCLs operate by engineering the electron energy levels and tunneling coefficients in a multilayer structure. The device is an all-electron device, with the only the conduction band having any influence on its operation, and it can be fabricated in many material systems but is typically made with InGaAs/InAlAs or AlGaAs/GaAs heterostructures. While many design variations exist, a single cell or "unit period" of the QCL can be thought of as a three-level structure where the energy separations between the levels are completely engineered, allowing the designer to choose the operating wavelength. Electrons are injected electrically into the upper energy level and transition to the middle level by emitting a desired photon. The electron transition to the lowest level from the middle level is engineered to keep the middle energy level at a very low population, enabling population inversion between the top two levels. Since the electrons are still in the conduction band, by clever use of band structure engineering and tunneling, the electrons are transported from the lowest level into the highest level of the next cell, allowing the process to be repeated. By stacking many cells together—up to 200 or more for the longest wavelengths—sufficient gain can be achieved that the structure will produce lasing. Thus, a single electron will emit a photon for each cell it traverses, resulting in a cascade-like motion as it moves through the QCL structure, which is of course the origin of the name for the device.

QCLs are a triumph of band structure engineering, simulation and modeling, and high-precision epitaxial growth techniques. The energy levels, tunneling probabilities, wavefunction distributions, and decay rates must all be extremely well designed and controlled. A typical design is to space the middle and lowest levels apart by the optical phonon energy, ensuring that the middle level is rapidly depopulated so that population inversion can occur.

QCL emission wavelengths are limited to less than the conduction band offset in the host ternary compound semiconductor system—for example, to less than the conduction band offset energy in the material system (and in actuality about half the offset). In practice, QCLs have been demonstrated with wavelengths between 3 to 24 microns and between 60 and 200 microns, covering large portions of the electromagnetic spectrum from the mid-infrared out to the terahertz. Their advantages, in addition to a broad range of wavelength ranges, include high power and high-temperature operation. (Of course, achievable powers and operating temperatures are a strong function of wavelength. Record powers are near 10 watts (W) in the mid-IR and 250 milliwatts (mW) in the terahertz, while record operating temperatures are >300 K in the mid-IR and up to 164 K in the terahertz.

Terahertz Quantum Cascade Lasers

The first quantum cascade laser to operate in the terahertz frequency range was reported in 2001 (Kohler et al., 2002). Now terahertz QCLs have been demonstrated to operate with frequencies from 1.6 THz to 4.9 THz and record powers of 250 mW (pulsed) and 140 mW (continuous wave) (Williams et al., 2006). Prior to this, the standard for continuous-wave terahertz lasers was molecular gas lasers. These bulky and expensive systems consist of a meter-long gas tube, pumped by a CO_2 laser in another meter-long tube, and weigh on the order of 100 kilograms (kg). The development of terahertz QCLs enables highly compact (less than 1 mm long), low-weight, and inexpensive laser sources in this frequency regime. By integrating terahertz QCLs with coherent detectors, it may be possible to build compact terahertz transceivers with far greater sensitivity and frequency resolution than that of direct detection techniques. At present, such a system would still need to be cooled, limiting the extent to which it could be miniaturized. However, numerous schemes are being developed for higher-temperature operation, and much progress has been made. It is conceivable that room-temperature operation could be achieved in the not-too-distant future.

As discussed in the applications section, the terahertz portion of the spectrum is important for a number of reasons. First, the rotational frequencies of many molecules, from simple diatomic chemicals to complex macromolecules, have stronger and more distinctive absorption and emission resonances in the terahertz than in either microwave or near-IR regions. Thus, terahertz has great promise for the chemical and biological (especially chemical) detection of various threats. (However, due to the severe attenuation of terahertz radiation in the atmosphere, this detection would have to be relatively short range.) In addition, terahertz has considerable promise for through-object imaging, including inspection of passengers for hidden objects and packages. The shorter wavelength of terahertz renders the imaging resolution far superior to that of microwaves, when needed. Finally, because of the atmospheric attenuation and the ability to produce highly directional beams of radiation, terahertz may also be useful for covert communication.

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3

Enabling Technologies

The development of enabling technologies, along with significant infrastructure, will be essential for the implementation of commercial and military applications of nanophotonics. This chapter describes essential enabling technologies, including the synthesis, growth, and fabrication of nanomaterials and nanostructures; modeling and simulation; characterization techniques for nanophotonics; and the packaging and integration of nanophotonics devices. The development of these enabling technologies in a country is often an important indicator of the state of maturity of nanophotonics in that country.

REALIZING HIERARCHICAL SYNTHESIS, GROWTH, AND FABRICATION STRUCTURES AT THE NANOSCALE

Introduction

Traditionally, synthesis, growth, and fabrication have been separately identified stages in the development of functional devices. An example is a semiconductor laser: the synthesis is in developing the nearly defect-free substrate (gallium arsenide [GaAs], for example) and in developing the feed materials for the epitaxial crystal overgrowth. The growth stage as related to a semiconductor laser is the epitaxial formation of an optical cavity and gain structure for the appropriate confinement of both the photons and the electronic carriers using molecular-beam epitaxy or metal-organic chemical vapor deposition (MOCVD), typically on a wafer scale. The fabrication stage uses processes adapted largely from integrated circuit manufacturing to batch fabricate diode lasers with contacts for electrical input and optical output as required for the device application. In the nanoscale era, these distinctions among synthesis, growth, and fabrication are blurring. The steps outlined above are being employed in mix-and-match ways to produce novel functional nanostructured materials and to arrange them with the necessary hierarchical organization to produce new functionalities.

This subsection describes the traditional categories of synthesis, growth, and fabrication, and then comments on the blurring of the boundaries among these stages. As the terms are used here, *synthesis* includes not only the starting materials, but also the formation of isolated nanostructures, such as metal and dielectric nanospheres and quantum dots, and fabricated multilayer combinations. Additionally, the chemical synthesis of starting materials such as copolymers and liquid crystals is included. *Growth* as used here is specifically limited to the epitaxial growth of semiconductor materials; it also includes self-assembled arrays via nanoparticle formation, such as Stranski-Krastanov formation of quantum dots by the interplay between strain and surface tension. *Fabrication* refers to the creation of ensembles of nanostructures—for example, photonic crystals composed of nanoparticles.

Traditional top-down processing derived from the integrated circuit industry is reaching to scales of direct relevance to nanophotonics and beyond and certainly will be an important component of any nanophotonics fabrication suite. This is so in part as a result of the strong ability of traditional top-down processing to engineer hierarchical structures incorporating multiple, disparate length scales and the proven mass production capabilities of batch wafer processing. *Self-assembly* is bottom-up processing; a simple example is the assembly of colloidal nanoparticles into photonic crystal arrangements. A related approach is the use of multiphase systems, such as block copolymers[1] along with surfactant-covered nanoparticles, to spontaneously form complex patterns driven by an external forcing function such as evaporation.

Increasingly, techniques are being developed that combine top-down and bottom-up approaches and blur the distinctions of the categories described above. One example is nanoscale crystal growth, in which a pattern is defined by fabrication and a subsequent growth process results in an array of nanoscale semiconductor structures. The fabrication can occur either by self-assembly (as, for example, porous anodization of a continuous metal film) or by traditional lithographic pattern definition and etching. As opposed to the subtractive etching of a large-area semiconductor film (the growth described above), this sequence allows much more flexibility and often produces materials with fewer defects and improved functionality. Generically, this combination is referred to as *directed self-assembly*.

Figure 3-1 shows a lithographic template that serves to guide the self-organizing crystals, block polymers, or colloids to pack and orient into a predetermined pattern, thus bringing the ultrasmall length scales achievable by molecular self-organization into play with the somewhat larger engineered structures to create hierarchical devices.

Synthesis

Nanoparticles

The need for improved optical materials has driven researchers in chemistry, materials science, and chemical engineering to create new synthetic pathways to afford better control over the composition, size, and shape of nanoparticles in order to produce new types of supramolecular building blocks. As mentioned in Chapter 2, metallic nanoparticles, such as gold nanostars, can be useful for localized surface plasmon resonance. Thus, it is important to control not only particle size but particle shape. Moreover, it is absolutely critical to have monodispersity in size and shape.

Researchers have found that absorbed surfactants can influence the relative growth rate of various facets (surfactant binding and size-dependent facet surface energies) resulting in the growth of complex-shaped nanoparticles. For example, Alivisatos and colleagues found that they could create tetrapod gold (Au) or cadium selenium (CdSe) nanoparticles. The Au particles are composed of a set of (111) twin

[1] *Block copolymers* are made up of two or more homopolymer subunits linked by covalent bonds. Block copolymers with two (or three) distinct blocks are called *diblock* (or *triblock*) *copolymers*.

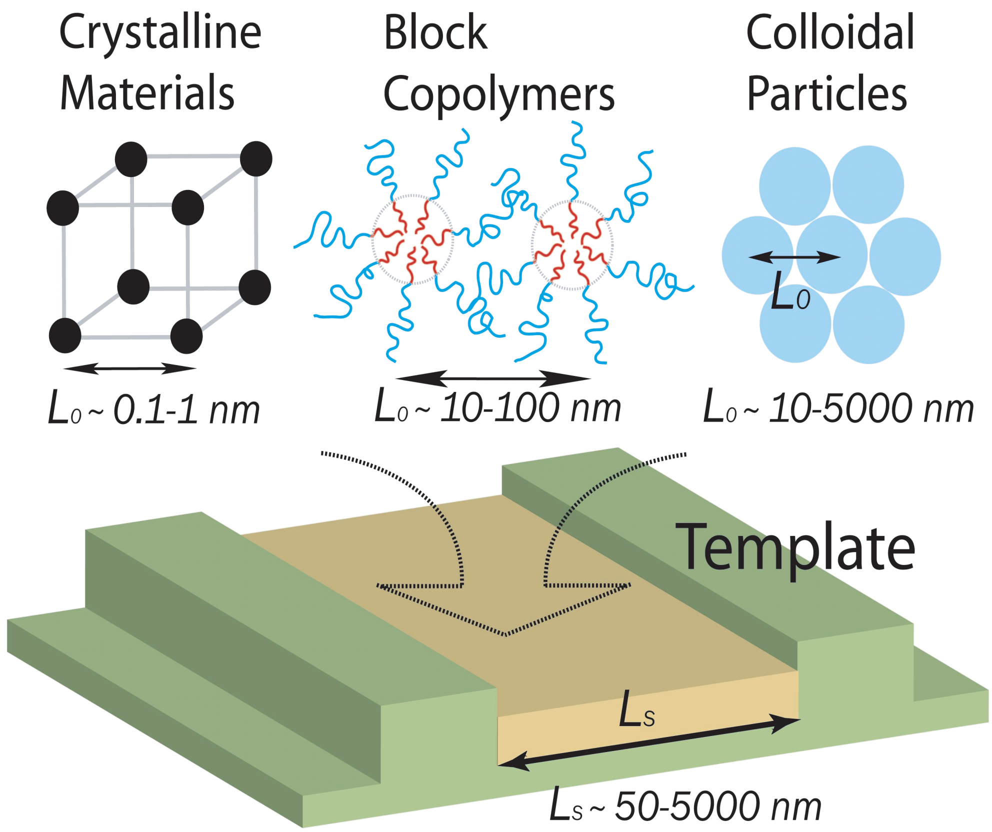

FIGURE 3-1 A top-down lithographically defined template can guide the bottom-up self-assembly of materials, creating a system with several length scales: a structural hierarchy. SOURCE: Cheng et al. (2006b). Copyright 2006 Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

Au crystals (Manna et al., 2002). Additionally, hollow nanoparticles can be produced by the oxidation of metallic nanocrystals and directional diffusion of species (the Kirkendall effect) (Yin et al., 2004).

Traditional solution synthesis has recently been extended to microfluidic reactors, in which on-chip in situ monitoring of the growing entities and the ability to add chemical feed streams and to adjust residence times provide opportunities for dynamic adjustment and tuning of the targeted materials. An example is shown in Figure 3-2, where an overcoating of zinc sulfide (ZnS) onto CdSe quantum dots (QDs) increases the quantum yield from ~10 percent to ~40 percent along the reactor pathway. The meandering synthesis channel is fabricated in silicon and is thermally isolated from the room-temperature inlets and outlet. ZnS overcoating reagents enter through the side inlets to enable core-shell particle growth without secondary nucleation.

Advances in microfluidic reactors will increasingly impact the ability to engineer many types of nanoparticles because, instead of batch reactions with a Schlenk line apparatus with multiple step-function injections of reactants, one can tailor concentration-time schedules and use gradients and can separate and remix-recycle, impinge, and sinter or stack the growing targets to achieve desired structures and properties. Currently most particles are homogeneous or core-shell and either spherical

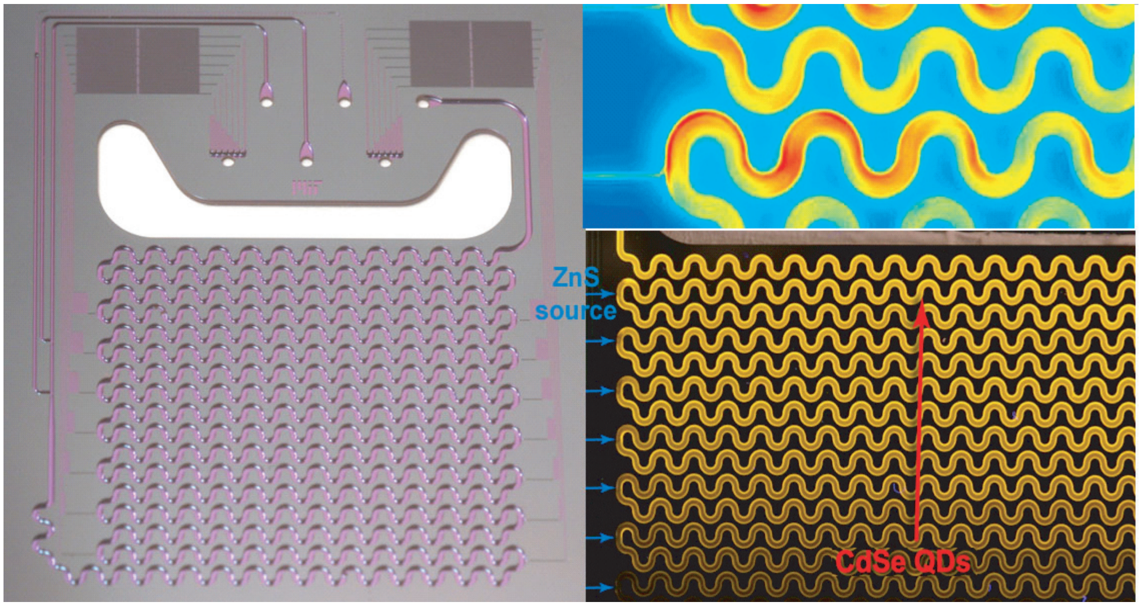

FIGURE 3-2 Microfluidic reactor for the synthesis of zinc sulfide (ZnS) overcoated cadium selenide (CdSe) quantum dots. The brightness in the lower right image increases from bottom to top, indicative of the increased quantum efficiency as the ZnS overcoat layer forms on the CdSe dots. SOURCES: Yen (2006), Yen et al. (2005). Reproduced with permission.

or cylindrical; however, multicomponent, complex-geometry particles are possible and can provide structural and functional anisotropy.

Layered-Nanoparticle Fabrication Techniques

Layered nanoparticles with a core-shell geometry in which the core and shell layers consist of either a dielectric material or a noble metal are of scientific interest, as the optical properties of these particles can be controlled by adjusting the thickness of each layer. The most common types of core-shell particles are nanoshells, which consist of a silica core coated with a thin layer of gold or silver (Oldenburg et al., 1998). The opposite particle consisting of a gold or silver colloid as the core particle coated with a silica shell of varying thickness can also be made (Liz-Marzan et al., 1996). The optical properties of these particles are controlled by the ratio of the core radius to the total particle radius. Similar to these, but nonspherical in shape, are spindle-shaped iron oxide particles coated with a thin layer of gold (Wang et al., 2006b). Core-shell semiconductor particles are also important—for example, a thin (<1 nm) ZnS outer shell passivates CdSe quantum dots.

The silica core particles are typically synthesized using the Stöber process (Stöber et al., 1968). The Stöber method involves the base catalyzed hydrolysis and condensation of tetraethylorthosilicate (TEOS). Typically, TEOS and ammonium hydroxide (NH_4OH) are mixed in varying ratios in ethanol to produce silica nanoparticles in the 80 nm to 500 nm diameter size regimes. After the silica particles are synthesized, the surface is functionalized with a silane, such as 3-aminopropyltriethoxysilane (APTES).

This chemical functionalization of the silica surface provides an amine moiety at the surface, which is used to attach ultrasmall gold colloid. Ultrasmall gold colloid particles of 1 nm to 3 nm in size are synthesized by reducing chloroauric acid using tetrakis (hydroxymethyl) phosphonium chloride (THPC) as a reducing agent. The ultrasmall gold attached to the silica surface act as nucleation sites for the electroless deposition of Au (or silver [Ag]) to form a complete shell on the silica core. The technique for depositing gold layers on spindle-shaped hematite particles is similar to depositing a gold layer on silica particles.

The growth of silica layers on gold or silver colloidal particles follows an inverse process. A solution of gold particles with an average diameter of around 15 nm and 10 percent polydispersity is used to form the core of these layered particles. A freshly prepared aqueous solution of APTES (2.5 milliliters [ml], 1 millimeter [mm]) is added to 500 ml of the gold solution under vigorous magnetic stirring. The mixture of APTES and gold dispersion is allowed to stand for 15 minutes to ensure complete complexation of the amine groups with the gold surface. A solution of active silica is prepared by lowering the pH of a 0.54 weight percent sodium silicate solution to 10 to 11 by the progressive addition of cation exchange resin. Twenty milliliters of active silica are then added to 500 ml of the surface-modified gold solution, again under vigorous magnetic stirring. The resulting dispersion (pH ~8.5) is then allowed to stand for at least 1 day, so that the active silica polymerizes onto the gold particle surface. The silica shell thickness is about 2 nm to 4 nm after 24 hours. The particles can then be transferred into ethanol if further growth or chemical modification of the silica layer is intended. At this point, thicker silica shells can be grown using the Stöber method.

Another class of these layered particles consists of monolayers of silica or polystyrene nanoparticles coated with a layer of metal (Dieringer et al., 2006). This geometry has also been used for plasmonic applications such as surface-enhanced spectroscopy. The fabrication process begins with the self-assembly of monodisperse nanospheres to form a two-dimensional colloidal crystal. A substrate is prepared so that the nanospheres freely diffuse until they reach their lowest energy configuration. This is achieved by chemically modifying the nanosphere surface with a negative charge that is electrostatically repelled by a negatively charged substrate such as chemically treated glass. As the solvent (water) evaporates, capillary forces draw the nanospheres together, and they crystallize in a hexagonally close-packed pattern on the substrate. Following self-assembly of the nanosphere mask, a metal (typically silver) is deposited by physical vapor deposition from a collimated source normal to the substrate through the nanosphere mask to a controlled mass thickness. The resulting surface is referred to as a metal (e.g., Ag) film over nanosphere (AgFON) surface.

Nanorods and Nanowires

Nanorods and nanowires are another promising type of nanoparticle that can be made a variety of ways. Nanowires are quasi–one-dimensional single-crystalline structures and, in contrast to nanorods, they have a much larger length-to-radius aspect ratio, with diameters as small as a few nanometers and lengths up to several hundreds of micrometers. Sized controlled nanorods (Hu et al., 2001) can be made by thermal decomposition of organometallic precursors in a coordinating organic solvent. The discovery that various ligands and co-ligands can promote anisotropic growth has led researchers to create a number of nanorods that afford uniform size and shape and good electrooptical properties, controlled by the molar ratio of the components to the coordinating solvent as well as annealing time.

Nanowires are typically grown using chemical vapor deposition (CVD) by means of a catalyst-mediated vapor-liquid-solid (VLS) mechanism. The growth is initiated by the dissolution of gaseous reactants in nanosized liquid particles, followed by nucleation and growth on the substrate. In this way, the nanowire diameter is predefined by the size of catalytic particles, length depends on the growth time, and often there is an epitaxial relationship between the nanowire and the substrates allowing control of the nanowire growth direction (Lu and Lieber, 2006). In addition, nanowires can be grown in place by a number of techniques, allowing an ensemble of wires to be grown all having the same crystal orientation. One technique uses VLS growth with a low concentration of nickel nitrate catalyst on a sapphire substrate to produce dense arrays of gallium nitride (GaN) nanowires, well aligned to each other and having a vertical orientation (Wang et al., 2006a). Another extremely promising technique is that of using conventional MOCVD growth to produce uniformly oriented and ordered arrays of GaN nanowires by growing through a nanopatterned mask material of silicon nitride or silicon dioxide onto a GaN film. By using a "pulsed" growth mode in which precursor gases are introduced alternately in sequence, the diameter of the quantum wires can be made extremely uniform along their length (Hersee et al., 2006). Additional description of the latter technique is provided later in this chapter.

Semiconductor nanowires can simultaneously act as interconnects and as active components and therefore have emerged as attractive building blocks for applications ranging from nanoelectronics to photonics or sensing. Through the rational growth of nanowire heterostructures with controllable doping, the functionality of such devices has been enhanced, and nanowire-based light-emitting devices, high-performance field-effect transistors (FETs), and arrays of single-nanowire silicon FETs for sensing have been demonstrated (Xiang et al., 2006).

Central to future applications will be the ability to assemble and position such nanoscale devices at different length scales, as well as the ability to address individual elements in high-density arrangements. For example, microfluidic flows can be used for aligning an array of nanowires in devices (see Figure 3-3), while for the manipulation of individual nanowires several techniques have been proposed: optical tweezers, or manipulation using electrical and magnetic fields.

Organic Materials

Organic nanophotonic materials are more difficult to control with the structural precision of inorganic materials, but chemists can create intricate molecules and supramolecular assemblies with extremely highly specific interactions with chemicals and biological agents. Also, organics have an enormous range of electrooptical properties and are flexible hosts for metallic and inorganic materials to create multifunctional devices. In addition, their huge tunability across the ultraviolet (UV) to infrared (IR) spectral regions by means of a host of stimuli (e.g., temperature [Wiersma and Cavalieri, 2001], mechanical stress, pH, ionic strength, specific binding to biological agents, response to electric fields, and so on) makes them excellent sensors (Gaillot et al., 2007; Moreira et al., 2004).[2] Many industrial processes have been developed for the deposition of uniform organic films. Spin casting is the most familiar and produces films with nanometer-thickness resolution and control. Dry film-deposition processes have also been commercialized. For many device applications—for example, organic light-emitting diodes (OLEDs)—this approach has been very successful. Other device concepts require a precision placement and/or contacting of individual molecular moieties. A challenge for solution-based synthesis is to be able to place and to orient, contact, and interconnect these individual molecular moieties into nanoscale

[2]Certainly, chromonic liquid crystals are being used (two companies are developing this scheme) for the detection of specific biological agents. For more information, see (http://dept.kent.edu/biology/woolver.htm), (http://www.blackwell-synergy.com/doi/pdf/10.1111/j.1472-765X.2006.01916.x). The current schemes are not PBG-based, but certainly can be and very likely will be.

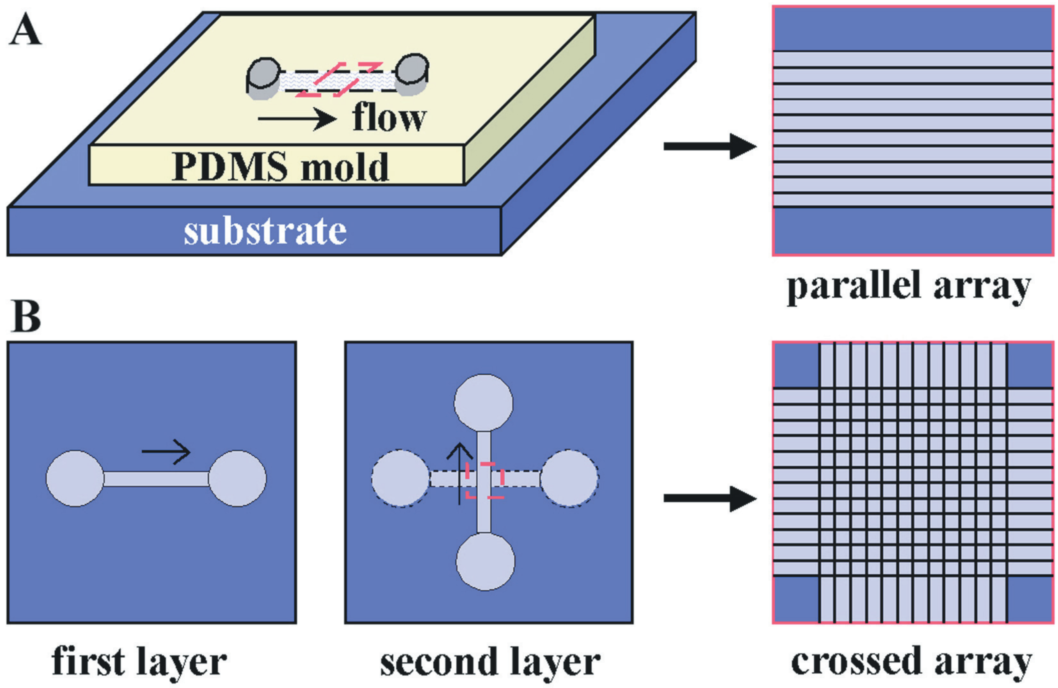

FIGURE 3-3 Use of microfluidics to flow-align nanowires and form crossed arrays by using a polydimethylsiloxane (PDMS) stamp and successive directional flows. SOURCE: Lu and Lieber (2006). Reproduced with permission from *Journal of Physics D: Applied Physics.*

devices. The use of nanoimprint lithography[3] to create surface patterns with variable chemical affinity is emerging as a viable pathway to direct the assembly of organics.

Co-assembly

Instead of the self-organization of a single type of molecule during solvent evaporation, co-assembly encompasses the idea that multiple types of entities—various molecules, quantum dots, and so on—can be simultaneously organized from a liquid mixture as the temperature is lowered or as the solvent evaporates to form more-complex and often multiscale, multifunctional structures. An example is a two-size colloidal assembly to form Laves phases. The structure depends on the size and molar ratio of the small and large spheres and basically seeks to achieve maximum packing density. This idea has been used

[3]"Conventional nanoprint lithography often involves exposing the patterned polymer to high temperatures, UV exposure and etching processes. These processes result in a harsh environment that potentially degrades the electrical properties of the polymeric semiconductor. . . . Still other techniques use a surface-energy pattern on a substrate to pattern a polymer. C. R. Kagan et al. in Appl. Phys. Lett. 79 (21) 3536 (2001) describes patterning self-assembled monolayers using such a surface-energy pattern. Such patterns are typically generated using surface energy modulation. However, use of such a system in electronic device fabrication is restricted to surfaces on which a self-assembled monolayer can be deposited (typically the noble metals such as gold or palladium). An additional coating step, typically accomplished through dip-coating the surface-energy pattern of the substrate over the entire substrate area is complex and slow, lowering throughput and yield" (see http://www.freepatentsonline.com/20060279018.html).

to make novel superlattices of metallic nanoparticles, magnetic nanoparticles, and semiconductor nanoparticles (Shevchenko et al., 2006). Co-assembly of a block copolymer (BCP) and one or more types of nanoparticles can produce interesting hierarchically structured materials. The high-molecular-weight BCP acts as a nanostructured host matrix with a periodicity on the order of the wavelength of light, and the sequestration of various types of the much smaller nanoparticles (see the following subsection) can be used to locally alter the refractive index of the larger block structures.

Synthesis of Block Polymers

The synthesis of polymers is being extended to an ever-greater range of monomers to create unique diblock and multiblock polymers with both linear and highly branched architectures. The ability to combine two or more polymeric species into a block polymer presents the possibility for multifunctionality of properties owing to the self-assembly of the blocks into equilibrium one-, two-, and three-dimensional periodic nanophases and microphases having a variety of geometries. BCPs can also be used to sequester nanoparticles where, by appropriate choice of the surface ligand on the nanoparticles, the particles co-assemble with the BCP from solution into the targeted microdomains (Bockstaller et al., 2005). Incorporation of metallic and inorganic (semiconducting) particles can modify the dielectric properties of the assembly to provide, for example, increased dielectric contrast for photonic crystals.

Liquid Crystals

Liquid crystals spontaneously form modulated phases that are photonic band-gap materials and hence are interesting and useful for nanophotonics applications. The structures of the phases that are formed are determined by the properties of the molecules that are the building blocks of the liquid crystal. Rod-like, chiral low-molecular-weight molecules with aromatic cores and flexible alkyl chains form cholesteric and ferroelectric phases, which are periodic in one dimension. These are photonic band-gap materials, with a pitch that can be made to vary from tenths to tens of microns. Such structures can also be polymerized to make rigid cholesteric plastics, as well as weakly cross-linked to make mechanically deformable cholesteric “rubbers.” One application is the resulting tunable rubber distributed feedback (DFB) lasers shown in Figure 3-4.

Liquid-crystal elastomers may also be used as photoactuators and nano-optomechanical system elements.

Chiral molecules also exhibit the cholesteric “blue” phases, which are periodic in three-dimensions. Although in the past these have only existed in a very narrow temperature range, recent work (Coles et al., 2006) enabled the realization of materials that are stable over a range of 50ºC. Such robustness is expected to enable the synthesis of easily processible large-area flexible plastic photonic band-gap materials in the near future, although of lower index contrast ($n_2 - n_1 < 0.3$).

Examples of such self-assembled structures are the helical phases of cholesteric liquid crystals, which are periodic in one-dimension and show strong Bragg reflection for a range of wavelengths and one polarization mode and mirrorless lasing at the band edge (see Figure 3-5).

As shown in Figure 3-6, liquid crystals that are periodic in three-dimensions exist as well. These are the cholesteric and smectic blue phases, twisted grain-boundary phases, forming self-assembled three-dimensional photonic band-gap structures.

Other relevant new materials developments are chromonic liquid crystals, in which the mesogenic building blocks are molecular aggregates without covalent bonding, and “banana” liquid crystals of achiral bent-core molecules that form periodic chiral phases.

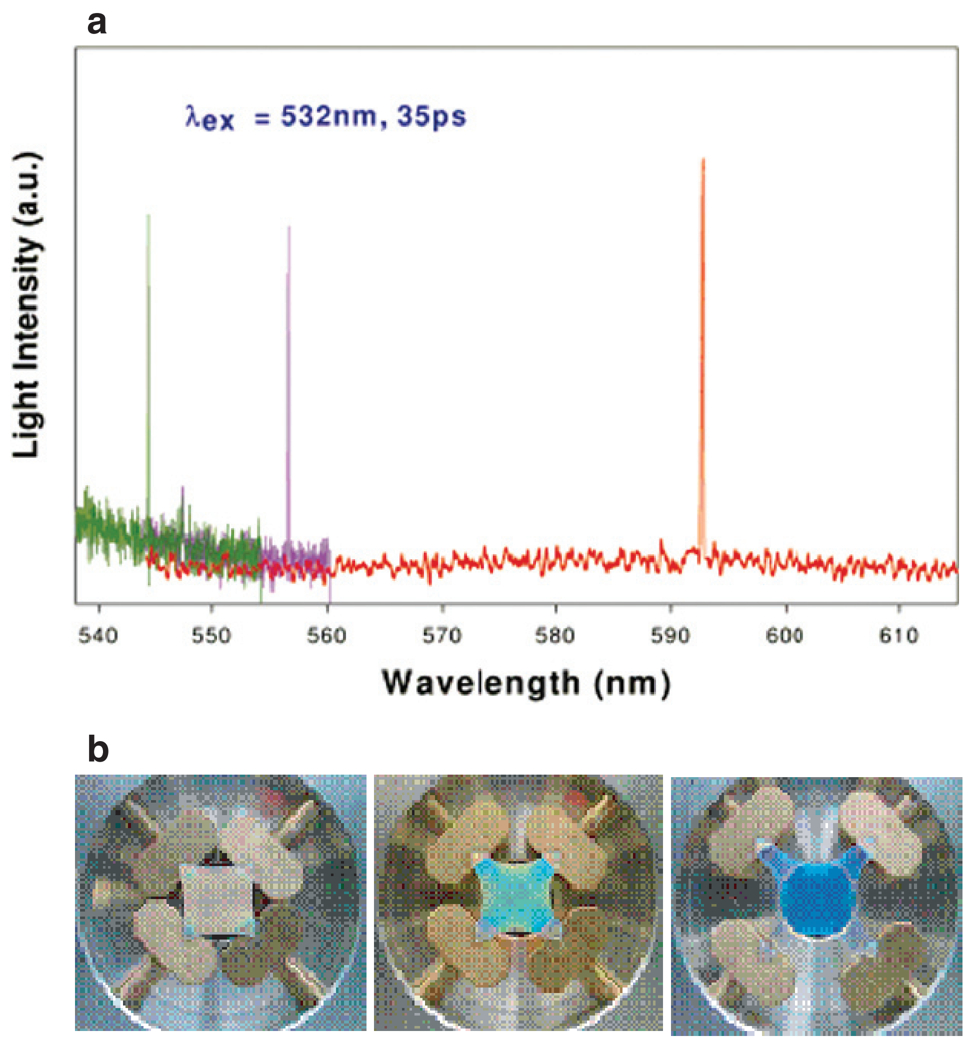

FIGURE 3-4 Optically pumped mirrorless lasing by a dye-doped cholesteric liquid- crystal elastomer. The lasing wavelength is tuned by stretching the rubber laser (which results in compression of the one-dimensional Bragg reflector in the direction of the film thickness). (a) Demonstration of tunable lasing by deformation (DCM dye optically pumped at 532 nm); (b) changes in normal incidence reflectivity of cholesteric rubber structure due to biaxial deformation. SOURCE: Finkelmann et al. (2001). Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

Nanoparticles with functionalized surfactants and tethers have the potential to self-assemble into a tremendous variety of structures. One example, predicted by numerical simulations and observed experimentally, is the spontaneous formation of flat sheets of cadmium telluride (CdTe) nanocrystals without the presence of templating surfaces. Figure 3-7 shows experimental demonstration of this type of structure formation, with CdTe nanocrystals forming into nanometer-thin sheets.

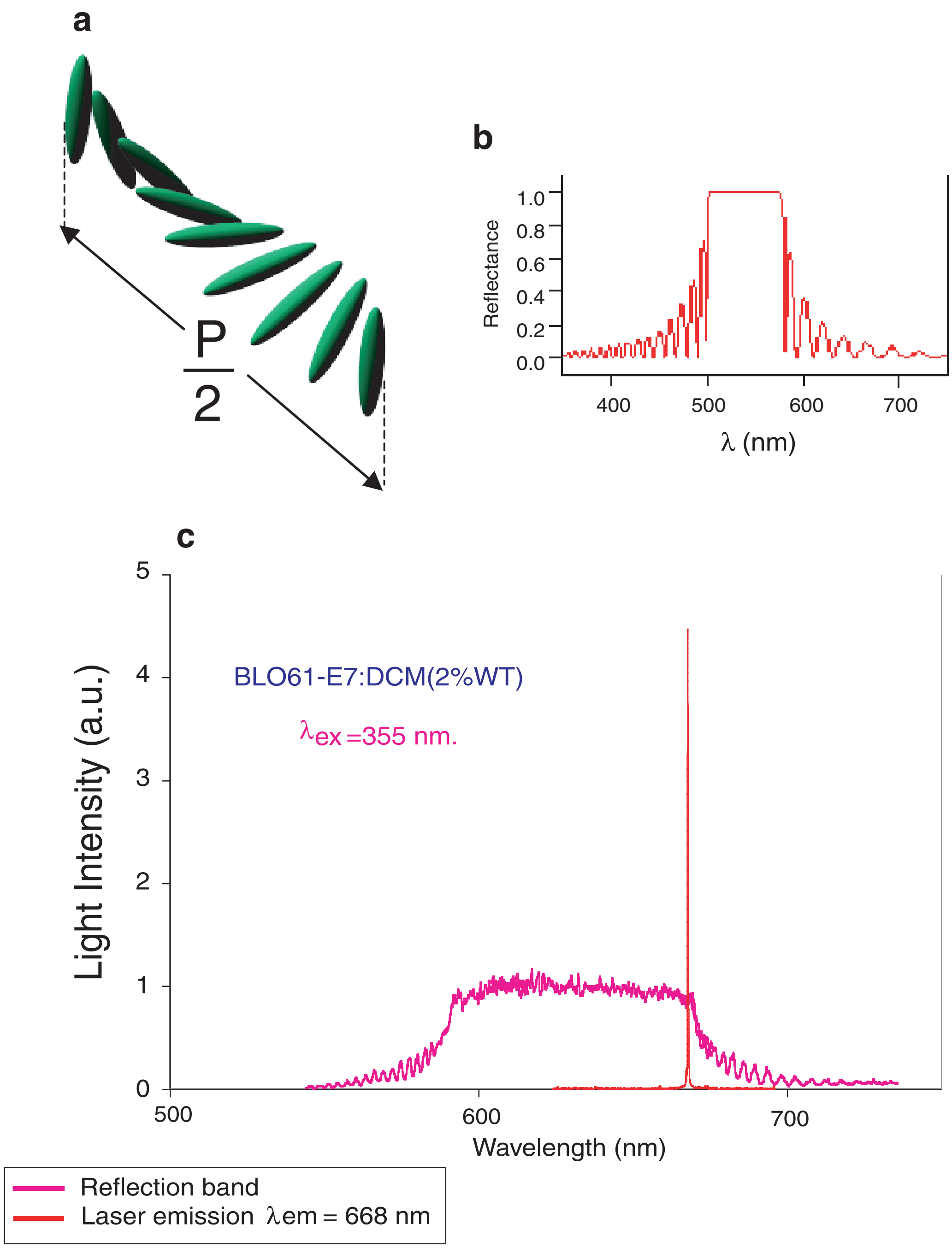

FIGURE 3-5 Self-assembled liquid crystals can form one-dimensional reflectors and exhibit band-edge lasing. SOURCES: (a, c) Palffy-Muhoray et al. (2006), reproduced with permission of SPIE; and (b) provided by committee member Peter Palffy-Muhoray.

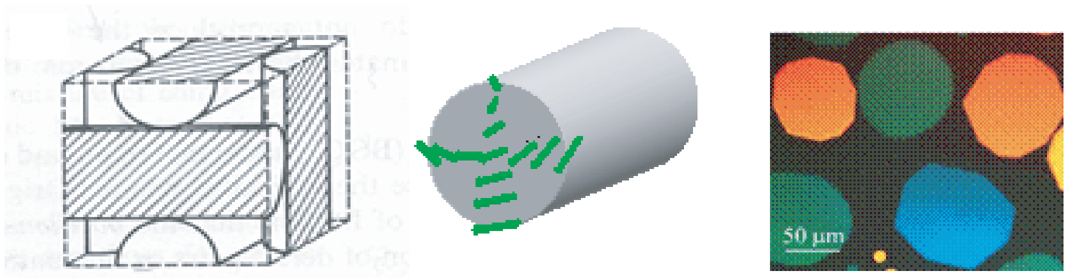

FIGURE 3-6 The blue phase is composed of an ordered array of linear defects that pack on a cubic lattice. SOURCE: Reprinted by permission from Cao et al. (2002). Copyright 2002 by Macmillan Publishers Ltd.

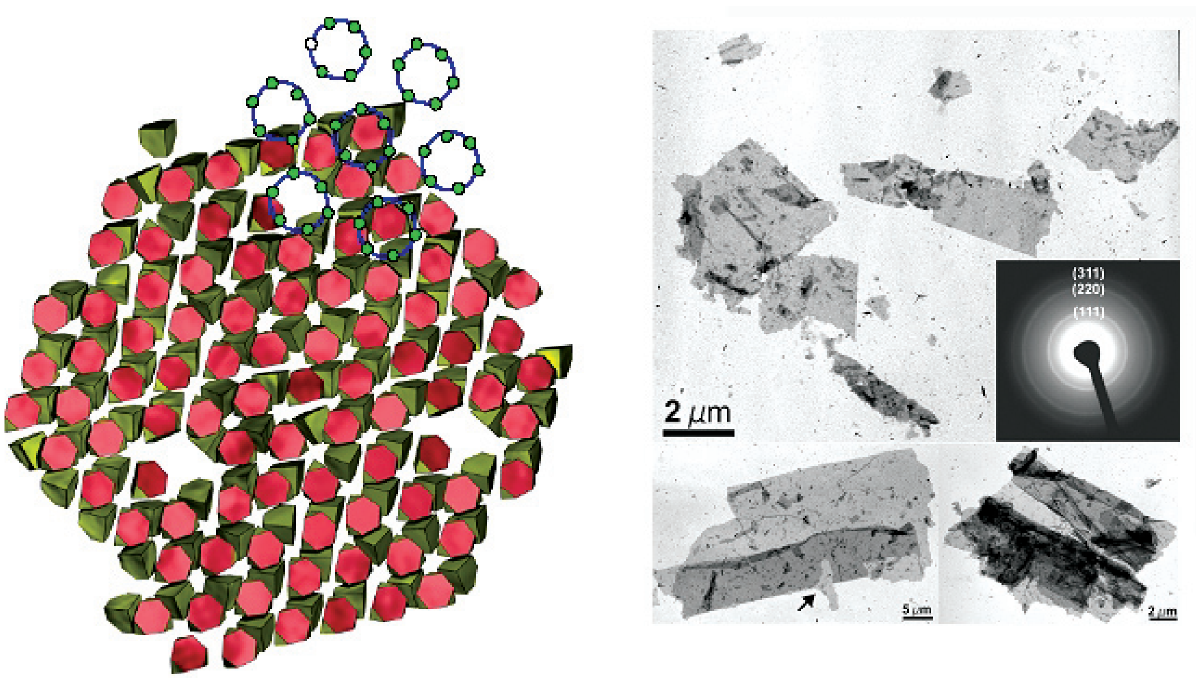

FIGURE 3-7 Self-assembly of cadmium telluride nanocrystals (left) into free-floating sheets (right). SOURCE: Tang et al. (2006). Reprinted with permission of AAAS.

Recent research shows that materials, whose building blocks are not molecules, but nanoparticles, also show liquid-crystal phases. Examples are clays and mineral suspensions, such as gibbsite platelets and goethite nanorods, as well as synthesized semiconductor nanorods and viruses such as tobacco mosaic virus. The resulting anisotropy provides an additional degree of freedom in the design of the optical properties of these metamaterials. Advances in the synthesis of molecules and of nanoparticles that aggregate to form hierarchical structures are certain to play a key role in the development of materials for emerging nanophotonics device applications.

SELF-ASSEMBLED RESPONSIVE MATERIALS

The self-assembly of block copolymers and liquid crystals and even liquid-crystalline block polymers can lead to a variety of photonic crystals whose properties can be externally tuned (Park et al., 2003). Block copolymers microphase separately on a length scale of the blocks driven by the competition between the tendency to reduce the interfacial free energy and to increase the conformational entropy of the chains. A variety of BCP-based photonic crystals have been made, including one-, two-, and three-dimensional periodic materials (Edrington et al., 2001; Urbas et al., 2002). Since these materials are "soft," they can readily accommodate organic dyes and quantum dots, adding to their functionality, including the ability to form self-assembled lasers (Yoon et al., 2006). Essential to their responsive functionality, the strong variation of refractive index with temperature, the variation of the segment-segment interaction parameter with temperature and with solvent content, and the ability to swell the polymers with solvents and homopolymers as well as to significantly deform the periodicities give rise to a host of thermochromic, solvatochromic, and mechanochromic materials. The greatest tunable response arises from the coil-globule collapse transition where changes in volume can be up to 1,000 percent, affording highly responsive pH, ionic strength, electric field, and humidity sensors. A hydrophobic-hydrophilic BCP can have its stop band tuned from about 400 nm to 1,600 nm by varying salt content.

COLLOIDAL SYNTHESIS

The large effort at creating self-assembled photonic crystals to create a band gap in the visible spectrum employing colloids demands the synthesis of highly monodisperse spheres at targeted diameters (on the order of the wavelength). Much effort has been made to create the inverse opal structure by directed assembly of spheres (typically polystyrene or silica) into a "face-centered cubic" structure, followed by infiltration of a high-dielectric material into the intersphere void space (e.g., by a sol-gel route to titanium dioxide [TiO_2]), followed by etching of the spheres and the air/dielectric inverse opal structure with a band gap between the 8th and 9th bands for $n_2/n_1{\sim}3$. Recently, diamond- packed spheres and spheres in the pyrochlore structure have been proposed to produce much-improved low-order, easily opened band gaps due to a preferred structural geometry. The idea is to create a binary colloid analogue of the $MgCu_2$ Laves phase that has two sublattices with diamond-like symmetry (Shevchenko et al., 2006).

The desire to achieve large-area periodic patterns at nanoscale dimensions has also led to a number of approaches that incorporate "self-assembly" strategies, generally using natural building blocks, such as nanocrystals, that can serve as the template for three-dimensional photonic crystal structures (Norris and Vlasov, 2001; Schroden et al., 2002; Xia et al., 2001). The challenges in those approaches lie in the achievement of perfect, long-range order, and at the same time being able to engineer important non-periodic features (such as waveguide "defects"). It is also not always possible with currently available materials to achieve a sufficient contrast in index using this approach.

EPITAXIAL GROWTH

Much of the nanophotonic enterprise is dependent on epitaxial growth techniques, particularly for semiconductor-based devices. *Epitaxial* refers to the crystallographic deposition of atoms onto a regular crystal lattice substrate, so that the entire grown optoelectronic device is very precisely arranged.

Nanophotonics is dependent on state-of-the-art crystal growth methods in two ways: (1) the quantum well structures must be precisely controlled in both material composition and thickness in order to make optoelectronic structures at specific wavelengths of light, and (2) the purity must be sufficiently high (and material disorder sufficiently low) that electronic energy levels in reduced-dimensionality structures (quantum wells [QWs], quantum wires, and quantum dots) are not broadened beyond fairly specific requirements, typically determined by the particular application.

Molecular-Beam Epitaxy

One of the more sophisticated techniques for growing complex and extremely precise nanophotonic structures is molecular-beam epitaxy (MBE). Here, material is deposited with atomic precision using evaporated molecular beams from heated elemental sources, in an ultrahigh vacuum environment. The impurity background of the material can be made extremely low. The composition of the material is controlled by moving shutters over the elemental sources so as to block or unblock the beams. This technique enables subatomic-layer precision over the thickness of the deposited layers, such as quantum wells and barriers, with a ≤1 percent control over the material composition—for example, the amount of aluminum (Al) in an $Al_xGa_{1-x}As$ layer.

Many forefront nanophotonic devices require astonishing levels of precision and control over the growth. One example is quantum cascade lasers (QCLs) operating at terahertz frequencies. In these structures, the electron transitions between two quantum well-defined energy levels are only a few millielectronvolts (meV) apart in energy. Thus, the background disorder potential in the QWs (the result of ionized impurities, interface roughness, and dopants) must be well below 1 meV in order for the energy levels to be well defined. Further, change in the thickness of the QW by less than a single atomic layer (averaged over the surface area, of course) will result in an unacceptably large change in wavelength. In addition, not only must the QW and barrier thicknesses be controlled with submonolayer precision, but the same identical QCL "unit cell" must be repeated on the order of 200 times in a single QCL stack in order to achieve sufficient gain for lasing. Each of the 200 periods must be identical to the others within the same subatomic-layer precision. Because the total thickness of the QCL structure is on the order of 10 microns, the flux rate of material leaving the elemental sources actually changes during the growth of a single structure and must be compensated for (Williams et al., 2006). These types of challenges are perhaps responsible for the fact that groups at only three or four institutions in the world have succeeded in repeatedly growing terahertz QCLs. These include groups at Cambridge University's Cavendish Laboratories, the Vienna University of Technology, the Swiss Federal Institute of Technology in Zurich, and the Department of Energy's Sandia National Laboratories. Just recently, successful terahertz QCL growth has also been reported by the University of Massachusetts at Lowell and by Spire Corporation and Trion, Inc., in the United States.

Metal-Organic Chemical Vapor Deposition

Although molecular-beam epitaxy gives the greatest degree of precision and control over the growth of compound semiconductor structures, it suffers from a number of drawbacks. One of them is the slow growth rate; in order for the mechanical shutter operations to achieve subatomic-monolayer precision, the growth rate must be very slow, on the order of 1 angstrom (Å) per second. Further, MBE growth machines typically accommodate a relatively small number of substrate wafers, since beam flux divergence over the growth area must be minimized. These two factors, taken together with the ultrahigh vacuum requirements, conspire to make MBE growth very expensive.

The other major technique for producing nanoscale semiconductor heterostructures is metal-organic chemical vapor deposition, also known as metal-organic-vapor-phase epitaxy (MOVPE). In this case, precursor gases consisting of metal-organic complexes (e.g., trimethylaluminum, trimethylgallium, arsine) flow through a reactor across a heated substrate wafer surface, at pressures of 10 torr to 100 torr. The gases decompose at the wafer surface to leave the elemental constituents of the semiconductor compound being grown.

Because of the relatively high pressure and the fact that MOCVD growth typically operates in the laminar flow regime and is controlled by gas-flow valves, the ability to control composition and thickness of epitaxial layers is not quite as good as in MBE. Nonetheless, it continues to improve and is by far the current major means of producing optical components. Similarly, the background impurity levels of MOCVD-grown material are not as high as in MBE.

These shortcomings, however, are compensated for by the fact that the growth rates of MOCVD are 10 to 100 times greater than in MBE. Furthermore, the laminar flow nature of MOCVD renders the reactors amenable to scalable designs with multiwafer platens. This enables the cost of the material to be substantially reduced, and it is for this reason that MOCVD is by far the dominant growth technique for the production of optoelectronic devices for both military and civilian applications. (Note, however, that MOCVD cannot yet produce the most demanding growth structures, such as terahertz QCLs.)

Growth Challenges

Continuing research needs and challenges in crystal growth will, if successfully addressed, expand the ability to create new nanophotonic structures with new levels of sophistication and precision. Key areas of need include (1) understanding the relationship between stress, nanoscale compositional structure, and transport and optoelectronic properties; (2) better understanding of MOCVD growth chemistry, including nonlinear relationships between precursor flow rates and film composition, parasitic reactions, nanoscale precipitants, and metastable solid phases on reactor walls; and (3) new techniques for the in situ monitoring of growth conditions, surface structures, and chemical reactions. Examples of the latter include reflectometry to determine surface structure, reflectivity-corrected pyrometry for accurate surface temperature monitoring, in situ x-ray diffractometry, and stress-monitoring of thin films during deposition.

International Semiconductor Crystal Growth Expertise

Expertise in semiconductor crystal growth largely mimics the development of a sophisticated semiconductor-based photonics industry. Thus, the United States, Europe, and Japan and Korea are today in leadership positions. There are extensive development efforts in Taiwan, especially aimed at consumer products such as light-emitting diodes (LEDs), and this expertise is rapidly migrating to China. Overall, semiconductor growth is an expensive and complex process that requires a substantial infrastructure (raw materials, growth apparatus, ancillary equipment, and large, dedicated laboratory facilities) and an end user to justify the investments. Thus, development of these capabilities requires long lead times, and new activities of this type should be very apparent; it is unlikely that new participants in such activities would appear abruptly.

FABRICATION

Planar Processing Approaches

The integrated circuit industry has developed a broad suite of manufacturing tools that allow fabrication on scales that are immediately relevant to nanophotonics. At the writing of this report, the industry is just beginning the volume production of circuits incorporating 45 nm gate transistors, beyond the scales necessary for many nanophotonic applications, with promise of reaching scales of approximately 10 nm within the 15-year outlook of this report (Semiconductor Industry Association, 2005a). Industrial manufacturing processes encompass a suite of techniques both to define an image on a wafer and to transfer that image into hard materials (semiconductors, metals, and dielectrics). Emerging nanophotonics techniques extensively leverage these techniques, with much work focused on single or layered two-dimensional structures. Extensions to three-dimensional patterning such as multibeam interference are being explored specifically for photonic crystal applications.

Optical Lithography

Optical lithography is well established as the manufacturing technology of choice. With recent developments such as immersion lithography and double-exposure techniques, it now appears that the hegemony of optical lithography still has a significant run ahead of it, despite the continuing refrain that the end of optical lithography as we know it is virtually upon us. In this context, it is worth noting that predictions of the end of optical lithography have held steady at "two generations out" for roughly the past 35 years!

Any discussion of tools for nanophotonics necessarily involves consideration of the associated costs—in resources and in time. Thus, for example, electronic (e)-beam lithography can produce structures at scales smaller than are possible from optical lithography and with an almost complete pattern flexibility (within the limits imposed by proximity effects) and is a staple of nanoscience research. Nonetheless, many applications require large areas (many square centimeters of nanopatterned material), for which e-beam lithography is not a viable approach as a result of its serial point-by-point writing modality and the consequently long times involved in addressing the large number of pixels in a large-area nanoscale image. A linear pixel resolution of 20 nm corresponds to a density of 2.5×10^{11} cm^{-2} (and at a typical e-beam writing speed of 50 megahertz [MHz], writing a square centimeter takes about 10 hours!). This issue only gets worse as the patterning gets deeper into the nanoscale.

As an aside, this is a powerful argument applying to any technique, such as the various approaches to maskless lithography, that requires the storage and transfer of information on an individual-pixel basis. The data transfer demands are very difficult, even with today's advances in computing and communications technologies.

Optical lithography, in contrast, is a parallel writing technique. Traditional optical lithography uses a mask-based approach along with optical reduction to ameliorate the demands on both the mask fabrication and on the optical system. Once the mask is fabricated, all of the information on the mask is transferred onto the wafer in the lithography step. The economics of the integrated circuit industry have put a premium on throughput performance. Current lithography tools expose approximately 100 wafers per hour. Each 300-mm-diameter wafer contains about 125 die with an area of 22×36 mm^2. This corresponds to a sustained information data rate onto the wafer of ~1 THz!

Nonetheless, the cost of optical lithography remains an issue for nanotechnology, both at the research and the early-stage commercialization phases. The impressive and very capable lithography tools used by the integrated circuit industry are very expensive both in initial costs (approximately $25 million) and in operating costs (the typical mask set costs for a modern microprocessor approach $2 million). Clearly these numbers only make sense in a high-volume, high-product-value manufacturing context and are out of reach for a typical research venue or a fledgling product-development endeavor.

Fortunately, many applications in nanophotonics require only a periodic pattern and a much simpler laboratory-scale technology, interferometric lithography (IL); based on the interference of a small number of coherent laser beams, IL can produce useful patterns over large areas and large volumes with considerable, but not total, pattern flexibility, and with dimensions that today are approaching the 20 nm scale. IL creates photonic crystal structures in two and three dimensions by using light to fabricate structures that interact with light. The IL pattern can be written into both positive and negative photoresists. After exposure, the resist is developed to remove, for example, in the case of a negative resist, the unradiated regions, leaving a bicontinuous air/polymer structure that is rationally designed by choice of the set of beam parameters. Combining multiple interferometric exposures and mix-and-match with lower-resolution, laboratory-scale optical lithography and with a limited use of higher-resolution e-beam lithography dramatically expands the available range of patterns (Brueck, 2005).

There are at least two approaches to three-dimensional structures. Structures can be built up in a layer-by-layer fashion very analogous to traditional semiconductor manufacturing. In particular, quite a bit of attention has been devoted to a woodpile structure, with alternating layers of long bars oriented in the x and y directions, with each sequential layer in the same direction offset by one-half the pitch (Ho et al., 1994). Most often the fabrication has used standard semiconductor processing technologies (Lin et al., 1998; Yamamoto, 2006). Alternatively, using multiple-beam, noncoplanar interferometric lithography, the entire three-dimensional photonic crystal pattern can be produced in a single series of exposures in a thick, photosensitive material (Campbell et al., 2000; Shoji et al., 2003; Wang et al., 2003). Many crystal symmetries are accessible by adjusting the number, intensity, and polarizations of the various beams (Cai et al., 2002; Ullal et al., 2003). This interferometric technique has been extended to the fabrication of compound (interpenetrating) lattices such as the woodpile structure and the diamond lattice (Lin and Fleming, 1999; Zhong et al., 2005). However, because of the low-dielectric constant of photoresists, the as-made structure is ineffective as a photonic crystal. One approach is to use the structure as a template for infiltration and then etching/burning out of the polymer to yield a high-dielectric inverse structure (Blanco et al., 2004).

Another promising route to very large area photonic crystals is to use phase masks. Here, the phase mask is placed above the photoresist and a single-incident-plane wave source creates a set of exit beams emanating from the phase mask that interfere inside the resist and create a periodic structure. The challenge is to learn how to design the structure of the phase mask in order to create the desired set of beams for the targeted photonic crystal. Phase masks are usually made of polydimethylsiloxane (PDMS) from an initial master (up to 4 inches in diameter, which itself is made by e-beam lithography or by interference holography). PDMS is inexpensive, transparent, and conformal material (self-aligning to the photoresist) that can be used multiple times. Figure 3-8 shows a two-dimensional quasi-crystalline master made by eight successive exposures with 45 degree rotations between exposures, using a Lloyd's mirror IL set up. The PDMS phase mask is made by replicating the laser, and the three-dimensional quasi-crystalline structure is created by IL from the set of beams launched from the two-dimensional quasi-crystalline PDMS phase mask.

The incorporation of design defects into photonic crystals is essential for devices. Laser writing (etching) and focused ion-beam etching and/or material deposition can be used to place defects in two-dimensional photonic crystals. For three-dimensional writing, the use of two-photon polymerization using a confocal microscope with an x,y,z stage drive can be used to serially write defects (Lange et al., 2006).

Two-photon approaches that rely on the nonlinear response of materials are an alternative approach to three-dimensional fabrication that have met with considerable success. Photopolymerization is an example that has been used extensively (Cumpston et al., 1999; Sun et al., 1999). The throughput of two-photon approaches can be substantially improved with the use of multiple spots formed by microlens arrays (Kato et al., 2005).

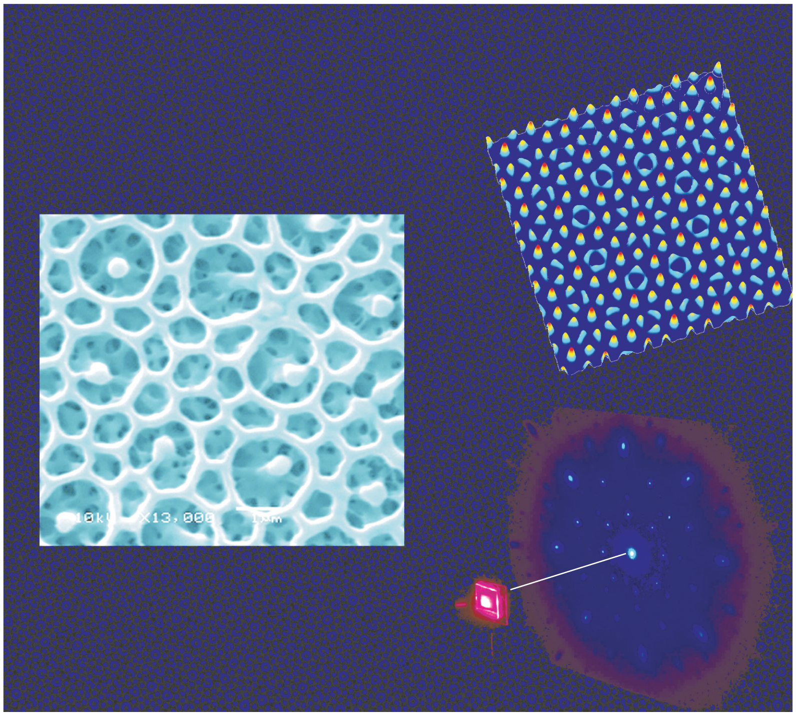

FIGURE 3-8 A novel method for producing large-area three-dimensional nanostructured quasi-crystalline materials uses two-dimensional multiple-exposure lithography to produce an octagonal quasi-periodic surface-relief template (background image). A replica in polydimethylsiloxane is then used as a phase mask to create three-dimensional bicontinuous axial quasi-crystalline SU-8 epoxy nanostructures magnified to show subsurface structural details (see insert at left). At bottom right is a corresponding diffraction pattern produced by a narrow laser beam, while at top right is a simulation of a binarized surface-relief template. SOURCE: Bita et al. (2007). Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

Nanoimprinting

Nanoimprint technology, replicating a pattern from a three-dimensional mask into a polymer film on a substrate, is a rapidly developing approach that has demonstrated resolutions to about 10 nm. This approach is a very appealing alternative to optical lithography for planar manufacturing (Chou et al., 1997). Issues with this technology involve defining the three-dimensional mask (which is most often made using e-beam lithographic approaches) and the chemical interaction between the mask and the pattern that allows a clean separation and continued reuse of the mask. Nanoimprint lithography has evolved into an important research and commercial-product area with many active participants and a wide range of alternative techniques being explored. A recent review is provided by Guo (2004).

Stacking Membrane Structures

Gas-phase etch processes such as reactive ion etching (RIE) or inductively coupled plasma etching generally have the commensurate resolution for transfer of the lithographic pattern into the substrate.

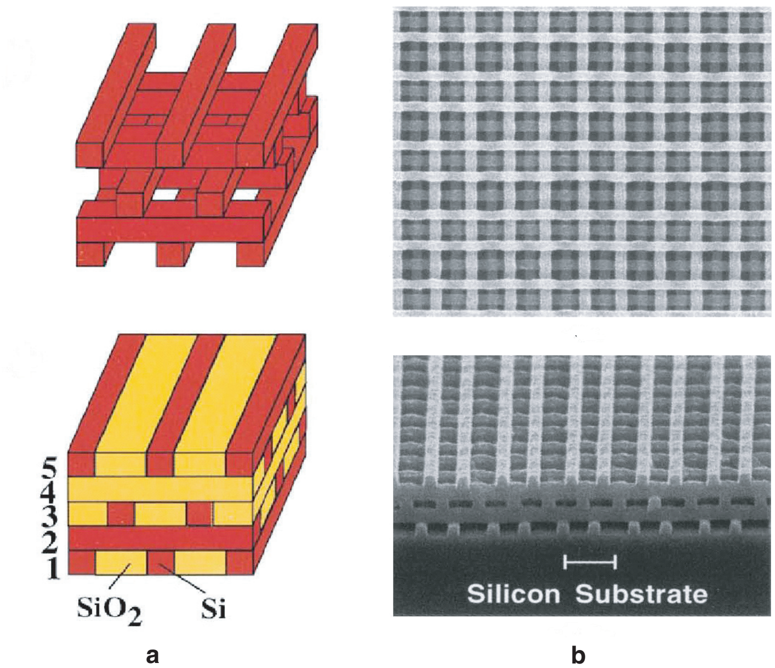

FIGURE 3-9 (a) Schematic of fabrication process and (b) electron micrographs of fabricated three-dimensional photonic crystal lattice. SOURCE: Reprinted with permission Lin and Fleming (1999). Copyright 1999 IEEE.

Early realization of two-dimensional photonic crystal structures in GaAs- and silicon-based materials were achieved through e-beam lithography (Wendt et al., 1993) or x-ray lithography (Foresi et al., 1997) and RIE processes. Similar processes serve to define the highest-resolution photonic crystal structures currently fabricated, but there are still difficulties in forming truly three-dimensional structures in this way: controlled etching of very high aspect ratio structures remains a challenge, and the various three-dimensional angles and symmetries are not always easily obtained through planar processes.

One approach is to form "membrane" structures, where optical confinement in the vertical direction is achieved through the contrast in the index of refraction between the semiconductor (or high index material) and air (Reese et al., 2001). Lin and colleagues developed a means of forming three-dimensional photonic crystals by planar processing using a repetitive succession of formation of silicon (Si) nanorods, filling in with silicon dioxide (SiO_2), and planarization. Using that kind of processing approach, three-dimensional photonic structures have more recently been produced in tungsten (Li et al., 2003).

Another method for fabricating photonic crystals is that of using direct laser writing. There are currently international research efforts, notably in Germany and Japan, using direct laser writing to fabricate three-dimensional nanophotonic structures and other nanophotonic structures. Other top-down processes have been developed, as described in a recent review paper by Lopez (2003). Figure 3-9 illustrates photonic crystal fabrication.

Photonic Crystal Fibers

Photonic crystal fibers are typically fabricated using a "stack-and-draw" technique (see Figure 3-10) by which silica capillary tubes are assembled into a two-dimensional periodic preform bundle. Photonic

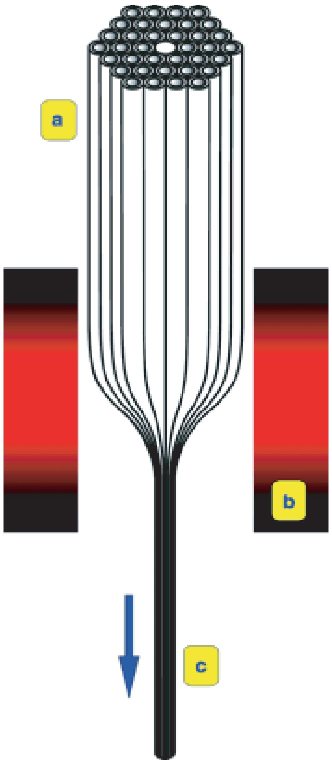

FIGURE 3-10 A stack of glass tubes and rods (a) is constructed as a macroscopic “preform” with the required photonic crystal structure. It is then fused together and drawn down to fiber (c) in two stages using a standard fiber drawing tower. To soften the silica glass, the furnace (b) runs at 1800°C to 2000°C. SOURCE: Russell (2003). Reprinted with permission from AAAS.

crystal fiber preforms are fabricated by building a close-packed arrangement of silica tubes around a central silica rod or tube and together these replicate the desired fiber structure. Precision-machined jigs are used to facilitate this process, and the completed preform is typically held together with platinum wire during drawing. The entire stack can then be drawn in a conventional fiber drawing tower to achieve the much smaller, desired dimensions (Russell, 2003). Exceptional precision is essential during the assembly of the preform, together with fine control of all drawing conditions, to ensure that viscous forces do not distort the fiber during formation and to preserve the integrity and geometry of the structure. While modified chemical vapor deposition is not used directly to create the preform, the process can still be used to fabricate the high-purity, fused-silica components that make up the preform.

One of the major disadvantages of this stack-and-draw technique is the contamination of glass elements, as only small amounts of dust on the glass surface can result in a significant increase in fiber attenuation as well as leading to fiber breaks during fabrication and subsequent rewinding. Therefore, this fabrication must occur under strict clean-room conditions.

In the past, other techniques such as extrusion (Hori et al., 2003) and drilling have been used to fabricate photonic crystal fiber preforms using soft materials such as polymers and soft glass, since with soft materials the structure can collapse during the drawing process. Such techniques are less suitable for producing long fiber lengths. Recently, the stack-and-draw technique has been successfully used to fabricate photonic crystal fibers from sulfur hexafluoride glass (Wolchover et al., 2007), a soft glass with high optical nonlinearity. For the fabrication of polymer-based photonic crystal fibers, a two-stage draw method is typically used (van Eijkelenborg et al., 2003). The primary preforms (typically 50 mm to 100 mm in diameter) are fabricated by drilling the required hole pattern in the polymer material using computer-controlled milling. The primary preforms are drawn to 5 mm to 10 mm diameters. They are then sleeved 10 about twice this diameter and drawn down to their final size, typically 100 microns to 400 microns in diameter.

The first successful photonic crystal fibers were demonstrated using silica in 1995 (Knight et al., 1996). Currently, four companies provide commercial fibers.[4]

DIRECTED SELF-ASSEMBLY AND DIRECTED EPITAXIAL GROWTH

An important emerging trend is the combination of top-down lithographic approaches with bottom-up self-assembly. Lithography allows hierarchical structures over many length scales, from macro- to nanoscales, but it is having increasing difficulties at the lower end of the nanoscale range (as discussed above). Self-assembly, in contrast, shows its greatest strength at smaller scales (and in short-range correlations) and tends to have more difficulty with long-range order (over many lattice constants). A strategy is to marry the two approaches: define a pattern with top-down lithography and build in the hierarchical length scales, and continue the fabrication with self-assembly processes that integrate with the lithographic structure. This concept is applicable both to traditional self-assembly such as colloidal crystallization and to epitaxial growth (Cheng et al., 2006b). Figure 3-11 shows an example of top-down and bottom-up directed assembly.

Polymerization-Induced Phase Separation

Polymerization-induced phase separation (PIPS) is an IL technique whereby a miscible mixture of a photopolymerizable monomer and a low-molar-mass liquid crystal are irradiated by multiple coherent light beams, and the resultant polymerization causes the liquid crystal to phase separate around the regions of highly cross-linked polymer. The final composite material has an index variation on the scale of the incident wavelength, and depending on the choice of beam parameters it can exhibit one-, two-, or three-dimensional periodicities. Because the liquid-crystal component can be reoriented by an external field, by index matching the polymer matrix with one of the principal indices of the liquid crystal, PIPS samples can be switched to have a stop band or to be transparent to incident radiation. The ability to turn on the index difference also allows beam steering using PIPS materials and is a means to enable sensor protection (Urbas et al., 2004).

Nanoscale Crystal Growth (Nanowires)

As shown in Figure 3-12, one example of the combination of lithography and epitaxial growth is the recent growth of gallium nitride nanowires in defined positions and without the need for catalysts as is commonly used in the vapor-liquid-solid growth process. This example also provides a case in point of the blurring of the distinctions between fabrication and growth. In this case the starting material includes a silicon carbide (SiC) substrate with an epitaxial (MOCVD) GaN buffer layer and a thin (~30 nm) silicon nitride (SiN) selective-growth mask layer. Interferometric lithography is used to pattern a hexagonal array of circular holes in the SiN mask layer (~200 nm diameter and 500 nm pitch). MOCVD growth is then

[4]Manufacturers of photonic crystal fibers include Crystal Fiber (Denmark) (see http://www.crystal-fibre.com/); IVG Fiber (Canada) (see http://www.ivgfiber.com/custom.htm); Paradigm Optics (United States) (see http://www.paradigmoptics.com/structures/fiberstructures.html#nano); and TEGS Ltd. (Russia) (see http://www.tegs.ru/en/apps/pcf.shtml). Last accessed on April 15, 2007.

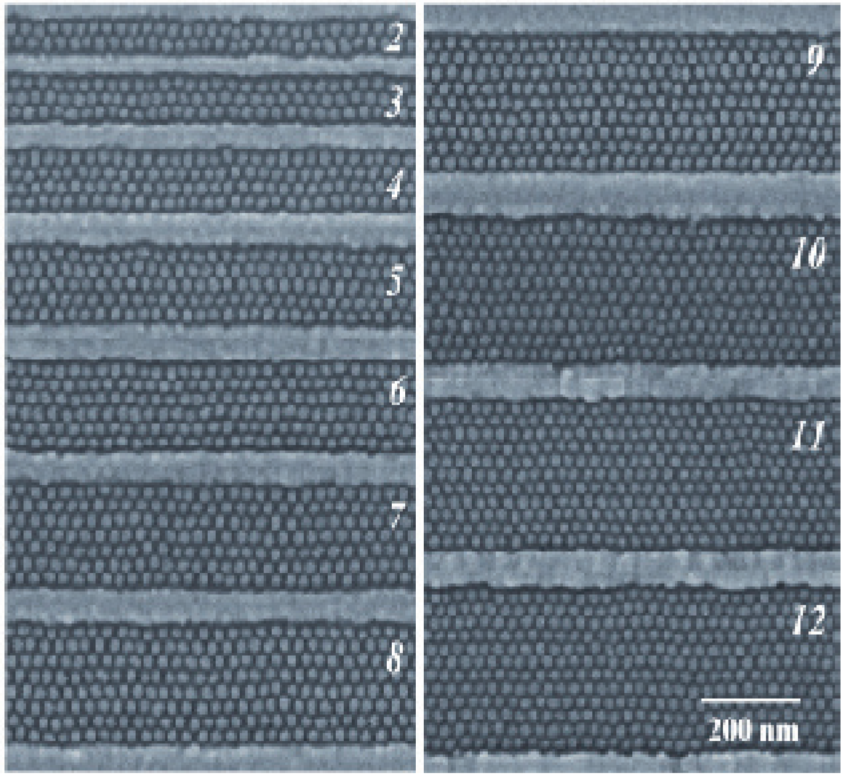

FIGURE 3-11 Example of top-down and bottom-up directed assembly. Templating of spherical block polymer domains within one-dimensional templates of varying width and scanning electron microscope micrographs of ordered arrays of spherical domains with $N = 2$ to 12 rows. SOURCE: Adapted with permission from Cheng et al. (2004). Copyright 2004 by Macmillan Publishers Ltd.

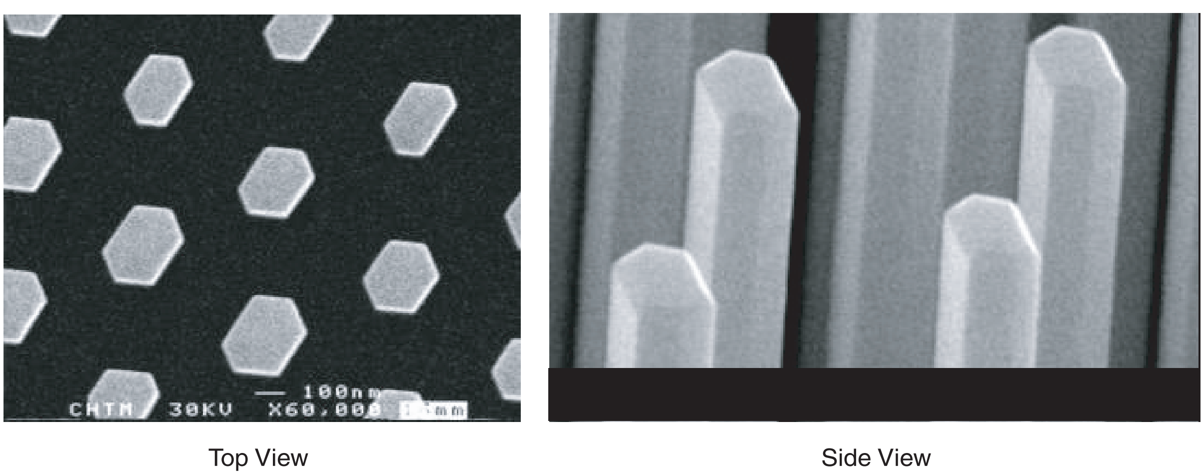

FIGURE 3-12 Scanning-electron-patterned gallium nitride (GaN) nanowires. The hexagonal pattern of the nanowires is created by using a mask layer on top of single-crystal GaN. SOURCE: Reprinted with permission from Hersee et al. (2006). Copyright 2006 American Chemical Society.

used to grow the nanowires directly; in contrast to the nanowires described above, no catalyst is required (and no unintentional doping occurs), and the nanowires are precisely defined in size and position.

FINDINGS

Finding 3-1. Developments in synthesis, growth, and fabrication for photonic nanostructures extend across a wide range of materials and techniques and follow nontraditional paths. While it is tempting to assume that those countries which today have an extensive infrastructure for traditional photonics and microelectronics will continue to be the dominant developers of this new technology, this infusion of new ideas and new technologies means that new players can emerge over the 10-to-15-year time frame covered by this report.

Finding 3-2. Traditional electronic-device fabrication employs well-defined and largely separate stages of synthesis, growth, and fabrication. In contrast, the generation of nanophotonic materials and devices blurs these distinctions, and certainly the order of these stages, interleaving them in new and novel ways.

Finding 3-3. Nanophotonic devices increasingly incorporate a wide range of materials and processing methods. Photonic crystals made of or incorporating organic materials are likely to provide sensitivity and specificity for the detection of chemical and biological agents.

MODELING AND SIMULATION IN NANOPHOTONICS

One major reason for the rapid progress in the field of nanophotonics globally is the increasing availability of powerful computational methods for the design and simulation of nanophotonic structures, devices, and systems. Because of the pervasiveness of electromagnetic phenomena and the necessity of understanding radiation-matter interactions, a broad set of computational tools that have applicability to nanophotonics has been developed. An interesting feature of electromagnetic interactions with dielectric material is the *scalability* of the solutions of Maxwell's equations. For example, if one solves for the characteristic modes (wave functions) of a photonic crystal with characteristic lattice constant a, and frequency ω, and if one scaled up that structure by a factor s, to form a new lattice constant sa, then the characteristic resonant frequencies would similarly scale up to values of $s\omega$. Although first developed for radio-frequency modeling and analysis, computational approaches for solving Maxwell's equations scale directly to optical frequencies and subwavelength structures in this regime, with appropriate modifications in materials parameters. Scalability was critically important in the earliest experimental exploration of photonic crystal structures, with critical dimensions of millimeters, probed at microwave frequencies. This phenomenon established the validity of predictions made for current-day 100 nm structures (Yablonovitch and Gmitter, 1989). Since most nanophotonic elements can be modeled using Maxwell's equations to a sufficiently high degree of quantifiable accuracy, the existence of predictive design and simulation capabilities in this field is uniquely mature relative to other nanotechnology disciplines. This section discusses some of the most popular computational methods currently in use in nanophotonics.

Finite Element Method

Historically, scalar finite element methods (FEMs) were initially developed by and for civil and mechanical engineers for the analysis of structural and materials problems. However, since FEM is useful for the solution of sets of partial differential equations, its development as a numerical modeling method for electromagnetics has been very successful. With the availability of powerful computers and commercial finite element software packages, three-dimensional electromagnetic modeling of complex systems and structures by this method is now a major tool in the development of nanophotonics. In finite element analysis, the computational space is divided into a number of small, homogeneous pieces, or *elements*. The model contains information about device geometry, material constants, incident field properties, and boundary constraints. The element size can be varied; it can be small where geometric details exist and much larger elsewhere. In each finite element, a simple, frequently linear, variation of each field quantity is assumed. The goal of any finite element analysis is to determine the field quantities at the nodes, literally the corners of the individual elements.

Generally, finite element analysis techniques solve for the unknown field quantities by minimizing an energy functional, describing all the energy associated with the configuration being analyzed. In order to obtain a unique solution, it is necessary to constrain the values of the field at all boundary nodes. A major weakness of the finite element method is that it is relatively difficult to model *open* configurations (i.e., configurations in which the fields are not known at every point on a closed boundary). Various techniques such as absorbing boundaries are used in practice to overcome this characteristic. An advantage that FEMs have over other electromagnetic modeling techniques stems from the fact that the electrical and geometric properties of each element are defined independently. This permits the problem to be structured with a large number of small elements in regions of complex geometry and fewer, larger elements in relatively open regions. It is therefore possible to model configurations with complicated geometries and many arbitrarily shaped regions in a relatively efficient manner.

One major reason for the popularity of FEM for electromagnetic problem solving is the availability of a highly popular, commercially available software package, COMSOL Multiphysics (formerly Femlab). COMSOL is based on FEM code developed within the research group of the late Germund Dahlquist of the Royal Institute of Technology in Stockholm, Sweden. This tool, rapidly becoming a world standard in both academia and industry, provides FEM solvers for electromagnetics as well as all major engineering disciplines, including heat transport and fluid flow, in a user-friendly environment that allows for the simultaneous solution of multiple coupled problems, such as electromagnetics and heat dissipation in a device structure. COMSOL is currently used by scores of nanophotonics research groups worldwide.

Finite-Difference Time-Domain Method

A particularly widely used modeling technique is the finite-difference time-domain (FDTD) method, initially described by Yee and given its acronym by Taflove (Taflove, 1980; Yee, 1966). Since Maxwell's equations relate time-dependent changes in the electric (magnetic) field to spatial changes in the magnetic (electric) field, FDTD programs implement an explicit time marching algorithm for solving Maxwell's curl equations on a spatial grid (Sullivan et al., 2000). Modeling a new system is reduced to grid generation, instead of deriving geometry-specific equations. Thus, previously uninvestigated and potentially complex geometries do not require new formalisms. The time marching aspect of the method allows one to make direct observations of both near- and far-field values of the electromagnetic fields, and at any time during the simulation. With these "snapshots" the time evolution of the electromagnetic fields can be calculated and visualized (Lazzi and Gandhi, 2000; Young-Seek et al., 2000).

Because FDTD is a time-domain technique, when a broadband pulse (e.g., a Gaussian) is used as a source, a single simulation can model the response of the system over a broad range of frequencies. This is highly useful for simulations for which the resonant frequencies are not known precisely (such as in the modes of a photonic crystal waveguide or resonator). A typical implementation of this method, for example, may involve an incoming light pulse or wave that illuminates a target containing one or several nanoparticles or structures. The electromagnetic fields excite plasmons or polaritons in the individual nanoparticles. The plasmons on the individual nanoparticles interact, resulting in a complicated and time-dependent electromagnetic field. Since the dimensions of the composite target may be of the same order of magnitude as the wavelength of the light, retardation effects are included naturally. Thus, the FDTD method is well suited to transient analysis problems and to modeling complex inhomogeneous complex nanostructures of arbitrary geometry, as well as arrangements of multiple nanostructures (Yu et al., 1997). With the implementation of periodic boundary conditions, for example, this method is extremely useful for modeling photonic band-gap-based structures and devices.

The FDTD method has several features that make it a highly desirable algorithm. It is fully retarded and fully explicit, which reduces the computational overhead needed to solve a particular problem. The sources of errors in the method are well known and bounded (Kashiwa et al., 2003; Wang and Teixiera, 2004).

The dielectric function, $\varepsilon(\omega, \vec{r})$, is used to simulate the materials in the grid. A value for ε is specified at every grid point. For a realistic modeling of the optical properties of nanostructures, it is important to use experimentally measured dielectric functions appropriate for the nanostructure. The use of the electric flux density form of Maxwell's equations provides two major benefits: a simpler time-domain implementation of dielectric functions and programming modularity. The electric and magnetic field update equations are independent of the choice of dielectric function. Thus, if an object to be modeled requires a different dielectric function, only the electric field update equations need to be modified.

Additionally, the method is easily parallelizable owing to the local nature of finite differences. This localized aspect enables the use of simple parallel methods, on either shared or distributed memory systems. For example, the FDTD method can be parallelized using domain decomposition, where the computational grid can be broken into several smaller grids, where each subgrid is updated by a different central processing unit (CPU). To complete the update, subgrids only need to exchange boundary values with adjacent subgrids. This type of functionality enables faster and more efficient use of computational resources. The possibility of using variable grid size drastically reduces the data size and execution time and, more importantly, enables the modeling of larger and more complex nanostructures and nanostructure aggregates (Amon et al., 2006).

Boundary Element Method

The boundary element method (BEM) is a method of moment approach applied to the solution of surface integral equations. BEM is outstanding in analyzing unbounded radiation problems, perfect conductors, extended configurations, and homogeneous dielectrics. It is best suited for modeling thin or long wires or surfaces, for substrates, boundaries, or layered media, and as such BEM complements the FDTD code previously described. The method solves the integral form of Maxwell's equations on the discretized boundary of the intended problem (Massoud and White, 2002a; Massoud and White, 2002b; Matsuhara et al., 1991; Taotao et al., 2004). The surface discretization in BEM leads to fewer numbers of unknowns than those in volumetric methods. Volumetric methods usually generate a global mesh for all parts of an analyzed structure and for surrounding external space. This causes the number of unknowns to increase significantly. Solving this large generated linear system requires excessive memory and consumes much CPU time, which makes the analysis of complex three-dimensional nanostructures sometimes impractical. Gaussian elimination is a standard method to solve linear systems resulting from BEM formulation, but it is computationally expensive since it requires on the order of n^3 operations (Bängtsson and Neytcheva, 2005).

Other Numerical Methods

Various other numerical methods are currently used in the analysis of electromagnetic fields in microstructured materials with complex geometry. They include the T-matrix method and its variants, which are multiple scattering approaches, formulated in terms of interior and exterior spherical harmonic expansions; and the discrete dipole approximation and its variants, essentially volume integral equation methods discretized using a simple quadrature rule on a regular lattice (Draine and Flatau, 1994; Mishchenko et al., 2002).

An emerging new approach is fast multipole methods (FMMs) based on boundary integral equations. Boundary integral equations have the advantage that, by placing the degrees of freedom on the dielectric (or metal) interface itself, it is possible to construct fast, robust, high-order accurate solvers. One disadvantage is that FMMs require significantly more complex numerical algorithms. From a historical perspective, despite their advantages in terms of accuracy and robustness, integral equations were often avoided in favor of other methods because they led to dense linear systems for which fast algorithms were not available. In the past decade, progress was made in many areas, and the state of the art now combines high-order accurate surface discretizations, high-order accurate quadratures, and multilevel fast algorithms. In an iterative solution procedure, the fast multipole method, for example, reduces the cost of applying the integral operator from $O(n^2)$ to $O(n \log n)$, n is the number of nodes in the discretization of the domain boundaries (Cheng et al., 2006a; Chew et al., 2001; Contopanagos et al., 2002; Darve, 2000; Greengard et al., 1998).

These new methods have yielded speedups of several orders of magnitude, bringing previously intractable problems within reach of modest computing platforms. Electromagnetic scattering from objects with millions of points in the surface discretization can be computed in minutes or hours. FMM-based schemes now lie at the heart of some of the leading chip-design software packages and have dramatically changed the standards for capacitance extraction and other "physical verification" tools. Their incorporation into metamaterial optics is likely to have an equally important effect—that of enabling accurate simulation of large-scale, physically realistic systems.

Analytic Methods

While not as generally applicable as the techniques described above, various analytic approaches to solving Maxwell's equations for various geometries and materials continue to be widely used because of the physical insight that they provide and because of the ability to vary the parameters of the design over wide ranges with only minimal computing time, again for purposes of physical insight.

The most widely used of these analytic approaches is the rigorous coupled wave analysis (RCWA) first introduced by Gaylord and Moharam (1985) for grating diffraction problems. The basic idea of RCWA is to expand the fields in the regions away from the grating and in the grating region in a Floquet expansion (infinite series with the wave vector in the direction of the grating varying by integer multiples of the grating period). The electromagnetic properties of the grating (the permittivity in the case of a simple metal grating) are similarly expanded and substituted back into Maxwell's equations. This procedure results in coupling between the various terms in the Floquet expansion. The series is then truncated with appropriate consideration for convergence, and the result is a simple linear equation eigenvalue problem for which there are many available solution approaches. This approach has been extended to two-dimensional gratings and to negative index materials and plasmonic aperture array problems (Minhas et al., 2002). Pendry has introduced the transfer matrix approach, a related calculational procedure (Pendry and Bell, 1996).

Another set of tools arises from the bandstructure calculations of solid-state physics. One specific example is the Kronig-Penney model for a one-dimensional grating. In this case, Maxwell's equations are solved exactly in the grating region by matching boundary conditions across the teeth of the grating, and these exact solutions are again expanded in a Fourier series and matched to the Floquet expansions above and below the grating. This again leads to a truncated linear algebra eigenvalue solution. The advantage of this approach is that it directly provides the modal solutions in the grating region that can provide additional physical insight.

In the field of plasmonics, plasmon hybridization is one important analytical approach that has been highly useful in determining the resonances of complex nanoparticles and nanostructures, including the coupling between localized plasmons of nanoparticles and the propagating plasmons on macroscope films and wires (Prodan et al., 2003; Wang, 1991). It has recently become apparent that the plasmons of metallic nanostructures, while describable by classical electromagnetic theory, exhibit certain characteristics that are analogous to electrons in quantum systems. This is seen most clearly in complex nanostructures, where plasmons on neighboring structures or surfaces interact, for then the plasmons mix and hybridize just like the electron wave functions of simple atomic and molecular orbitals. This property, termed *plasmon hybridization,* governs the optical properties of metallic nanostructures of increasingly complex geometries, providing the scientist with a powerful and general design principle that can be applied to guide the design of metallic nanostructures and to predict their resonant properties.

Although similarities between plasmons in nanostructures and atomic and molecular wave functions have long been a casual observation of workers in this field, it is only recently, where breakthroughs in the controlled chemical fabrication of metallic nanostructures of various shapes and sizes have been combined with powerful computational methods, that this analogy has been realized and verified, and subsequently exploited in the design of complex plasmonic nanostructures. Plasmon hybridization theory deconstructs a composite nanostructure into more elementary shapes and then calculates how the plasmon resonances of the elementary geometries interact with each other to generate the hybridized plasmon modes of the composite nanostructure. This theory enables scientists to draw on decades of intuition from molecular orbital theory to predict the plasmonic response of complex nanostructures correctly.

CHARACTERIZATION TECHNIQUES FOR NANOPHOTONICS

Developing new techniques for the characterization of the optoelectronic properties of materials on a nanometer scale is essential for nanophotonics. There are various methods now under development for such characterization capability.

Advanced Microscopies

The wavelength of light limits the ultimate size of an object that we can see directly using conventional optics. Thus, even with the best optical microscopes, it is not possible to resolve objects less than approximately 400 nm apart, because the wavelength of the light is longer than the separation, and the two objects therefore appear blurred together. One route to improved resolution is to reduce the wavelength of the light used for viewing. Shorter-wavelength light, corresponding to the UV and x-ray regions of the electromagnetic spectrum, provides better resolution than that possible with conventional optical microscopes. To date, soft x-ray microscopes have achieved a resolution of a few nanometers. In principle, shorter-wavelength, harder x-rays should allow even better resolution, but to date such microscopes have been limited to a resolution of about 20 nm. This resolution is limited not by the wavelength but rather by the ability to fabricate the appropriate x-ray lens (known as a zone plate) that is used to focus the x-rays (Chao et al., 2005). Advances in nanofabrication techniques will one day override this limitation, allowing x-ray microscopes with subnanometer resolution to be built. Other characterization techniques for nanophotonics based on linear and nonlinear optical spectroscopies, both in the time and the frequency domains, are described in Chapter 2 of this report, in the section entitled "Techniques for Imaging and Spectroscopy of Plasmonic Structures."

Other nonlinear optical microscopies can be used to provide even more information. For example, nonlinear optical techniques such as multiphoton excitation and Raman spectroscopy are now being used to image specific chemicals or nanostructures, with three-dimensional submicron resolution, and to study time-dependent processes involving these species. Such techniques are useful for the characterization of three-dimensional nanophotonic structures.

Scanning Probe Microscopy

Scanning probe microscopy (SPM) covers several related technologies for imaging and measuring surfaces on a nanometer scale. SPM technologies share the concept of scanning an extremely sharp tip (3 nm to 50 nm radius of curvature) across the object surface. The tip is mounted on a flexible cantilever, allowing the tip to follow the surface profile (see Figure 3-13). See, for example, Sakurai and Watanabe (2000).

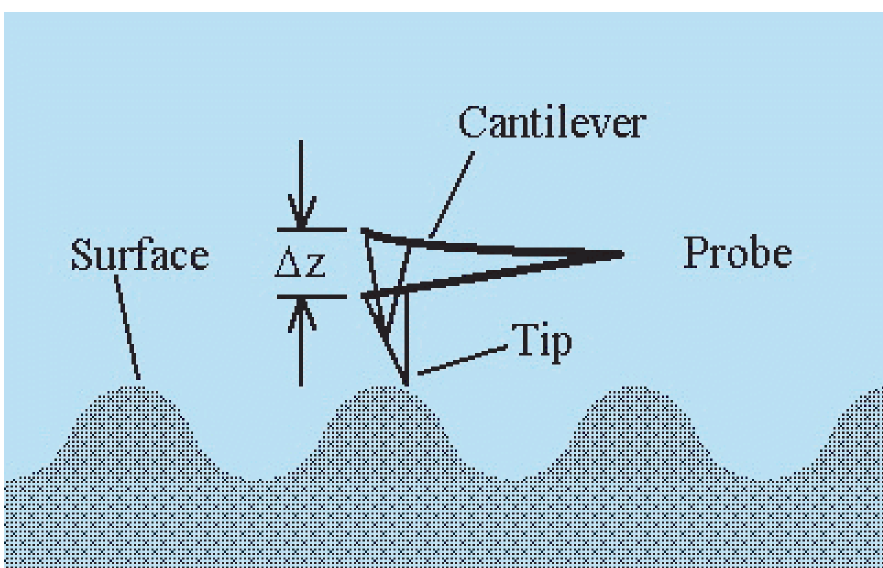

FIGURE 3-13 The movement in scanning probe microscopy to map out the surface profile of an object. SOURCE: Committee member Antoinette Taylor, Los Alamos National Laboratory, 2007.

When the tip moves in proximity to the investigated object, forces of interaction between the tip and the surface influence the movement of the cantilever. These movements are detected by selective sensors. Various interactions can be studied, depending on the mechanics of the probe. Following are the three most-common scanning probe techniques:

- *Atomic force microscopy (AFM):* AFM measures the interaction force between the tip and surface. The tip may be dragged across the surface or may vibrate as it moves. The interaction force will depend on the nature of the sample, the probe tip, and the distance between them. As an example, consider having a probe only a nanometer in diameter scanning across some molecules sitting on a surface. The displacement of this probe as it crosses the molecules, similar to that of the tip of an atomic force microscope, allows one to create a nanoscale map of the surface roughness by measuring the deflection of an ultrafine tip on a cantilever as it is "dragged" across the surface. The atomic force microscope is but one of a wide range of scanning probe microscopies, each of which relies on a different local nanoscale effect for its contrast mechanism.
- *The scanning tunneling microscope (STM):* The STM is a particularly powerful tool that relies on the measurement of tiny electrical currents that pass between the tip and the surface, with changes in these currents reflecting the local densities of electrons on the surface. Such STMs have been used to map out the positions of individual atoms on the surface of a crystal, as well as the positions of atoms within a molecule. Perhaps even more exciting, the tips of these STMs have been used to move and position individual atoms sitting on a crystal surface, allowing the creation of controlled structures with atomic dimensions. This approach has also been pursued using ultrafast lasers, allowing the study of time-dependent optical phenomena with unprecedented spatial resolution (Yarotski and Taylor, 2004).
- *The near-field scanning optical microscope (NSOM):* The NSOM scans a very small light source very close to the sample. Detection of this light energy forms the image. The NSOM provides subwavelength resolution that is well below the conventional limit of optical microscopy. In one form of NSOM, the tip used in an atomic force microscope or an STM is replaced by an optical fiber tapered to a tip approximately 50 nm across; this tip is positioned a few nanometers above the surface of interest and then scanned across it. Laser light is sent down the fiber and tunnels out of the tip, illuminating the sample over an area approximately equal to the diameter of the tip. Scattered light or fluorescence from the sample is then detected, allowing an optical image with approximately 50 nm resolution when a laser wavelength of 500 nm is used. The image in Figure 3-14 shows an NSOM image employing femtosecond white light sources to perform extinction measurements of individual gold colloids and assemblies of gold nanoparticles.

These SPM approaches have also been pursued using ultrafast lasers (both an ultrafast STM and an ultrafast NSOM), allowing the study of time-dependent optical phenomena with unprecedented spatial resolution. Many additional new techniques, such as multiphoton microscopy and ultrafast confocal microscopy, are now being developed to apply optical methods to probe nanoscale and even single-molecule processes in exquisite detail.

Scanning Electron Microscopy

The scanning electron microscope (SEM) is capable of producing high-resolution images of the sample surface. Acquired images have a three-dimensional appearance and are useful in determining the surface structures of the sample. A focused beam of electrons scans the surface producing secondary

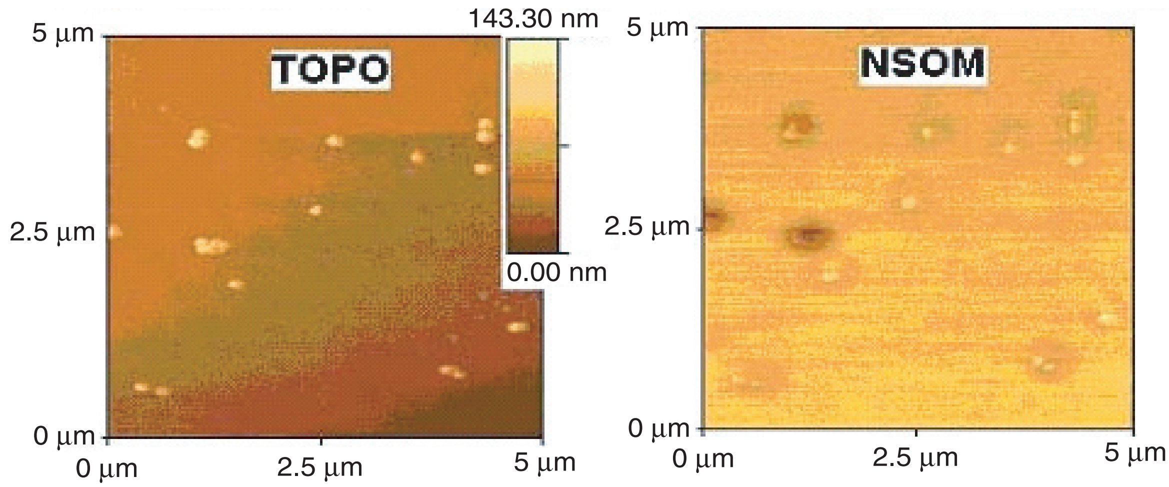

FIGURE 3-14 Topographic image (left) and near-field scanning optical microscope (NSOM) image (right) of assemblies of gold nanoparticles. SOURCE: Victor Klimov, Los Alamos National Laboratory, 2006.

electrons that are registered with the detector in a line-by-line fashion. Electronics then captures all lines, displaying them on the screen as an image. When the surface is struck with electrons, other effects also take place. The nature of the SEM's probe, energetic electrons, makes it uniquely suited to examining the optical and electronic properties of materials. Typical spatial resolution of a high-end SEM is on the order of 2 nm to 5 nm. Figure 3-15 shows a typical SEM and images of three- and two-dimensional photonics lattices fabricated using standard processing techniques.

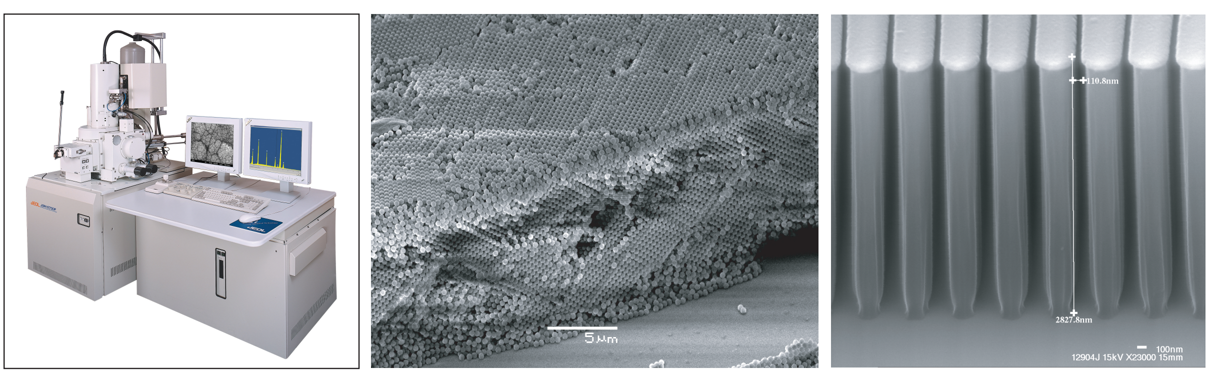

FIGURE 3-15 A scanning electron microscope (left) and a typical image of the three-dimensional photonic lattice (middle) and the two-dimensional photonic lattice (right). The scale (bar) in the middle panel is 5 microns. The scale (bar) in the right-hand panel is 100 nm. SOURCES: Left: JEOL Company, reprinted with permission; middle, right: Elshan Akhadov, Los Alamos National Laboratory, 2006.

Transmission Electron Microscopy

In the transmission electron microscope (TEM), a beam of electrons is transmitted through a specimen and detected by a sensor yielding information about the material's internal structure. Unlike scanning electron microscopy, TEM samples need to be prepared (thinned down) in order to be useful for measurements. With the typical resolution of 0.1 nm, TEMs have found great use across many fields of science: biological samples and materials could be investigated at much finer length scales, allowing for investigation of hidden internal lattice defects and shedding light into areas inaccessible with other techniques. Figure 3-16 illustrates the typical TEM instrument and two images acquired from quantum dots.

NANOPHOTONICS DEVICES

Wavelength-Scale Devices

Wavelength-scale devices include photonic crystal-type devices that have a periodicity on the order of a vacuum wavelength, but they do incorporate precision at the nanometer scale, justifying the nanophotonic appellation.

Of particular note is the success of fabrication methods for photonic crystal fibers. A stack-and-draw technique assembles silica capillary structures into bundles, forming photonic crystal structures; the capillaries are fused together; and then the entire structure is drawn out to form a much-smaller-diameter fiber with the correct structure (Lim et al., 2004). The first successful photonic crystal fibers were formed in 1995, and the committee believes that the ease in fabrication has led to the rapid commercialization and availability of photonic crystal fibers.

Conventional semiconductor processing has emerged as a practical method for the creation of nanophotonic structures. The ability to control light down to a level smaller than a quarter-wavelength is the hallmark of nanophotonic structures.

The canonical wavelength for optical communications and signal processing is λ = 1,550 nm. But allowing for the typical refractive index of semiconductors, n ~3.5, the actual wavelength inside a material is only ~450 nm. Reducing this to a quarter-wavelength results in a critical dimension for

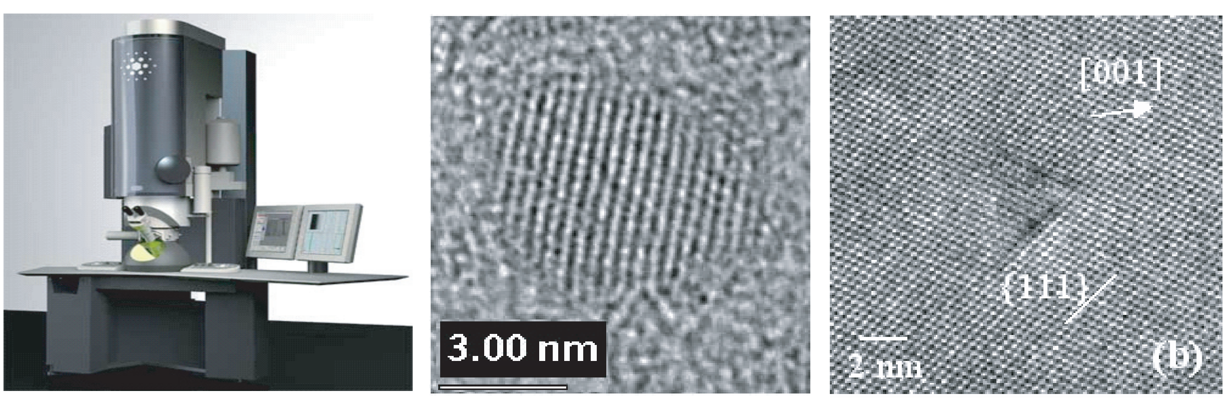

FIGURE 3-16 A transmission electron microscope (left) and images of a quantum dot used in photonics applications (each dot in a periodic array represents an atom). SOURCE: left: Image courtesy of FEI Company; center and right: Paul Alivisatos, University of California, Berkeley, 2007.

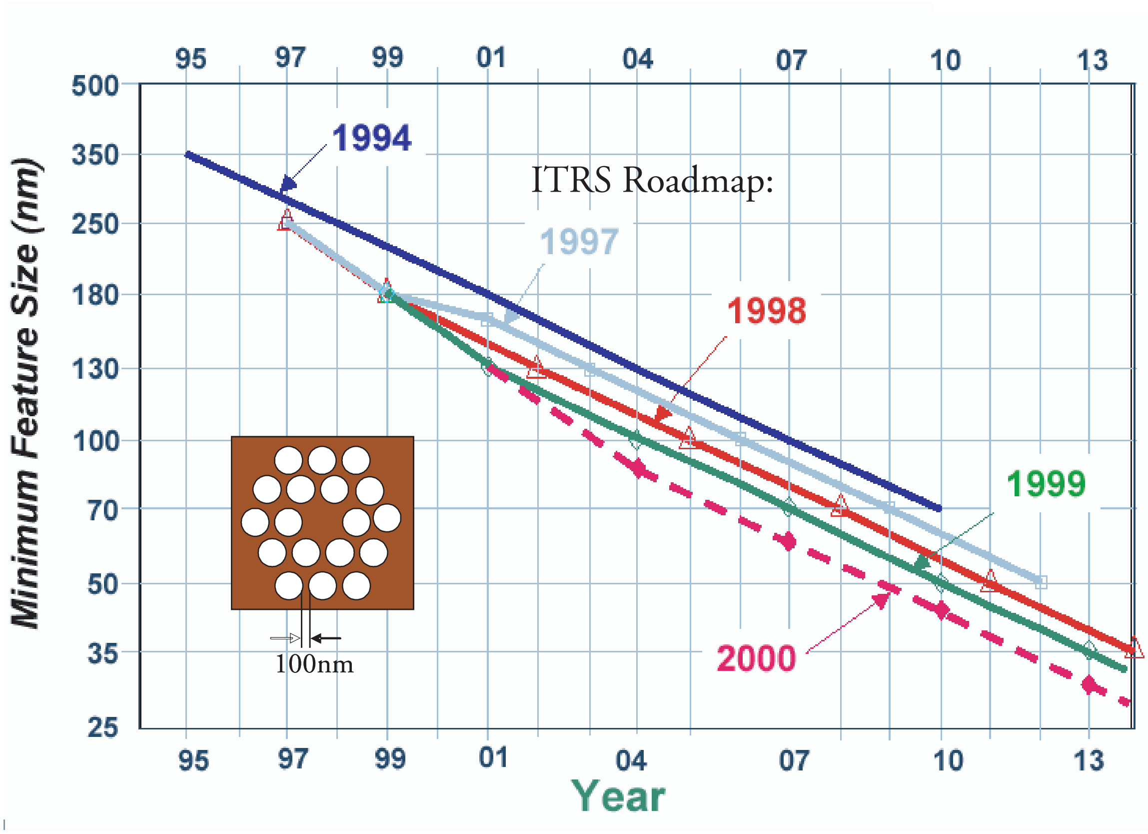

FIGURE 3-17 Minimum refractive size on semiconductor devices decreases steadily, per Moore's law. NOTE: ITRS, *International Technology Roadmap for Semiconductors*. SOURCE: Van den hove (2002). Reproduced with permission.

nanophotonics of about 100 nm. This has been a challenging size scale to control, but the semiconductor industry passed that dimensional threshold in 2003. See Figure 3-17.

Moore's law tracks the minimum feature size that the semiconductor industry has been able to manufacture commercially. Since 2003, all of the usual optoelectronic components and devices needed for optical routing of signals have been demonstrated in a commercial silicon foundry manufacturing process. All, that is, except for the light source itself, which remains external to the silicon but coupled to it by means of lithographically produced nano-optical grating couplers.

These lithographic grating couplers have now demonstrated mode-matching and insertion loss of less than 1 decibel (dB) and are part of the normal process flow in integrated circuit manufacturing. Indeed these nanophotonic chips[5] are also fully electronic chips, since they are made in the same process flow that produces normal integrated circuits. Thus, full optoelectronic integration is achieved, and the nano-optics is accommodated without any changes in the normal operation of a silicon fabrication plant.

[5]A nanophotonic chip is a silicon chip that is made in a modern silicon foundry, taking advantage of the fact that a modern silicon foundry can control the position of the silicon/silicon dioxide boundary to within less than 5 nm, justifying the name "nanophotonic."

Among the individual components that have been demonstrated are optical modulators that run at 20 gigabits per second (Gbps) integrated with driver electronics that currently run at 10 Gbps. Waveguides, splitters, frequency filters, and high-quality (Q) resonators have all been demonstrated and are now reduced to a library of devices, whose graphics files can be called up by an optoelectronics system designer (Kalra and Sinha, 2005; Sohler et al., 2005).

Selective-area grown epitaxial germanium on silicon has become a standard part of silicon processing in modern foundries, largely exploiting the strains that are induced, which increase the mobility and speed of transistors. Serendipitously, the germanium now permits high-speed photodetectors, as part of the standard silicon process. Moreover, these integrated photodetectors are probably the first nanophotonic integrated component that is actually superior to the best discrete component. The reason is that the electronic preamplifier can be part of the photodetector, diminishing detector capacitance. This saves many decibels in optical communications link margin, permitting performance competitive with the best discrete optical communications systems. Thus, the entire suite of optoelectronic signal processing components has recently become available as a standard commercial silicon electronic manufacturing process, and has become a standard optoelectronic manufacturing process. An example is illustrated in Figure 3-18.

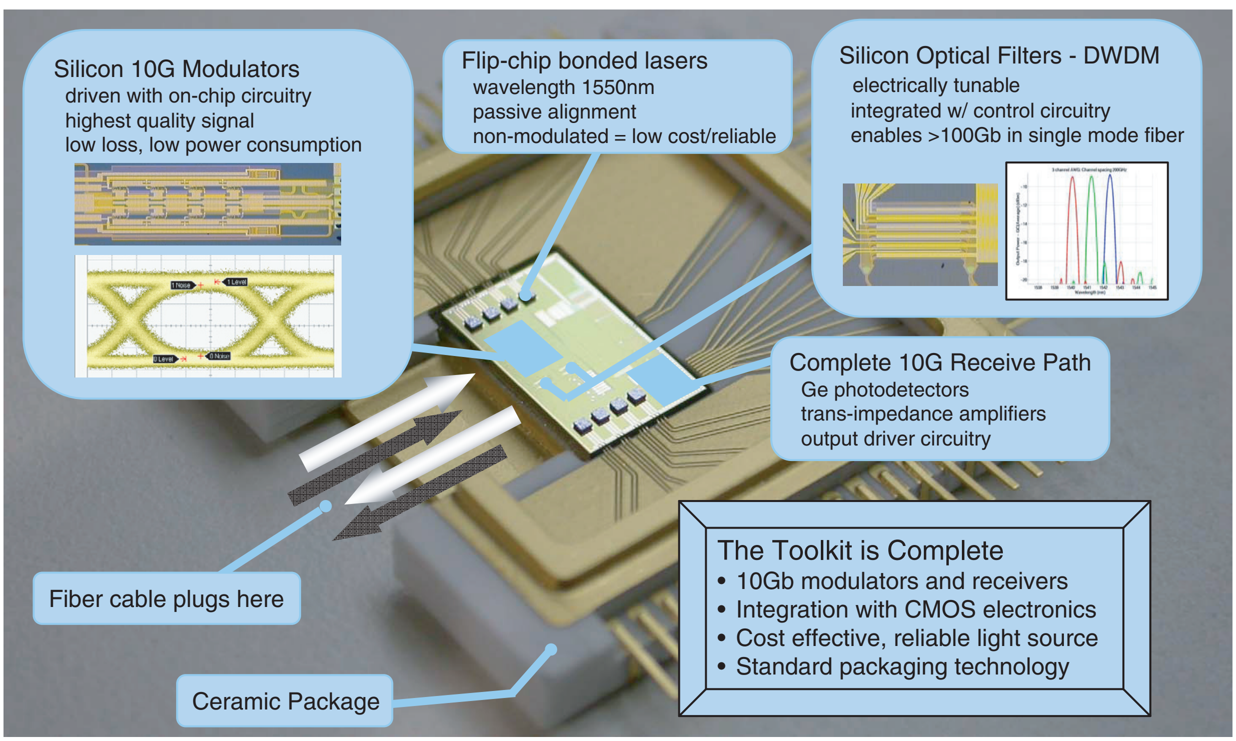

FIGURE 3-18 Luxtera complementary metal oxide semiconductor (CMOS) photonics technology. SOURCE: Gunn (2007). Reproduced with permission of Luxtera, Inc.

Deep Subwavelength-Scale Nano-Optical Devices

Deep subwavelength-scale nano-optical devices are enabled by the new-found recognition that metallic wires and waveguides can be used to control and focus light down to the scale length of a few nanometers. Such a device has already existed for a long time, in the form of the near-field scanning optical microscope, a commercial imaging instrument in the form of a nanoscopic optical pinhole.

New types of focusing structures that resemble tapered waveguides have emerged, allowing for efficient optical focusing to the nanoscale. These focusing structures are in turn fed by some type of antenna structure that converts a free-space laser beam to optical frequency currents and voltages along the metal surfaces. The optical antenna structures can be in the form of dipole antenna, monopole antenna, slot antennas based on Babinet's principle, grating couplers that resemble Yagi rooftop television antennas, and so on.[6] Among the recent insights in this field is the recognition that well-designed focusing structures can focus light down to dimensions of a few- nanometers with reasonable efficiency. Some examples of these optical nano-antennas are shown in Figures 3-19 and 3-20.

One of the important applications for these nano-optical focusing structures is for concentrating infrared radiation to improve the signal-to-noise performance of infrared sensors. Another important application is for localized laser heating to accomplish heat-assisted magnetic recording (HAMR), and for other, more speculative applications such as maskless scanning lithography. On the magnetic storage roadmap, HAMR is to appear commercially within about 5 years. Among the many issues in making HAMR practical are the many options remaining for the antenna and focusing structure. It is not clear which of these focusing options, represented in Figures 3-19 through 3-21, will emerge as the best for the HAMR application.

PACKAGING AND INTEGRATION

Although the importance of packaging and advanced integration for future nanophotonic technologies will vary vastly with the specific applications, the Committee on Nanophotonics Accessibility and Applicability believes generally that packaging and integration will play a key role in the enablement of nanophotonics.

Because nanophotonics is still an infant technology with much potential but at present relatively few specific applications, and because packaging and integration comprise a very broad subject with many different details depending on the particulars of the respective applications, the committee limits the discussion here to the "first level" of packaging technologies, thereby excluding "system-level" packaging aspects. In addition, this discussion focuses on technologies, which enable the integration of optical and electrical devices (e.g., remote sensing, night vision, computing, communications, eavesdropping, and so on) because in these areas packaging and integration technologies are particularly critical to enabling the respective nanophotonic applications. Specifically, military applications, which could be enabled by the combination of (nano)photonics and high-performance complementary metal oxide semiconductors (CMOSs), may include supercomputers on a chip for massive parallel and high-throughput real-time data processing for purposes such as the control of rockets and unmanned vehicles or for uses such as data mining (Kumagai, 2001). The types of applications often entail solving large sets of linear equations and performing many matrix operations as well as Fourier transform analysis, and they will thus require unmatched computing capabilities in conjunction with enormous data rates—potentially larger

[6] A Yagi rooftop television antenna is the standard type of rooftop television antenna that has a periodic array of metallic elements.

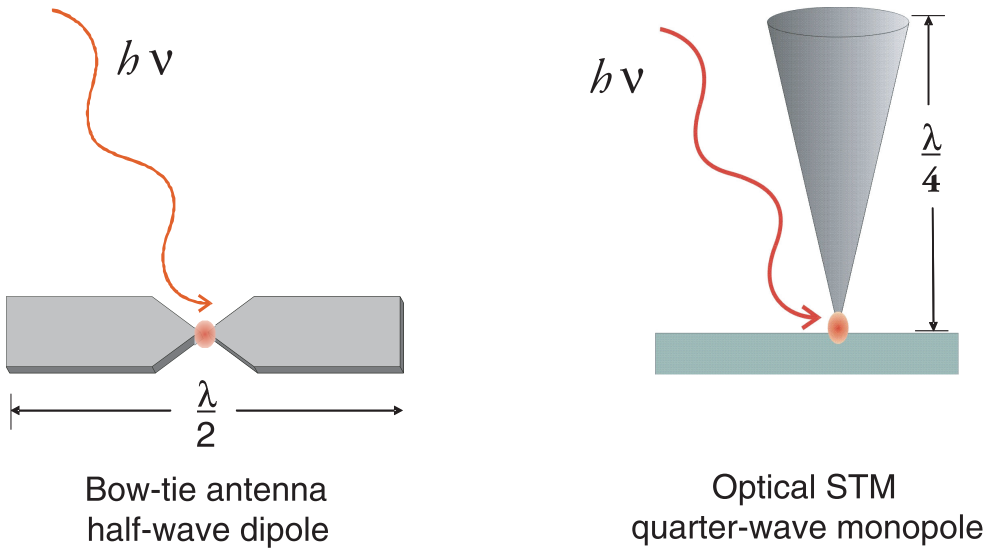

FIGURE 3-19 Two different options for an optical antenna structure that would capture optical waves and focus them to a small spot for heat-assisted magnetic recording. It is not all clear which of these designs or which other options are best. SOURCE: Eli Yablonovitch, University of California, Los Angeles, 2007. Reproduced with permission.

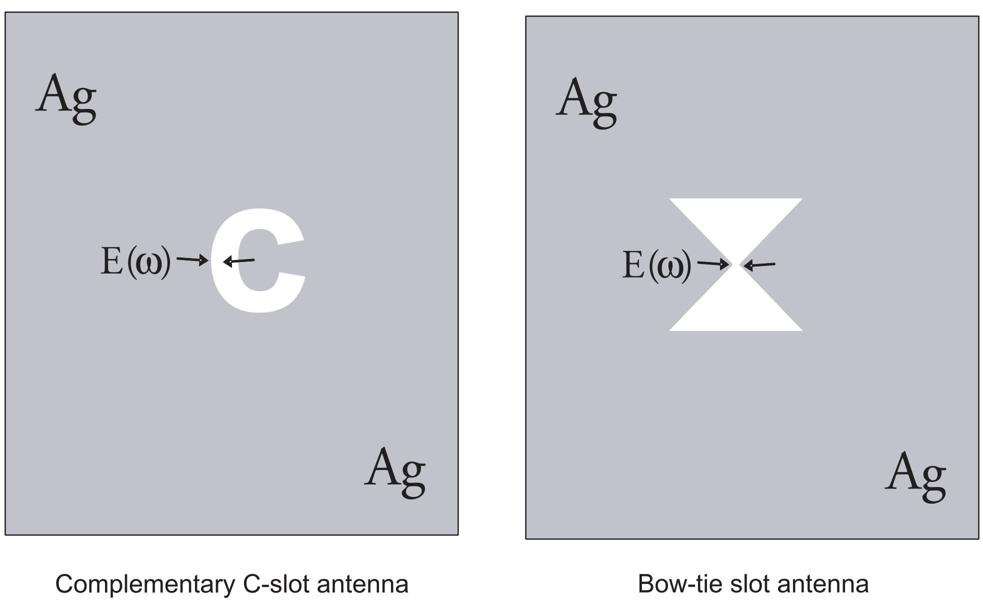

FIGURE 3-20 Some slot antenna options that are being promoted for capturing free-space lightwaves and focusing them to produce a high optical electric field $\mathcal{E}(\omega)$. These options have more metal than do the antennas in Figure 3-19, suggesting that they might possibly be more efficient against resistive losses. SOURCE: Eli Yablonovitch, University of California, Los Angeles, 2007. Reproduced with permission.

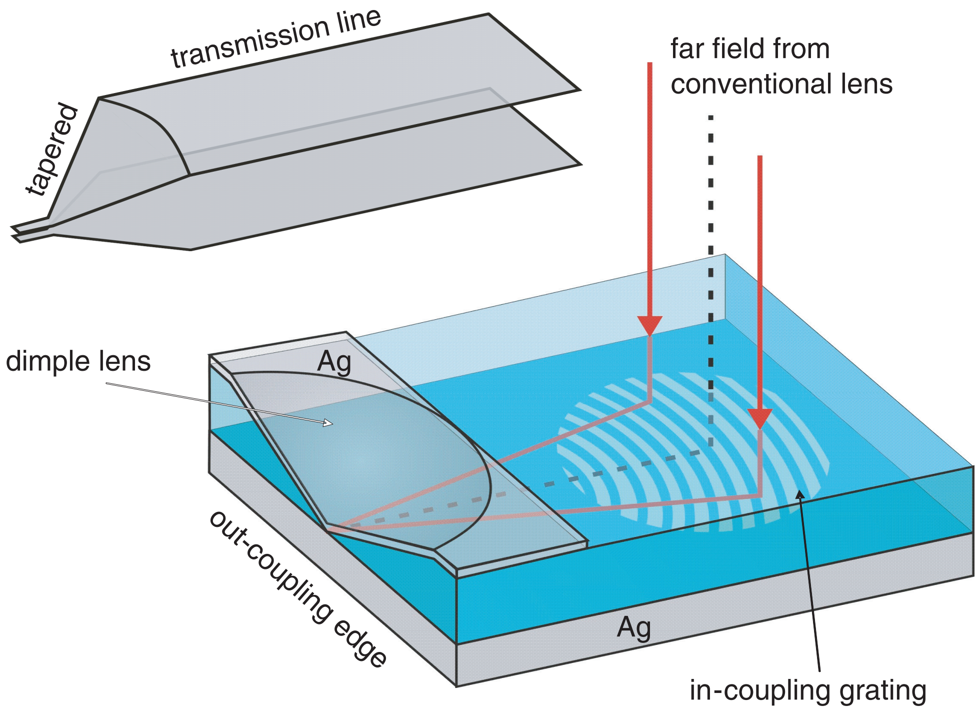

FIGURE 3-21 The dimple lens takes advantage of the wave properties of plasmons as they propagate down to the nanoscale. The net effect is somewhat analogous to a tapered parallel plate transmission line (upper left). Progressively higher wave impedance toward the vertex of the dimple ensures high efficiency, relative to the inevitable resistive losses in the metallic components. SOURCE: Eli Yablonovitch, University of California, Los Angeles, 2007. Reproduced with permission.

than 50 terabits per second, which probably only (nano)optics closely integrated with high-performance CMOS will be able to deliver.

Technology Environment

Nanophotonics—at least in its current form—relies heavily on semiconductor and CMOS fabrication capabilities and their associated package and integration technologies. In fact, nanophotonics depends—at least to some extent—on the continued progression of semiconductor manufacturing and integration capabilities as projected by the *International Technology Roadmap for Semiconductors* (ITRS) (International Roadmap Committee, 2005). Because of this strong dependence, some relevant semiconductor technology trends are discussed here, as these will be driving new packaging and integration technologies, which could be very important for the general enablement of nanophotonics.

Because of increasing technology challenges, discussed in more detail below, the committee considers an increasing likelihood of diminishing returns on investment in the semiconductor industry. Such a trend could result in the possibility of fewer investment dollars in the further development of these manufacturing capabilities, which could have potentially important implications for the general development of future nanophotonic devices (especially in the optical frequency range). This is particularly true if nanophotonics fails to identify applications that are commercially important enough to warrant the major investments necessary to improve current semiconductor manufacturing capabilities. The tight interdependence of nanophotonics on semiconductor manufacturing will possibly make nanophotonics much more readily accessible in foreign countries (especially India, China, and Taiwan, for example), as some segments of the semiconductor industry may commoditize, which warrants a continued reduction in cost by offshoring and outsourcing.

In the past there were two major incentives for the semiconductor industry to keep shrinking the size of the transistor ("transistor scaling"), creating a "win-win" situation for clients and manufacturers. Not only did the performance of the transistor increase significantly with every technology node (about 15 percent per generation), but also the actual cost per transistor decreased (typically by gradually increasing the wafer sizes). In addition, smaller transistors enable higher transistor package densities, resulting in more transistors per die and thus even more performance and functionality on the chip level. While there is still a significant economic benefit to be gained from shrinking transistor sizes further, the performance improvements have been lagging recently and the rate of scaling may be slowing down—mostly because of the inability to scale the gate dielectric thickness in a power-constrained environment.

Today the semiconductor industry is facing two major technical challenges. First, the combination of higher transistor densities and the emergence of leakage current (due to short-channel effects and other causes) has led to an explosion of power dissipation on CMOS circuitry (Frank, 2002). Today's semiconductor chips are generally considered power-limited, and no additional power consumption can be tolerated (Horowitz, 2007). The second major technology challenge originates from the emergence of "physics-based" or pure statistical variations (Bernstein et al., 2006). For example, the numbers of dopant atoms within a transistor channel approaches levels at which the location of individual dopant atoms starts to matter. For example, for 100 dopant atoms (with a current manufacturing scheme of implanting), the statistical dopant fluctuation from device to device is already about 10 percent ($\sqrt{N} / N$), affecting transistor threshold voltages (Stolk et al., 1998). Other "physics-based" variations include line-edge roughness or contact resistances.

While major technology innovations such as high-k dielectrics will play a key role in the mitigation of the power crisis and novel device structures will be critical to reducing the variability impact, it is generally believed that the semiconductor industry has to find additional ways of enhancing performance besides traditional device scaling (Chen et al., 2006). This trend opens up significant opportunities for nanophotonics and nanophotonic integration. New materials, novel device structures, innovative designs (such as Fin-field-effect transistors, ultrathin silicon on insulator [SOI]), and new CMOS processes will be the key drivers for improving device performance and thus will be more rapidly and readily incorporated. For example, the semiconductor industry has already started aggressively to adopt more materials and elements into the CMOS process, redefining CMOS compatibility. While before the 1990s all CMOS circuits were made of only seven elements (silicon, hydrogen, arsenic, boron, oxygen, aluminum, and phosphorus), today semiconductor devices have many more elements (more than 15), which could enable and accelerate CMOS-compatible nanophotonic integration, as nanophotonics undoubtedly requires a more diverse selection of elements and materials.

The continued challenges with respect to increasing power and variability and the insatiable demand for more computing performance have led to the rise of multicore processors, in which instead of one very high power density and speed processor core with a deep pipeline, several cores at less frequency and power are implemented, yielding more performance per unit of power on the chip level. The numbers of cores on a single die chip will be drastically increasing in the near future. For example, the International

Business Machines (IBM) cell processor already has nine different processor cores, and the trend is expected to be continued (Kahle et al., 2005).

These emerging chip multiprocessors (CMPs) are fundamentally different from past unicore microprocessors because their performance is much more determined by the efficiency and throughput of the global intrachip communications infrastructure. However, conventional electrical interconnects are starting to reach limitations such as increased latency; increasing power consumption (because of the power consumption of multiple repeaters, which worsens the power problem of an already power-limited microprocessor); and resonant-cavity bandwidth limitations to an extent that only a small fraction of the die can be reached within one clock cycle (time-of-flight problem). As a consequence, the semiconductor industry has started looking at more densely integrated optical interconnects and nanophotonic solutions, which could enable vastly superior, higher-throughput, distance-independent, potentially less-power-consuming and less-latency-prone on-chip communication systems. This activity is consistent with a general trend in the computing industry, which has been gradually introducing optics in its system getting closer and closer to the microprocessor (see the trend in Figure 3-22). This trend is very important because it may imply that optics will be introduced closer and closer to the chip level, making nanophotonics devices commercially highly relevant.

As for the chip design, and in sharp contrast to the past when a high-performance core was individually custom-designed, CMPs are using more modular system-on-chip (SoC) design techniques in order to deal with the increased complexity at growing design costs. It is expected that these more modular design strategies will more readily enable outsourcing and offshoring of circuit design and possibly eventually fabrication work, which could enhance the accessibility of nanophotonics in foreign countries.

	MAN/WAN	Cables–long	Cables–short	Card-to-card	Intra-card	Intra-module	Intra-chip
Length	Multi-km	10–300 m	1–10 m	0.3–1 m	0.1–0.3 m	5–100 mm	0–20 mm
No. of lines per link	One	One to tens	One to tens	One to hundreds	One to hundreds	One to hundreds	One to hundreds
No. of lines per system	Tens	Tens to thousands	Tens to thousands	Tens to thousands	Thousands	Approximately ten thousand	Hundreds of thousands
Standards	Internet Protocol, SONET, ATM	LAN/SAN (Ethernet, InfiniBand, Fibre Channel)	Design-specific, LAN/SAN (Ethernet, InfiniBand)	Design-specific and standards (PCI, backplane InfiniBand and Ethernet)	Design-specific, generally	Design-specific	Design-specific
Use of optics	Since the 1980s	Since the 1990s	Present time, or very soon	2005–2010 with effort	2010–2015	Probably after 2015	Later

FIGURE 3-22 Evolvement of the role of optical communication in server computing systems. NOTE: MAN/WAN, mobile area network/wide area network; SONET, synchronous optical networking; ATM, asynchronous transfer mode; LAN/SAN, local area network/storage area network; PCI, peripheral component interconnect. SOURCE: Benner et al. (2005). Reproduced with permission of IBM Research.

Two very important implications can be gleaned from these general semiconductor technology trends. First, because of power limitations and statistical variability, the semiconductor industry is undergoing a major paradigm shift to multicore processing with increased on-chip communication requirements. This shift is quite likely to accelerate the introduction of (nano)photonic solutions, which provide an attractive alternative to traditional electronics. Second, the continuously increasing technological challenges associated with exploding development and fabrication costs for the next-generation technology (which has already led to the formation of large international alliances in the semiconductor industry) (Isaac, 2003), in combination with more modular design strategies, will make it more likely that the industry seeks cost reduction by outsourcing its design and (possibly) fabrication work to foreign countries.

Packaging and Integration Technologies

In response to the realization that future enhancements of chip performance require major innovations and more heterogenous technology components, it is expected that the focus on integration and packaging will continue to increase, which is consistent with the view of the ITRS (see Figure 3-23).

In Figure 3-23, *monolithic* system-on-chip (SoC) and *polylithic* system-in-package (SiP) technologies are viewed to be critical to enabling the continued growth of information technology beyond Moore's

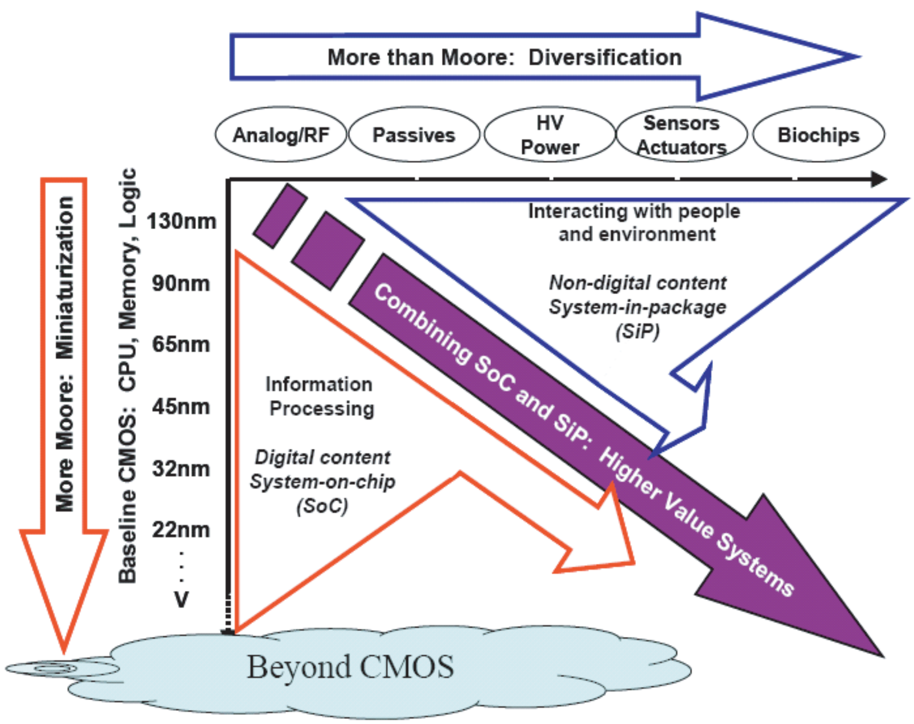

FIGURE 3-23 The minimum feature sizes of integrated circuit manufacturing have already passed the required scales for nanophotonic components, at least at telecommunication wavelengths, making the integration of photonics and electronics readily achievable using standard integrated circuit nanofabrication tooling. NOTE: CMOS, complementary metal oxide semiconductor; CPU, central processing unit; RF, radio frequency; HV, high voltage. SOURCE: Semiconductor Industry Association (2005b). Reproduced with permission of SEMATECH.

law (i.e., "more Moore"). Figure 3-24 illustrates the balance between SoC and SiP solutions, which is naturally governed by the respective cost function. While certain system complexities and heterogeneousness can be integrated cost-effectively using a modular SoC approach, the integration of highly complex and heterogenous systems—possibly including nanophotonic devices, but also microelectromechanical systems (MEMS) and bioelectronics—is more economically addressed by SiP technologies with a higher degree of miniaturization and flexibility.

Because nanophotonics is still an infant technology, it is arguably a very difficult task to understand which packaging and integration technology is most relevant for its enablement. The complicated interplay between limitations of existing technologies, the potential enablement of new computing architectures by optics and nanophotonics, the appropriate level of integration, and the advances of the different nanophotonic technology platforms is still an ongoing research topic. However, it is likely that the accessibility of nanophotonics will be significantly influenced by the way that computer manufacturers decide to integrate optics and nanophotonics (i.e., How close does optics have to get to the device and microprocessor to harness the benefits of optics cost-effectively?).

The committee recommends the close monitoring of these trends in the integration of optics and nanophotonics by computer manufacturers because they will most likely determine the direction of massive investments. If indeed nanophotonics can be integrated cost-effectively and monolithically with high-performance CMOS, the respective suitable nanophotonic technology platforms will be more limited (Si-based and CMOS-compatible nanophotonics). Special attention has to be directed toward CMOS-compatible nanophotonics research and development activities because the nanophotonic technology platform will have to be attuned with CMOS processes and materials. However, if optics will be integrated polylithically or heterogeneously, then the nanophotonic technology platforms can be much more diverse, and a corresponding technology watch would have to encompass a much wider range of activities. In the latter case, the role of packaging will be even more central.

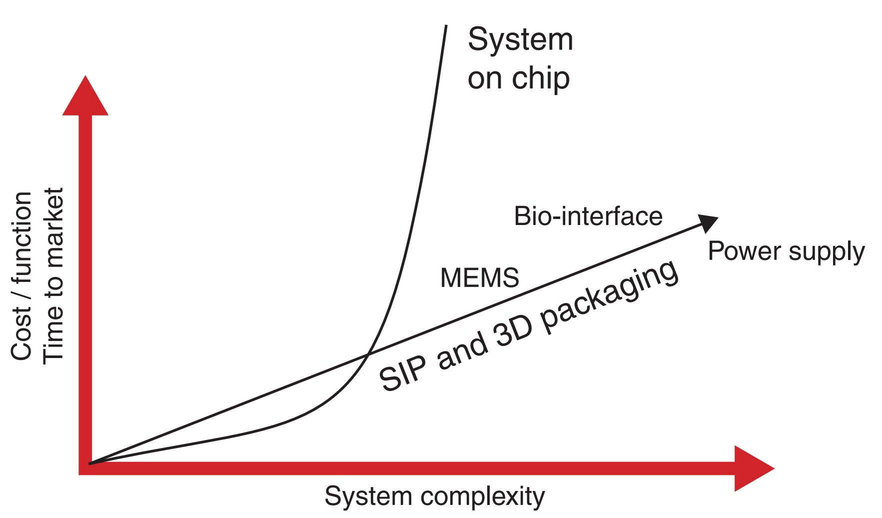

FIGURE 3-24 Cost versus complexity for system-on-chip, system-in-package (SiP), and 3D Packaging integration approaches. NOTE: MEMS, microelectromechanical systems; 3D, three dimensional. SOURCE: Semiconductor Industry Association (2005a). Reproduced with permission of SEMATECH.

The following subsections first discuss monolithic (i.e., Si photonics) and then polylithic/heterogenous integration and packaging approaches (three-dimensional Si, Si-carrier). For purposes of discussion, the committee distinguishes between monolithic and polylithic (heterogeneous) integration, but it realizes that this boundary is somewhat blurred with the introduction of new integration and packaging technologies such as three-dimensional silicon.

Monolithic Integration: Silicon Photonics

Monolithic integration using silicon photonics drives toward the seamless fabrication of CMOS and photonic circuits on the same circuit layer, creating an SoC-like chip with an on-chip communication layer (Reed and Knights, 2004). The United States is a leader in this field, driven by its dominant semiconductor industry, but there are also significant and technically relevant activities in Europe (in particular, at IMEC in Belgium, COM [Communications, Optics, and Materials] Research in Denmark, RWTH Aachen University, Germany); in Japan (at NTT); and also more recently in China, Korea, and India.

The promise of Si photonics lies in the exploitation of the maturity and precision of CMOS technology as well as in the synergy of ultracompact integration of optical and electrical functions on the same chip. Silicon is transparent in the range of optical telecommunication wavelengths (at 1.55 micrometers [μm]) and has a high refractive index that allows for the fabrication of densely packed nanophotonic structures. The general concept of Si as a waveguide and of modulating its index using electrons and holes had been proposed for quite some time; only recently, however, has significant progress been made, in which CMOS-compatible waveguides (and other passive devices such as splitters), modulators, deflection switches, wavelength demultiplexers, delay lines, and detectors have been demonstrated (Bogaerts et al., 2005; Soref and Bennett, 1987; Soref and Lorenzo, 1986). In addition, complete chip-level demonstrations have been also been reported, which have implemented monolithic integration between Si photonics and CMOS using a standard CMOS fabrication line (Gunn, 2006; Jalali et al., 2005). While these demonstrations are clearly major stepping-stones, the monolithic integration between "high-performance" CMOS in the form of a microprocessor or application-specific circuits has not been done yet—partially because of integration issues (as discussed in more detail below) but also because the required optical components are not available yet.

Waveguides and Passives

The recent progress in silicon-based waveguides has been helped by the general availability of silicon on insulator (SOI) wafers, which can be readily used to fabricate Si waveguides supported by the buried oxide (BOX). SOI-based single mode (SM) and multimode (MM) waveguides have been fabricated with cross-sectional dimensions of approximately $0.3 \times 0.3\ \mu m^2$ and $0.3 \times 2.0\ \mu m^2$, respectively (Bogaerts et al., 2004; Vlasov and McNab, 2004). Despite the fact that propagation losses increase drastically with an increasing index of refraction contrast ratio ($\Delta n = n_{Si} - n_{SiO_2} = 2$), the unprecedented accuracy of CMOS fabrication capabilities (by fabricating waveguides with extremely small roughness) has yielded ultradense (pitch of less than 2.0 μm with negligent cross-talks) waveguide structures with quite low losses of less than 1.6 dB/cm and 0.2 dB/cm for SM and MM, respectively (Lee et al., 2001; Vlasov and McNab, 2004). Despite this progress, it remains an ongoing challenge because any losses directly impact the link budgets, which can be very tight in a power-limited design environment. Consequently, the optical properties of Si waveguides are still an active research topic, because propagation (as well as coupling and/or insertion losses) is dependent sensitively on group index, BOX thicknesses, exact waveguide dimensions, wavelengths, optical modes, distance to electrical contacts, and other interconnects. Following the successful fabrication of these waveguides, low-loss splitters, bends, directional couplers, and other passives such as wavelength demultiplexers and delay lines have been fabricated (Dumon et al., 2006; Xia et al., 2006; Xia et al., 2007). The dispersion properties of SM Si waveguides are shown to have a dispersion length of several centimeters at data rates of larger than 200 Gbps, which is suitable for on-chip communications (Dulkeith et al., 2006). It is also established that these waveguides can carry up to 20 dBm of power, which is limited by nonlinear effects in the Si waveguides, fundamentally constraining the link budgets (Hsieh et al., 2006).

Modulators

Several recent demonstrations have shown the feasibility of compact modulators on SOI with up to 10 Gbps bandwidth (e.g., 6.5 Gbps and 1 milliwatt [mW] power dissipation) (Almeida et al., 2005). Fundamentally, there are two simple mechanisms (thermooptic and carrier injection) for modulating the refractive index in silicon, which can be exploited for building modulators. Modulators with both mechanisms have been demonstrated in several optical device configurations, such as Mach-Zehnder interferometers and ring resonators (Almeida et al., 2005; Espinola et al., 2003). The disadvantage with thermooptic modulators (typically realized in a Mach-Zehnder configuration) is the limited bandwidth, which is governed by the typically slow thermal diffusion times. While carrier-injection-based modulators can be very fast (limited by carrier lifetimes), they can suffer from poor overlap between the optical mode and the injected carriers, which require high Q resonator devices (to boost the sensitivity) and which are very temperature-sensitive. At this stage it remains a research topic to balance bandwidth, power consumption, losses, extinction ratio, temperature stability, and footprint requirements for these types of modulators. The committee notes that recently Si-based electrooptical modulators have also been demonstrated using quantum wells, although still with a low extinction ratio (Kuo et al., 2005).

Detectors

Compared with III/V detectors, Si-based receivers are lacking performance, although recently a very high bandwidth germanium-on-silicon-on-insulator (Ge-on-SOI) photodetector was demonstrated with a very small footprint (Dehlinger et al., 2004; Schow et al., 2006). CMOS-compatible detector design will be governed by a trade-off between CMOS compatibility (materials, processes, process flow), required bandwidth, wavelength range, sensitivity (quantum field, absorption depth), voltage requirements, and packaging approach. The detector will be closely integrated with the waveguide structure with minimum footprint to limit capacitance (Dehlinger et al., 2004; Schow et al., 2006). Other complementary detector approaches comprise tunnel junctions such as metal-insulator-metal, where nanoscopic optical antennae may be used to increase the coupling and detection efficiency (Zia et al., 2006).

Light Sources or Gain Elements

Despite intensive research, an Si laser or light source is still the central missing piece needed to enable the complete monolithic integration of Si photonics. As is well known, the reason for the difficulties in engineering a suitable light source lies in the fact that Si is an indirect band-gap material, which makes nonradiative processes more probable than the actual light emission. Heterogeneous approaches involve silicon evanescent amplifiers, which employ silicon waveguides and an evanescent tail extending into indium gallium aluminum arsenide (InGaAlAs) quantum wells. These quantum wells, which are deposited by low-temperature, oxygen plasma-enhanced bonding, are very promising because these devices can be quite small, with low power consumption (Fang et al., 2006).

The committee believes that nanophotonics will play an important role in the potential enablement of an Si-based light source and/or gain element. In the absence of an on-chip light source, light needs to be coupled on and off the chip, which is a technically difficult task owing to the high index of refraction contrast of the Si waveguides. However, significant progress has recently been made on two fronts. First, several groups managed to mode-match the different optical profiles between a large single-mode fiber and the Si waveguides by using a smart waveguide taper coupling the light adiabatically into the submicron waveguide (Day et al., 2003; Salib et al., 2004). Second, passive alignment techniques for the external optical fiber with respect to the waveguide have been demonstrated (by creating lithographically defined structures on the silicon surface in order to align the fiber to the waveguide aperture); these techniques remove the need for a closed-loop optimization/coupling scheme.

In summary, the emergence of Si photonics is likely to have a profound impact in large distance-communication systems. As Si photonics relates to the enablement of chip-scale supercomputers (enabling the unmatched communication between many cores), it is currently not clear how Si photonics will be integrated with the high-performance CMOS for many reasons and issues ranging from BOX thickness, metallization, circuit and device integration, and process compatibility.

Heterogeneous Integration: Silicon Carrier, Three-Dimensional Silicon

The monolithic integration of Si photonics with high-performance CMOS circuitry could be eventually the most cost-effective integration way; it may turn out, however, that the optimization of electrical and optical components leads to such different competing requirements that only heterogeneous packaging approaches can rectify this. As discussed, these heterogeneous approaches will provide openings for more diverse technology platforms. Although the general trend to use Si as a package material somewhat favors Si photonic-based approaches (even if they are not entirely compatible with high-performance CMOS): specifically, an Si chip carrier can provide via densities, which make heterogeneous assembly approaches more feasible, where one needs very high-interconnect densities—formerly not supported by traditional carriers (Knickerbocker et al., 2005). The Si carrier technology components are manifold (Si through micro-C4, high-density wiring, and many supporting testing, assembly, and fabrication technologies) and have been demonstrated recently. In essence, an Si carrier provides a general way of very tightly integrating different chip technologies and achieving SoC performances with a system on a package (SoP) solution, thereby creating a "virtual" chip. This technology can play a key role in the enablement of nanophotonics—especially in conjunction with high-performance CMOS—without the burden of being "fully" CMOS-compatible. For example, a chip including nanophotonic devices (e.g., a receiver chip) can be readily integrated and packaged with a microcontroller or microprocessor using SoP technologies. Figure 3-25 illustrates a roadmap for this technology, with a trend toward increasing integration from two to three dimensions. It also shows that the Si carrier is the first important step toward even tighter three-dimensional integration, which is a trend consistent in the industry's advancing chip-stacking techniques.

OVERARCHING RECOMMENDATION

Recommendation 3-1. The committee recommends that the intelligence technology warning community be especially aware of countries and groups that have access to a combination of advanced packaging and integration technologies and nanophotonics.

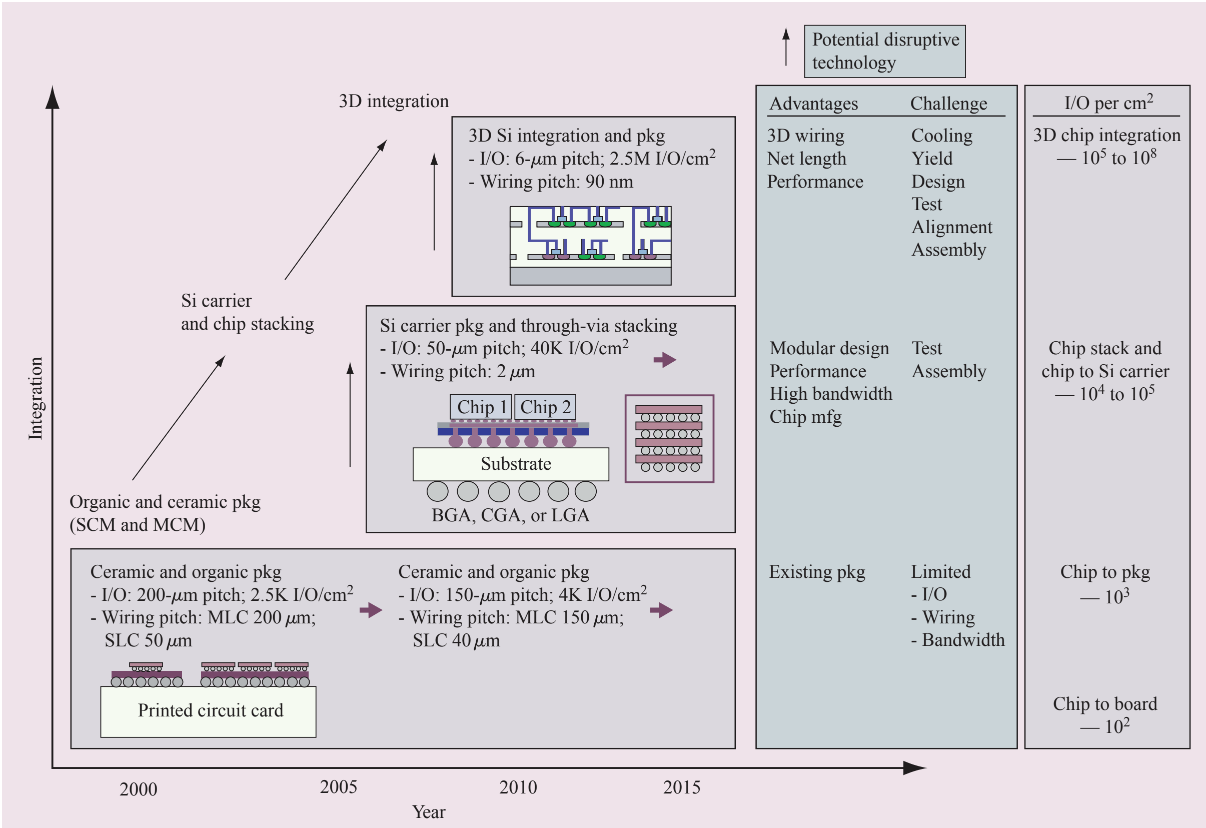

FIGURE 3-25 Silicon integration and packaging roadmap. NOTE: SCM, single-chip module; MCM, multichip module; Si, silicon; 3D, three-dimensional; I/O, input/output; BGA, ball grid array; MLC, multilayer ceramic; CGA, column grid array; LGA, land grid array; SLC, surface laminar circuit. SOURCE: Knickerbocker et al. (2005). Reproduced with permission of IBM Research.

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4

Potential Military Applications of Nanophotonics

INTRODUCTION

The Committee on Nanophotonics Accessibility and Applicability believes that there is clearly potential for nanophotonics to have a significant impact on military systems, in both symmetric and asymmetric warfare. In order to assess the potential applications, the committee made reference to the National Research Council's (NRC's) report *Avoiding Surprise in an Era of Global Technology Advances* (NRC, 2005), which describes a framework that is suitable and methodologies that are pertinent for assessing potential applications in the present study. The present committee points out that even as there is clear potential for the significant impact of nanophotonics as described above, it is also likely that nanotechnology insertion into disruptive technologies that could pose threats is difficult to anticipate by the very nature of such threats and the sometimes embryonic state of research in nanophotonics relative to other technologies. Some applications may take substantial investments and time before they are realized. The committee also understands that nanophotonics will require a fabric of supporting and enabling technologies. This technology environment (at least in part) does not exist today, which further complicates the outlook. Within the predefined framework that the committee employed, strong emphasis was placed on information technology (IT) as a possible "game changer," with nanophotonics being a technology that could potentially enable a much more ubiquitous and pervasive data-processing (and sensing) capability than is currently available. It is also understood that the present study is not intended to promote the potential of nanophotonics, but to make certain that the technology parameters identified are real and can be translated into military applications.

Finding 4-1. The committee believes that, because of the infancy of nanophotonics, the probability of near-term revolutionary changes using nanophotonics is small but not negligible, for both domestic and foreign entities.

REPORTING PROCESS AND METHODOLOGY

The process and methodology defined in *Avoiding Surprise in an Era of Global Technology Advances* (NRC, 2005) is being employed in this report (with modifications) for consistency, to convey the response of this committee in a traceable way as it seeks to predict a potential adversary's military utilization of nanophotonics during a 10-to-15-year time frame (i.e., from 2017 to 2022).

This section identifies and describes the methodology that is used to gauge the importance of nanophotonics to the different applications areas. In the next section, "Potential Enabling Technologies and Applications," the committee members report their assessments of some exemplary applications vignettes using this methodology. Each of the eight such committee assessments on pros, cons, and military risks; and presents recommendations to address the Defense Intelligence Agency's (DIA's) concerns about the applications with respect to *Joint Vision 2020* (JCS, 2000). As illustrated in the sample Chart 4-1, "Example of Technology Assessment Chart," the methodology employed addresses the following 10 areas:

1. *Application area:* area in which a nanophotonics-based technology can be employed.
2. Potential *technology:* described briefly (in general terms) with respect to the application.
3. *Observables:* which are indicators of research progress and investments or products derived from nanophotonics, such as publications, funding sources and amounts, and open-market artifacts that the sponsor should monitor to determine growth within the realm of potential military usefulness.

CHART 4-1 Example of Technology Assessment Chart

<table>
<tr><th colspan="3">Application Area</th></tr>
<tr><td colspan="3">Text and/or graphical representation</td></tr>
<tr><th colspan="2">Technology</th><th>Observables</th></tr>
<tr><td colspan="2">Brief description of technology</td><td>Brief description of observables</td></tr>
<tr><th>Accessibility</th><th>Maturity</th><th>Consequence</th></tr>
<tr><td>Level 1, 2, or 3</td><td>Technology Futures
Technology Watch
Technology Warning
Technology Alert</td><td>Short characterization of consequences</td></tr>
<tr><th colspan="3">Enablers and Key Technical Parameters</th></tr>
<tr><td colspan="3">Put the technology into a lay person's perspective</td></tr>
<tr><th colspan="3">Triggers</th></tr>
<tr><td colspan="3">List new developments to watch that may enable warfare capability.</td></tr>
<tr><th colspan="3">Narrative(s)</th></tr>
<tr><td colspan="3">Summarize current research and development.</td></tr>
<tr><th colspan="3">Assessment Summary</th></tr>
<tr><td colspan="3">Include pros, cons, overall view, and military utilization, where available.</td></tr>
</table>

4. Three levels of a*ccessibility* of the technology to allies or adversaries in terms as stated in the NRC's *Avoiding Surprise in an Era of Global Technology Advances* (NRC, 2005, p. 25):

The accessibility variable focuses on the question, *How difficult would it be for an adversary to exploit the technology?* It addresses the ability of an adversary to gain access to and exploit a given technology. This assessment is divided into three levels:

- *Level 1.* The technology is available through the Internet, being a commercial off-the-shelf item; low sophistication is required to exploit it.
- *Level 2.* The technology would require a small investment (hundreds of dollars to a few hundred thousand dollars) in facilities and/or expertise.
- *Level 3.* The technology would require a major investment (millions to billions of dollars) in facilities and/or expertise.

In general, Level 1 technologies are those driven by the global commercial technology environment; they are available for exploitation by a diverse range of potential adversaries. Level 3 technologies, by contrast, are typically accessible only to state-based-actors. The indicators likely to be of value in determining an adversary's actual access to a given technology vary by level as well as by the type of technology.

5. *Maturity* of the technology in terms of its readiness level, as expressed in *Avoiding Surprise in an Era of Global Technology Advances* by Futures, Watch, Warning, and Alert (NRC, 2005, p. 25):

The maturity variable focuses on the question, *How much is known about an adversary's intentions to exploit the technology?* It integrates what is known about an adversary's actions, together with an evaluation of the state of play with respect to the technology of interest. At the highest level, called Technology Alert, an adversary has been identified and an operational capability has been observed. At the lowest level, Technology Futures, the potential for a technology-based threat has been identified, but no positive indicators have been observed. The Maturity assessment is divided into four categories: the first two (the lower levels) suggest further actions for the technology warning community; the other two indicate the need for immediate attention by military leadership:

- *Futures.* Create a technology roadmap and forecast; identify potential observables to aid in the tracking of technological advances.
- *Technology Watch.* Monitor (global) communications and publications for breakthroughs and integrations.
- *Technology Warning.* Positive observables indicate that a prototype has been achieved.
- *Technology Alert.* An adversary has been identified and operational capability is known to exist.

6. Strategic *consequences* to the sponsor if this technology development area is not monitored, viewed from a defensive military perspective as defined in *Avoiding Surprise in an Era of Global Technology Advances* (NRC, 2005, p. 26):

Characterization of a technology in terms of the consequence variable involves addressing the question, *What is the impact on military capability should the technology be employed by an adversary?* It involves assessing the impact of the postulated RED technology on the capability of BLUE forces. This impact can range from denial or negation of a critical capability to the less-consequential level of annoyance or nuisance. A corollary assessment may be made as to the locus of impact—that is, whether the technology affects a single person, as in the case of an assassination, or creates a circumstance of mass casualty and attendant mass chaos.

7. Technology *enablers and key technical parameters,* including packaging and interface requirements, described in lay terms.
8. *Triggers,* which may be unpredictable but which are nonetheless important in enabling significant revolutionary developments, particularly those deemed disruptive.
9. A *narrative* in which the current research and development (R&D) is summarized and where the leaders in the R&D may be identified by way of sources in the current literature.
10. An *assessment summary* that includes the assessment of the technology in terms of "pros, cons, overall view, potential military utilization and associated risks."

Graphic representations, such as photographic and other images, of the potential technology and its associated application are provided as appropriate to the particular applications.

POTENTIAL ENABLING TECHNOLOGIES AND APPLICATIONS

The committee deliberated on the potential technologies and applications that nanophotonics can enable, as well as the infrastructure needed to enable the nanophotonics base technology in the first place. Key aspects of this infrastructure are described in Chapter 3. Several general, militarily relevant applications categories and their respective specific subcategories are introduced below. The specific subcategories, shown in italics, are described in the example vignettes in Charts 4-2 through Chart 4-9. Although the general categories reflect a military emphasis, many of the specific applications have commercial and space utility as well.

The general categories are sensing; command, control, and communications; computing; countermeasures; and power. Sensing is the largest of these; its subcategories include *imaging sensors* (including *night vision* as well as *long wave* and *mid-wave infrared sensors*), *chemical sensors, biosensing* (including biometrics), and *advanced spectroscopy* for sensing and materials characterization. Other more mission-specific areas in which nanophotonics devices have been envisioned include health monitoring, tagging, tracking, locating, or eavesdropping, and situational awareness in general.

In the general category of command, control, and communications, applications can be enabled for a variety of potential needs, such as platform avionics, the remote actuation of devices, as well as *emissive displays* for monitoring. The field of secure communications, including quantum key distribution, is also potentially fertile ground for nanophotonics insertion.

Nanophotonics applications in the category of computing are especially anticipated in robust computation, *computing systems and microprocessors*, *data storage*, and optical signal processing.

This study's use of the term "countermeasures"—another general category—is actually rather broad. It spans active countermeasures and stealth but also includes sensor protection, bioremediation, and decontamination. Promising applications in the power category include *micropower*, *solar cells*, and energy harvesting.

Finally, in the section "Technologies in Their Infancy," a more detailed look at the state-of-the-art of quantum computing and nanophotonics is provided, and the adjunct field of *terahertz spectroscopy and nanophotonics* is also described.

CHART 4-2 Application Area: Solar Cells and Micropower

FIGURE 4-2-1 Efficient, lightweight photovoltaic cells provide battery rechargers, tents and shelters, and other electrical devices for the soldier in the field. SOURCE: Image provided by Steve Smith, SAIC. Reprinted with permission.

Technology	Observables
• Efficient absorption of solar energy and conversion of photons to electronic carriers to provide power to drive devices. • Incorporation of nanophotonic materials or phenomena to enhance photovoltaic efficiencies.	• Research and development activities related to nanoscale photovoltaic devices. • Start-up companies in this area.

Accessibility	Maturity	Consequence
Level 3	Technology Watch	Pervasive, lightweight sources of power would enable continual access to computation and communications, facilitating the capability to pursue military goals.

chart continues

CHART 4-2 Continued

Enablers and Key Technical Parameters

Single-crystal silicon solar cells comprise the dominant photovoltaic (PV) technology, with module efficiencies of about 10 to 12 percent and module costs of about $3.50 per watt. Solar power costs, even with a subsidy, are not competitive with more traditional energy sources; this has prevented solar power's more widespread commercial appearance. Cost may not be the dominant issue for military or other specialized applications, where high energy conversion efficiency and the existence of lightweight, renewable energy sources may be of paramount importance. The single bandgap (single junction) cell limits the total range of the solar spectrum that can be captured, thus limiting the efficiency, while the single-crystal substrate provides constraints to achieving lower cost and manufacturability of large-area solar cells. Multiple-junction solar cells (e.g., the gallium indium phosphide/gallium arsenide/germanium [GaInP/GaAs/Ge] cell developed by the National Renewable Energy Laboratory [NREL] and Spectrolab) with semiconductors that collectively span a greater fraction of the solar spectrum have shown efficiencies well in excess of 30 percent, but the epitaxial or pseudomorphic matching of the layers and the critical tolerances on device design set limits to cost and manufacturability.

Key innovations in improving the efficiency of solar cells while maintaining reduced costs focus on (1) creating low-cost absorbers that will fully capture the full range of the solar spectrum, (2) maximizing solar absorbance while not compromising electron-hole formation, separation, and collection. In recent years, engineering of nanoscale components has offered new approaches for PV enhancement. Regular arrays of nanocrystals (quantum dots) are predicted to form mini-bands or "multiple energy level" solar cells that more efficiently convert absorbed photons to electrical carriers, rather than creating dissipated heat. Plasmonic structures could serve as antennas or amplifiers that could resonantly couple photons to the PV material (Lewis et al., 2005).

Triggers

Potential revolutionary opportunity: Portable, lightweight sources of power for the battlefield.

Narrative(s)

Two new solar cell companies cited as offering nanostructured PV materials are Konarka and Nanosolar.

FIGURE 4-2-2 Konarka's flexible solar cells. SOURCE: Image courtesy of Konarka Technologies, Inc. Reprinted with permission.

chart continues

CHART 4-2 Continued

The first of these, Konarka, was founded in July 2001 and focused on the development and advancement of nano-enabled polymer photovoltaic materials that are lightweight, flexible, and more versatile than traditional solar materials. Konarka's technology represents a new breed of coatable plastic flexible photovoltaic material that can be used in many applications where traditional photovoltaics cannot compete. The resulting plastic-based photovoltaic cells (see Figure 4-2-2) are efficient across a much broader spectrum of light than traditional solar cells.

The second company, Nanosolar, founded in 2002, incorporates nanostructured material components as the basis of large-area, printable photovoltaic structures (see Figure 4-2-3).

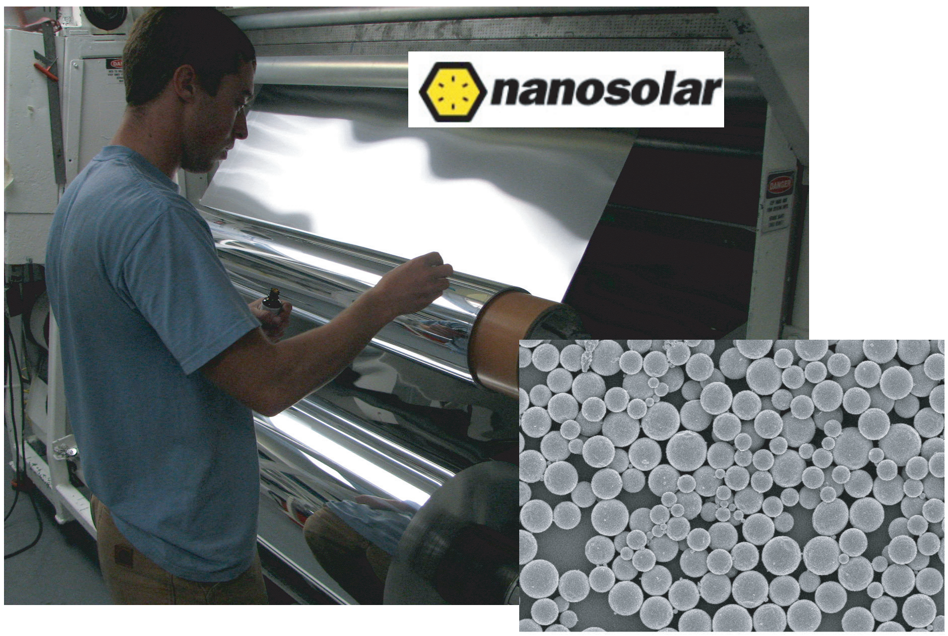


FIGURE 4-2-3 Nanostructured and roll-to-roll processed materials. SOURCE: Image courtesy of Nanosolar, Inc. Reprinted with permission.

Assessment Summary

- **Pro(s):** Much of this technology requires long-range development, and there are many open scientific and technological questions. Plasmonic antennas and amplifiers integrated into semiconductor structures may instead promote optical loss. It may not be possible to achieve the requisite control of nanocrystal size and placement to produce multiple-energy-level solar cells.
- **Con(s):** Large-scale development and deployment of photovoltaics may be accelerated by other countries regardless of initial issues of cost. Alternative systems-level strategies may produce higher-efficiency, compact photovoltaics, without requiring nanophotonic concepts.
- **Overall View:** The committee views this as a Technology Watch item. Various nanophotonics-related ideas are being pursued to enhance photovoltaic performance, but each approach currently faces important scientific and technology uncertainties. The committee believes that this area should be (1) reassessed yearly and/or that (2) a database should be employed to obtain real-time critical information from the science and technology (S&T) communities involved in nanophotonics R&D efforts.
- **Military Application Considerations/Suggested Risks:** Lightweight, portable sources of energy for the battlefield are of paramount importance. In 2006, tens of millions of dollars were spent on batteries alone for deployment in the battlefield (Bennett, 2007). It is not only the savings in funds but the reduction in bulk and weight and the reliability of power that would be a critical enabler for the soldier. In addition, there are obvious, enormous commercial benefits in realizing highly efficient, low-cost solar energy sources.

CHART 4-3 Application Area: Remote Sensing

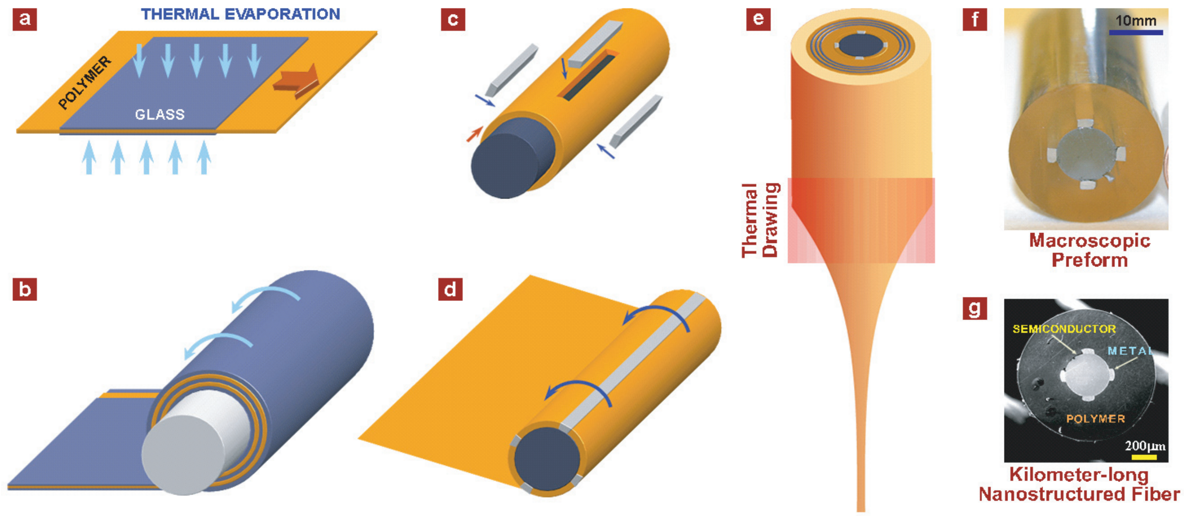


FIGURE 4-3-1 Nanostructured functional device fibers. SOURCE: Bayindir et al. (2006). Reprinted with permission. © 2006 IEEE.

Technology	Observables
• Remote sensing uses a device to gather information about the environment from a distance. • Nanophotonics can sense a wide range of chemicals, (e.g., explosives) and organisms (e.g., viruses) as well as physical effects on materials (temperature, strain, vibrations, etc.) because of its noninvasive nature. • Photonic nanostructures can be integrated into a variety of different media: fibers, nanocomposites, fabrics, and so on. • Optical methods can provide both sources and detector sensors. • Prior work on silica and polymer optical fibers arranged to create two-dimensional air/material photonic crystal fibers demonstrated useful materials as optical waveguides and sensors. • Multimaterial fiber sensors are linear versions of the familiar finite, essentially two-dimensional planar devices incorporating insulating, semiconducting, and metallic elements that are used in traditional electronic, optoelectronic, and thermal detection devices. • The approach is to prepare a preform and to thermally draw the preform into fine-diameter, kilometer-long fibers (see panel e in Figure 4-3-1).	• Sensing is a trade-off between sensitivity, selectivity, response time, and cost. • A directed beam of light can excite characteristic optical response from the analyte(s), which may be detected back at the source location. Difficulties are that the spectral response from laser excitation (e.g., infrared or Raman spectroscopy) is poor at the most useful distances, and critical emissions may be absorbed or scattered by the path medium between the source (agent) and the detector due to the long path lengths involved. • Alternatively, a set of sensors can be placed in an environment, and these devices can locally detect changes resulting from interaction with the analyte(s) and then send the information back to a base wirelessly, or be interrogated by a laser excitation or use the change in the optical properties of the device by the interaction with the analyte(s) to modulate a lasing output from the device. • The multimaterial fibers can be made into a very large area cross-array that offers N^2 local detectors while requiring only $2N$ I/O (input/output) readers.

chart continues

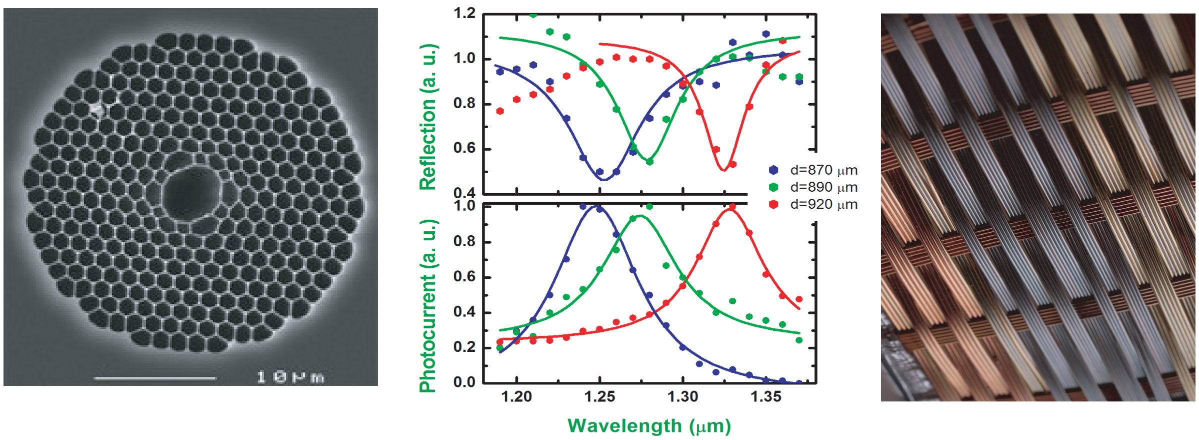
CHART 4-3 Continued

Accessibility	Maturity	Consequence
Level 3	Technology Watch	These fibers have been under development only recently and in a university setting, but the know-how of fiber drawing is well established in the fiber telecommunications industry. The multimaterial preform approach allows rapid exploration of device designs at millimeter scale, that are demagnified thousands of times during the drawing process.
Enablers and Key Technical Parameters		
Wearable devices that can be integrated (by weaving the fibers into a fabric) into common items that people wear or carry (e.g., clothes, knapsack, etc.) could make every person a mobile sensor platform. Additionally, fibers can be fabricated into simple flat arrays and attached to buildings or vehicles. Because they are linear and can be shaped into two- and three-dimensional arrays, they are no longer point detectors but area and volume detectors. Use of a photoconductive material would make the fibers responsive to light; placement of concentric filters around the photoconductive core makes the fibers able to "see" different colors of light. There are a host of known ways to make the optical characteristic of materials change due to the presence of a substance (e.g., chemical or explosive agent), and thus these fibers can sense their environment and either broadcast their information or be interrogated from a distance. The fibers can have a central hollow core and thus can hold coatings for binding analytes that would change the optical properties of the fibers (see Figure 4-3-2 in the "Narrative" section below).		
Triggers		
Potential revolutionary opportunities: • Very large arrays that are ultralightweight (due to open fiber constructs) and N^2 detectors for $2N$ fibers. • Warfighter-wearable, light unmanned aerial vehicle (UAV) payload, skins of buildings, aircraft, ships for full area coverage. • Low power consumption.		

chart continues

CHART 4-3 Continued

Narrative



(a) (b) (c)

FIGURE 4-3-2 (a) Hollow core fiber; (b) results of optical and electrical measurements through fabric; (c) spectrometric fabric. SOURCES: Reprinted by permission of Macmillan Publishers Ltd: Nature, Bayindir et al. (2004); Venema (2004); Luan et al. (2004). Reprinted with permission. © 2004 IEEE.

Assessment Summary

- **Pro(s):** Nothing like this is available for creating large-area or volume sensing.
- **Con(s):** Only the Massachusetts Institute of Technology group has done the multi-material fiber work; the University of Bath, United Kingdom, leads in the two-dimensional photonic crystal fiber work. The Danish company Crystal Fibre A/S produces and markets the two-dimensional photonic crystal fibers.
- **Overall View:** The committee views this technology as a Technology Watch item. Companies that can do fiber drawing (e.g., telecommunications fibers [Corning, etc.]) would be able to commercially produce these fibers.
- **Military Application Considerations/Suggested Risks:** Warfighter-wearable, light UAV payload, skins of buildings, aircraft, ships for full area coverage. Robustness against environment, stresses, and high and low temperatures needs to be assessed.

CHART 4-4 Application Area: Emissive Displays

FIGURE 4-4-1 Examples of emissive displays. SOURCE: (left and right) Images courtesy of the U.S. Army; (middle) L-3 Communications (2007). Reprinted with permission.

Technology	Observables
• The technology has two nanophotonic components: —The use of nanoparticles as emitters, and —The use of photonic band-gap structures. • Periodic dielectric structures can be used to control bandwidth and directionality of light emitted by a variety of sources. • These structures can act as large-area vertically emitting lasers, which do not require an external cavity. • The structures can be mechanically flexible. • The structures can be electrically, mechanically, or optically tunable. • Band-gap structures can be efficiently formed using self-assembly. • They are ideally suited for emissive display applications.	• Photonic band-gap structures exhibit a strong reflection band over a range of wavelengths. • The spectrum of light emitted by sources in band-gap materials is altered; emission is suppressed in the band and enhanced at the band edges. • The direction of emitted light is modified; emission is enhanced along the crystal axes. • Photonic bandgap structures can be used to modify light emitted by conventional phosphors, as well as by fluorescent, electro-luminescent, light-emitting diode, and other light sources. • If a gain medium is present, band-gap materials can exhibit low-threshold mirrorless lasing due to distributed feedback. • The optical properties of band-gap structures can be tuned (via strain, temperature, fields, etc.). • They can be used as — Agile active filters for sensor (eye) protection, — Tunable laser sources, and — Reflective elements in transflexive displays.

chart continues

CHART 4-4 Continued

Accessibility	Maturity	Consequences
Level 2	Technology Watch and Technology Alert	• This is a rapidly emerging technology, well described in the scientific literature. • Considerable expertise exists in Japan, Europe, China, and Russia. • Soft self-assembled materials, such as polymers, liquid crystals, and colloids, offer much potential.

Enablers and Key Technical Parameters

Periodic dielectric structures (such as multilayer coatings) give rise to multiple internal reflections and destructive interference of light. As a consequence, light in some band of wavelengths cannot propagate inside these materials. If light in this band is incident on such band-gap structures, it is completely reflected. Light emission, say by fluorescent dyes, is suppressed inside the gap, but it is enhanced at the band edges, where the material acts as a resonant cavity. Band-gap materials can therefore be used to control the spectrum and emission direction of conventional light sources. If a gain medium, such as a fluorescent laser dye, is introduced into the band-gap structure and the system is pumped, it will lase at the band edges without any external cavity. The lasing threshold is very low, and these materials can therefore be effective light sources for display applications.

A variety of materials are available for producing photonic band-gap structures. Recently, “soft” organic materials have received considerable attention, due to the ease of processing, via self-assembly and other schemes; their low cost; the ability to make large flexible structures; and their ease of tunability.

Key challenges are the understanding and reduction of losses, and increasing the contrast in the dielectric properties of the constituents.

Triggers

Potential revolutionary opportunities:

- Lightweight sunlight-readable, high-resolution, low-power-consumption displays;
- Large-area flat, flexible vertically emitting laser sources;
- Agile filters for sensor protection; and
- Sensors, due to sensitivity to excitations.

chart continues

CHART 4-4 Continued

Narrative(s)

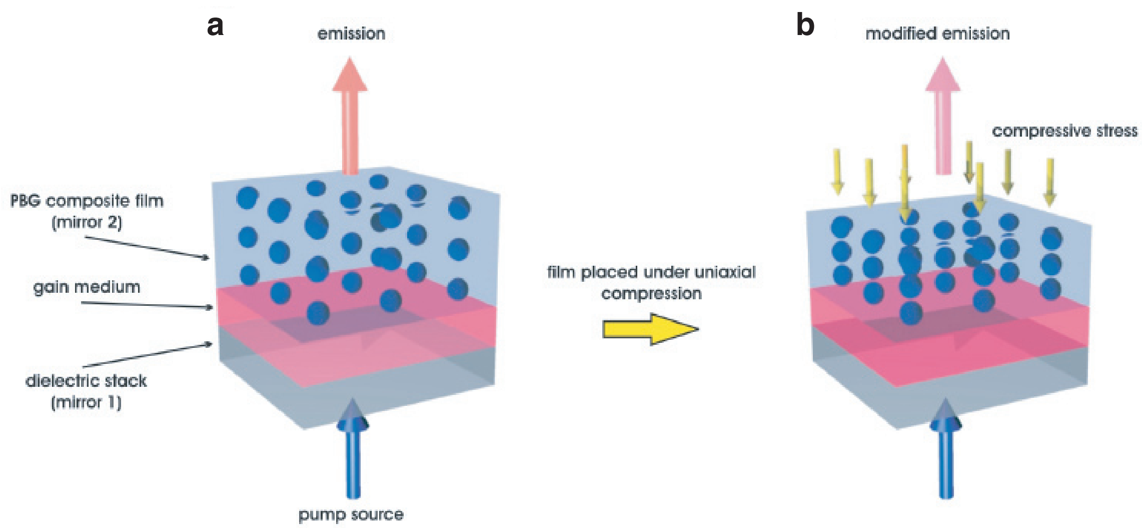


FIGURE 4-4-2 Emission tunable thin film. NOTE: PBG, photonic bandgap. SOURCE: Lawrence et al. (2006). Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

Displays and networks could benefit a low-cost, thin-film tunable organic laser development in the United States.

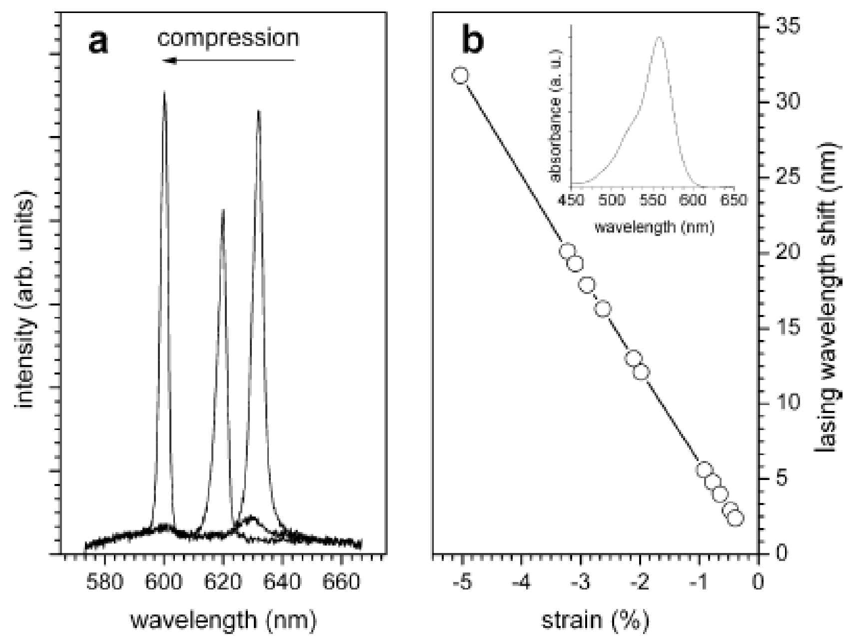


FIGURE 4-4-3 Shift in lasing wavelength with compression and strain. SOURCE: Lawrence et al. (2006). Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

chart continues

CHART 4-4 Continued

Assessment Summary
• **Pro(s):** Emissive displays are an emerging technology, with great potential. This technology has not yet fully made the transition to emissive display prototypes. • **Con(s):** Foreign countries (Japan, Europe, China, and Russia) are very active in the field. • **Overall View:** The committee views this technology as a Technology Watch item because the technology is rapidly advancing in many countries. • **Military Application Considerations/Suggested Risks:** The applications discussed in this chart have very significant commercial as well as military potential; the former will most likely drive the development of this technology. Robustness and temperature sensitivity may be issues.

CHART 4-5 Application Area: Ultrahigh Density Storage Exploiting Nanophotonics

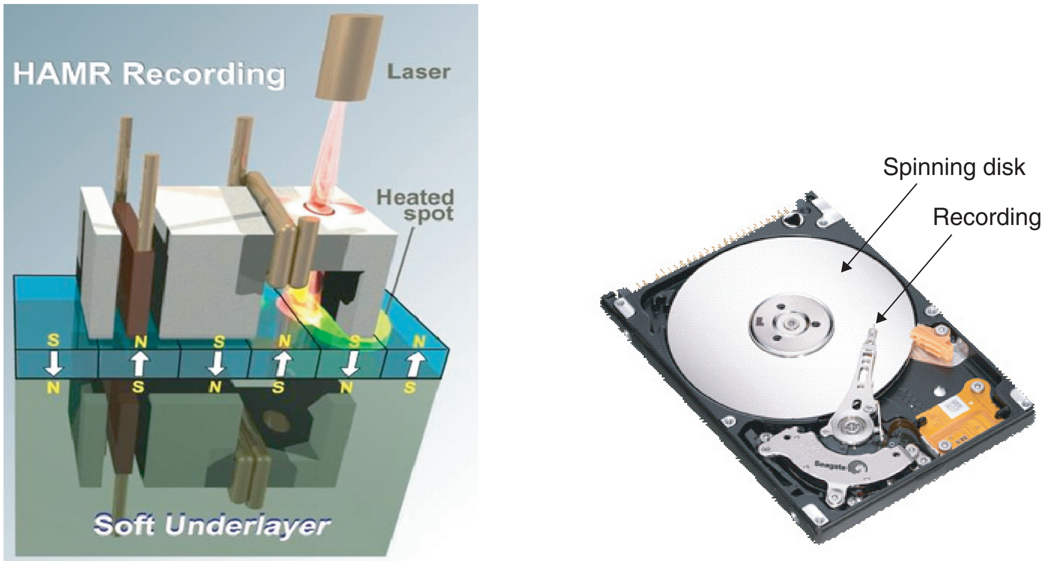


FIGURE 4-5-1 Schematic of recording head with near-field optical source. SOURCE: Kryder (2006). Reproduced with permission.

chart continues

CHART 4-5 Continued

Technology	Observables
• Near-field optics allows focusing or concentrating electromagnetic radiation far beyond the diffraction limit, which can be exploited for ultrahigh-density data-storage applications. • While the propagation of light over distances longer than its wavelength (λ) acts as a spatial filter of finite bandwidth (resulting in the familiar diffraction-limited resolution of ≈λ/2), the spatial extent of nonpropagating near fields is not constrained by this limit. • These near fields can be readily generated in the close vicinity of an object or scatterer with high spatial frequencies (e.g., nanoscopic antennae, nanoapertures, negative refractive materials, superlenses, etc.), which is typically illuminated by a far-field electromagnetic wave such as a laser. • By matching the dimensions and materials of the scatterer to the spectrum of the incident light, the resulting near fields can be very strong (in fact enhanced by several orders of magnitude over the incident radiation). • Because the lateral extent of the near field is very short-ranged, it has to be very close (typically less than a few nanometers) to the storage media. • While there are many possible ways for utilizing near-field concepts for high-density information processing, it is likely that the first storage systems will exploit these nanoscale light sources for localized heating in magnetic and optical storage materials. • Specifically, in magnetic storage, localized heating is seen as a solution to the superparamagnetic limit by lowering temporarily the coercivity of the magnetic film, thereby enabling the writing with the limited magnetic fields from recording heads on these harder (and thus higher-density-capable) magnetic materials. • In optical storage devices, a subdiffraction-limited light source can be used to switch phase-changeable materials such as chalcogenides reversibly back and forth between amorphous and crystalline phases by applying appropriate heat pulses at very high spatial resolution.	• It is expected that this technology will be driven by the mass storage industry, in particular by the hard disk drive (HDD) manufacturers (where it might show up first), as well as possibly by the optical storage industry. • Although major challenges still have to be overcome, nanophotonic-based storage systems are believed to be (somewhat) compatible to hard disk (HD) magnetic storage media since the existing recording head technologies provide a platform to integrate a nano-optical light source within the very close vicinity of a storage medium. In today's HDDs the recording head "flies" only a few nanometers above the magnetic storage media. • In optical storage systems, it is likely that near-field optical recording will first be realized by solid-state immersion optics or using superresolution near-field structures in the recording disk. • The introduction of nano-optical technologies into HDD recording heads and optical storage systems will be widely advertised by the respective industries and companies (e.g., heat-assisted magnetic recording or thermally assisted recording). • Nanophotonics-enhanced storage devices will enable drastic improvement in storage densities of typically larger than 100 gigabits per square inch for optical, and 1 terabit per square inch for magnetic storage. • As one of the major observables, most systems will employ a laser source built into or onto the recording head, which could thus be quickly realized with some minor reverse-engineering. • However, in future embodiments this near-field source may comprise quantum dots or other more in situ light sources.

chart continues

CHART 4-5 Continued

Accessibility	Maturity	Consequences
Level 2	Technology Watch	• This technology is currently explored by academia and industry. Specifically, the subject is studied worldwide, including in Japan (mostly by industry, by such companies as Hitachi and Fujitsu), Singapore, Europe (mostly by academic institutions), as well as China. • Although the general concepts are openly discussed in the literature, no viable technology demonstration has been reported yet. The challenge lies in the integration with the existing (and ever-progressing) storage technologies, which will require significant amounts of investment to enable commercially viable solutions.

Enablers and Key Technical Parameters

The ability to "concentrate" strong electromagnetic fields at very high spatial resolution is undoubtedly of major importance for future storage technologies. Electromagnetic fields can be focused tightly using a high numerical aperture lens, but the potential spatial resolution is fundamentally limited by the diffraction to $\approx\lambda/2$ (e.g., for optical frequencies ≈300 nm). Nanophotonics provides a solution to this limit by exploiting nonpropagating or near fields, which do not obey the diffraction limit and show local variations over distances much smaller than λ. Although these near fields are generated at basically any object or scatterers with dimensions much smaller than the wavelength of the incident propagating electromagnetic field, the physics and accurate engineering of near-field optical light sources is very challenging due to very small dimensions involved. In this technology the subdiffraction-limited light source is used to record and read information patterns at very high spatial resolution, which enables the opportunity to drastically increase storage densities.

Triggers

Potential revolutionary opportunities:

- Enhanced information storage capabilities,
- Reduced bit error rates, and
- Possibly less power consumption of high-density storage devices.

Narrative(s)

The committee provides an example for near-field storage: (1) Example of an enabling laboratory demonstration (see Figure 4-5-2) and (2) "Open Literature Study" data to highlight the activities in the field of "near-field storage" (and associated phenomenology and techniques). The committee notes that this field is moving rapidly, and thus the situation should be reassessed every 12 months.

chart continues

CHART 4-5 Continued

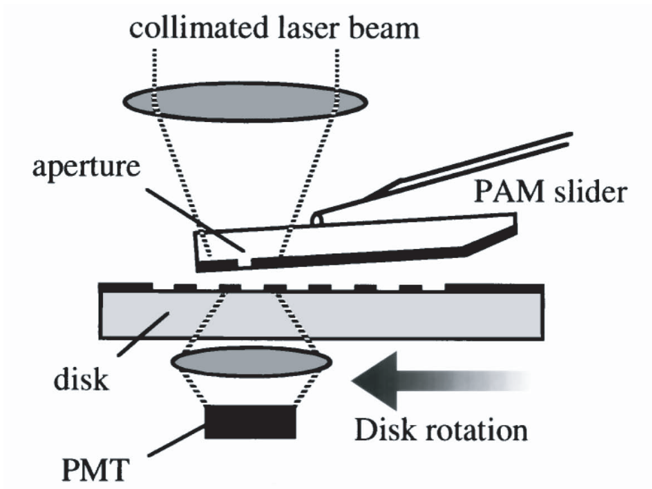


FIGURE 4-5-2 Superresolution near-field structure storage system. SOURCE: Yoshikawa et al. (2000). Reproduced with permission. NOTE: In the example shown above, competitive data rates and improved storage densities were demonstrated using near-field optics. NOTE: PAM, planar aperture-mounted; PMT, photomultiplier tube.

Assessment Summary

- **Pro(s):** Currently ultrahigh density storage exploiting nanophotonics is not mature enough for broad deployment in commercial storage systems.
- **Con(s):** Although there is some activity in the United States, the majority of near-field storage work is done in Japan.
- **Overall View:** The committee views this technology as a Technology Watch item because it has not been demonstrated yet.
- **Military Application Considerations/Suggested Risks:** Improved data-storage devices will enhance information-processing capabilities. Since the commercial sector is driving these technologies and because the products will be widely available, the committee recommends monitoring closely the application of these technologies to military systems.

CHART 4-6 Application Area: Quantum Information Processing for Secure Transmission

FIGURE 4-6-1 Quantum cryptography. SOURCE: Risk and Bethune (2002). Reproduced with permission.

Technology	Observables
• Mapping computation (bits) or communications to quantum mechanical states (qubits); use of phase (as well as amplitude) of state. • For some (but not all) computation, possibility of exponentially faster computation rates. • Applications to secure communications or quantum cryptography.	• Research and development activities related to quantum information processing, algorithms, and state coherence. • Procurement and utilization of existing quantum information processors. • Deployment of large-scale fiber-optic-based secure communications systems.

Accessibility	Maturity	Consequence
Level 3	Technology Watch	• Rapid computation can lead to rapid asymmetric advantage in reconfiguring logistics. • Quantum secure communications provides asymmetric advantage in information transmission.

Enablers and Key Technical Parameters

Mapping computation onto quantum mechanical rather than classical elements can provide an exponential increase in speed for *some* computational problems, and holds immense advantages for secure communications. The first demonstration of quantum-secure communications was made in 1991, only 7 years after the initial concept was described in the literature. Nanophotonics may further improve performance in this area by supplying true, controlled single-photon sources.

Primary challenges (and hence enablers) have been (1) determining a broad set of areas that would enjoy major benefits from quantum computing and quantum information processing, (2) constructing realistic (solid-state) quantum systems with minimal decoherence, and (3) determining means of scaling such systems up to sizes and complexity (e.g., number of qubits) to be able to accomplish appropriate computation or communications tasks. Therefore, many of the theoretical assumptions and promises of quantum information processing and quantum cryptography remain to be evaluated. With all of the considerable technical challenges inherent in points (2) and (3), on February 13, 2007, D-Wave Systems, Inc., a Canada-based company, announced a 16-qubit superconducting adiabatic quantum computing processor (D-Wave Systems, 2007).

chart continues

CHART 4-6 Continued

Triggers

Potential revolutionary opportunities:

- Exponentially faster computation times, and
- Secure communications.

Narrative(s)

The committee herein provides the following (1) example of quantum cryptography systems available commercially (see Figure 4-6-2) and (2) a photograph of a 16-bit superconducting quantum computer announced by D-Wave Technologies, Inc. (see Figure 4-6-3). These technologies are clearly being developed and realized; major enhancements made possible by nanophotonics include (a) generation of single photon sources, (b) incorporation of concepts of “entanglement” through the use of complementary polarization states, and (c) the formation of compact systems with nanoresonators isolating photonic qubits and allowing controlled interaction of qubits. Techniques such as plasmonic concentrators could augment signals and photonic crystal waveguides and efficiently route signals.

- *Example 1:* Quantum Cryptography Networks and Systems
  Under Defense Advanced Research Projects Agency (DARPA) sponsorship, BBN Technologies in Cambridge, Massachusetts, together with Harvard University and Boston University, built and operated the world’s first Quantum Key Distribution (QKD) network in October 2003. The DARPA Quantum Network employs 24 × 7 quantum cryptography to provide unprecedented levels of security for standard Internet traffic flows such as Web browsing, e-commerce, and streaming video. A number of commercial ventures have begun to market optical-fiber-based quantum communications systems. The companies include id Quantique in Switzerland, QinetiQ in England, MagiQ Technologies in New York, and NEC in Japan.

FIGURE 4-6-2 Swiss company id Quantique’s Vectis quantum cryptography system. SOURCE: id Quantique (2007). Reproduced with permission.

chart continues

CHART 4-6 Continued

- *Example 2:* Quantum Computers
  On February 13, 2007, D-Wave Systems, Inc. (a privately held Canadian firm headquartered near Vancouver, British Columbia) announced the world's first commercially viable quantum computer. "D-Wave's breakthrough in quantum technology represents a substantial step forward in solving commercial and scientific problems which, until now, were considered intractable. Digital technology stands to reap the benefits of enhanced performance and broader application," said Herb Martin, D-Wave Systems' chief executive officer.

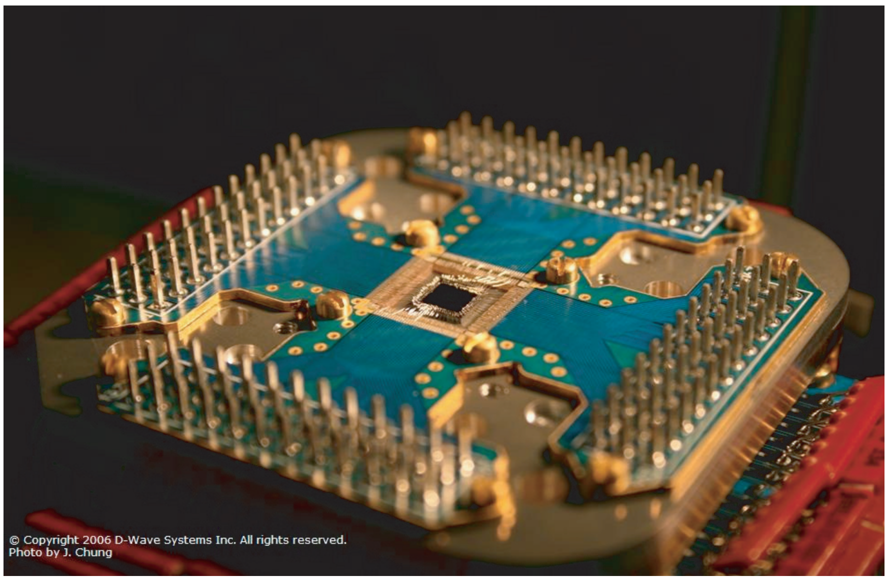


FIGURE 4-6-3 D-Wave Systems' 16-qubit quantum computer. SOURCE: D-Wave Systems (www.dwavesys.com). © 2006 by D-Wave Systems, Inc. Photo by J. Chung. Reproduced with permission.

Assessment Summary

- **Pro(s):** Much of the technology requires long-range development, and critical technological choices and implementations are yet to be made. The United States has had a strong presence in this area, both in algorithmic development and physical implementation of quantum information schemes. Major U.S. federal funding has stimulated research and innovation.
- **Con(s):** There have been considerable international activity and contributions in this area, notably in Europe. Commercial ventures have already developed worldwide, and the initial commercial announcement of a quantum computer was made from a Canadian firm.
- **Overall View:** The committee views this as a Technology Watch item. Although prototypes have been demonstrated in both quantum cryptography systems and most recently in a quantum computer, the implementations utilizing nanophotonics are at an earlier stage of development. The committee believes that this area (1) should be reassessed every 6 months and/or that (2) a database should be employed to obtain real-time critical information from the science and technology communities involved in nanophotonic R&D efforts.
- **Military Application Considerations/Suggested Risks:** The commercial application (depicted in this chart) is an example of an enabling capability that can be leveraged for military warfare both symmetrically and asymmetrically. The following risks have been assessed by the committee to indicate where it believes the state of applications are with respect to the phenomenology:
-
  1. Situation Awareness: Risk: High—Technology allows for secure, encrypted communications.
  2. Rapid Computing: Risk: High—Technology allows for exponentially rapid computation in certain applications, and hence much more rapid data analysis.

CHART 4-7 Application Area: Nanophotonics-Enhanced Microprocessors and Computing Systems

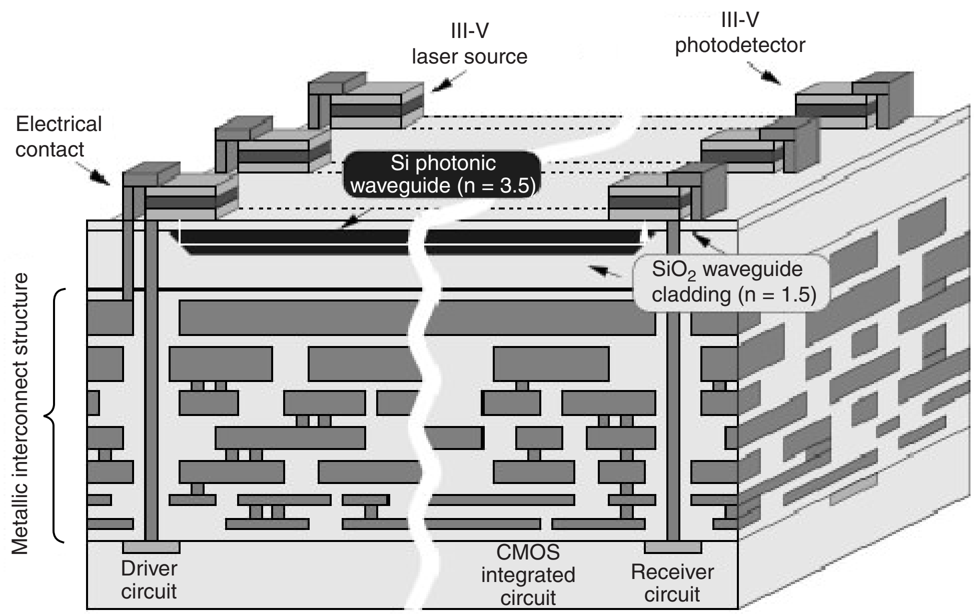


FIGURE 4-7-1 Example: On-chip optical communication network. NOTE: Si, silicon; SiO_2, silicon dioxide; CMOS IC, complementary metal oxide semiconductor integrated circuit. SOURCE: O'Connor and Gaffiot (2004). Reproduced with permission.

chart continues

CHART 4-7 Continued

Technology	Observables
• Nanophotonics has the potential to enable high speed on-chip optical communication, which could result in drastically enhanced computing performances of microprocessors and computing systems. • In this technology, high index contrast waveguides (e.g., stripped silicon [Si] waveguides) or plasmonic wires are implemented to manipulate and guide light between parts of the electrical circuitry or even transistors providing potentially ultrahigh throughput, minimal access latencies, and low power dissipation; other nanophotonic components may include modulators, detectors, on-chip light sources, fiber couplers, and other passive components. • For example, high index contrast ratio waveguides utilize silicon on insulator (SOI) technologies, where an etched Si strip is used as the core and the surrounding oxide as the cladding. The high-contrast index of refraction serves to confine the mode to very small dimensions (~300 × 300 nm^2), which enables a high packaging density of the optical components. • Plasmonic waveguides exploit plasmon excitations on metallic surfaces to provide a way of confining, transmitting, and manipulating light at a scale that is substantially smaller than the wavelength of the incident light; plasmons are electron density waves propagating along a metal/dielectric interface. • In order to enhance microprocessor or computing performances, the nanophotonic devices have to be integrated very closely with high-performance complementary metal oxide semiconductor (CMOS) circuitry, which represents a major challenge, as CMOS and optics requirements often differ significantly. Various integration and packaging technologies such as three-dimensional, new bonding strategies and advanced chip carriers, will have to be employed to overcome this obstacle.	• It is expected that the commercial sector will incorporate these technologies incrementally. In today's high-end computing systems, optical links are connecting several microprocessor circuit boards within the same box. • In the future, optical components and possibly nanophotonic devices will first be integrated heterogeneously on the same circuit board, then on the chip carrier, and then possibly monolithically on the same silicon chip. The committee believes that the rate of progress toward tighter integration between optics and microprocessor is a direct gauge for progress of this technology. • Since nanophotonic technology components are highly diverse and involve noncomplementary metal oxide semiconductor materials and processes, the technology is likely to be accompanied by novel package, integration, and processing innovations. These enabling technologies will be a very important indicator to gauge whether this technology can be accessed and realized. • This technology will require light sources integrated very close to the chip. The committee believes that earlier embodiments of the light sources will be externally coupled to the processor chip, while later implementations using III/V chips or III/V devices will be integrated onto the same carrier or chip stack. • An important observable will be a massive parallel, multicore (probably above 32 cores) microprocessor (individually, cores are running faster than 1 gigahertz with unprecedented data throughput and low power consumption). It is likely that such microprocessors will be designed with system-on-chip technologies with an optical data bus connecting the individual cores.

chart continues

CHART 4-7 Continued

Accessibility	Maturity	Consequences
Level 2	Technology Watch or Technology Warning	• Although significant progress toward monolithic integration of nanophotonics and CMOS has been accomplished, the actual enhancement of computing performances using nanophotonic devices still has be demonstrated. Despite substantial investments of the U.S. military in these technologies, the committee believes that the industry will still be the main driver, which will steadily but also carefully introduce nanophotonic devices in their microprocessors and computer systems. • Nanophotonics-enhanced computing is a subject studied worldwide, including in Japan (Nippon Telegraph and Telephone Corporation [NTT], NEC), Europe, China, and India.

Enablers and Key Technical Parameters

Recent trends in the computing industry, specifically the emergence of multicore microprocessors and power limitations, have made inter- and intrachip interconnects the bottleneck (increased resonant-cavity delay, power consumption, and cross talk) for future performance growth. Consequently, optical interconnects have been steadily making inroads toward the microprocessor where nanophotonics can eventually play a key role in achieving vastly improved communications in high-performance computing systems. The opportunities for nanophotonics are manifold, ranging from CMOS integrated silicon photonics to plasmonic interconnects.

Triggers

Potential revolutionary opportunities:

- Can possibly change fundamentally performances of microprocessor and computing systems (supercomputers);
- Vastly improved data-mining capabilities for collecting and processing complex data for producing foreign intelligence information and protecting U.S. information systems; and
- Significant cryptography opportunities.

Narrative

The committee provides the following example of progress in this field: (1) an example of an enabling laboratory demonstration and (2) open literature study data that highlight the activities in the field of "near-field storage" (and associated phenomenology and techniques). The committee notes that this field is moving rapidly, and thus the situation should be reassessed every 12 months.

chart continues

CHART 4-7 Continued

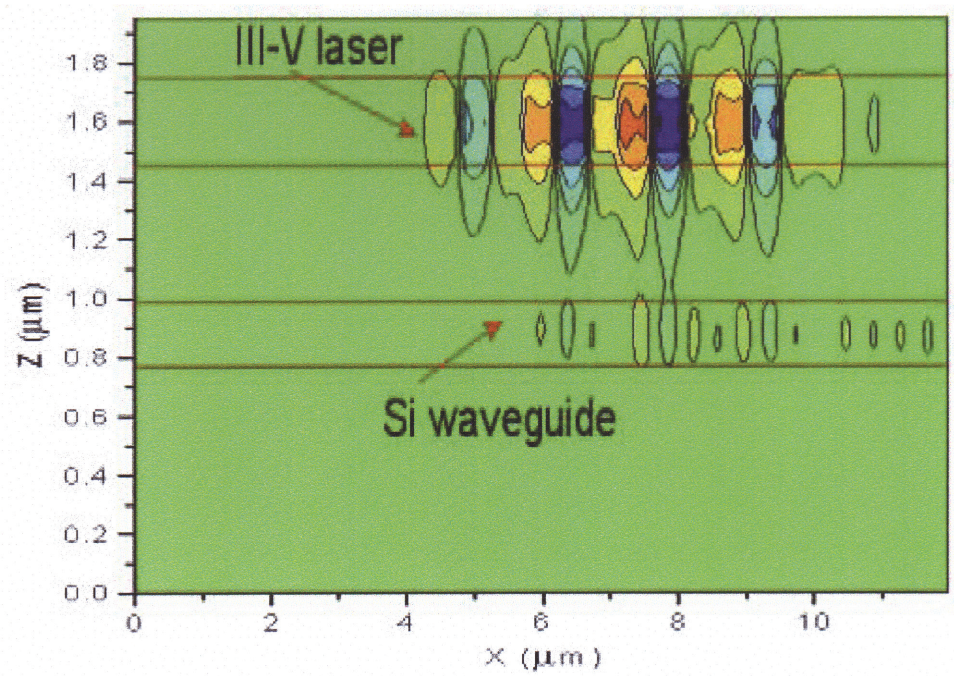


FIGURE 4-7-2 Heterogeneous integration of III-V devices with ultracompact silicon-on-insulator waveguides. SOURCE: Hattori et al. (2005). Reproduced with permission.

A typical example of progress in this area is shown in Figure 4-7-2, where heterogenous integration schemes of III/V devices with ultracompact SOI waveguides are investigated. The goal of this research is to provide a viable light source to enable on-chip optical communication.

Assessment Summary

- **Pro(s):** The United States, and to a lesser extent Japan and Europe, are leading this field. The United States leverages its strong semiconductor industry base. The committee believes that the time frame of the emergence of this technology will be predictable if the commercial industrial sector is driving the technology.
- **Con(s):** The committee believes that commercialization will make this technology accessible basically everywhere.
- **Overall View:** The committee views this technology as a Technology Watch or Technology Warning item.
- **Military Application Considerations/Suggested Risks:** Nanophotonics-enhanced microprocessors could lead to a supercomputer on a chip with vastly improved processing and computing capabilities. Since the commercial sector is driving these technologies and because the products will be widely available, the committee recommends close monitoring of the application of these technologies to military systems.

CHART 4-8 Application Area: Infrared Imaging and Night Vision

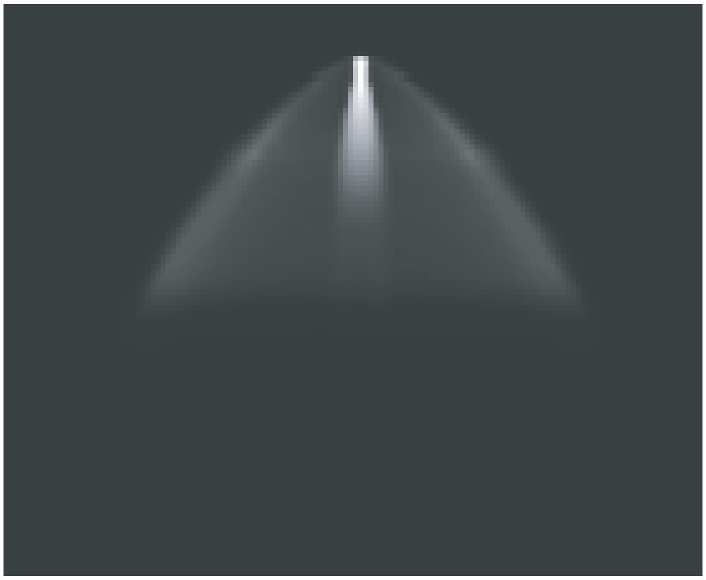


FIGURE 4-8-1 Picture of rocket plume. SOURCE: Peters and Nichols (1997). © 1997 IEEE. Reproduced with permission.

FIGURE 4-8-2 Forward-looking infrared radar (FLIR). SOURCE: FLIR Systems (2007). Reproduced with permission.

chart continues

CHART 4-8 Continued

Technology	Observables
• The infrared (IR) spectral region is of particular importance to military systems. • Night vision typically refers to high-gain systems (photomultipliers and avalanche photodiodes) that amplify and detect near-IR ambient radiation, e.g., from 780 nm to almost 3 μm. • Both 3 μm to 5 μm mid-wave infrared (MWIR) and 8 μm to 12 μm long-wave infrared (LWIR) spectral regions are of critical importance for thermal and spectroscopic detection, especially in surveillance systems, weapons systems guidance, and missile seekers. • The best MWIR and LWIR imagers are typically cooled semiconductor focal plane arrays such as indium antimoride (InSb) and mercury cadmium telluride (HgCdTe), which are used in expensive platforms but are not suitable for human-carried applications. • Microbolometer arrays offer 300 K operation, but at lower sensitivity and several-orders-of-magnitude lower speed than their cooled semiconductor counterparts.	• Nanophotonics offers for the first time the potential of bringing the performance comparable to cooled semiconductor focal plane arrays to operation at room temperature (and thus human-portable operation). • This would be a significant development that would change the nature of warfare by providing more detailed information at lower levels of operation. • In particular, plasmonic structures can be used to concentrate IR energy striking a pixel area in the focal plane array to a much smaller detector area that can be subwavelength in extent. Since 300 K IR semiconductor detectors are volumetric leakage (dark) current limited, the sensitivity is improved to the extent that the detector volume is reduced while still collecting the signal. The figure of merit is $\eta / \sqrt{A_{detector} / A_{pixel}}$, where η is the intrinsic quantum efficiency and the square root of the areas arises because the noise scales as the ½ power of the dark current. The speed scales as $A_{pixel}/A_{detector}$ as a result of the reduced capacitance. Actual implementation will also require lenslet array registration with the small detector area to maximize optical throughput.

Accessibility	Maturity	Consequence
Level 1	Technology Futures	Greatly enhanced capabilities for thermal detection on the battlefield, increased situational awareness at lower levels of the command chain, vulnerability of large-platform assets.

Enablers and Key Technical Parameters
Not applicable.

Triggers
Potential revolutionary opportunities: • Research developments; • Reports of field concentration in scales less than a wavelength; and • Advances in nonlinear optical processes resulting from similar field concentrations in photonic and metamaterial experiments.

Narrative(s)
Not applicable.

chart continues

CHART 4-8 Continued

Assessment Summary
• **Pro(s):** The potential is enormous. • **Con(s):** The technology is immature, with active research programs under way at the basic research level. • **Overall View:** The committee views this as a Technology Futures item because the technology is in the research stage and in the open literature. The trigger will be when the research is no longer reported openly; the question will be—Is that because results are no longer forthcoming, or because the results are so important that military secrecy prevails?

CHART 4-9 Application Area: Nano-Enabled Advanced Spectroscopies for Chemical-Biological Threat Sensing (e.g., Surface-Enhanced Raman Spectroscopy)

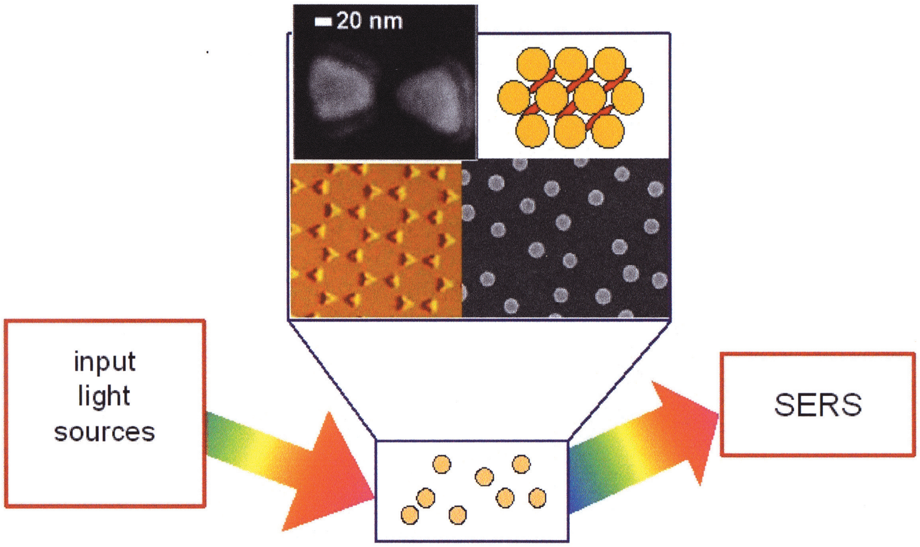


FIGURE 4-9-1 A selective and sensitive detection method for chemical and biological analyte molecules. NOTE: SERS, surface-enhanced spectroscopy. SOURCE: (top left) Schuck et al. (2005); (bottom left) Willets and Van Duyne (2007); (top and bottom right) Halas Research Group, Rice University (2007). Reproduced with permission.

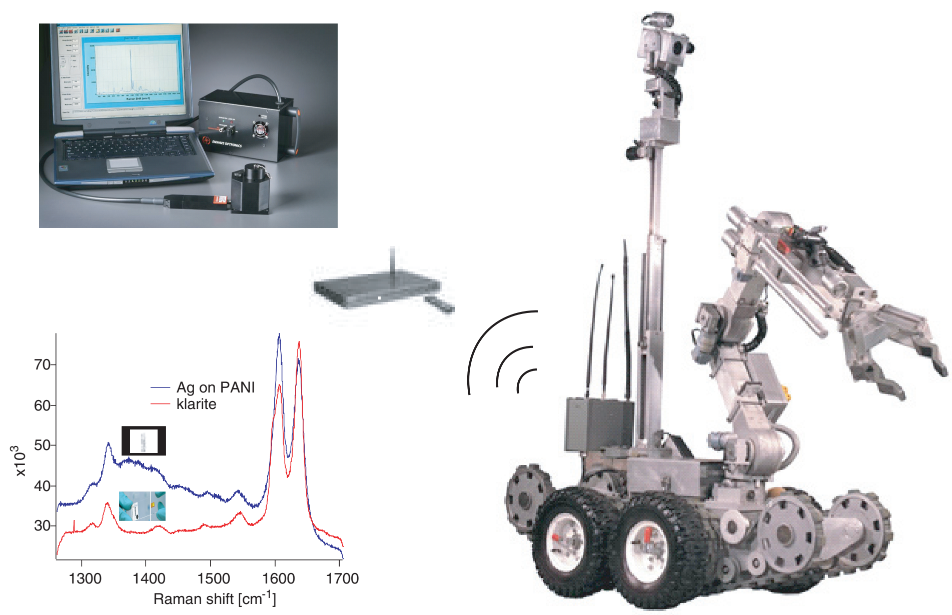


FIGURE 4-9-2 Possible detection platform installed on unmanned ground vehicle for the detection of chemical/biological agents. SOURCE: (robot) Northrop Grumman Corporation (2007); (left top and bottom) Hsing-Lin Wang, Los Alamos National Laboratory (2007). Reproduced with permission.

chart continues

CHART 4-9 Continued

Technology	Observables
• The Raman spectrum of each molecule is a "fingerprint" that uniquely identifies the molecule. • Surface plasmons have been used to enhance the surface sensitivity of these techniques, and the effects can be further enhanced using nanostructured metals such as silver (Ag) and gold (Au). • The synthesis and growth of these Ag and Au nanoparticles are well established in the literature, including innovative new types of nanostructures that provide further enhancements. • With the development of special substrates using plasmonic nanoparticles, enhancements of the Raman signal on the order of 10^9 are easily attainable. This allows for specific detection of very low concentrations of the analyte molecules using surface-enhanced Raman spectroscopy (SERS). • The large enhancement factor for SERS enables the detection of molecules with extremely weak Raman cross sections.	• SERS detection is the most mature of the various surface-enhanced spectroscopies. • Currently, detection of simulants of bioterrorist agents, such as *Bacillus subtilis* (a harmless simulant of *Bacillus anthracis*) and half-mustard gas has been reported using SERS. • Laser systems for SERS are getting cheaper and smaller, with the development of solid-state lasers. These technologies have been developed comparatively recently and offer an attractive route for continued cost and size reduction over time. • There is a need to develop a larger library of "fingerprints" of molecules and compounds of interest.

Accessibility	Maturity	Consequences
Level 1	Technology Alert	• This technology is already everywhere in the literature. It has grown tremendously in the past 8 to 10 years. • This technology is currently being studied in many countries, including Japan, China, Russia, and Europe.

chart continues

CHART 4-9 Continued

Enablers and Key Technical Parameters
Raman scattering is the inelastic scattering of light by molecules. The number of photons that undergo Raman scattering is very small. Thus, traditional Raman scattering is observed for few molecules that have a large Raman scattering cross section. Raman spectroscopy is a well-known technique that has been around for decades. The observation of large enhancements in the signal when the molecules are adsorbed onto, or brought in close proximity to, specially designed substrates, has led to the recent interest in SERS as a technique for sensitive and rapid detection of molecules. The large enhancement also allows for detection of molecules with weak Raman scattering cross sections and low concentrations of the analyte molecules. Metal nanoparticles of various shapes and geometries have been employed successfully as SERS substrates. Metal nanoparticles support surface plasmons (a collective oscillation of the electrons in the metal), which leads to an enhancement of the electric field near the surface of the nanoparticles and in the small junctions between nanoparticles. Molecules adsorbed onto the surface of the nanoparticles, or in close proximity to the nanoparticle surface, experience this enhanced electric field, which in turn leads to an enhancement in the SERS scattering by the molecules. Substrate development for use with various laser systems from the visible to the near infrared has been achieved. SERS using near-infrared lasers is of interest, as near-infrared light can penetrate human tissue without causing damage to the tissue. This allows for in vivo sensing using SERS. The SERS signal and the number of molecules available for interrogation determine the resultant SERS signals. An important related nanophotonics technology involves surface plasmon resonance (SPR) reflectivity measurements, surface-sensitive, spectroscopic methods that can be used to characterize the thickness and/or index of refraction of ultrathin organic and biopolymer films at noble metal (Au, Ag, copper) surfaces. SPR spectroscopy has become widely used in the fields of chemistry and biochemistry to characterize biological surfaces and to monitor binding events. The success of these SPR measurements is primarily due to three factors: (1) with SPR spectroscopy the kinetics of biomolecular interactions can be measured in real time, (2) the adsorption of unlabeled analyte molecules to the surface can be monitored, and (3) SPR has a high degree of surface sensitivity that allows weakly bound interactions to be monitored in the presence of excess solution species. SPR spectroscopy has been used to monitor such events as antibody-antigen binding, deoxyribonucleic acid (DNA) hybridization, and protein-DNA interactions. Use of nanoparticle arrays functionalized with antibodies enables the bio and biomedical interactions.
Triggers
Potential revolutionary opportunities: • Development of SERS spectra library of molecules of interest such as chemical and biological hazards; • Ruggedized packages; • Low-cost manufacturability: compact tunable photon sources for asymmetric warfare; • Hand-held (portable): lightweight, low power, miniaturized packages; and • Deployable units: packaging suitable for extreme environments and light-on-a-chip integrated systems.

chart continues

CHART 4-9 Continued

Narrative(s)
The example cited below of an enabling application is readily available in the public domain, which makes extending research and development in this area unpredictable (with unrealized and unbounded applications), and subsequently should be reinvestigated at least every 6 months.

- *Example:* Stable SERS substrates for anthrax biomarker detection. (See Figure 4-9-3). In 2006 it was reported in the literature that a modified SERS substrate with a shelf life greater than 9 months had been developed. The SERS signal from calcium dipicolinate (extracted from *Bacillus subtilis,* a harmless stimulant of *Bacillus anthracis*), a biomarker for anthrax, was measured. A 10 second data collection time is capable of achieving a limit of detection of 1.4×10^3 spores. These substrates demonstrate twice the sensitivity with 6 times shorter data-acquisition time and 7 times longer temporal stability. The modifications proposed expand the palette of available chemical methods to functionalize SERS substrates, which will enable improved and diverse chemical control over the nature of analyte-surface binding for biomedical, homeland security, and environmental applications.

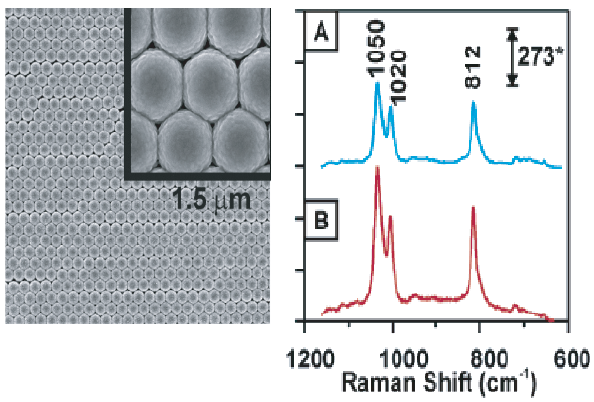


FIGURE 4-9-3 (Left) A silver film over nanosphere surface-enhanced Raman spectroscopy (SERS) substrate modified with a layer of alumina. (Right) (A) SERS spectrum of the anthrax biomarker on the unmodified SERS substrate; (B) the same on the alumina modified substrate. SOURCE: Reprinted with permission from Zhang et al. (2006). © 2006 American Chemical Society.

Assessment Summary

- **Pro(s):** The technology is rapidly maturing, and the United States is a leader in this field.
- **Con(s):** The technology is maturing; however, foreign countries **(**Japan, China, and Europe**)** are equally strong in this area. Most of the leading instrumentation and commercially available SERS substrates are manufactured by European countries.
- **Overall View:** The committee views this technology as a Technology Alert item because the technology is rapidly maturing in many countries. The committee believes that this area (1) should be reassessed every 6 months and/or that (2) a database should be employed to obtain real-time critical information from the science and technology communities involved in nanophotonics R&D efforts.
- **Military Application Considerations/Suggested Risks:** The application (depicted in this chart) is an example of an enabling capability that can be leveraged for military warfare both symmetrically and asymmetrically. The following risks have been assessed by the committee to indicate where it believes the state of applications is with respect to the phenomenology.
  - — This technology allows for sensitive detection of materials (possibly harmful agents in the field or at specific sites) before personnel are exposed to them.
  - — Situational Awareness: Risk: High—Technology allows for advanced analysis of materials enabling chemical/biological sensing. Nanophotonics offers opportunities for concentrating optical energy on scales of less than the wavelength. The chemical/biological sensing capability is enabled because the resulting large fields will lead to increased importance of nonlinear material response.

TECHNOLOGIES IN THEIR INFANCY

Quantum Computation and Nanophotonics

Mapping computation onto quantum mechanical rather than classical elements affords the possibility of far more powerful computational schemes. Feynman was among the first to explore quantum computation and the possibility of computer algorithms that could be more efficiently processed by quantum systems than by classical systems (Feynman, 1982, 1984, 1986). Deutsch provided some initial examples of such algorithms, and also demonstrated how *any* physical process, in principle, could be modeled perfectly by a quantum computer (Deutsch, 1985). A key advance then came with Shor's recognition that an important problem, the determination of prime factors, could be solved in *exponentially* less time using a processor based on quantum systems, that is, a quantum computer (Shor, 1994). Grover soon developed another important algorithm for quantum computers, showing increased speed in searching through unsorted databases (Grover, 1997).

In the same time frame, related developments explored the unique properties of quantum systems in enhancing secure communications. In 1984, Bennett and Brassard introduced the idea of quantum key distribution (QKD), a method for the secure distribution of a cryptographic key (Bennett and Brassard, 1984). In addition to more secure communications, quantum dense coding would allow communications at far higher rates than those possible with classical communications (Bennett and Wiesner, 1992).

The compelling potential of quantum computation and communications has recently led to a plethora of research efforts to provide the experimental verification of key quantum information concepts. In quantum computation, the quantum bit, or *qubit,* replaces the bit as the unit of computation, and in principle, any two-level system that behaves quantum mechanically can serve as a qubit. Recent experimental explorations have used discrete atomic states, the spin states of an electron, and superconducting states as the basis for quantum computation. Elementary quantum logical operations can then correspond to controlled transitions between the states of a qubit. Scaling up the size and complexity of a quantum system brings additional challenges, and some early candidates for scalable systems have included linear arrays of ions within an ion trap, or collections of nuclear spins that are addressed and controlled using the methods of nuclear magnetic resonance (Cirac and Zoller, 1995; Gershenfeld and Chuang, 1997). Superconducting systems, with macroscopic quantum effects, have also served as the basis of quantum computation, and on February 13, 2007, D-Wave Systems, Inc., a Canada-based company, announced a 16-qubit superconducting adiabatic quantum computing processor (D-Wave Systems, 2007).[1]

In evaluating these and other possible physical bases for quantum computers, DiVincenzo (2000) provided a useful, widely cited guideline, comprising five criteria:

1. The system should be a scalable physical system with well-defined qubits.
2. It should be initializable to a simple reference state such as |000...>.
3. The system should have long decoherence times.
4. It should have a universal set of quantum gates.
5. It should permit high-quantum-efficiency, qubit-specific measurements.

[1]The committee did not have time to conduct a thorough quality assessment of these different products. The committee mentions these products as a random sampling of possible applications. The companies listed are pioneers in these areas and have only recently been formed. It is too early to fully assess the quality of their products: that determination will be made as their products are more widely used. The D-Wave Systems product is still rather controversial and under evaluation. Experts in the field were called in to assess the performance of the D-Wave System computer, which is based on "superconducting qubits." The committee considered it important to note that even in the very demanding and futuristic area of quantum information processing, technological progress is such that products are being generated and introduced into the commercial sector.

Nanophotonic systems can be critical in creating the critical elements of a quantum computation scheme that is either based on well-defined photon states (with different states of polarization comprising the different qubit states) or mediated by the controlled transmission of photons between qubits. Quantum dot environments can localize charged carriers, excitons, or individual electron spins, increasing coherence lifetimes. High-Q nanocavities can form a lossless, well-isolated environment for qubits (minimizing decoherence), with spatially remote qubit interactions determined through the engineered coupling of photons to well-defined modes of the nanocavity. Therefore, the combination of quantum dots within high-Q nanocavities can prove exceptional testbeds for the development of quantum computation strategies (Imamoglu et al., 1999). In addition, correctly engineered nanophotonic cavities may produce an efficient means of creating and manipulating entangled photon (polarization) states (Irvine et al., 2005, 2006).

Beyond computation, quantum information technology holds direct benefits to the technology of secure communications, also referred to as quantum key distribution or quantum cryptography (Bennett and Brassard, 1984). The advantages of a quantum information system in detecting eavesdroppers between sender and receiver lie in the essential quantum mechanical property of a state: once measured, the state itself is altered. The first experimental demonstration of QKD was carried out in 1991 by Bennett and co-workers, with transmission of information over a distance of 32 centimeters (Bennett et al., 1991). Within 10 years, subsequent free-space and fiber-enabled experiments demonstrated secure transmission over distances of tens of kilometers (Hughes et al., 2000; Stucki et al., 2002). None of these systems explicitly depended on the implementation of nanophotonics; however, a critical enabling technology for this and other computation and communications applications are true, controlled single photon sources. Some of the successful recent approaches for the formation of such sources rely on elements such as quantum dots, embedded within, and controlled through the mediation of a high-Q nanocavity (Michler et al., 2000; Yamamoto, 2006).

In many regards, the notion of accessing and taking advantage of the quantum nature of matter should not be a surprising one, given the manifestation of quantum mechanical behavior at sufficiently small spatial scales. Primary challenges have been in (1) determining the application areas of clear benefit for quantum computing and quantum information processing, (2) constructing realistic (solid-state) quantum systems with minimal decoherence, and (3) determining means of scaling such systems up to sizes and complexity (e.g., number of qubits) to be able to accomplish appropriate computation or communications tasks.

With regard to the existence of compelling applications, substantial impetus to the field of quantum computation was given by Shor's prime factoring algorithm (Shor, 1994). In the case of quantum cryptography, a scant 7 years transpired between Bennett and Brassard's introduction of quantum key distribution in 1984 and the first experimental demonstration of a secure communications system in 1991 (Bennett et al., 1991; Bennett and Brassard, 1984).

The physical realization of secure photon-based communications has been less challenging than the realization of a quantum computer, where the issues of decoherence (and error correction) pose formidable challenges. Basically, the fidelity of a quantum mechanical state must have coherence lifetimes well in excess of typical computation times (nanoseconds or less). With all of these challenges, many researchers have in recent years demonstrated coherence of atomic, ion, spin, and photon states. Further evaluation must be made of D-Wave Systems' 16-qubit quantum processor, but such an announcement presages only in small part the possibilities of the future. It is still too early to predict the best physical implementations of quantum computation, but many aspects of nanophotonics are expected to play critical enabling roles in these areas.

Terahertz Spectroscopy and Nanophotonics

Terahertz may be the best frequency range in the electromagnetic spectrum for high-confidence, high-specificity detection of chemicals in the vapor phase. This is because many molecules, from simple diatomic chemicals to complex macromolecules have stronger and more distinctive absorption and emission resonances in the terahertz range than in either microwave or near-infrared-to-visible ranges (Siegel, 2002; Woolard et al., 2002).[2] At lower pressures, smaller molecules generally have very sharp terahertz signatures, with Doppler limited widths around 1 megahertz (MHz), providing significantly enhanced spectral resolution as compared with that of infrared signatures. While compared with microwave spectroscopy, interaction strengths are generally larger in the terahertz regime since the strength of the interaction increases by greater than the square of the frequency, with a peak located in the terahertz regime that is specified by the molecular mass.

Nearly all non-centrosymmetric molecules have resonances between 0.1 THz to 10 THz that are predominately rotational modes or hybrid rotational-vibrational modes, determined by a molecule's moment of inertia. Since the moment of inertia depends on the distribution of mass within the molecule as well as on total mass, a spectrum based on moment of inertia will discriminate between molecular species better than any form of spectroscopy based only on mass. In fact, at high spectral resolution, each molecular signature is unique enough that only a few lines are generally needed to identify a molecule, which is important, given the atmospheric propagation properties described below.

An advantage of terahertz spectroscopy is that analysis of the rotational constants can be performed using fundamental quantum mechanics theories. With these measured rotational constants, one has an absolute identification of the molecule quantitatively as well as qualitatively. In most cases of interest, molecular absorption/emission cross-sections are also very large in the terahertz range, leading to potentially excellent detection signal-to-noise levels and thus high sensitivity to small concentrations.

For most environments, the thermal energy available exceeds the rotational energy transitions; thus, molecules will emit as well as absorb at the rotational transitions. Thus, for gas molecules that are at a higher temperature than that of the background, the characteristic spectral features will be observable passively as well as actively.

The most mature terahertz application is remote sensing by atmospheric scientists and astrophysicists. Thus, a large database of terahertz signatures of most atmospheric constituents already exists, reducing measurement uncertainties by providing potential background signals for a real measurement. Efforts by these communities have demonstrated the strength of the terahertz spectrum and provided a solid foundation on which to expand.

These basic physical facts mean that the terahertz regime has enormous potential in the area of remote spectroscopy, with unprecedented, unsurpassed species-discrimination capability and a minimized probability of error due to either missed detection or misidentification. Success in developing the terahertz regime for remote vapor detection will create a new modality in remote sensing that stretches frequency agility, complements conventional microwave and infrared detection by providing hitherto inaccessible primary and corroborative spectral information, and decreases operational predictability by deploying a new and unconventional frequency technology that will make counterdetection and interdiction more difficult.

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[2]Probably the most complete information on molecular resonances for a large number of common molecules, at frequencies from microwave through ultraviolet, is compiled in the high-resolution transmission molecular absorption database currently maintained by the Harvard-Smithsonian Center for Astrophysics. The database is accessible from the Web site http://cfa-www.harvard.edu/hitran//.

RECOMMENDATION

Recommendation 4-1. To enable a more efficient technology watch and warning process for the U.S. intelligence community, the committee recommends that a data-mining tool be developed to uncover "triggers" and "observables" that will enable the U.S. national security establishment to preserve the dominance of the nation's warfighting capability. In order to uncover pertinent information, the U.S. government could provide a mechanism to leverage critical information from the nanophotonics community. Such a secure and structured database could reveal (across all of the military services) technologies that can support multiple service needs, while also stimulating domestic nanophotonics developments.

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5

Foreign Investment Capabilities

In line with the task of the Committee on Nanophotonics Accessibility and Applicability to "review the scale and scope of offshore investments and interest in nanophotonics," this chapter provides a broad overview of international research and investment in nanophotonics. It does not seek to provide great detail on any particular country or investment capacity but rather to give a general, high-level picture of where interest and research exist and thus to provide a sense of the scale and scope of these matters.

INTERNATIONAL NANOPHOTONICS

The committee performed a literature search, using the program "Science Citation," for the period January 2005 through April 2007 and using the terms "quantum dot (QD) lasers" or "photonic crystal*" or "plasmonics" or "metamaterials" and found 5,440 publications. The results, categorized according to the home institution of the authors and plotted in Figure 5-1, are neither exhaustive nor conclusive.

Specific, publicly available information about nanophotonic developments internationally is detailed in the subsections that follow.

Asia

Much of the advancement in nanophotonics in Asia is driven by the semiconductor industry. For example, the NEC corporation has developed silicon (Si) optical interconnectors for data transmission in large-scale integration chips (Nikkei Electronics Asia, 2007).

On a national level, the People's Republic of China (PRC) is also endeavoring to enter this field, as evidenced by its hosting of a June 2007 conference on nanophotonics at Zhejiang University, Hangzhou, China.[1] Although held in China, this conference was sponsored by Osanano, the nanotechnology division of the Optical Society of America (OSA), making it a truly multinational endeavor. China also offers a

[1]For more information, see http://opt.zju.edu.cn/osanano. Last accessed on April 10, 2007.

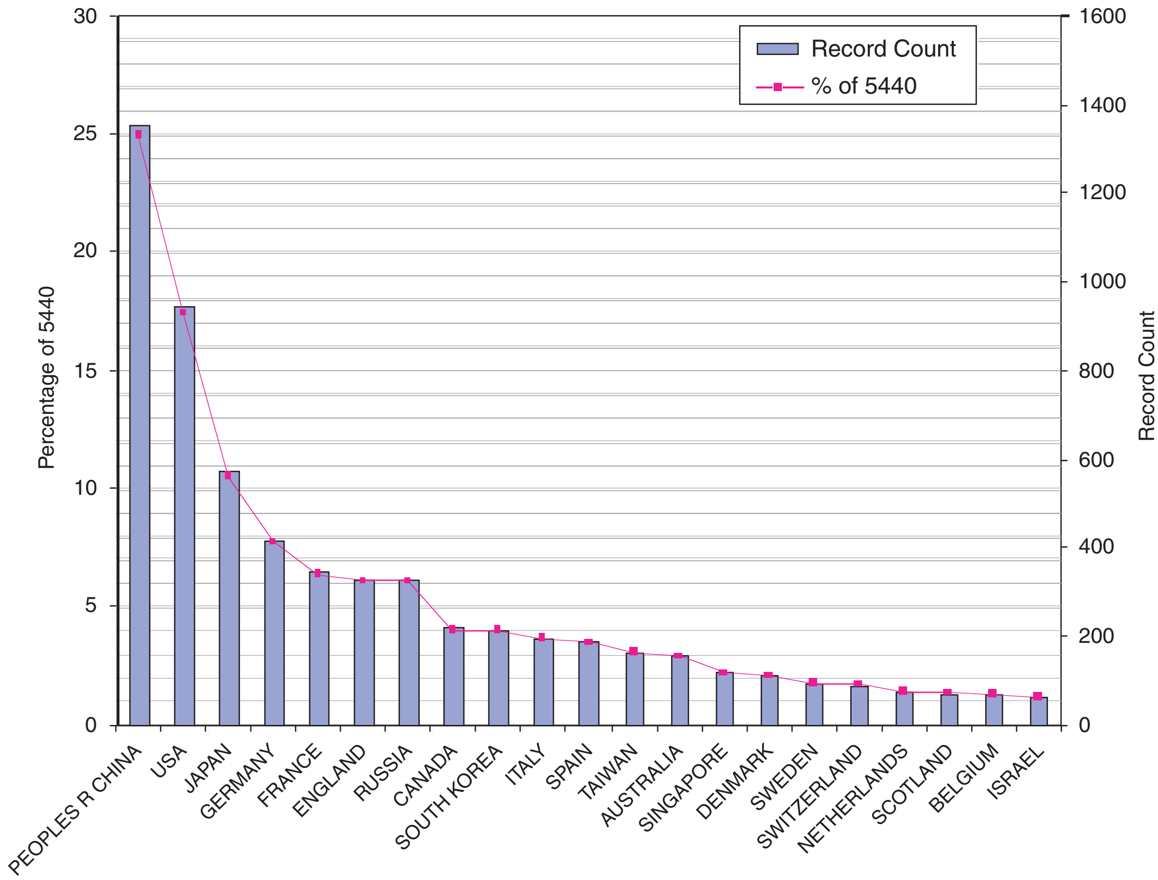

FIGURE 5-1 Results of the committee's keyword search, using the program "Science Citation," of papers published from January 2005 through April 2007 whose authors had home institutions in the country indicated. The keywords used were "quantum dot (QD) lasers" or "photonic crystal*" or "plasmonics" or "metamaterials."

publication of relevance, *Chinese Optics Letters* (Journal).[2] This, too, is in conjunction with OSA. At the national level, the Chinese government makes major investments through its university programs in science and engineering.

Japan funds nanotechnology research primarily through its Ministry of Education, Culture, Sports, Science, and Technology (MEXT) (Strategies Unlimited, 2005). Researchers in Japan such as Baba's group at Yokohama National University and Noda's group at Kyoto University have made seminal contributions in the achievement of photonic crystal devices for low-threshold lasing, low-loss waveguiding, and other applications. Researchers at the University of Tsukuba in Japan are exploring high-speed switching applications with photonic crystal devices. Major research activities are also located at the University of Tokyo. The Ohtsu research group has developed theories of optical near-field interactions with nanomaterials and is working toward the fabrication of prototype nanophotonic devices. This group is in

[2]Available online at http://col.osa.org/Issue.cfm. Last accessed on April 10, 2007.

the process of developing an Industry-University Cooperative supported by New Energy and Industrial Technology Development Organization (NEDO). Yasuhiko Arakawa's group at the University of Tokyo is carrying out work on efficient optical sources, including quantum dot lasers. Finally, Notomi's group at Nippon Telegraph and Telephone Corporation (NTT) has developed extremely high quality photonic crystal elements and is exploring their application to all-optical circuit switching.

Korea, too, is funding a great deal of research in order to harness the opportunities offered by this technology, and much of the government funding is geared toward an extension of research and development (R&D) and the financing of venture capital. The country's major academic centers are the Korean Advanced Institute of Science and Technology (KAIST) and the Gwangju Institute of Technology Research.[3] Research conducted at the latter center has focused primarily on microelectromechanical systems and the development of optoelectric switches.

Europe

Under the auspices of the European Union (EU), much of the nanotechnology research in this region of the world is now cooperative, and funding for all photonics R&D projects was over €50 million in 2004. Studies funded include the following: P*h*OREMOST, for nano and molecular photonics research; ePIXnet, the European Photonic Integrated Components and Circuits Network of Excellence; FUNFOX, the Functional Photonic Crystals for Metropolitan Optical Networks; PHAT, which creates two- and three-dimensional designs in silicon for the integration of routing and emission; and PICMOS, which deals with photonic interconnects on silicon (Strategies Unlimited, 2005).[4] Also of note is the EU-funded virtual technology platform for nanophotonics (VIRGIN), which provides a platform for the development of photonic hybrid-integrated systems.[5] At an industrial level, the EU houses the European NanoBusiness Association and the European Photonics Industry Association.

In addition to the EU-wide programs, most European countries also fund independent efforts. The Technical University of Denmark has a research program that has specific programs focused on silicon nanophotonics, quantum photonics, theory and numerical modeling, semiconductor devices, plasmonics, terahertz technology and spectroscopy, slow light, and optical signal processing.[6] Also in Denmark, the University of Aalborg conducts research on photonics and photonic bandgap structures.[7] Denmark also has an interdisciplinary Nanoscience Center, iNano, that endeavors to merge nanoscale biology, chemistry, and physics.[8]

In Finland, the majority of academic research takes place at the Tampere School of Technology Research. Research there focuses on semiconductor lasers, optoelectronic components, and photochemistry.[9]

Germany's endeavors in this field are both academic and commercial. On the commercial front is the semiconductor company NanoPhotonics.[10] Academically, Germany has funded research at the Max Planck Institut. Notably, research coming from this center has focused on near-field optical microscopy.[11]

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[3]For more information, see http://mems.kjist.ac.kr/. Last accessed on April 10, 2007.

[4]For additional information, see http://www.phoremost.org/. Last accessed on April 10, 2007.

[5]For additional information, see http://virtual.vtt.fi/virtual/fp6virgin/. Last accessed on April 10, 2007.

[6]For additional information, see http://www.com.dtu.dk/English/Research/Nanophotonics.aspx. Last accessed on April 10, 2007.

[7]For additional information, see http://www.physics.aau.dk//page.php?id=70. Last accessed on April 10, 2007.

[8]For additional information, see http://www.inano.dk/sw174.asp. Last accessed on April 10, 2007.

[9]For additional information, see http://www.tut.fi/index.cfm?MainSel=1604&Sel=14965&Show=21555&Siteid=32. Last accessed on April 10, 2007.

[10]For additional information, see http://www.nanophotonics.de/. Last accessed on October 9, 2007.

[11]For additional information, see http://www.biochem.mpg.de/en/research/rg/hillenbrand/index.html. Last accessed on April 10, 2007.

The University of Würtzburg also has conducted research in this area.[12] The current research there is focused on the development of a tunable photonic crystal laser with wavelength monitor and a photonic crystal distributed feedback laser.

The Research Council of Norway is currently funding coordinated research on nanostructures for optics. This cooperative effort at nine different research centers in the country is focused on two specific applications: namely, photonic crystal films and the manipulation of nanoparticles with optical fields in waveguides.[13]

Research funded by the Russian Academy of Sciences conducted in Russia's Institute of Semiconductor Physics reveals that Russia, too, has an interest in this topic.[14] Specific applications studied include quantum dot structures, thin films, and semiconductors.

In the United Kingdom, which has funded research since the late 1980s, the NanoPhotonics Portfolio Center exists as a coordinating center for much of the work done within the University of Southampton. Other research centers include the Microphotonics and Photonic Crystal Research Group at the University of St. Andrews and the Photonic Nanostructures Group and other groups carrying out work in nanophotonics within the Tyndall National Institute at the University of Cork. The Tyndall National Institute was created in 2004 by the Department of Enterprise Trade and Employment to bring together a multiplicity of resources and personnel in order to become a focal point of information and communications technology in Ireland.

NANOPHOTONICS AND GLOBAL COMMERCIAL DEMAND

The committee believes that nanophotonics will increasingly provide foundational building blocks for militarily-relevant capabilities. Based on the close intercoupling between nanophotonics and microelectronics technologies, the committee also concluded that as nanophotonics matures, the commercial markets will be much larger than the military market. This belief is supported by a study performed by the National Science Foundation (NSF) that predicted the global marketplace for goods and services using nanotechnologies will grow to $1 trillion by 2015.[15] The committee believes that when nanophotonics matures, the most significant advances in nanophotonics will be driven largely by global-scale commercial demands rather than by militarily-specific demands. Industry has recognized this trend, as evidenced by the rapid fivefold rise in R&D investment in the 2001-2005 time frame, reaching $1 billion in Europe in calendar year 2005. According to the NSF's President's Committee of Advisors on Science and Technology, in 2005, the United States, Japan, Europe, and Asia each expended in the neighborhood of $1 billion in nanophotonics.[16]

In 2003, the United States was dominant in issued patents in nanotechnology, with Japan, France, and the United Kingdom being notably behind (Huang et al., 2004). It is not apparent from these published data how many of the U.S. patents belonged to foreign companies that filed with the U.S. Patent Office to seek protection in the forecasted large U.S. commercial market in nanophotonics. The advances in

[12]For additional information, see http://tep.physik.uni-wuerzburg.de/index.php?id=108. Last accessed on April 10, 2007.

[13]For additional information, see http://www.forskningsradet.no/servlet/Satellite?c=Page&cid=1138785830860&pagename=ForskningsradetEngelsk%2Fpage%2FStandardSidemal. Last accessed on October 9, 2007.

[14]For additional information, see http://www.isp.nsc.ru/newface/index.php?ACTION=part&id_main=3&lang=en. Last accessed on April 10, 2007.

[15]Rajinder P. Khosla. Nanotechnology at the National Science Foundation: Indo-US Workshop Nanotechnology: Issues in Interdisciplinary Research and Education. Presentation to the Indian Institute of Science, Bangalore, August 10-13, 2004. Available at http://www.nnin.org/doc/Khosla.pdf. Last accessed on April 10, 2007.

[16]For additional information, see http://www.nsf.gov. Last accessed on April 10, 2007.

Si-based nanophotonics have been impressive and are expected eventually to merge nanophotonics and microelectronics together in commercial products. Based on this information, the intelligence technology warning community (ITWC) is advised to monitor nanophotonics developments outside the United States, especially in those countries that have strong backgrounds in related technologies (e.g., integrated optics, semiconductor lasers, compound semiconductors, Si-based semiconductor/microelectronics technologies, nanoscale photolithography, and so on) that will enable them to exploit nanophotonics in their military systems. Some of these countries include China, Japan, Taiwan, South Korea, the EU, India, Israel, and others.

In this present early developmental stage, the U.S. R&D-funding agencies can accelerate the development of nanophotonics technology by funding R&D in the technology as they have repeatedly done in the past for other technologies. Two past examples are Si-based microelectronics and lasers. Such R&D funding action matures the technology faster, so it becomes clearer at an earlier stage how the technology can uniquely contribute to military applications. It also will increase the probability that the U.S. military will be first to deploy the technology in its weapons systems. The committee is pleased to recognize that in 2004, as a result of the emphasis on nanotechnology represented by the National Nanotechnology Initiative, the National Science Foundation, Department of Defense (DOD), Department of Energy, National Institutes of Health, National Institute of Standards and Technology, and National Aeronautics and Space Administration had a total nanotechnology budget of approximately $1.1 billion (National Nanotechnology Initiative, 2007).[17]

The extensive investment in nanotechnology research and development (R&D) by industry suggests the need for the ITWC to establish a sustained relationship with the nongovernmental nanophotonics scientific, technical, and industrial communities—that is, universities, professional societies, and trade organizations—in order to bolster its understanding and anticipation of nanophotonics technology trends (NRC, 2005, 2007). The ITWC needs to become knowledgeable as nanophotonics breakthroughs occur throughout the world, particularly in countries that do not have strong coupling to the U.S. defense community.

With globalization, it is folly to assume that the United States will lead in all technologies relevant to military applications. This reality is believed by the committee to hold true also for nanophotonics. Nanophotonics components, modules, and subsystems will play a large role in future U.S. weapons systems. In order to have the best and most affordable weapons systems, some of the nanophotonics items used in this nation's future weapons systems will probably not be produced within the United States, as is currently the case for increasing numbers of other technologies components, modules, and subsystems. It is a fact that U.S. weapons systems at present have appreciable foreign content (NRC, 2006). The DOD has learned to manage the content and the advantages and risks associated with the foreign content in U.S. weapons systems (NRC, 2006).[18] The Defense Intelligence Agency's Technology Warning Division, in collaboration with other related intelligence organizations that focus on technology warning, should establish, maintain, and systematically analyze a comprehensive array of indicators pertaining to the globalization and commercialization of nanophotonics techniques in order to complement and focus intelligence collection and analysis on the topic. It is expected that this task should have a strong focus on monitoring the developments of nanophotonics technologies in countries not friendly to the United States.

[17]Additional information on U.S. research can be found in the reports entitled *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (NRC, 2007) and *Engineering Research and America's Future: Meeting the Challenges of a Global Economy* (NRC, 2005).

[18]Additional information on foreign contents is provided in Appendix C in this report.

It is relatively easy to create a list of potential future general military applications in which nanophotonics may have some probability of playing a role within the next 10 to 15 years; however, the committee believes that such a list may be of limited use at this early phase of nanophotonics technology development. It is harder to identify with a high degree of confidence those specific applications in which nanophotonics offers a high probability of being a potential "game changer" in the hands of U.S. adversaries; nonetheless, because such a list is believed by the committee to be much more useful to the sponsor, it has done its best to create such a list, presenting it in Chapter 6.

The committee warns against entirely disregarding nanophotonics applications that are envisioned to have little military application but which may have such significant commercial potential that if the United States does not engage in this area that has global interest, its technological edge may be eroded.

If the United States were to become dependent on a foreign industrial base for nanophotonics items that are of strategic importance and critical to its weapon systems and for which the generation of a U.S. industrial base would take a long time, the risk would be unacceptable. The potential of nanophotonics to be an enabling technology for creating new military capabilities means that the government must ensure that U.S. industry can and will engage energetically and be competitive in nanophotonics products that will produce strategic and critical capabilities for this nation's security. As stated previously, the committee believes that nanophotonics will eventually be driven largely by global commercial markets rather than by the U.S. military and U.S. national security agencies. For the DOD to have assured access to nanophotonics capabilities, it will be necessary for the United States to have a healthy commercial nanophotonics industry and to conduct pioneering R&D in the field. Since World War II, the DOD has taken a lead in funding R&D in technologies that show promise of being important to the nation's military capability. The committee is pleased that the DOD is continuing this funding tradition in nanophotonics. World progress in the nanophotonics sector needs to be monitored, and the DOD must intervene if necessary to ensure that the United States grows and maintains an in-country capability.

One of the major advantages that the U.S. military enjoys over its adversaries is its systems capabilities. The U.S. military is advised to maintain vigilance on how nanophotonics technology can enhance its military systems capabilities should some of the nanophotonics devices, modules, and applications on the horizon materialize.

RECOMMENDATION

Recommendation 5-1. The committee recommends that the intelligence technology warning community establish, maintain, and systematically update and analyze a comprehensive array of indicators pertaining to the globalization and commercialization of nanophotonics technologies that would complement and focus intelligence collection on and analysis of the topic. This effort should have a strong focus on monitoring the developments of the technology in countries not predisposed to selling such technology for use in U.S. military systems. The ITWC is advised to monitor those countries that have strong backgrounds in related technologies, integrated optics, semiconductor lasers, compound semiconductors, microelectronics, and nano-scale photolithography.

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6

Overall Comments

THE RELEVANCE OF NANOPHOTONICS TO STRATEGIC AND CRITICAL MILITARY TECHNOLOGIES

Many capabilities and technologies are properly considered important to U.S. security, but some are considered strategic and critical, such as those listed in Table 6-1. Consistent with current policies and practices, the nation has retained the domestic industrial capacity in the selected strategic and critical military capabilities listed in the left-hand column of Table 6-1. The Committee on Nanophotonics Accessibility and Applicability thus assumes that none of the critical capabilities listed in Table 6-1 are likely to be left for foreign industries to fill. The intelligence technology warning community is encouraged to monitor the worldwide development of the specific nanophotonics technologies listed in Table 6-1 that have been assigned probability levels of impacting the listed strategic and critical military capabilities.

Table 6-1 lists the four main categories of nanophotonics technologies—plasmonics, photonic crystals, metamaterials, and confined semiconductor structures—and the committee's estimate concerning whether these technologies will have an Extremely High (EH), High (H), Medium (M), Low (L), or No probability of impacting the military strategic and critical capabilities of the United States listed in the left-hand column of the table. Making such a ranking in these early stages of the development of nanophotonics is a "judgment call"; it had to be based on the committee's expertise in nanophotonics technology and on the data that the committee considered during the course of the study.

MAJOR STRATEGIC AND CRITICAL MILITARY CAPABILITIES AND THE PROBABILITIES OF NANOTECHNOLOGIES IMPACTING THEM

The committee expects that some foreign nanophotonics products will be included in the military systems making up the strategic and critical capabilities listed in Table 6-1. The committee further expects that foreign nanophotonics products will be introduced under the management of a U.S. supplier that would be under close government oversight. The committee expects that such a U.S. supplier

TABLE 6-1 Committee Estimates of the Probability of Impact of Four Areas of Nanophotonics on U.S. Strategic and Critical Military Capabilities

Strategic and Critical Military Capabilities	Plasmonics	Photonic Crystals	Metamaterials	Confined Semiconductor Structures
Mid- and long-wavelength in infrared imaging	EH	M	EH	EH
Chemical/biological threats	EH	H	H	H
Secure communications (encryption, decoding, electromagnetic eavesdropping)	H	H	H	H
Situational awareness	H	H	H	H
Secure computing	H	H	H	H
Electronics systems on weapons platforms	H	H	H	H
Battlefield control	H	M	H	H
Stealth	H	L	H	L
Countermeasures—infrared and visible	M	L	M	H
Weapons platforms	—	—	—	—
Nuclear weapons	—	—	—	—

NOTE: Code for estimated probability of impact: EH = Extremely High; H = High; M = Medium; L = Low; — = None.

would have the opportunity, obligation, and competence to prohibit unacceptably risky nanophotonics components, modules, or subsystems from being used in each of the militarily critical capabilities listed in Table 6-1. A summary of the rankings given in Table 6-1 follows.

- The committee believes that plasmonics and metamaterials could eventually play an important role in this nation's stealth capability, especially in the shorter electromagnetic (EM) wavelength region of the spectrum—namely, the ultraviolet (UV), visible, and near- and far-infrared (IR) regions. This is the EM region where nano dimensions play a role, thus falling within the nanophotonics purview of the committee. The committee believes that photonic crystals and confined semiconductor structures have a low probability of playing a role in stealth technology. The committee recommends that the Defense Intelligence Agency's Technology Warning Division pay particular attention to the two nanophotonics technologies (plasmonics and metamaterials) assigned a High impact probability in the stealth area because, while large obstacles still remain to be overcome before nanophotonics can impact the short-wavelength (i.e., visible, near IR, and far IR) stealth area, one needs to be prepared to take advantage of any technical breakthroughs that may occur.

- The committee believes that there is a High probability that the physics of negative-index materials, plasmonics, and metamaterials may play an important role in stealth technology when applied in the longer-wavelength regions of the EM spectrum where nano dimensions do not play a major role (i.e., in the terahertz, millimeter-wave, and microwave regions).
- The ability of nanophotonics materials and/or devices to selectively scatter, emit, and absorb UV, visible, and IR radiation makes this technology potentially fruitful for research concerning its application in enhancing U.S. countermeasures capabilities. The committee's estimated rankings are two Medium (plasmonics and metamaterials), one Low (photonic crystals), and one High (confined semiconductor structures) ranking regarding the probability that the four nanophotonics technologies listed in Table 6-1 will eventually play a role in the area of IR and visible countermeasures.
- Detectors for night-vision applications are already highly developed for both military and commercial applications. Unfortunately, the technology is now already globally dispersed. The committee believes that nanophotonic antennas and nanoscale semiconductor/photonics technology will enhance the nation's night-vision capability by making smaller detectors possible and by improving detector sensitivities without requiring the use of cryogenic cooling in the 5 to 12 micrometer region. Such a capability is believed to be game-changing by the committee. Consequently, in the area of mid- and long-wavelength in infrared imaging, the committee has assigned three Extremely High (plasmonics, metamaterials, and confined semiconductor structures) and one Medium (photonic crystals) ranking regarding the probability that nanophotonics will impact the U.S. night-vision capability to the extent that the technology would represent an upheaval of the U.S. military's "control of the night" capability.
- Control of the battlefield requires military superiority over the sea, under the sea, on the ground, in the air, and in space and is a strategic and critical goal of the U.S. military. The committee believes that nanophotonics will eventually play a role in stealth, countermeasures, secure communications, secure computing, night vision, fiber communications eavesdropping, and improvements in the performance of electronic systems onboard air, space, sea, ground, and undersea systems, as well as in miniature sensors and remote sensing. The committee has thus assigned three High (plasmonics, metamaterials, confined semiconductor structures) and one Medium (photonic crystals) ranking regarding the probability that the four fundamental nanophotonics technologies will impact the nation's capability in the area of control of the battlefield.
- The committee believes that a non-negligible probability exists that nanophotonics in the form of negative-index materials and metamaterials could experience a breakthrough so as to have a major impact on one's ability to tap into fiber-optics communications lines. The committee believes that nanophotonics has a high probability of impacting secure communications, encryption, decoding, and electromagnetic eavesdropping. Consequently, this area deserves close attention by the intelligence technology warning community.
- Quantum computing can have a high probability of impacting secure computing systems, but the committee believes that it would occur beyond the 15-year time horizon of this study. Even though it is difficult at present to foresee how nanophotonics can impact secure computing, the committee's vision is that nanophotonics will eventually impact this field. The committee has assigned four High probability rankings for this area of secure computing.
- The change in optical and IR transmission, scattered through or by nanophotonics devices, materials, or structures, makes nanophotonics a rich area of research for miniature sensors and in the remote sensing of biological agents. These technologies can be game-changing if the sensor can be made small enough to be used widely by individual soldiers. The committee has assigned one

Extremely High impact probability ranking (plasmonics) and three High probability rankings (photonic crystals, metamaterials, and confined semiconductor structures) that nanophotonics will impact the area of chemical/biological threats.
- The committee sees little direct application of nanophotonics in weapons platforms, such as aircraft, spacecraft, and sea-surface/undersea, or land-based platforms. The committee believes that the use of nanoscale semiconductor or photonics devices, modules, and structures will bring improvements in the electronic systems deployed in U.S. weapons platforms by replacing standard semiconductor devices and night-viewing detectors incorporated within these electronic systems and improving their performance. The electronic systems are radars, communications, controls, jamming, night vision, countermeasures, and so on.
- The committee believes that nanophotonics will not have a major impact on this nation's nuclear weapons capability. There is no probability that plasmonics and nanoscale semiconductor or photonics devices or structures could eventually play a role in fusing such weapons.

CONCLUSIONS

Accessibility

Following are the conclusions of the committee regarding the accessibility of nanophotonics technology in a 10-to-15-year time frame (between 2017 and 2022):

- Nanophotonics will increasingly provide foundational building blocks for militarily relevant capabilities.
- Advances in nanophotonics device technology will enable new applications and systems, both commercial and military.
- As nanophotonics matures, the field will be driven largely by commercial markets rather than by the U.S. military and intelligence agencies.
- Advancements in nanophotonics are expected to enhance the nation's critical military capabilities, as summarized in Table 6-1.

More-specific important expected technological advances are described below:

- Optical wavelength limitations in electronic devices may be surmounted with advances in nanophotonics technology, enabling breakthroughs in quantum computing, sensing technology, and imaging systems.
- Dramatic enhancements in computation, sensing, and secure communications are predicted as a result of confining photonic elements and devices to the nanoscale.
- Profound advances in the control of single photons, the increased efficiency of photonic devices, and the interaction of photons with matter have been realized over the past 15 to 20 years. The committee expects that the pace of innovation and implementation will only increase with the availability of novel nanophotonics building blocks, the development of enabling technologies, and the insights gained by characterizing nanophotonics devices and phenomena.
- The ability to alter the optical properties of virtually any material in a top-down manner will be possible, profoundly altering the capabilities for signaling, switching, detection, and concealment.

Applications

Nanophotonics-based systems will have far-reaching applications, including the following, in both military and commercial markets:

- Power, weight, and volume savings with higher speed and functionality on all military systems, including these:
  —Uncooled infrared sensors and night vision,
  —Ultrasecure communications and quantum information processing, and
  —Photovoltaic power sources.
- External photonic communications between nanophotonic-enabled silicon chips, having widespread application within a few years.
- Heat-assisted magnetic recording, using plasmonic focusing, part of the roadmap in the hard disk drive industry.
- Internal photonic communication within chips, enabling militarily significant functions such as these:
  —Power savings within computing systems,
  —Image recognition, and
  —Multicore processor interconnects.
- Biosensing systems based on fluorescent molecules, plasmonics, and quantum dots, for use in the following:
  —Medical in-field diagnostics,
  —Bioagent detection, and
  —Bioremediation.

Foreign Capabilities and Investments

There are very large, focused foreign investments under way in nanophotonics, including these:

- In *Europe:* Large multicountry collaborations in plasmonics, metamaterials, and nanocavity quantum electrodynamics are being promoted in the European Union;
- In *Japan:* Nanophotonics research takes place at two primary centers—the Nanotechnology Researchers Network Center, founded in 2002,[1] and the Research Institute of Nanophotonics,[2] founded in 2005. Both research centers are coordinated through the Japanese Ministry of Education, Culture, Sports, Science, and Technology and are funded primarily through the Japan Science and Technology Agency. Some of the more recently funded projects include the Localized Photon Project, which was coordinated under the Exploratory Research Agency for Advanced Technology with a total budget of U.S. $8.3 million between 1998 and 2003, and the Nanophotonics Team research occurring under the Solution-Oriented Research for Science and Technology Program, which was supported at a budget of U.S. $2.5 million between 2003 and 2008.[3]

[1]For more information, see http://cnfrs.get-telecom.fr/pages/pages_evenements/journees_scient/docs_journees_2007/5.3%20-%20TANAKA_JS07.pdf. Last accessed on October 11, 2007.

[2]See the Research Institute of Nanophotonics Web site at http://www.nanophotonics.info. Last accessed on October 11, 2007.

[3]See http://cnfrs.get-telecom.fr/pages/pages_evenements/journees_scient/docs_journees_2007/5.3%20-%20TANAKA_JS07.pdf. Last accessed on October 11, 2007.

- In *China:* China continues to make huge investments in education and research infrastructure. In the past 5 years (through 2006), the Chinese publication rate in areas related to nanophotonics has increased enormously. A closer inspection of the publication topics indicates a large proportion of research related to the simulation and modeling of nanophotonic structures and devices rather than to demonstrations of fabricated devices and systems. However, as the required experimental infrastructure is further developed and employed, further technological demonstrations of nanophotonic systems can be expected. A critical precursor technology, silicon integrated circuit planar fabrication, is already gaining a large foothold in China (JTEC, 1996).
- *Foreign technical capability in nanophotonics:* It is likely that certain foreign nations will have equal or superior technical capability in nanophotonics compared with that of the United States within the next 10 to 15 years. These capabilities include fabrication, design and systems integration, fundamental research, and trained and talented workforce and educators. The military capabilities (strategic and critical items or subsystems) listed in the left-hand column of Table 6-1 are not outsourced. The committee thus assumes that the United States will continue to follow this past course of action of not outsourcing these capabilities and technologies to foreign industries.

FINDINGS AND RECOMMENDATIONS

Finding 6-1. Nanophotonics is a highly interdisciplinary field requiring expertise in many areas of materials science, chemistry, applied physics, optics, electrical engineering, systems engineering, and modeling and simulation, among other disciplines.

Recommendation 6-1. The committee recommends that the intelligence technology warning community monitor the worldwide development of nanophotonics technologies that have a high probability of impacting U.S. strategic and critical military capabilities, such as in mid- and long-wavelength infrared imaging systems, chemical and biological threat detection with compact and rugged instruments, secure communications, situational awareness, secure computing, enhancement of the electronics systems capabilities on U.S. weapons platforms, and enhancement of U.S. battlefield control capabilities.

Finding 6-2. The necessary fabrication facilities are becoming increasingly expensive and difficult for U.S. research institutions to maintain.

For the United States to maintain a leading role in the development of the interdisciplinary field of nanophotonics, a stable funding profile must be maintained. For the Department of Defense to have assured access to nanophotonics capabilities, a healthy commercial nanophotonics sector is essential, with the ability to conduct pioneering research and development. Historically, feedback from basic research to applications and back to basic research has been a major factor in U.S. technological success; in an interdisciplinary field this cycle is even more vital.

Recommendation 6-2. The committee recommends that the U.S. government funding agencies continue to support the research and development of nanophotonics technology in the United States across all phases from basic research to applications development.

Finding 6-3. It is likely that certain foreign nations will have equal or superior technical capability in nanophotonics compared with that of the United States within the next 10 to 15 years. These capabilities include fabrication, design, and systems integration; fundamental research; and a trained and talented workforce and educators.

Recommendation 6-3. The intelligence technology warning community should develop a sustained relationship with nanophotonics scientific and technical communities, not only within government agencies, but also in industry, academia, and technical societies, to bolster its understanding and anticipation of nanophotonics technology trends.

REFERENCE

JTEC (Japan Technology Evaluation Center). 1996. Optoelectronics in Japan and the United States. Baltimore, MD: Loyola College. February. Available online at http://www.wtec.org/loyola/opto/toc.htm. Last accessed on January 17, 2008.

Appendixes

Appendix A

Biographical Sketches of Committee Members

Antoinette Taylor, *Chair,* received her B.S., M.S., and Ph.D. degrees from Stanford University, where she was a Hertz Foundation (predoctoral and doctoral) Fellow. Her thesis work on novel molecular spectroscopy was supervised by Professor Arthur Schawlow. She pursued postdoctoral research at Cornell University, where she investigated ultrafast dynamics in dye molecules in solution and semiconductors with Professor C.L. Tang. Dr. Taylor then became a member of the technical staff at AT&T Bell Laboratories in the Lightwave Systems Department, where she worked on optical communications systems and developed a robust electro-optical sampling system based on light wave technology for characterizing high-speed circuits. In 1986 she went to Los Alamos National Laboratory (LANL) to work on the Los Alamos Bright Source, an ultrahigh-intensity laser system used to investigate the light-matter interaction in the high-field regime. In 1994 Dr. Taylor joined the Electronic Materials and Devices Group as a deputy group leader, a position that she held for more than 3 years before transferring to the Condensed Matter and Thermal Physics Group in 1998, where she remained until 2004. During that period she was project leader for the advanced diagnostics for the Pulsed Power Hydrodynamics Program, responsible for leading the diagnostic development activities for the Atlas pulsed-power facility. She is currently the associate director of the Center for Integrated Nanotechnologies, a joint Sandia National Laboratories/LANL nanoscience center funded through the Department of Energy (DOE) Basic Energy Sciences program. Dr. Taylor also leads a photonics-based team that carries out research on Atlas and on ultrafast dynamics of complex materials on the nanoscale, including spin-charge-lattice interactions in correlated electron materials, nonlinear optical effects in microstructured fibers, the ultrafast dynamics of phase transitions in solids, the development of terahertz technology for threat-reduction applications, and the development of spatially and temporally local probes. She is a former director-at-large of the Optical Society of America and topical editor of the *Journal of the Optical Society B: Optical Physics*. She is a fellow of the American Physical Society (APS), the Optical Society of America (OSA), and the American Association for the Advancement of Science (AAAS). In 2003, Dr. Taylor won the inaugural Los Alamos Fellow's Prize for Outstanding Leadership in Science and Engineering.

Anthony J. DeMaria, *Vice Chair,* is chief scientist at Coherent-DEOS, LLC, and professor in residence at the University of Connecticut School of Engineering. He was chairman/chief executive officer and founder of DeMaria ElectroOptics Systems, Inc. (1994-2001). He held several positions at the United Technology Research Center before he retired as assistant director of research for electronics and photonics technology. Dr. DeMaria's research expertise is in the area of utilization of laser devices; interaction of elastic waves with coherent light radiation; generation, measurement, and application of picosecond light pulses; gas laser research and applications; acoustic-optics; laser physics and devices; and optics. Dr. DeMaria has been adjunct professor of Rensselaer Polytechnic Institute, a consultant to government and industry, editor of the *Journal of Quantum Electronics*, and a member of government and industry advisory boards. He was the Distinguished Fairchild Scholar at the California Institute of Technology. Dr. DeMaria is a member of both the National Academy of Sciences and the National Academy of Engineering. He was president of the Connecticut Academy of Science and Engineering (1997-2003). He was a research professor at the Electrical Engineering Department of the University of Connecticut (1994-1998).

Bradley G. Boone is currently a physicist in the Space Department's Radio Frequency Engineering Group at the Johns Hopkins University Applied Physics Laboratory (APL) working on optical communications and laser radar for deep-space applications. He is a member of APL's principal professional staff. After earning his Ph.D. in physics from the University of Virginia in 1977, Dr. Boone joined APL and became involved in a variety of advanced missile-guidance projects. He was the principal investigator on numerous independent research and development projects in active electro-optical systems, optical signal processing, superconducting electronics, and pattern recognition. He served as a section supervisor in APL's Fleet Systems Department from 1983 to 1996 and as supervisor of the Electro-Optical Systems Group from 1997 to 2000. Dr. Boone has published more than 50 technical papers and 1 book and holds 5 U.S. patents. He has taught extensively for the G.W.C. Whiting School of Engineering and was visiting professor in its Electrical and Computer Engineering Department in 1990-1991.

Steven R.J. Brueck is the director of the Center for High Technology Materials (CHTM) and a professor of electrical and computer engineering and a professor of physics and astronomy at the University of New Mexico. He received his Ph.D. in electrical engineering from the Massachusetts Institute of Technology (MIT) in 1971. As CHTM director, he manages research and education at the boundaries of two disciplines. The first, optoelectronics, is found in CHTM's emphasis on semiconductor laser sources, optical modulators, detectors, and optical fibers. The second, microelectronics, applies semiconductor technology to the fabrication of electronic and optoelectronic devices for information and control applications. Examples of these unifying themes at work are silicon (Si)-based optoelectronics and optoelectronics for Si manufacturing sensors. Dr. Brueck is also a former research staff member of the MIT Lincoln Laboratory. He is a member of the American Physical Society and the Materials Research Society and a fellow of the Institute of Electrical and Electronics Engineers (IEEE), the Optical Society of America, and the American Association for the Advancement of Science.

Nancy (Naomi) Halas is currently the Stanley C. Moore Professor of Electrical and Computer Engineering and professor of chemistry at Rice University. She received her undergraduate degree in chemistry from La Salle University in Philadelphia and her master's and Ph.D. degrees in physics from Bryn Mawr College, the latter while she was a graduate fellow at the IBM Thomas J. Watson Research Center, Yorktown Heights, N.Y. Following her postdoctoral research at AT&T Bell Laboratories, she joined the faculty at Rice University. She is best known for her invention of nanoshells, a new type of nanoparticle with tunable optical properties especially suited for biotechnology applications. She has been the recipient of a National Science Foundation (NSF) Young Investigator Award, three Hershel Rich Invention Awards, the 2003 Cancer Innovator Award of the Congressionally Directed Medical Research Programs of the Department of Defense, and the 2000 CRS-Cygnus award for Outstanding Work in Drug Delivery. She was also awarded Best Discovery of 2003 by Nanotechnology Now, the world's leading nanotechnology news and information site, and was named a finalist for *Small Times Magazine*'s 2004 Nanotechnology Researcher of the Year. She is the author of more than 100 peer-reviewed publications, has presented more than 170 invited talks, and has 9 issued patents. Dr. Halas is a fellow of the American Physical Society and of the Optical Society of America. She is also the founder and director of the Rice University Laboratory for Nanophotonics, a multidisciplinary research network whose mission is the design, invention, and application of nanoscale optical components.

Hendrik F. Hamann is currently a research manager for photonics and thermal physics in the Physical Sciences Department at the IBM Thomas J. Watson Research Center, Yorktown Heights, N.Y. He received a diploma in 1992 and a Ph.D. in 1995 from the University in Goettingen in Germany. In 1995 he joined JILA (joint institute of the University of Colorado and National Institute of Standards and Technology) as a research associate in Boulder, Colorado, where he explored novel applications for near-field optics. In 1999 he joined IBM Research as a visiting scientist. Since 2001, Dr. Hamann has been leading the Thermal Physics program in IBM Research, first as a research staff member and currently as a research manager. He has authored and coauthored more than 20 peer-reviewed scientific papers and holds more than 15 patents and has more than 25 pending patent applications. In 2006 was named an IBM Master Inventor. He is a member of the American Physical Society, the Optical Society of America, and the Institute of Electrical and Electronics Engineers.

Evelyn Hu currently holds joint appointments in electrical and computer engineering and materials and is the scientific codirector of the newly formed California Nanosystems Institute, a University of California at Los Angeles (UCLA)-University of California at Santa Barbara (UCSB) collaborative California Institute for Science and Innovation. She received her B.A. in physics (summa cum laude) from Barnard College and her M.A. and Ph.D. in physics from Columbia University. From 1975 to 1981, Dr. Hu was a member of the technical staff at Bell Laboratories at Holmdel, N.J. From 1981 to 1984, she served as a supervisor for very-large-scale integration patterning processes at Bell Laboratories at Murray Hill, N.J. In 1984 she jointed UCSB as a professor of electrical and computer engineering. Her research focuses on the high-resolution fabrication of compound semiconductor electronic and optoelectronic devices, on candidate structures for the realization of quantum computation schemes, and on novel device structures formed through the heterogeneous integration of materials. Recently her work has involved the interaction of quantum (Q) dots in high Q microdisk and photonic crystal cavities. Dr. Hu is a member of the National Academy of Engineering, a member of the Academia Sinica, and a recipient of the AAAS Lifetime Mentor Award, and she was named an NSF Distinguished Teaching Scholar. She was also named the 2005 UCSB Faculty Research Lecturer. She is a fellow of the IEEE, the APS, and the AAAS, and holds an honorary doctorate of engineering from the University of Glasgow.

Peter Palffy-Muhoray is professor of chemical physics and associate director of the Liquid Crystal Institute at Kent State University. He received his Ph.D. in physics from the University of British Columbia in 1977. Dr. Palffy-Muhoray joined Kent State University in 1987. During 1989-1990, he served as consultant for AT&T Bell Laboratories in Summit, N.J. His areas of expertise include nonlinear optics, pattern formation, and nonequilibrium phenomena in liquid crystals. His recent work involves light-driven Brownian ratchets, self-assembled photonic band-gap materials, mirrorless lasing in liquid crystals, liquid-crystal elastomers, and orientationally ordered nanoparticle assemblies. He is a member of the APS, the OSA, the Society for Photo-Optical Instrumentation Engineers (SPIE), and the Society for Industrial and Applied Mathematics (SIAM). He directs the New Liquid Crystal Materials Facility at Kent State University, and he is chief scientific officer of AlphaMicron, Inc.

Stanley Rogers is currently the senior research scientist/engineer, team leader, and technology manager for the United States Air Force Research Laboratory at Wright-Patterson Air Force Base in Dayton, Ohio. He is also a major in the U.S. Air Force Reserve and holds the position of senior combatant command liaison and strategic manager. His service is also extended as an adjunct professor in the Electrical and Computer Engineering Department at the University of Dayton. He received two national awards in 2005, for his leadership and outstanding contributions and for devoted service in photonics, optical engineering, and outreach activities. He received a bachelor's degree in electrical engineering at a historically black institution, Tennessee State University. He graduated at the top of his electrical engineering class in 1985 and scored so well in the Reserve Officers Training Corps that the Air Force commissioned him as a regular appointee. He received his master's and Ph.D. degrees in electrical engineering from the University of Dayton. In 2005, Dr. Rogers submitted applications for three patents in the areas of plasma-enabling technologies. He submitted another patent application in 2006. In 2005, he also authored, had published, and presented many papers and/or talks at various forums for military, engineering, and national as well as international audiences. In 2006, he gained approval to publish and/or present 4 more publications in the areas of material synthesis, photonic/optics beam steering, nanotechnology/microelectromechanical systems enabling technologies, and plasma-gas-based broadband infrared beam steering. Dr. Rogers referees journal articles for the international journal *Optical Engineering* and is on the SPIE executive organizing committee for the Great Lakes Photonics Symposium. He currently has membership with the IEEE, the SPIE, the OSA, AOC, BIG, and Alpha Phi Alpha.

Jerry A. Simmons is the deputy director for energy sciences of the Center for Physical, Chemical, and Nano-Sciences at Sandia National Laboratories (SNL). Dr. Simmons received his bachelor of art's degrees in philosophy and in physics from New College of Florida and a master's and Ph.D. in electrical engineering from Princeton University. He worked as a technician in the Optoelectronic Device Department under Mort Panish at Bell Laboratories, Murray Hill, N.J., from 1982 to 1984. Dr. Simmons joined SNL as a senior member of the technical staff in 1990 and became manager of the Semiconductor Material and Device Sciences Department in 2000; he served as program manager for the $8.3 million Solid State Lighting Grand Challenge Laboratory Directed Research and Development (LDRD) Project, a Defense Advanced Research Projects Agency project on deep ultraviolet light-emitting diodes for chemical-biological detection, a Joint LANL/SNL Nanoscience LDRD Project on Active Photonic Nanostructures, and a DOE Basic Energy Sciences project on Interacting Nanoelectronic and Nanophotonic Structures. He has also managed several internal projects on semiconductor physics, including terahertz quantum cascade lasers and detectors, Bloch oscillations produced in lateral semiconductor superlattices, and collective quantum electronic states at low temperatures. In 2004, Dr. Simmons assumed his present position, in which he oversees SNL's portfolio of DOE Basic Energy Sciences materials science research projects ($9 million per year), and serves as a liaison to the Department of Defense military technology business units at SNL. He has served as the nanoelectronics and nanophotonics thrust leader for the joint SNL/Los Alamos Center for Integrated Nanotechnologies, one of five DOE Nanoscience Research Centers. Dr. Simmons has authored more than 100 publications and serves as a reviewer for NSF, DOE, the APS, *Physical Review*, and several other institutions and scientific journals. He received an *Industry*

Week Technology of the Year Award in 1998 for the invention of a quantum tunneling transistor and was appointed a fellow of the APS in 2002. He was organizer and chair of the 16th International Conference on the Electronic Properties of Two-Dimensional Systems, held in Albuquerque, New Mexico, in July 2005.

Edwin Thomas currently serves as the department head for materials science and engineering at the Massachusetts Institute of Technology (MIT). He and others from MIT cofounded OmniGuide Communications, Inc., in Cambridge. He has served as associate head of the Department of Materials Science and Engineering, as director of MIT's Program in Polymer Science and Technology, and as founding director of the Institute for Soldier Nanotechnologies. Before going to MIT, he founded and served as codirector of the Institute for Interface Science and was head of the Department of Polymer Science and Engineering at the University of Massachusetts. Dr. Thomas is the recipient of the 1991 High Polymer Physics Prize of the APS and the 1985 American Chemical Society Creative Polymer Chemist Award. He was elected a fellow of the APS in 1986 and a fellow of the AAAS in 2003. Dr. Thomas has been a visiting professor and senior scientist at the Institut Charles Sadron at the Centre National de Recherche Scientifique for Macromolecules in Strasbourg, France; visiting professor at the Chemistry Department of the University of Florida; visiting professor in the Department of Physics at Bristol University; a Bye Fellow in the Department of Physics and Materials Science at Robinson College, Cambridge University; a visiting professor in the Department of Chemical Engineering and Materials Science at the University of Minnesota; the Alexander von Humboldt Fellow at the Institute for Macromolecular Chemistry at the University of Freiburg; and assistant professor in the Department of Chemical Engineering and Materials Science at the University of Minnesota. He wrote the undergraduate textbook entitled *The Structure of Materials*, has coauthored more than 350 papers, and holds 11 patents. His research interests include polymer physics and engineering of the mechanical and optical properties of block copolymers, liquid-crystalline polymers, and hybrid organic-inorganic nanocomposites.

Eli Yablonovitch is the Northrop Grumman Opto-Electronics Chair, Professor of Electrical Engineering. He graduated with a Ph.D. in applied physics from Harvard University in 1972. He worked for 2 years at Bell Telephone Laboratories and then became a professor of applied physics at Harvard. In 1979 he joined Exxon Corporation to do research on photovoltaic solar energy. Then in 1984, he joined Bell Communications Research, where he was a Distinguished Member of Staff and also director of solid-state physics research. He is a fellow of the Institute of Electrical and Electronics Engineers, the Optical Society of America, and the American Physical Society. Dr. Yablonovitch is a life member of Eta Kappa Nu and a member of the National Academy of Engineering and the National Academy of Sciences. He has been awarded the Adolf Lomb Medal, the W. Streifer Scientific Achievement Award, the R.W. Wood Prize, and the Julius Springer Prize. Dr. Yablonovitch was a founder of the Workshop on Photonic and Electromagnetic Crystal Structures series of Photonic Crystal International Workshops that began in 1999. His work has covered a broad variety of topics: nonlinear optics, laser-plasma interaction, infrared laser chemistry, photovoltaic energy conversion, strained-quantum-well lasers, and chemical modification of semiconductor surfaces. Currently his main interests are in optoelectronics, high-speed optical communications, high-efficiency light-emitting diodes and nano-cavity lasers, photonic crystals at optical and microwave frequencies, and quantum computing and quantum communication.

Appendix B

Presentations to the Committee

MEETING 1, AUGUST 28-29, 2006
WASHINGTON, D.C.

A Sponsor's Perspective
Stephen Thompson
Defense Intelligence Agency

Intelligence Community Perspective
Jeff Hamilton

Army Research Laboratory Presentation
George Simonis
Army Research Laboratory

Nanophotonics in Defense Policy
Ravi Athale
Center for Innovative Computing
MITRE Corporation

Controlling the Quantum World
Philip Bucksbaum
Michael Moloney
National Research Council

MEETING 2, OCTOBER 16-17, 2006
ALBUQUERQUE, NEW MEXICO

Status of Current Research
Steve Brueck
Center for High Technology Materials
University of New Mexico

Peter Palffy-Muhoray
Liquid Crystal Institute
Kent State University

Nancy (Naomi) Halas
Rice University

Functional Nanocrystal Quantum-Dot Assemblies: Putting Dots to Work
Victor Klimov
Los Alamos National Laboratory

Active Terahertz Metamaterials
Richard Averitt
Los Alamos National Laboratory

California Institute of Technology Presentation
Harry Atwater
California Institute of Technology

Sandia National Laboratories Presentation
Michael Wanke
Sandia National Laboratories

MEETING 3, JANUARY 23-24, 2007
WASHINGTON, D.C.

Plasmonics—A New Wave of Opportunities
Mark Brongersma
Stanford University

Negative-Index Metamaterials and Cloaking in Optics
Vladimir Shalaev
Purdue University

Photonic Crystals and Negative Index Materials
Costas Soukoulis
Iowa State University and Ames Laboratory

Air Force Office of Scientific Research Presentation
Gernot Pomrenke
Air Force Office of Scientific Research

Biosensors Based on Fluorescence Detection Technology
Alan Waggoner
Molecular Biosensor and Imaging Center
Carnegie Mellon University

Naval Research Laboratory Presentation
Craig Hoffmann
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Appendix C

Previous Studies

The following information is taken from a sampling of recent reporting on topics that are directly related to the overarching issues discussed in the main body of this report. This appendix provides the reader with additional background and context for the report.

DEFENSE SCIENCE BOARD TASK FORCE ON HIGH PERFORMANCE MICROCHIP SUPPLY (2005)

The following is reprinted from Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, *Defense Science Board Task Force on High Performance Microchip Supply*, February 2005, pp. 8-14. Available online at http://www.acq.osd.mil/dsb/reports/2005-02-HPMS_Report_Final.pdf. Last accessed on September 19, 2007.

> *Recommendation:* The Task Force recommends that the Department of Defense (DOD), directed by the Secretary and the Undersecretary for Acquisition, Technology and Logistics, lead in guaranteeing its needs are supported by ensuring that the United States policy and industry together transform and enhance the United States (U.S.) position in onshore microelectronics. Providing for assured supplies by DOD contracts with today's trusted foundries helps solve the immediate problem, but is only a temporary measure; foundry agreements will not address the structural issue of funding research that will sustain our information superiority. Long term national security depends upon U.S.-based competitiveness in research, development, design and manufacturing. DOD should advocate that these are not only DOD objectives but also national priorities. . . .
>
> *Recommendation:* DOD must determine classes of [integrated circuits] ICs incorporated in its weapon systems and other key mission products that require trusted sources and how many such circuits are needed. This requires that DOD identify device and technology types of microelectronics devices that require trusted sources as well as the length of time it will need such special supply arrangements. This identification must include the full range of technologies needed for DOD as well as its suppliers. . . .

Recommendation: Led by the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD(AT&L)), DOD and its Military Departments/Agencies, working with their system suppliers, must develop a plan of action that encompasses both short- and long-term technology, acquisition and manufacturing capabilities needed to assure on-going availability of supplies of trusted microelectronic components. This plan of action requires both a steady-state vision and implementation plans for both standard and special technology components. . . .

Recommendation: The Wassenaar Arrangement covering exports of sensitive, leading edge semiconductor manufacturing equipment (SME) is not an effective tool for assuring that potential adversaries do not have access to leading edge design and wafer fabrication equipment, technology and cell libraries. The U.S. should act to strengthen export controls by:

- Negotiating bilateral agreements or understandings with Wassenaar members in which advanced SME and design tools are made with the objective of harmonizing export licensing practices and standards,
- Concluding a similar bilateral agreement or understanding with Taiwan,
- Giving the Department of Commerce a mandate and resources to compile an up-to-date catalogue of the global availability (including foreign availability) of state-of-the-art SME and design tools in designated foreign countries. . . .

Recommendation: DOD must continue to support research and development of the special technologies it requires. This includes ongoing radiation hardened and electromagnetic pulse (EMP)-resistant component design and process development. The emergence of requirements for trustworthiness requires new efforts in technologies to embed, assure and protect component trust. The Department will require additional technology development efforts, including:

- Reducing barriers to radiation-tolerant "standard" designs,
- Increasing efforts to develop tamper protection technology, and
- Developing design and production techniques for disguising the true function of ICs. . . .

Recommendation: Accurate characterization and assessment of adversaries' "dirty tricks" is essential to develop an effective U.S. counter tamper strategy. The Task Force addressed many of these issues relative to the security challenges of information sharing, but opportunities, methods and threats change continuously. The Director, Defense Research & Engineering (DDR&E) in conjunction with the Intelligence Community should develop risk mitigating technical approaches to support the risk management function. DDR&E should take the lead in defining the requirements and making the necessary investments to realize the needed security breakthroughs.

FOREIGN SOURCES OF SUPPLY: ASSESSMENT OF THE UNITED STATES DEFENSE INDUSTRIAL BASE: REPORT REQUIRED BY SECTION 812 OF THE NATIONAL DEFENSE AUTHORIZATION ACT FOR FISCAL YEAR 2004 (PUBLIC LAW 108-136) (2004)

The following is reprinted from Office of the Secretary of Defense, *Foreign Sources of Supply: Assessment of the United States Defense Industrial Base: Report Required by Section 812 of the National Defense Authorization Act for Fiscal Year 2004 (Public Law 108-136)*, November 2004, p. 22. Available online at http://www.acq.osd.mil/ip/docs/812_report.pdf. Last accessed on September 19, 2007.

Conclusions

The information presented in this report indicates that the Department [of Defense] employs foreign contractors and subcontractors judiciously, and in a manner consistent with national security requirements. Furthermore, an ongoing, comprehensive, *forward-looking*, DoD examination of the most important warfighting capabilities, critical supporting technologies, and associated industrial capabilities indicates that the U.S. industrial base is well positioned to maintain its world leadership position.

The Department procures very few defense articles and components from foreign suppliers. In Fiscal Year 2003, DoD procurement actions totaled $209 billion. Of that amount, DoD contracts for defense articles and components totaled just over $65 billion. Of that $65 billion, the Department awarded contracts to foreign suppliers for defense articles and components totaling just over $1 billion. Therefore, DoD contracts for defense articles and components awarded to foreign suppliers represented less than one-half of one percent of all DoD contracts; and only about 1.5% of DoD contracts for defense articles and components. The top five recipient nations (by value) of DoD contracts (Canada, United Kingdom (UK), Israel, Germany, and Sweden) collectively received contracts totaling almost $821 million (about 81% of the total for all such contracts). All five nations are long-standing, reliable, trading partners of the United States.

The January 2004, DoD report *Study on Impact of Foreign Sourcing of Systems* examined the extent and implications of foreign subcontractors for twelve operationally important defense systems. The report concluded that foreign suppliers provide limited amounts of materiel for the systems; and that using those foreign subcontractors does not impact long-term military readiness or the economic viability of the national technology and industrial base. For the systems studied, foreign subcontracts collectively represented about 4% of the total contract value and less than 10% of the value of all subcontracts.

The Defense Industrial Base Capabilities Studies (DIBCS) series of assessments completed to date (*Battlefield Awareness*, *Command and Control*, and *Force Application*) highlight those warfighting capabilities most important to 21st century warfighting; where U.S. leadership over adversaries is most important; and where Department attention and resources should be focused. The United States has a lead in the vast majority of the most critical technologies and associated industrial capabilities. For the most part, there are sufficient U.S. suppliers available now, and projected to be available in the future, to preclude vulnerabilities resulting from foreign supplier dependencies.

STUDY ON IMPACT OF FOREIGN SOURCING OF SYSTEMS (2004)

The following is reprinted from Office of the Deputy Under Secretary of Defense for Industrial Policy, *Study on Impact of Foreign Sourcing of Systems*, January 2004, pp. iv-vi. Available online at http://www.acq.osd.mil/ip/docs/study_impact_foreign_sourcing_of_systems.pdf. Last accessed on September 19, 2007.

Conclusions

Foreign sources provide limited amounts of materiel for the identified programs.

For the twelve programs evaluated as part of this study of foreign sources in defense programs, the Department [of Defense] identified a total of 73 first, second, and third tier foreign subcontractors. The total value of the prime contracts totaled $2.23 billion. The total value of the subcontracted effort for the programs totaled $986 million; about $96.5 million of that amount was subcontracted to foreign sources. Collectively, foreign subcontracts represent about four percent of the total contract value and less than ten percent of the value of all subcontracts for these programs.

Program	# Foreign Subcontractors	Value of Foreign Subcontracts ($M)	Value of Foreign Subcontracts as a % of Total Subcontracts	Value of Foreign Subcontracts as a % of Prime Contract Value
JSLIST	8	$35.0	62.5%	12.5%
PAC-3	25	$23.1	12.3%	6.2%
F414	4	$19.1	10.9%	4.6%
PREDATOR	5	$1.0	14.5%	3.3%
WCMD	11	$2.0	4.3%	3.2%
TACTICAL TOMAHAWK	3	$6.8	5.5%	2.8%
SFW	4	$2.9	7.8%	2.5%
GMLRS	3	$2.6	6.1%	2.3%
SLAM-ER	5	$1.0	3.3%	1.6%
ATACMS	3	$2.2	3.8%	1.5%
PAVEWAY	1	$0.7	0.4%	0.2%
JSOW	1	$0.1	0.1%	0.1%
Subtotal without JSLIST	65	$61.5	6.6%	3.2%
Total	73	$96.5	9.8%	4.3%

The aggregate value of foreign subcontracts is skewed by the inclusion of the Joint Service Lightweight Integrated Suit Technology (JSLIST) chemical protective suit. The JSLIST suit is unusual in that it is not a weapon system, nor a component of a weapon system. It is a piece of vital protective equipment; its cutting edge technology originates overseas; and the Department is bringing this cutting edge technology into the United States. The total value of program subcontracts, exclusive of JSLIST suits, awarded to foreign sources is significantly smaller ($61.5 million versus $96.5 million)—about six percent of the total subcontract value and about three percent of the prime contract value.

Utilization of these foreign sources for these programs does not impact long-term readiness.

The use of foreign sources has not negatively impacted long-term readiness or national security. In fact the use of non-U.S. suppliers: (1) permits the Department to access state-of-the-art technologies and industrial capabilities; (2) promotes consistency and fairness in dealing with U.S. allies; (3) encourages development of interoperable weapons systems; (4) encourages development of mutually beneficial industrial linkages that enhance U.S. industry's access to global markets; and (5) exposes U.S. industry to international competition, helping to ensure that U.S. firms remain innovative and efficient.

Going forward, utilization of the identified foreign sources is not likely to impact the long-term readiness of the Armed Forces. The foreign sources are as likely to be able to meet program cost, performance, and delivery requirements as are domestic sources. Additionally, the identified foreign sources do not constitute a foreign vulnerability that poses a risk to national security. The vast majority of the foreign sources are from NATO nations or other nations with whom we have had enduring military and commercial relationships. Despite very public opposition of some of the firm's host nations to U.S. actions during operations in Afghanistan or Iraq, at no time did the foreign suppliers (including twenty German and two French suppliers) restrict the provision or sale of these components to the Department because of U.S. military operations.

Utilization of these foreign sources does not impact the economic viability of the national technology and industrial base.

The national technology and industrial base is not put at risk by the use of the foreign suppliers reflected within this study. The value of total program subcontracts, exclusive of JSLIST suits, awarded to foreign sources is very limited (about $61.5 million). The vast majority of the total contract value, in excess of 95 percent, is retained domestically. In some cases the national technology and industrial base is being enhanced as domestic capabilities are being established for several key items now procured from foreign sources.

In most cases, domestic suppliers are available for the parts, components, and materials provided by the foreign sources.

The Department identified only four instances where domestic sources were not available to compete for items subcontracted to foreign suppliers.

The Department generally does not mandate supplier selections to its contractors. The Department expects its contractors to select reliable, capable suppliers consistent with obtaining best value, encouraging effective competition, and meeting national security requirements. Although the sampled programs contained several instances of offsets and an international cooperative program (Guided Multiple Launch Rocket System), generally, prime contractors and first and second tier suppliers indicated they selected foreign subcontractors for specific items because those subcontractors offered the best combination of price, performance, and delivery.

The results of this study are consistent with recent related studies.

An October 2001 *Study on Impact of Foreign Sourcing of Systems* (eight weapons systems, including several weapons platforms) identified a total of 86 first, second, and third tier foreign subcontractors. The value of the subcontracted effort for the programs totaled $4.07 billion; about $66 million of that amount was subcontracted to foreign sources. Collectively, foreign subcontracts represented less than two percent of the value of all subcontracts for the programs.

An August 2003 report, *Department of Defense Fiscal Year 2002 Purchases from Foreign Entities,* reported that DoD prime contract procurement actions during Fiscal Year 2002 totaled $170.8 billion. Of that amount, approximately $7.0 billion (about four percent) was for contracts with a place of performance outside the United States. Of the $7 billion, about $1.6 billion (23 percent of foreign purchases and less than one percent of all procurements) was expended for military hardware. (The balance was for subsistence, fuel, construction services, and other miscellaneous items.)

GOING GLOBAL? U.S. GOVERNMENT POLICY AND THE DEFENSE AEROSPACE INDUSTRY (2002)

The following is reprinted from Mark A. Lorell, Julie Lowell, Richard M. Moore, Victoria Greenfield, and Katia Vlachos, *Going Global? U.S. Government Policy and the Defense Aerospace Industry*, 2002, pp. xxii-xxiv. Available online at http://www.rand.org/pubs/monograph_reports/2005/MR1537.pdf. Last accessed on September 19, 2007. Reprinted with permission from RAND Corp., Santa Monica, Calif.

Conclusions

The Response of U.S. Industry to Globalization

- Numerous innovative cross-border strategic market sector agreements initiated by U.S. and foreign companies are emerging. Leading U.S. aerospace prime contractors and subcontractors are aggressively seeking creative new forms of cross-border linkages in efforts to gain or maintain foreign market access. The most innovative of these linkages appear to be long-term strategic teaming or joint venture agreements aimed at entire market sectors rather than the more traditional approach focusing on specific projects or systems.

- U.S. aerospace firms are not significantly increasing their acquisition of wholly owned subsidiaries of foreign defense aerospace firms. There are few indications that U.S. defense aerospace firms have dramatically increased their interest in acquiring wholly owned foreign subsidiaries, although there seems to be some increase in U.S. mergers and acquisitions (M&A) activity overseas in the defense industry as a whole. As noted above, the preferred industry-initiated cross-border business relationships appear to take the form of teams and joint ventures.
- Teaming and joint ventures with non-UK and non-Europe-based firms are increasing. Over the past several years, there has been an apparent increase in M&As, teaming, and joint ventures with non-UK-headquartered European companies as well as with non-European companies. This represents a shift from traditional U.S. practice, in which most direct investments and U.S.-initiated cross-border investments involved UK firms.

Implications of European Consolidation and Increased Aerospace Globalization

- U.S. industry collaboration with one country's firm increasingly means collaboration with many countries' firms. The consolidation that is taking place both with the European defense aerospace industry and with that of other important foreign industrial bases has made it increasingly problematic for U.S. government policymakers and industry leaders to think in terms of bilateral collaborative relationships between the United States and specific European or other foreign countries. As a result, the traditional U.S. government and U.S. industry approach of negotiating bilateral, country-specific agreements may have to be modified or adjusted.
- Consolidated European and other foreign firms mean potentially more equal partners as well as stronger competitors. The consolidation of the European defense aerospace industry is producing pan-European companies of roughly the same size and sales turnover as the leading U.S. firms in many product sectors. These new, consolidated pan-European firms are eager to offer European solutions for European and third-country weapon system requirements that are fully competitive with U.S. products. Similar consolidation trends are visible in other countries.
- European and other foreign firms seek U.S. market access but resent barriers. With an overall smaller market and smaller R&D funding base, the newly emerging pan-European firms and other foreign companies strongly desire greater access both to the U.S. market and to U.S. technology. However, European and other foreign firms are insisting with increasing aggressiveness on more equal business relationships with U.S. firms as well as on less restrictive U.S. policies regarding access to the U.S. market, technology transfer, and third-party sales of technology and products.
- European and other foreign firms view the acquisition of U.S. firms as the most effective means of penetrating the U.S. market. The most successful recent penetrations of the U.S. market by European firms have been through acquisition of existing U.S. firms rather than through joint ventures or programs. To date, however, newly acquired foreign subsidiaries primarily service DoD and are often restricted with regard to technology flow back to Europe. Thus, such market penetration does not necessarily promote equipment standardization or interoperability or help close the capability gap with Europe.
- Non-European foreign firms are forming strategic relationships with European and U.S. firms, potentially enhancing competition but complicating standardization and interoperability objectives. The defense industries of some other important non-North Atlantic Treaty Organization (NATO) allies have been aggressively seeking U.S. and European market access through the forging of new business relationships based on strategic alliances. Israeli industry has been particularly active in this area. In many cases, these alliances have clearly increased competition in key niche product sectors within both the U.S. and European markets in a manner that would appear to be beneficial to the Air Force. In some cases, however, these relationships seem to have undermined U.S. attempts to promote equipment standardization if not interoperability.

- The findings above suggest that European and other foreign industry consolidation present U.S. government and industry with unprecedented opportunities as well as risks. If new, mutually beneficial cross-border collaborative business relationships take hold, the consolidation of European and other foreign industries greatly increases the prospects for allied procurement of standardized or interoperable systems while potentially reducing system costs. On the other hand, the persistence of frictions over technology transfer and security issues as well as foreign direct investment, combined with the increased capabilities and competitiveness of European and other multinational defense industries, means that the Europeans and other allies may be tempted to move increasingly toward indigenous solutions and more widespread global competition with U.S. firms.

FINAL REPORT OF THE DEFENSE SCIENCE BOARD TASK FORCE ON GLOBALIZATION AND SECURITY (1999)

The following is reprinted from Office of the Under Secretary of Defense for Acquisition and Technology, *Final Report of the Defense Science Board Task Force on Globalization and Security*, December 1999, pp. vii-xii. Available online at http://www.acq.osd.mil/dsb/reports/globalization.pdf. Last accessed on September 19, 2007.

Key Task Force Recommendations [Selected]

DoD has not been aggressive in capturing the benefits of or mitigating the risks posed by globalization. Change has come slowly due to a range of factors, including cultural impediments, legal and regulatory obstacles, and restrictive and unclear policies. The Department needs to change the way it does business in a number of areas:

The Department needs a new approach to maintaining military dominance.

Globalization is irresistibly eroding the military advantage the U.S. has long sought to derive through technology controls. Accordingly, the more the United States depends on technology controls for maintaining the capability gap between its military forces and those of its competitors, the greater the likelihood that gap will narrow. To hedge against this risk, DoD's strategy for achieving and maintaining military dominance must be rooted firmly in the awareness that technology controls ultimately will not succeed in denying its competitors access to militarily useful technology.

DoD must shift its overall approach to military dominance from "protecting" military-relevant technologies—the building blocks of military capability—to "preserving" in the face of globalization those military capabilities essential to meeting national military objectives. Protection would play a role in an overall strategy for preserving essential capabilities, but its primacy would be supplanted by three other strategy elements: direct capability enhancement, institutionalized vulnerability analysis and assessment, and risk mitigation efforts designed to ensure system integrity.

To shift its approach from *technology protection* to essential *capability preservation*, the Task Force recommends that DoD: 1) establish a permanent process for determining a continuously-evolving "short-list" of essential military capabilities, and 2) develop strategies for preserving each essential capability. Both the list of essential military capabilities and the strategies for their preservation are needed to inform the development of: U.S. warfighting strategy and the forces to underpin that strategy (by identifying how and with what the U.S. will need to fight to remain dominant), DoD positions on technology and personnel security (by helping to identify those capabilities and/or constituent technologies which DoD should attempt to protect and how vigorously they should be protected); and DoD acquisition risk mitigation measures (by identifying those systems that should be the focus of intense efforts to ensure system integrity).

DoD needs to change substantially its approach to technology security.

The United States has a national approach to technology security, one in which the Departments of State and Defense both play essential roles. The Task Force does not challenge the propriety of the Department of State's statutory obligation to evaluate proposed defense technology transfers against U.S. foreign policy objectives. That said, the leveling of the global military-technological playing field also necessitates a substantial shift in *DoD's* approach to technology security, the principal objective of which is to help maintain the U.S. military-technical advantage.

DoD should attempt to protect for the purposes of maintaining military advantage only those capabilities and technologies of which the U.S. is the sole possessor and whose protection is deemed necessary to preserve an essential military capability. Protection of capabilities and technologies readily available on the world market is, at best, unhelpful to the maintenance of military dominance and, at worst, counterproductive (e.g., by undermining the industry upon which U.S. military-technological supremacy depends). Where there is foreign availability of technologies, a decision to transfer need only be made on foreign policy grounds by the Department of State. DoD should no longer review export license applications as part of its role in the arms transfer process when foreign availability has been established. This will allow the DoD licensing review to concentrate on cases where the availability of technology is exclusive to the United States.

Moreover, military capability is created when widely available and/or defense-unique technologies are *integrated* into a defense system. Accordingly, DoD should give highest priority in its technology security efforts to technology integration capabilities and the resulting military capabilities themselves, and accordingly lower priority to the individual technologies of which they are comprised.

For those items and/or information that DoD can and should protect, the Task Force believes security measures need improvement. The means for such an improvement might come from a redistribution of the current level of security resources/effort, whereby DoD relaxes security in less important areas and tightens up in those most critical. In short, DoD must put up higher walls around a much smaller group of capabilities and technologies.

DoD must realize fully the potential of the commercial sector to meet its needs.

To leverage fully the commercial sector, DoD must do more than simply acquire available commercial products and adopt commercial practices. In some cases, DoD must engage commercial industry in an effort to shape the development of new products and services to better meet its needs. In many cases, DoD must adapt its often-bloated system requirements to, and develop new concepts that fit, operationally acceptable commercial solutions. The Task Force makes two primary recommendations designed to help DoD meet this overarching objective.

First, the Secretary of Defense should give commercial acquisition primacy and broader scope by establishing it as the modernization instrument of first resort. DoD should seek to meet its modernization needs, whenever possible, with commercial solutions (including integrated services, systems, subsystems, components and building-block technologies) acquired using commercial acquisition practices. The Secretary should grant waivers to the acquisition of commercial *products* and *services* only when program managers can demonstrate that either no commercial options exist or that available commercial options cannot meet all critical performance requirements. DoD should employ commercial acquisition *practices* in all cases. The Task Force recognizes that some integrated, military-specific systems (e.g., precision-guided munitions and combat aircraft) are not and will likely never be provided by the commercial sector. Even here, DoD should meet its needs, whenever possible, with commercial components and subsystems. DoD can and should tap the commercial market to support virtually all of its modernization requirements.

Second, the Under Secretary of Defense for Acquisition and Technology should form and routinely employ "Commercial Acquisition Gold Teams" to provide and manage advocacy for expanded DoD leverage of the commercial sector. The Task Force believes that Gold Teams should be employed during the earliest stages of the acquisition process (the concept definition phase), where they will have the best opportunity to reduce both the time and cost of developing and fielding new systems. Gold Teams should be focused initially on the commercial industry sectors from which the Task Force believes DoD can derive immediate and profound benefit: air and sea transportation; logistics and sustainment; communications and information systems; space-based surveillance; and high-efficiency ground transportation. The organizational character and composition of the Commercial Acquisition Gold Teams are best determined by the USD(A&T). Teams could be either standing or ad hoc in character. Personnel could be either in-house (i.e., DoD), drawn from the contractor/ Federally Funded Research and Development Center (FFRDC) community, or a mix of the two.

In addition to these two core recommendations, DoD must also: 1) engage proactively in commercial standards management; 2) conduct a comprehensive review of the Federal Acquisition Regulations (FAR) and Defense Federal Acquisition Regulations Supplement (DFARS) with the intent of asking Congress to eliminate remaining statutory barriers to DoD procurement of commercial products and services and also commercial sector disincentives for doing business with DoD; and 3) field on the World Wide Web interactive "distance-learning' software that would allow commercial firms to quickly familiarize themselves with the FAR/DFARS; rapidly determine which regulations apply to their specific contracts; and comply fully with those regulations.

DoD should take the lead in establishing and maintaining a real-time, interagency database of globally available, militarily relevant technologies and capabilities.

Such a database, which would facilitate rapid and authoritative determination of the foreign availability of a particular technology or military capability, would serve two principal functions. First, it would allow those involved in the export licensing and arms transfer decision making process to determine which technologies and capabilities are available abroad and thus no longer U.S.-controllable. Second, it would facilitate enhanced access by U.S. government and industry weapons developers to the global technological marketplace by illuminating potential foreign sources and/or collaborators.

DoD should facilitate transnational defense industrial collaboration and integration.

Greater transnational, and particularly transatlantic, defense-industrial integration could potentially yield tremendous benefit to the United States and its allies. The Task Force, however, identified a range of factors working to inhibit foreign industrial interest in greater integration with their U.S. counterparts. These include insufficient clarity in DoD policy on cross-border defense industrial mergers and acquisitions, and an overly burdensome regulatory environment surrounding both foreign direct investment in the U.S. defense sector and the transfer of U.S. defense technology, products and services.

The Task Force makes three principal recommendations to erode these barriers to effective defense sector globalization. First, DoD should publicly reaffirm, on a recurring basis, its willingness to consider a range of cross-border defense industrial linkages that enhance U.S. security, interoperability with potential coalition partners, and competition in defense markets. Special attention should be paid to illuminating—to the extent practicable—DoD's broad criteria for merger and acquisition approval, and DoD's policy rationale (e.g., the national security benefits of cross-border defense consolidation). Second, the Department of Defense should engage the Department of State to jointly modernize the regulatory regime and associated administrative processes affecting the export of U.S. defense articles. Third, DoD should also modernize the administrative and regulatory processes associated with foreign direct investment (FDI) to facilitate FDI in the U.S. defense sector.

The Task Force also recommends that DoD adapt existing bilateral industrial security arrangements to respond to the emergence of multinational foreign defense industrial organizations. The change in the structure of the defense industry raises a question about whether the existing security practices are appropriate to its inevitable globalization.

Appendix D

Selected Research Groups In Plasmonics

INTRODUCTION

Appendix D presents supporting material for Chapter 2, "Nanoscale Phenomena Underpinning Nanophotonics." Not intended to be exhaustive, this appendix describes a representative sampling of research efforts in 10 areas of plasmonics. In addition, it provides an approximate scale of international research in these specific scientific areas. Reference is made to Appendix D within subsections of the major sections entitled "Plasmonics," "Emerging Topics of Phonon Polaritons," and "Terahertz Waveguides" in Chapter 2.

Presented in the same order as their corresponding subsections in Chapter 2, following are the 10 areas of plasmonics research addressed below:

- Localized Surface Plasmon Resonance Sensing,
- Surface-Enhanced Spectroscopy,
- Techniques for Imaging and Spectroscopy of Plasmonic Structures,
- Extraordinary Transmission, Subwavelength Holes,
- Plasmonic Waveguides and Other Electromagnetic Transport Geometries,
- Plasmon-Based Active Devices,
- Plasmon-Enhanced Devices,
- Plasmonics in Biotechnology and Biomedicine,
- Phonon Polaritons, and
- Emerging Topics in Plasmonics.

The research groups within each area listed above are alphabetized by the last name of the group's leader.

LOCALIZED SURFACE PLASMON RESONANCE SENSING: SELECTED RESEARCH GROUPS

- *Jason H. Hafner, Rice University, Houston, Texas*—Gold nanostars are asymmetric nanoparticles that show polarization-dependent scattering spectrum. This has been demonstrated to show large surface plasmon resonance (SPR) shifts in single-particle scattering measurements. Dr. Hafner's group is currently pursuing single-particle, single-binding-event sensing using nanostars (Nehl et al., 2004).
- *Naomi J. Halas, Rice University, Houston, Texas*—Dr. Halas's group has developed a variety of nanoparticles that exhibit large SPR sensitivities. These include silica core gold nanoshells and "nanorice" particles (Tam et al., 2004; Wang and Mittleman, 2006).
- *Mikael Käll, Chalmers University of Technology, Göteborg, Sweden*—LSPR sensing of single holes in gold films and the ensemble measurements have been used to demonstrate the LSPR sensitivity by functionalizing with alkanethiols of different lengths. Other geometries made by electron-beam lithography have also been developed. The group at Chalmers University has also developed techniques to study surface modifications in the lipid layer and other chemical changes that occur at the hole sites on lipid layers supported on gold films with nanometer-size holes (Rindzevicius et al., 2005).
- *Nicholas Kotov, University of Michigan, Ann Arbor*—Dr. Kotov developed a layer-by-layer assembly technique to fabricate thin films of mixed anisotropic nanoparticles and controlled surface plasmon absorption.
- *J.R. Sambles, University of Exeter, Exeter, United Kingdom*—Dr. Sambles's group has developed an acoustooptical tunable filter to enhance the SPR sensitivity of gold films used to detect NO gas close to the surface, the binding of biological molecules in solution, and the electrochemical modifications in the films as different molecules attach to the surface (Jory et al., 1995).
- *Jennifer Shumaker-Parry, University of Utah, Salt Lake City, Utah*—Dr. Shumaker-Parry's group has developed SPR microscopy as a technique for array-based molecular recognition studies. SPR microscopy using an asymmetric particles array (crescent-shaped particles) provides a label-free method for high-throughput, quantitative, real-time kinetic studies of biomolecule interactions (e.g., protein-DNA, protein-protein, protein-vesicle) (Shumaker-Parry et al., 2005).
- *Richard P. Van Duyne, Northwestern University, Evanston, Illinois*—Dr. Van Duyne's group has used nanosphere lithography silver triangles as localized surface plasmon resonance (LSPR) sensors to study chemical binding and unbinding events. Both ensemble measurements of silver triangle arrays and single-particle measurements have been used to study LSPR shifts that are due to molecules binding to the surface (Malinsky et al., 2001; McFarland and Van Duyne, 2003). This group has also used LSPR sensing to detect biomarkers for Alzheimer's disease.
- *Younan Xia, University of Washington, Seattle, Washington*—Dr. Xia's group has developed hollow gold nanoshells, and nanocube particles that show high LSPR sensitivity. Ensemble measurements on the nanoshells and single-particle measurements on the nanocubes have been performed (Sherry et al., 2005; Sun and Xia, 2002).

SURFACE-ENHANCED SPECTROSCOPY: SELECTED RESEARCH GROUPS

- *Louis Brus, Columbia University, New York, New York*—Dr. Brus's group is involved in studies relating to the origin of large enhancement factors in SERS from silver colloid particles (Michaels et al., 2000). The group is also investigating the chemical effect in the SERS enhancement.

- *Peter Griffiths, University of Idaho, Moscow*—Dr. Griffith's group has developed techniques to use surface-enhanced infrared absorption spectroscopy (SEIRA) to increase the sensitivity at which the molecules eluting from a gas chromatograph (GC) can be identified. This instrument has better sensitivity than a traditional GC/mass spectrometer (Bjerke et al., 1999). The group has also developed instrumentation to study SEIRA of the atmosphere to identify pollutants in the environment and gases formed in compost piles on dairy farms.
- *Naomi J. Halas, Rice University, Houston, Texas*—Dr. Halas's group has developed gold and silver nanoshell-based substrates for SES and explored many of the basic physics origins of SERS and SEF (Tam et al., 2007). The group has also developed a nanoscale pH sensor based on SERS of molecules adsorbed on nanoshells (Bishnoi et al., 2006).
- *Mikael Käll, Chalmers University of Technology, Göteborg, Sweden*—Dr. Käll's group has been involved with surface-enhanced Raman and surface enhanced fluorescence (SEF) on nanoparticle substrates as well as nanometer-sized holes in metallic films. The group has developed both experimental techniques for exploring plasmons in various nanostructures and theoretical background for SERS and SEF (Xu et al., 2004).
- *Satoshi Kawata, Osaka University, Osaka and Riken, Tokyo, Japan*—Dr. Kawata's research group looks at various enhanced nonlinear spectroscopic techniques using a metallized tip to enhance the signal of the same, and to minimize the volume of the sample that is probed. The group has developed techniques for tip-enhanced Raman spectroscopy and tip-enhanced coherent Raman spectroscopy, a nonlinear Raman scattering technique that utilizes two lasers to overpopulate the excited state of the system. These techniques are then used to image biological molecules, such as adenine, and other biological systems (Ichimura et al., 2004).
- *Katrin Kneipp, Wellman Center for Photomedicine, Harvard University, Medical School, Massachusetts Institute of Technology*—Dr. Kneipp is one of the pioneers of single-molecule detection using SERS (Kneipp et al., 1997). Currently she is investigating SERS and surface-enhanced Raman optical activity in vivo for molecular and chemical probing of cell and biological structures and biomedically relevant molecules (Kneipp et al., 2006a).
- *Joseph R. Lakowicz and Chris D. Geddes, University of Maryland, Baltimore*—Dr. Lakowicz is the director for the Center for Fluorescence Spectroscopy. He has been involved with numerous techniques in advanced fluorescence spectroscopy, including surface-enhanced fluorescence, surface-enhanced multiphoton fluorescence spectroscopy, and so on. He is also the author of a number of review articles and books on fluorescence spectroscopy, including *Principles of Fluorescence Spectroscopy*.
- *Martin Moskovits, University of California at Santa Barbara*—Dr. Moskovits has been involved in surface-enhanced Raman spectroscopy and the development of different nanostructures for SES (Moskovits, 1985).
- *Lukas Novotny, University of Rochester, Institute of Optics, Rochester, New York*—This group has been involved in the development of tip-enhanced Raman spectroscopy as an imaging technique. Dr. Novotny's group developed a tip-enhanced Raman scattering microscope for the chemically specific imaging of surfaces. This technique is being applied for the study of carbon nanotubes, stress analysis in semiconductors, and membrane proteins. Currently the group is also utilizing this for tip-enhanced fluorescence spectroscopy. The group has demonstrated single-molecule fluorescence and the distance-dependent fluorescence profile as a gold or silver tip is moved closer to a fluorescent dye molecule on a surface (Anger et al., 2006). The Novotny group is also involved in surface-enhanced sum frequency generation using clusters of gold nanoparticles as substrates (Danckwerts and Novotny, 2007).

- *Masatoshi Osawa, Hokkaido University, Sapporo, Japan*—Dr. Osawa is one of the pioneers of SEIRA. His group studies SERS and SEIRA in ATR geometry of chemical reactions and confirmation of proteins in solution electrochemically. He is the author of a number of review articles on SERS and SEIRA (Osawa, 2001).
- *Bruno Pettinger, Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Germany*—This group's research is on the mechanism of SERS on gold and platinum surfaces. In addition, the group has developed techniques for TERS in the junctions formed between silver and gold scanning tunneling microscope tips with dye molecules adsorbed on smooth metal surfaces (Pettinger, 2006b, 2006a).
- *Annemarie Pucci, University of Heidelberg, Germany*—Dr. Pucci's group has been involved in SEIRA using different nanoparticle geometries for a long time (Enders and Pucci, 2006).
- *Vahid Sandoghdar, ETH, Zurich, Switzerland*—Dr. Sandoghdar's group has combined far-field fluorescence microscopy with scanning probe machinery to localize single molecules in a sample to a very small fraction of the wavelength of light. Using a single colloid attached to a scanning near-field optical microscopy tip, the group has studied single-molecule fluorescence. (Kuhn et al., 2006).
- *Vladimir M. Shalaev, Purdue University, West Lafayette, Indiana*—Dr. Shalaev developed semicontinuous silver films as SERS substrates (Genov et al., 2004). Currently developing a SERS-based sensor to examine differences in Raman spectra of two insulin isomers, human insulin and its analog insulin lispro, which differ only in the interchange of two neighboring amino acids (Drachev et al., 2004).
- *Richard P. Van Duyne, Northwestern University, Evanston, Illinois*—Dr. Van Duyne is one of the pioneers in the field of SERS. From studying the basic physics behind SERS, and development of optimal SERS substrates, Dr. Van Duyne's group is now actively involved in applications of SERS for biomedical sensing. These range from in vivo optical glucose sensors to the sensing of bioterrorism agents.
- *Renato Zenobi, ETH Swiss Federal Institute, Zürich, Switzerland*—The Zenobi group is actively involved in the fabrication and design of various TERS probes based on atomic force microscopy (AFM) tips. This group combines a laser scanning confocal microscope and an AFM capable of both tip and sample scan modes. This capability provides highly localized enhancements when the tip is present and offers more uniform enhancement when scanning over the sample (Vannier et al., 2006).

TECHNIQUES FOR IMAGING AND SPECTROSCOPY OF PLASMONIC STRUCTURES: SELECTED RESEARCH GROUPS

- *Franz R. Aussenegg, Joachim R. Krenn, and Alfred Leitner, Karl-Franzens-University, Graz, Austria*—This group has extensively applied photon scanning tunneling microscopy (PSTM) and leakage-radiation microscopy to study the propagation of surface plasmons in metallic strip and particle array waveguides, and has applied passive devices such as Bragg reflectors, beam splitters, and plasmon corrals. In addition, this group has applied other techniques such as surface-enhanced Raman scattering to image the fields around plasmonic devices and dark-field microspectroscopy to study the resonant modes of nanowire waveguides.
- *Sergey I. Bozhevolnyi, University of Aalborg, Aalborg, Denmark*—This group has applied collection mode near-field scanning optical microscopy (NSOM) to studying the propagation of surface

plasmons in particle-based and channel-based waveguides, including measuring the performance of passive devices such as Mach-Zehnder interferometers and waveguide-ring resonators.

- *Mark Brongersma, Stanford University, Stanford, California*—The Brongersma group is an engineering group focusing on the development of methods to guide and manipulate light using plasmonic nanostructures. To this end, the group extensively employs photon tunneling scanning microscopy utilizing microfabricated NSOM probes to measure the properties of plasmonic devices.
- *Jochen Feldmann and Thomas Klar, Ludwig-Maximilians-Universität München, Munich, Germany*—This group has pioneered the use of dark-field microspectroscopy to study the scattering properties of individual metallic nanoparticles and the application of this technique to single-particle surface plasmon resonance sensing of biomolecules. In addition, this group has studied enhanced photoluminescence from gold nanoparticles utilizing excitation with an ultrafast laser.
- *Reinhard Guckenberger, Fritz Keilmann, and Rainer Hillenbrand, Max-Planck-Institut für Biochemie Abteilung Molekulare Strukturbiologie, Martinsried, Germany*—This group has worked extensively on extending ANSOM into the infrared spectral region. In addition to looking at surface plasmon polartions in particles, the group has studied the closely related phenomenon of surface phonon polaritons on SiC in the infrared (IR). Recently the group developed a technique based on pseudo-heterodyne detection to eliminate the background in ANSOM images, which, unlike previous techniques, is suitable for use over broad wavelength ranges spanning the near-ultraviolet to far-IR spectral ranges (Ocelic et al., 2006). This group has been working on techniques for ANSOM in the IR and is studying surface photon polaritions on SiC in addition to surface plasmon polaritons.
- *Victor I. Klimov, Los Alamos National Laboratory, Los Alamos, New Mexico*—While primarily focused on quantum dots, Dr. Klimov's group has made important contiburtions to the study of plasmons in metallic nanoparticles by pioneering the use of femtosecond white-light continuum radiation for linear spectroscopy of single gold nanoparticles with an illumination-mode NSOM (Mikhailovsky et al., 2004).
- *Brahim Lounis, Centre de Physique Moleculaire Optique et Hertzienner, Centre National de la Recherche Scientifique (CNRS)—Université Bordeaux 1, Cedex, France*—Dr. Lounis's group has led the development of photothermal heterodyne to measure the absorption spectrum of small gold colloid plasmons. This group is focused on applying this technique to develop contrast agents for microscopy of the dynamics in biologically relevant systems.
- *Alfred Meixner, Eberhard-Karls-Universität Tübingen, Tübingen, Germany*—Dr. Meixner's group has developed a method for determining the orientation of nonsymmetric nanoparticles on a surface using far-field confocal microscopy with higher-order Guassian beams (doughnut mode). This is of importance, as previously either electron microscopy or topographic imaging with an AFM or NSOM tip was required to determine unambiguously the orientation of particles significantly smaller than the diffraction limit.
- *Hrvoje Petek, University of Pittsburgh, Pittsburgh, Pennsylvania*—Dr. Petek's group has been studying the dynamics of materials using a frequency-doubled 10 femtosecond Ti:sapphire laser and two-photon time-resolved photoelectron emission spectroscopy and imaging. The group recently applied this technique to two-photon photoelectron emission imaging of surface plasmon polariton propagation, obtaining the currently highest simultaneous temporal and spatial image of surface plasmon polariton wave-packet propagation.
- *Albert Polman, FOM [Fundamental Research on Matter] Institute for Atomic and Molecular Physics (AMOLF), Amsterdam, The Netherlands*—This group has developed techniques for measuring the propagation of surface plasmon polaritons (SPPs) on metal film structures by

cathodoluminescence (van Wijngaarden et al., 2006). This group has also investigated the propagation of purely bound infrared SPP modes on metal strips on the glass/silver interface at telecommunications wavelengths by looking at photoluminescence of Er+ deposited in the glass substrate of the waveguides and excited by the near field extending from the waveguide (Verhagen et al., 2006). Leakage radiation microscopy and PSTM are not able to image such modes propagating at the substrate-metal interface, because in the former case the phase-matching condition is not satisfied for the propagation of light in the glass, thereby forbidding the radiation into the glass (unlike waveguides using the metal-air interface), and in the latter case simply because the field is not physically accessible. This group has collaborated extensively with the Atwater group at the California Institute of Technology for their work in surface plasmons (see "Harry A. Atwater" in the section below on "Plasmonic Waveguides and Other Electromagnetic Transport Geometries").

- *Fabrice Vallée and Natalia Del Fatti, CNRS and Université Bordeaux 1, Talence, France*—This group has developed the technique of spatial modulation spectroscopy using supercontinuum to measure directly the absorption of single gold and silver nanoparticles. This technique has been demonstrated to accurately determine the particle ellipticity by measuring the spectrum with different incident polarizations and comparing the results to Mie theory (Muskens et al., 2006).

EXTRAORDINARY TRANSMISSION, SUBWAVELENGTH HOLES: SELECTED RESEARCH GROUPS

- *William L. Barnes, University of Exeter, Exeter, Devon, United Kingdom*—Dr. Barnes's group has extended the study of extraordinary transmission beyond subwavelength holes. This group has continued to study the basic processes underlying extraordinary transmission. His group has also studied how surface plasmons mediate light transmission through metal films that contain no subwavelength holes (Andrew and Barnes, 2004).
- *Steven Brueck, University of New Mexico, Albuquerque*—This group has pioneered both the fabrication and characterization of annular (coaxial) arrays and the use of these arrays for nonlinear optics applications (by etching the structures into a gallium arsenide matrix before depositing the metal films).
- *Thomas W. Ebbesen, ISIS [Institut de Science d'Ingenierie Supramoleculaires], Université Louis Pasteur, Strasbourg, France*—Dr. Ebbesen's group originally discovered the extraordinary transmission phenomenon. The group continues to study and characterize the fundamentals of the phenomenon as well as explore applications. Recently, Dr. Ebbesen's group has worked on using subwavelength hole arrays coupled with molecules to approach the realization of fast all-optical switching components (Dintinger et al., 2006).
- *F.J. García-Vidal, Universidad Autónoma de Madrid, Madrid, Spain; Luis Martín-Moreno, ICMA-CSIC [Instituto de Ciencia de Materiales de Aragon, Consejo Superior de Investigaciones Cientificas], Universidad de Zaragoza, Zaragoza, Spain*—This group focuses on theoretical studies of the extraordinary transmission phenomenon. The group has published many studies that support the surface plasmon view of extraordinary transmission. Recently they have continued to study the phenomenon as well as different geometries for extraordinary transmission. For example, they have recently studied the transmission of light through a rectangular hole (García-Vidal et al., 2006).
- *Henri J. Lezec, Thomas J. Watson Laboratories of Applied Physics, California, Institute of Technology, Pasadena, and Centre National de la Recherche Scientifique, Paris, France*—Dr. Lezec is

a proponent and co-originator of the controversial composite diffracted evanescent wave (CDEW) model for explaining the mechanism underlying the extraordinary transmission phenomenon. He has performed experimental measurements supporting this model.

- *Teri Odom, Northwestern University, Evanston, Illinois*—Dr. Odom's group has done experiments that support the surface plasmon model as the major process underlying extraordinary transmission. Conventional studies of extraordinary transmission rely solely on far-field optical data, but by definition, surface plasmons are confined to a surface and therefore cannot be directly detected using far-field measurements. However, using a near-field scanning optical microscope, the large electric field in close proximity to a surface due to surface plasmons can be directly detected, allowing the plasmon oscillations to be imaged. By combining far-field and near-field optical measurements, this group has shown direct evidence for the surface plasmon model of extraordinary transmission (Gao et al., 2006).
- *Evgeny Popov and Michel Nevière, Institut Fresnel, Domaine Universitaire de Saint Jérôme, Université d'Aix Marseille III, Marseille, France*—This group studies the theory underlying the extraordinary transmission phenomenon. It studies the basics of plasmons on films in the presence of different types of nanoapertures.
- *Tineke Thio, Arinna, LLC, Princeton, New Jersey*—Dr. Thio is a proponent and co-originator of the controversial CDEW model for explaining the mechanism underlying the extraordinary transmission phenomenon. She now has her own science consulting firm, Arinna, LLC, were she continues to research the CDEW model and its implications.

PLASMONIC WAVEGUIDES AND OTHER ELECTROMAGNETIC TRANSPORT GEOMETRIES: SELECTED RESEARCH GROUPS

- *Harry A. Atwater, Thomas J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena*—This group has explored using nanoparticle chains as plasmonic waveguides. Nanoparticles' plasmon resonances couple to each other via the optical near field, allowing highly localized waveguides that can support sharp bends quite well. Recently the group's efforts have shifted toward metal-insulator-metal structures for plasmon waveguiding. The group has experimentally achieved this structure and characterized its confinement and propagation characteristics, as discussed above (see "Albert Polman" in the section on "Techniques for Imaging and Spectroscopy of Plasmonic Structures").
- *Pierre Berini, School of Information Technology and Engineering, University of Ottawa, Canada*—Dr. Berini's group was the first to observe long-range propagation in metallic stripe waveguides. The group found plasmons that propagated out to several millimeters distance. The group has extensively studied this system both experimentally and theoretically. Recently, Dr. Berini defined figures of merit for plasmonic waveguides that seek to quantify the trade-off between losses that shorten propagation lengths and confinement of the plasmon mode to subwavelength sizes (Berini and Lu, 2006).
- *Sergey I. Bozhevolnyi, Aalborg University, Aalborg, Denmark*—Dr. Bozhevolnyi's group was the first to realize the channel plasmon polariton experimentally. After demonstrating that such structures can be fabricated and working to optimize the parameters of the groove-shaped waveguides, the group demonstrated that such structures could support both long distance propagation and high spatial confinement of the electromagnetic modes. This group has demonstrated the ability to make basic optical components from these waveguides such as Mach-Zendher interferometers,

Y-splitters, and resonant ring structures. Dr. Bozhevolnyi continues to study these waveguiding structures.

- *Mark Brongersma, Geballe Laboratory for Advanced Materials, Stanford University, California*—Mark Brongersma's group has extensively studied surface plasmon polariton propagation on metallic stripe waveguides. The group has demonstrated both experimentally and theoretically that while these types of waveguides are capable of long-range propagation of SPPs, they are not able to confine such guided modes in a subwavelength geometry. The group has shown the difference between true, guided modes and leaky modes of the metallic stripe, and has predicted and experimentally verified that at certain stripe widths, bound modes are cut off and no longer propagate.
- *Alain Dereux and Jean-Claude Weeber, Laboratoire de Physique de l'Université de Bourgogne, Optique Submicronique, Dijon, France*—This group has studied many of the plasmonic waveguiding structures discussed above. It has focused mostly on characterizing metallic stripe waveguides. Recently the group has studied right-angle bends in such waveguides and has managed to successfully route plasmon modes around such bends using tilted Bragg mirrors (Weeber et al., 2005). This group has also studied how metallic nanoparticle chains affect the modes propagating in microscale dielectric waveguides (Quidant et al., 2004).
- *Dimitri K. Gramotnev, Queensland University of Technology, Brisbane, Australia;D.F.P. Pile, The University of Tokushima, Japan*—Gramotnev and Pile have focused most of their attention on channel plasmon waveguides, although they have studied many waveguiding systems. Using finite difference time domain simulations, they conducted many of the first numerical simulation studies of this geometry and originally predicted many of its remarkable waveguiding properties, such as nearly zero loss at sharp bends and high spatial confinement of plasmon modes.
- *Joachim R. Krenn, Alfred Leitner, and Franz R. Aussennegg, Institut fur Experimentalphysik, Universitat Graz, Austria*—This group has studied many geometries for plasmonic waveguiding, including nanoparticle chains and metallic stripes and nanowires. The group was involved in many of the earliest studies in these areas and, recently has studied a new system for plasmon waveguiding that uses dielectric stripes on a gold substrate (Steinberger et al., 2006). The group found this type of waveguide to be able to propagate guided plasmons efficiently, as well as to direct plasmon modes around gradual bends in an analogous process to total internal reflection and through junctions without significant losses.
- *Stefan Maier, University of Bath, Bath, United Kingdom*—Stefan Maier, originally a graduate student in Harry Atwater's group, conducted many of the early studies using nanoparticle chains as plasmon waveguides. He has since studied other types of waveguides, and recently, terahertz waveguiding structures. He has suggested using structures with periodic grooves in order to support highly confined SPP-like modes that are ideal for waveguiding in the terahertz spectra range.

PLASMON-BASED ACTIVE DEVICES: SELECTED RESEARCH GROUPS

- *Franz R. Aussenegg, Joachim R. Krenn, and Alfred Leitner, Karl-Franzens-University, Graz, Austria*—In addition to its pioneering work in passive plasmonic devices, this group has developed a monolithically integrated organic diode surface plasmon polariton sensor allowing the direct detection of surface plasmons at the end of a plasmon waveguide.
- *Sergey I. Bozhevolnyi, University of Aalborg, Aalborg, Denmark*—This group is focused on developing plasmonic devices for subwavelength control of optical signals. Toward this end, the group

has developed an in-line plasmon modulator based on long-range surface plasmon polaritons propagating on metallic strips embedded in a polymer (Nikolajsen et al., 2004) and a number of passive devices based on strip, particle, and channel waveguides. The group has also studied near-field imaging techniques, including modeling in order to understand the collection properties of uncoated dielectric fiber probes for probing the near field of plasmonic waveguides.

- *Yang-Fang Chen, National Taiwan University, Taipei, Taiwan, Republic of China*—This group's primary focus is on semiconductor structures such as quantum dots and quantum wells, porous silicon devices, and the magnetic properties of semiconductor systems. Dr. Chen's group has demonstrated the use of electrically actuated liquid crystals to modulate the spectral position of the plasmon resonance of gold nanorods (Chu et al., 2006).
- *Raffaele Colombelli, Université Paris Sud, Orsay, France*—This group's focus is on the mid-infrared (IR), specifically the development of quantum cascade lasers and mid-IR surface plasmonics. One aspect of the research is that of combining the two fields to develop devices to directly create surface plasmons using electrical excitation by coupling surface plasmons to quantum well gain media. The group is simultaneously developing this technique for both the construction of active plasmonic devices in the mid-IR and the improvement of the far-field efficiency of quantum cascade lasers.
- *Christopher C. Davis and Igor I. Smolyaninov, University of Maryland, College Park*—The Maryland optics group works in a wide array of fields, from biodetection using tapered optical fibers to active plasmonic devices. In the latter area, the group has demonstrated all-optical devices for controlling the transmission of light using surface plasmons on metal hole arrays (Smolyaninov et al., 2002).
- *Lukas Eng, Dresden University of Technology, Dresden, Germany*—This group works on a range of fields involving nanophotonics, including imaging using NSOM techniques to study ferroelectric thin films, microfabricated NSOM tip fabrication, and active plasmonic devices. Of particular note with respect to active plasmonics is the demonstration of stimulated emission of surface plasmon amplification using an optically pumped dye gain medium on the surface of a silver film (Seidel et al., 2005).
- *Jochen Feldmann and Thomas Klar, Ludwig-Maximilians-Universität Munich, Germany*—This group has demonstrated that the plasmon resonance of spherical gold nanoparticles can be shifted significantly by applying an electrical bias across a cell containing nanoparticles and liquid crystals. In the presence of liquid crystals, the spherical particles become effectively spheroidal optically owing to the controllable anisotropy of the dielectric environment created by the liquid crystals.
- *Jaime Gómez Rivas, FOM [Fundamental Research on Matter] Institute for Atomic and Molecular Physics (AMOLF), Philips Research Laboratories, Eindhoven, The Netherlands*—Dr. Rivas's group is actively involved in developing methods to actively control low-frequency (THz) plasmons propagating on semiconductor surfaces. In particular, the group recently demonstrated a technique for all-optical switching of terahertz plasmons (Gomez-Rivas et al., 2006). Other research in the group focuses on the optical properties of semiconductor nanowires.
- *Mikhail A. Noginov, Norfolk State University, Norfolk, Virginia*—This group has worked in the areas of random lasers and composite laser media with nonlinear media. It has looked at enhancement of surface plasmons by coupling to a dye for gain in conjunction with Vladimir M. Shalaev's group at Purdue University in West Lafayette, Indiana (Noginov et al., 2006) (see "Vladimir M. Shalaev" in the section above on "Surface-Enhanced Spectroscopy").

- *Nikolay Zheludev, University of Southampton, Southampton, United Kingdom*—In the field of plasmonics, this group has studied active plasmonic switching, nonlinear plasmonic devices, the generation of plasmons by direct excitation with electron beams, and the effects of chirality and broken symmetry in nanophotonic devices. For active plasmonics, this group has developed a technique for the modulation of plasmons by using optical or thermal modification of the phase of gallium, which radically alters the dielectric function changing the propagation of plasmons on the gallium film (Krasavin et al., 2005). In thin films, this effect can be quite fast, on the order of several picoseconds, enabling the high-speed modulation of surface plasmons either optically or potentially electrically. This mechanism is distinctly different from other approaches, as it relies on modifying the waveguide itself rather than the surrounding medium.

PLASMON-ENHANCED DEVICES: SELECTED RESEARCH GROUPS

- *Harry A. Atwater, California Institute of Technology, Pasadena*—This group has wide-ranging interest in developing materials for nanophotonics including active devices based on semiconductor nanocrystals and plasmonics. In conjunction with Albert Polman's group in the Netherlands, this group has characterized the use of plasmons to enhance the radiative decay rate of silicon nanocrystals (Biteen et al., 2006) (see "Albert Polman" in the section above on "Techniques for Imaging and Spectroscopy of Plasmonic Surfaces").
- *Toshio Baba, Fundamental and Environmental Research Laboratories, NEC Corporation, Ibaraki, Japan; Kikuo Makita, System Devices Research Laboratories, NEC Corporation, Shiga, Japan*—These groups have demonstrated the use of plasmonics to concentrate light into high-speed silicon nanophotodiodes (Ishi et al., 2005). NEC Corporation is also investigating the use of plasmons on concentric ring structures to focus light emitted from diode lasers into nanoscale volumes for optical storage applications.
- *Federico Capasso, Harvard University, Cambridge, Massachusetts*—In the region of plasmon-enhanced devices, this group has been active in developing both plasmon-enhanced quantum cascade lasers (QCLs), and plasmonic nano-antennas. The group has developed in a nano-antenna deposited on the surface of a laser diode for generating intense subwavelength points of light (Cubukcu et al., 2006). It has also demonstrated a single-mode surface-emitting terahertz QCL using double-metal waveguide structures with periodic gratings in the top surface and efficient absorbers to terminate the waveguide to achieve low-divergence vertical output (Tredicucci et al., 2000).
- *Shanhui Fan and Mark L. Brongersma, Stanford University, Stanford, California*—The Fan group studies computational modeling of photonic crystals, micro- and nanophotonic structures, and solid-state devices. The Brongersma group experimentally studies plasmonic devices, plasmon-enhanced lithography, semiconductor nanophotonics, and microresonators. In collaboration, these groups have recently demonstrated theoretically the possibility of using surface plasmons to enhance mid-IR detectors using surface plasmons on metallic nanowire gratings.
- *Martin Green, University of New South Wales, Sydney, Australia*—Dr. Green is the director of the ARC Photovoltaics Centre of Excellence and therefore focuses on energy applications—specifically, on ways of developing highly efficient photovoltaic devices as well as on work to improve the emission efficiency of light-emission structures. To this end, he has made important contributions by demonstrating the enhancement both in emission and absorption by a thin-film silicon diode device operating near the band edge (Pillai et al., 2006).

- *David A.B. Miller, Stanford University, Stanford, California*—The Miller group is focused on developing optoelectronic materials, devices, and systems. This includes work on topics such as ultrafast all-optical switches, optical interconnects, and high-speed optical A/D converters. Of particular note is the development of C-apertures in metallic films to create plasmon-enhanced photodiodes at telecommunications wavelengths (Tang et al., 2006).
- *Axel Scherer, California Institute of Technology, Pasadena*—This group has investigated the coupling of surface plasmons to blue light emitters in order to enhance the output for use in high-efficiency illumination devices. Enhanced emission from indium gallium nitride quantum well structures and organic polymers using surface plasmons by radiative rate enhancement has been demonstrated in collaboration with Yukio Narukawa and Takashi Mukai of the Nichia Corporation in Tokushima, Japan (Okamoto et al., 2004). A similar mechanism has been demonstrated to work for enhancing the output of conjugate polymers which show potential for use as organic light-emitting diodes (Neal et al., 2006). While thus far this research has been with optically excited systems, the radiative rate enhancements should persist irrespective of pumping method and therefore would be applicable in electrically stimulated devices as well.
- *Alessandro Tredicucci and Fabio Beltram, NEST [National Enterprise for nanoScience and nanoTechnology] CNR-INFM [Consiglio Nazionale delle Recherche Insitutuo Nazionale per la Fisica della Materia] and Scuola Normale Superiore, Pisa, Italy*—This group is focused on the development of novel quantum cascade lasers using intersubband transitions in semiconductor superlattices to generate light in the terahertz spectral region. Toward this end, the group has employed surface plasmons to enhance the overall performance of QCLs and to control the mode structure to produce vertical-emitting single-mode lasers (Tredicucci et al., 2000).

PLASMONICS IN BIOTECHNOLOGY AND BIOMEDICINE: SELECTED RESEARCH GROUPS

- *Naomi J. Halas, Jennifer West, and Rebekah Drezek, Rice University, Houston, Texas*—The Halas group has exploited the plasmonic heating of gold nanoshells in a variety of biomedical applications. Nanoshells have been used to enhance the absorption of near infrared in laser tissue welding (Gobin et al., 2005) and in photothermal ablation of cancer cells (O'Neal et al., 2004; Hirsch et al., 2003). This work has led to a comprehensive scheme for the optical imaging of cancer cells using gold nanoshells and photothermal ablation (Loo et al., 2005). A nanoshell-based rapid immunoassay in whole blood has been developed that exploits the LSPR shift as nanoshells aggregate in the presence of a specific antibody (Hirsch et al., 2003).
- *Katrin Kneipp, Wellman Center for Photomedicine, Harvard University, Medical School, Massachusetts Institute of Technology*—Dr. Kneipp is one of the pioneers of single-molecule detection using SERS (Kneipp et al., 1999). Currently she is investigating cellular uptake of gold colloid and utilizing the gold colloid aggregates formed in the cells to probe the chemical composition of biological structures, inside cells at the single-molecule level and at the nanoscale (Kneipp et al., 2006b).
- *Catherine J. Murphy, University of South Carolina, Columbia*—Dr. Murphy's group has developed a novel optical technique that combines the light elastically scattered from gold nanorods with digital image analysis to track local deformations that occur in vitro between cells, in real time, under dark-field optical microscopy (Stone et al., 2007).
- *Richard P. Van Duyne, Northwestern University, Evanston, Illinois*—Dr. Van Duyne's group has successfully implemented localized surface plasmon resonance sensing to detect physiologically

relevant concentrations of a marker for Alzheimer's disease. The group has developed an optical biosensor using LSPR to monitor the interaction between the antigen, amyloid derived diffusible ligands (ADDLs), and specific anti-ADDL antibodies. Using the sandwich assay format, this nanosensor provides quantitative binding information for both antigen and second antibody detection that permits the determination of ADDL concentration and offers the unique analysis of the aggregation mechanisms of this Alzheimer's disease pathogen at physiologically relevant monomer concentrations (Haes et al., 2005). The group has also developed various surfaced-enhanced Raman spectroscopy (SERS) substrates for in vivo glucose sensing. In vivo glucose sensors are based on SERS using alkanethiol modified silver films on nanosphere substrates. The alkanethiol self-assembled monolayers (SAMs) allow the glucose to partition into the SAMs layer and can be detected using SERS (Lyandres et al., 2005; Stuart et al., 2006b). The Van Duyne group has also developed optical biosensors for the detection of anthrax biomarkers (Zhang et al., 2005; Zhang et al., 2006) and chemical warfare agent half-mustard agent (Stuart et al., 2006a).
- *Nikolay I. Zheludev, Southampton University, Southampton, United Kingdom*—Dr. Zheludev developed a new, noncontact high-capacity optical tagging technique based on the use of nanostructured barcodes. The tags are generated from a number of superimposed diffraction gratings. The capacity for up to 68,000 distinguishable tags has been demonstrated. These tags can be used to tag deoxyribonucleic acid (DNA) sequences for high-throughput genome sequencing (Galitonov et al., 2006).

PHONON POLARITONS: SELECTED RESEARCH GROUPS

- *Rainer Hillenbrand, Nano-Photonics Group, Max-Planck-Institute für Biochemie* and *Center for Nanoscience, Martinsried, Germany*—This group first observed near-field coupling of phonon polaritons to a subwavelength tip and characterized this phenomenon. The group suggested that this technique could allow for applications in the mid-infrared that are analgous to plasmon-based phenomena in the visible and near-infrared ranges. The group is currently exploring the use of the s-SNOM technique to study applications of surface phonon polaritons.
- *Gennady Shvets, Department of Physics and Institute for Fusion Studies, University of Texas at Austin*—This group has proposed the use of surface phonon polaritons on a silicon carbide surface to realize desktop particle accelerator technology. The group has designed a device based on this concept and has performed initial tests using numerical modeling techniques as well as experimental tests to observe and characterize the phonon modes propagating along the SiC surface. This group continues to develop this technology and progress toward a final product.

EMERGING TOPICS IN PLASMONICS: SELECTED RESEARCH GROUPS

- *Dan Grischkowsky, School of Electrical and Computer Engineering, Oklahoma State University, Stillwater*—This group has studied the surface propagation of plasmons on the cylindrical metallic wire system. It has also recently studied the propagation of surface plasmon polaritons on planar metal sheets (Jeon and Grischkowsky, 2006). Like the Sommerfeld waves of the cylindrical wire case, the group has identified these waves on a planar sheet as the classical Zenneck waves.
- *Stefan Maier, University of Bath, United Kingdom*—Dr. Maier originally focused his attention on plasmonic waveguides in the visible and near-infrared spectral range, but he has recently become involved with terahertz plasmonic waveguides as well. He has suggested that metal structures

with periodic grooves should support SPP-like waves on their surface that are highly confined to subwavelength sizes, and that these waves behave much like SPPs do in the visible range.

- *Daniel M. Mittleman, Electrical and Computer Engineering Department., Rice University, Houston, Texas*—Daniel Mittleman's group first proposed the use of cylindrical metal wires for terahertz plasmonic waveguides. He showed that such waveguides supported long distance propagation with very limited dispersion. This group has continued to extend its understanding of this system. For example, it has studied better methods of coupling terahertz radiation with the wire (Deibel et al., 2006).
- *Paul C.M. Plancken, Delft University of Technology, Delft, The Netherlands*—Dr. Plancken's group has also studied the cylindrical wire system as a terahertz waveguide and has extended this study to include metallic wires coated in a dielectric. The group has found that the relatively low dispersion of the metallic wire dramatically increases in this situation. It has suggested using this property for many types of sensing applications.

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