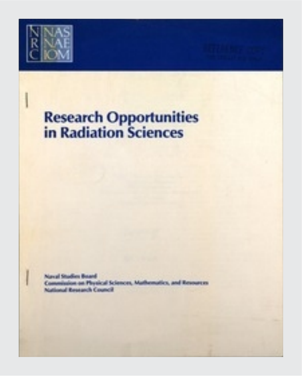

Research Opportunities in Radiation Sciences

DETAILS

28 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-31961-4 | DOI 10.17226/19136

AUTHORS

Panel on Research Opportunities in Radiation Sciences; Naval Studies Board; Commission on Physical Sciences, Mathematics, and Resources; National Research Council

NRC:NSB:033

RESEARCH OPPORTUNITIES IN RADIATION SCIENCES

Panel on Research Opportunities
in Radiation Sciences
Naval Studies Board
Commission on Physical Sciences, Mathematics,
and Resources
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1988

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This work related to Department of Navy Contract N00014-87-C-0018 issued by the Office of Naval Research under contract authority NR 201-124. However, the content does not necessarily reflect the position or the policy of the Department of the Navy or the government, and no official endorsement should be inferred.

Copies available from:
Naval Studies Board
National Research Council
2101 Constitution Avenue
Washington, D.C. 20418

Printed in the United States of America

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Commission on Physical Sciences, Mathematics, and Resources

PREFACE

The Panel on Research Opportunities in Radiation Sciences was established by the Naval Studies Board in response to a request from the Office of Naval Research (ONR). That request called for the appointment of a series of panels representing the scientific and engineering disciplines included in the ONR's basic research program. The task of each panel was to identify promising research opportunities for ONR consideration in planning the future direction of the program and maintaining the strong science base required to respond to future naval needs.

The panel held a two-day meeting on August 4-5, 1988, at the National Academy of Sciences in Washington, D.C. The first day of the meeting was devoted largely to briefings by Dr. Ronald N. Kostoff, on the organization and activities of the ONR, and by Dr. David J. Nagel, on radiation sciences research at the Naval Research Laboratory (NRL). The briefings were followed by discussion of radiation sciences research with these staff members. On the second day, the panel developed its recommendations and prepared the initial draft of its report.

The panel is grateful to Drs. Kostoff and Nagel for their briefings, which were especially helpful in focusing its deliberations on important aspects of the program and on naval needs. The panel compliments the NRL on the high quality of its radiation sciences research and hopes that this report will assist in further strengthening and enlarging the scope of the program.

EXECUTIVE SUMMARY

This panel is one of a series requested by the Office of Naval Research to recommend research opportunities in the fields of science and engineering that are included in its program. Radiation sciences in the context of the Navy program include the production of beams of charged or neutral particles and electromagnetic radiation, the detection of radiation, the interaction of radiation with materials, and the use of radiation to study the structure and properties of materials and to modify these properties.

The panel believes that the program should center on using radiation in the study and modification of the properties of matter; developing stronger sources of radiation; and achieving higher spatial, temporal, and energy resolution in the formation, transport, and detection of radiation beams to optimize their utility. In support of these goals, the panel identifies opportunities for research on coherent x-ray sources, x-ray imaging and optics, radiation-induced defects and materials processing, ultrafast materials responses, high-intensity ionizing transients in complex semiconductor devices, and radiation sensing and detection.

COHERENT X-RAY SOURCES

In regard to coherent sources, including synchrotron radiation (especially undulators in high-energy storage rings), the free electron laser pushed to ultraviolet and x-ray regions of the spectrum, and the plasma-based soft x-ray laser, the panel recommends research to make possible the further development of such sources. Such development will have a major impact on all areas of science and technology, with consequent application to a variety of Navy research and development efforts. Such an emphasis is consistent with the scope and capabilities of the present Radiation Sciences Program, and the likelihood of success and of broad impact on Navy objectives is great.

IMAGING AND OPTICS

New radiation sources of high intensity and reliability have removed a major barrier in the effort to achieve high-resolution images of matter. Needs for high spatial or energy resolution generally involve a tradeoff, depending on the nature of the experiment or application, but recent technological breakthroughs indicate that both kinds of resolution can be improved substantially. Coherent x-ray sources in the short-wavelength region of the electromagnetic spectrum can revolutionize the way in which materials are studied. Imaging involves both imaging a source on a target and imaging the target on a detector. The latter can be a formidable task, but so, too, can imaging a source on a target, the problems of which constitute a set of goals for an optics program.

Continued efforts to create high-intensity photon and charged-particle beams call for research in materials sciences using x-ray and other optical elements for focusing and reflecting radiation. The sophistication of new optical elements will require the development of dynamic control methods for maintaining optical properties within narrow limits. New combinations of optical materials will also be necessary to achieve minimum sensitivity to environmental/ambient conditions. Effective use of new optical elements will, in turn, require optimization of diffraction and scattering techniques to improve the signal-to-noise ratio and selectivity.

RADIATION-INDUCED DEFECTS AND MATERIALS PROCESSING

Further exploitation of new radiation-induced surface processing techniques should result in additional advances in, for example, microelectronics, optical windows and mirrors, detectors, and protective coatings, all of which are crucial to achieving improved stability and performance in high-radiation environments to which satellites, missiles, aircraft, and ships may be exposed. In regard to basic science, the panel recommends emphasis on studies of the time dependence of radiation-matter interactions and theoretical modeling of these interactions.

Although the basis of radiation-induced defect production in metals and semiconductors has been well established, there are two aspects of radiation-induced defect science that the panel regards as ripe for advance: defects produced during fabrication of microelectronic and optoelectronic devices, and production of defects in new materials and structures (e.g., composites and artificially structured materials). In addition, advances in the resolution and sensitivity of new techniques such as electron microscopy and synchrotron light scattering make possible the study of interfaces on a microscopic scale. The panel believes that a core program in radiation-induced interface effects, closely coupled to ongoing programs dealing with charge trapping and radiation sensitivity of microelectronic devices, would benefit materials programs in advanced electronics, optoelectronics, and composites, and help to ensure their radiation integrity.

To achieve deposition techniques with better spatial control and selectivity and to produce unique materials properties and structures, the panel recommends that research on the modification of materials focus on ion and laser techniques, with particular attention to the exploration and exploitation of radiation-assisted deposition and dry etching, especially in relation to compound semiconductor materials. Research on new, artificially structured materials and low-temperature processing should result in broader fabrication options for microelectronic and optoelectronic devices.

ULTRAFAST MATERIALS RESPONSES

In regard to ultrafast materials responses, research opportunities arise in situations in which pulsed radiation interacts with solids and leads to particle emission and to target changes. A particular need identified by the panel is research on the creation of high temperatures for a short time in ceramic materials, for which there is virtually no knowledge of the time constants for both equilibrium and critical phase changes, and in metals, for which knowledge is as yet incomplete. It should also be noted in regard to pulsed photon and electron sources, that photon sources are lacking for wavelengths below ~10 nanometers, and that most electron sources are not monoenergetic. Pulsed ion sources are essentially unknown for the nanosecond to picosecond time scale.

HIGH-INTENSITY IONIZING TRANSIENTS IN COMPLEX SEMICONDUCTOR DEVICES

In regard to high-intensity ionizing transients in complex semiconductor devices, the panel suggests that microbeam and fast transient measurement techniques should be extended to provide spatial resolutions in the range of 0.2 to 2.0 microns, and temporal resolutions in the range of 10 ps to 10 ns, thereby making possible the study of specific regions and structures in advanced microelectronic circuits and also the quantification of the influence of circuit variables (e.g., voltages) and environments. An essential aspect of this and other suggested research in the field of high-intensity ionizing transients is the combination of experimental and computer simulations of transient effects on microelectronic structures. The successful conclusion of these efforts to coordinate analytical and experimental understanding can lead to design solutions that will minimize the deleterious effects of transient radiation on the performance and reliability of microelectronic devices and systems.

RADIATION SENSING AND DETECTION

The detection of a wide spectrum of radiations is an integral part of the Navy program. Increased levels of sophistication anticipated in both electronic and directed energy warfare require advances in radiation sensing capabilities. Sensors can be improved in many respects such as spectral response, response time, efficiency, dynamic range, and multielement architectures supported by advanced signal processing. Two recent materials advances--heteroepitaxial semiconductor layers and high T_c superconductors--can be exploited for detector development. In addition to the development of individual detector elements, there is opportunity for multiple-element arrays for parallel multiparameter data acquisition. The panel identifies a number of recent developments that could advance research related to improved detection, sensing of ultrafast processes such as thermochemical reactions, and sensors that maximize the amount and rate of data collection and spectral and spatial selectivity, in conjunction with real-time computer-based analysis. In regard to threat detection, threat response, and hardening, arrays with spectral, spatial, and real-time analysis offer more definitive threat identification and at the same time display effectively increased reliability and hardness through built-in redundancy and computer compensation for element-to-element variation.

INTRODUCTION

"Radiation sciences" is not a standard term, so a few words of explanation will present this panel's understanding of it and will indicate the range of considerations leading to the identification of research opportunities. The radiation sciences include:

- The production and guiding of beams of charged or neutral particles and of electromagnetic radiation.
- The study of the structure and properties of matter, using radiation, and of radiation interacting with materials.
- Analyses of the modification of the properties of materials systems by radiation, for example, changes in conductivity, strength, and resistance to corrosion.
- The detection of radiation.
- The study of deleterious effects of radiation on materials and electronic devices and systems.

The Navy basic research program clearly has a strong interest in such efforts.

In regard to the Navy mission, radiation sciences are important for the production of radiation beams that may serve as weapons and as detectors for defensive purposes, and an understanding of radiation effects is essential for developing electronic circuits that will survive intense radiation environments.

The Radiation Sciences Program, cutting as it does across disciplinary lines, overlaps many other programs. Opportunities discussed here might also have been suggested in the reports of the panels on materials, energy conversion, astronomy, electronics, physics, and chemistry. This is *not* to say that this program should be subsumed by those in one or another of these fields. The features of this program--studying sources, optics, detection, and the interaction of radiation with matter--constitute an independent field of research in their own right and are sufficiently closely related that they deserve separate consideration and promotion.

The program should center on the use of radiation in the study and modification of the properties of matter, making stronger sources of radiation, and achieving high spatial, temporal, and energy resolution of these beams in order to optimize their utility.

The panel has identified the following opportunities for research programs by assessing both the potential impact of these developments on science and the Navy and on their chances for success:

- Coherent x-ray sources.
- Imaging and optics.
- Radiation-induced defects and materials processing.
- Ultrafast materials responses.
- High-intensity ionizing transients in complex semiconductor devices.
- Radiation sensing and detection.

Research in these fields, in which new breakthroughs are likely and need and potential benefit are great, should be strongly emphasized by the Radiation Sciences Program.

COHERENT X-RAY SOURCES

The development of a coherent source of short-wavelength (< 1 nm) x-rays would have a significant impact on almost all areas of science. Coherent radiation can be made to interfere with itself so that small changes in energy are easily detectable, and it can be used to produce holograms, as discussed in the following section on imaging. It is not possible to measure changes in x-ray energy of much less than 0.1 eV with incoherent sources, but an improvement of several orders of magnitude is possible with coherence. This capability would make possible the characterization of excitations in matter with an extraordinary degree of precision and would benefit many Navy research and development efforts.

The most familiar source of coherent radiation--the laser--has not produced radiation with wavelengths shorter than 10 nm, but the laser is not the only way to produce coherent radiation. A series of recent developments, coupled with the extraordinary possibilities of coherent x rays, leads this panel to recommend further work on a coherent source and to identify this as an important research opportunity in radiation sciences.

Synchrotron radiation sources, especially undulators in high-energy storage rings, can produce appreciable coherent power. In the near term, longer-wavelength devices, which have been installed at the National Synchrotron Light Source at Brookhaven National Laboratory, can be used as test facilities. Short-wavelength undulators are being put into place at high-energy physics storage rings at Stanford and Cornell Universities, and in the mid to late 1990s, with completion of the Advanced Light Source at Lawrence Berkeley Laboratory and the Advanced Photon Source at Argonne National Laboratory, there will be a complement of such sources in service. As coherent sources, however, undulators are not as good as lasers, and it is highly desirable to pursue several other approaches that can produce a high degree of coherence. These approaches are already part of Navy research programs.

The free electron laser (FEL) should be pushed to shorter wavelengths, first into the ultraviolet and subsequently to the x-ray regime. Problems encountered here include provision of highly reflecting mirrors in the short-wavelength region so that efficient cavities can be made. In addition, low-emittance electron beams in linear accelerators will require high-brightness electron guns, and new cathode materials may be required. Another approach based on the FEL is the "superradiant" amplifier, which does not require a cavity. The plasma-based soft x-ray laser, developed at the Lawrence Livermore National Laboratory, the Naval Research Laboratory (NRL), and the Princeton Plasma Physics Laboratory, is another promising device that warrants further attention. Finally, frequency doubling and tripling of longer-wavelength lasers should be pursued.

A program of this type is now very much in the interest of the Office of Naval Research (ONR). The development needed lies within the scope of present programs in radiation sciences, and success would have a broad impact.

IMAGING AND OPTICS

The advent of new radiation sources of high intensity and reliability has removed a major barrier in the quest for high-resolution images of matter. The needs for high spatial or energy resolution generally involve a tradeoff depending on the nature of an experiment or application, but recent technological developments have made it evident that both kinds of resolution can be improved substantially. The impetus provided by coherent x-ray sources alone would be sufficient reason to mount a serious effort to improve x-ray optics and imaging in order to take full advantage of such new sources.

GOALS FOR AN IMAGING PROGRAM

High spatial and energy resolution are the classic objectives of any experiment with or application of radiation in a twenty-first century setting. Electronic warfare depends for its success on accurate targeting or imaging of radiation. Microcircuitry is processed with precisely targeted radiation, and the materials that are studied and subsequently developed into electronic, optical, or optoelectronic devices must be probed with well-characterized, finely controlled beams of photons, charged particles, or neutrons.

Coherent x-ray sources in the short-wavelength (ultraviolet and x-ray) region of the electromagnetic spectrum can revolutionize the way in which materials are studied. X-ray holograms would enable us to examine atomic arrangements and changes in those arrangements that we know are the underlying causes of physical property changes. Moreover, we can imagine the three-dimensional imaging of random, extrinsic defect distributions, which govern solid-state reactions in all materials. These sources will require imaging techniques that are at the limits of current capabilities with respect to data collection rates and data processing, especially if real-time experiments are required.

The availability of large computing power at reasonable cost in money and space has introduced a new challenge in imaging. It is possible to think of arrays of detectors that sense and are read out independently. The central processor recreates a three-dimensional image of the desired information from the target. Thus, in addition to intrinsically three-dimensional holograms from coherent sources, it is now feasible to create three-dimensional images by probing matter with charged particles or x-ray photons. The field of microtomography is just beginning to emerge from this development and will become an important tool for probing matter when coupled to such radiation techniques as x-ray fluorescence, proton-induced x-ray emission, and Rutherford backscattering spectrometry.

A final point to be noted is that rapid imaging may in some cases involve more than one radiation source. For example, one source may be used to excite a solid and another to probe the solid simultaneously. In the most general definition of imaging, it becomes necessary to think of imaging a source on a target and imaging the target on a detector. Although the latter may in itself be a formidable task, the former has many potential problems that need urgent consideration and constitute a set of goals for an optics program.

GOALS FOR AN OPTICS PROGRAM

Intense coherent x-ray sources will impose the need for development of new materials and of concepts for combining them in ways that handle high power densities. Conventional alkali halides will not suffice, and innovative approaches such as the use of self-annealing optics and liquid-phase lenses will have to be explored. This problem presents a challenge to the materials sciences that is of immediate importance because of the current pressure toward invention of coherent sources. But, even now, the continued efforts to create high-intensity photon and charged-particle beams mandate an effort in materials sciences related to x-ray and other optical elements for focusing and reflecting radiation.

The sophistication of new optical elements will require the development of dynamic control methods for maintaining their optical properties within narrow limits. Serious thought should be given to this aspect of x-ray optics, for example, as well as to an overall objective of discovering new combinations of optical materials that have minimum sensitivity to environmental/ambient conditions.

Effective utilization of new optical elements will require optimization of diffraction and scattering techniques to improve the signal-to-noise ratio and selectivity. For example, applications of sophisticated x-ray scattering methods, such as anomalous dispersion, Rietveld analysis, polarization analysis, and fluorescence detection, can be most successfully exploited when coupled with detailed calculations of the physical and geometrical optics of imaging.

Finally, the high fields associated with intense sources create situations in which nonlinear phenomena become important. Indeed, nonlinear optics is already a major subject of investigation, and it will be necessary to examine the results from this fast-moving field and their implications for the science of x-ray optics.

RADIATION-INDUCED DEFECTS AND MATERIALS PROCESSING

Control of defects and the ability to fabricate materials with high dimensional precision are increasingly becoming limiting factors in many advanced systems for military applications, with microelectronics, optical systems, and composite structures being prime examples. The radiation sciences offer new approaches for improving performance in many of these applications. Radiation research is especially important for two reasons: first, new materials systems and structures must exhibit stable and reliable performance against increasingly high radiation threats; second, radiation increasingly offers new opportunities in materials processing. Low-temperature deposition, precise anisotropic etching, and the synthesis of new surface layers with improved properties have all become possible as a result of radiation-based processing techniques. The ability to fabricate high-performance materials offers the possibility of additional applications in satellites, missiles, aircraft, and ships, where improvements in weight, efficiency, and resistance to environmental degradation have been advanced by these new surface-processing techniques. Further advances in microelectronics, optical windows and mirrors, detectors, protective coatings, and other areas are likely if these radiation-induced processing techniques are more fully exploited.

FUNDAMENTAL INTERACTIONS OF RADIATION WITH MATTER

Success in utilizing radiation to modify materials properties, to develop materials to sense radiation, or to probe the properties of materials requires an understanding of fundamental interactions of radiation and matter. Consequently, all programs in radiation science need a strong fundamental research base. The diversity of radiation and of candidate materials spans an enormous range of potential interactions. Some of these, which offer particularly promising research opportunities, are included in the following sections. Two noteworthy areas in fundamental interactions are studies of the time dependence of radiation-matter interactions and theoretical modeling of these interactions.

The selection of materials to be used as radiation sensors or for radiation protection often requires a detailed understanding of the time response of these materials. The processes by which radiations are absorbed by matter, and the secondary interactions that distribute this energy, usually occur in very short times. Energetic heavy ions deliver their energy by displacement collisions with the atoms in solids and by ionizing collisions with electrons. It typically takes 10^{-13} to 10^{-9} s to dissipate the energy imparted to atoms in a collision cascade. Investigations involving the interactions of photons from short-pulsed (10^{-9} to 10^{-12} s) lasers with semiconductors have shown that the photons are absorbed into the electronic system and dissipate their energy by electron-photon interactions on time scales of 10^{-13} to 10^{-12} s. Surface melting and evaporation can occur within 10^{-12} to 10^{-11} s of pulsed laser processing, but bulk melting and plasma surface effects initiated by high-power pulses can persist much longer. The advent of picosecond and femtosecond lasers now makes it possible to pulse-and-probe solids within the time duration of some of these fundamental interactions. These techniques offer unique opportunities to understand fundamental radiation-matter interactions much more thoroughly than ever before. The insights offered by increased understanding will lead to improved sensors and detectors for radiation, as well as to ways to improve materials selection and applications in radiation environments. (See also N. Bloembergen, Pulsed Laser Interactions with Condensed Matter. In H. Kurz, G. L. Olson, and J. M. Poate [Eds.], *Beam-Solid Interactions and Phase Transformations*, MRS, Pittsburgh, Pa., 1986.)

Similarly, high-speed, large-capacity computers and new computational approaches offer opportunities for modeling and predicting many of these interactions. Computer simulation of ion-induced collision cascades can lead to an understanding of the time-dependent partitioning of energy in solids and of the role of exotic effects, such as thermal-spike phenomena, in initiating metastable phase formation. Particle ejection from surfaces, energy deposition, shock-wave profiles, and a host of other phenomena induced by intense radiation onto surfaces are similarly amenable to computational modeling and analysis.

PROCESS-INDUCED DEFECTS

Although the basis of radiation-induced defect production in metals and semiconductors has been well established, there are two new aspects of radiation-induced defect science that are ripe for advance. These are defects produced during fabrication of microelectronic and optoelectronic devices, and the production of defects in new materials and structures, such as in composites and artificially structured materials. On a fundamental level, the generation of defects on the surface of materials and the way that such defects can be incorporated into the bulk during the growth of materials are not well understood. For example, what are the fundamental radiation-induced defect structures on surfaces, how can they be used in ion- or laser-stimulated molecular beam epitaxy (MBE) or metal oxide chemical vapor deposition for low-temperature epitaxy, and how can defects be eliminated in plasma-enhanced etching and deposition? Not only are there fundamental questions to be answered, but there are also important consequences in terms of the ability to fabricate high-quality layered structures with better dimensional control and improved electronic, optical, adhesive, tribological, and corrosion-resistant properties. In addition, new electronic and optical device structures provide significantly improved means to study these processes with very high sensitivity, for example, by their charge trapping and nonradiative recombination effects. In particular, it may be appropriate to investigate the influence of x rays and other radiation sources for high-resolution lithography schemes on metal oxide semiconductor microelectronic devices. Here, the ability to process radiation-hardened circuits must be attained in advanced processing schemes if the circuits are to be useful to the Navy. In the area of new materials, radiation damage in such materials as ceramics and polymers is not understood at a fundamental level and needs further study. These materials will be used increasingly in Navy systems, yet their radiation sensitivity and their structural, optical, and electronic responses to radiation are still poorly understood. The objectives here could be to identify and understand subclasses of these materials with increased resistance to radiation and to improve long-time stability in various operational applications.

RADIATION-INDUCED INTERFACE EFFECTS

An aspect of radiation-induced defect production that deserves special attention is the influence of radiation at interfaces. New materials systems in which interfaces play a key role include next-generation microelectronic circuits with decreased feature size, superlattice quantum-well devices for advanced optoelectronics, and composites with nanoscale dimensions for improved structural properties. In all these materials systems, the interface-to-volume ratio has increased dramatically and has reached the point at which the interface properties can dominate materials performance. Yet we understand relatively little about how or where radiation can influence the properties of interfaces. Furthermore, rapid recent advances in the resolution and sensitivity of new techniques (such as electron microscopy and synchrotron light scattering) have made it possible to study interfaces on a microscopic scale. Thus, there is now considerable opportunity for fundamental scientific progress in this field. Particular attention should be given to the generation and stability of defects at heterogeneous interfaces, for example, metal-semiconductor, semiconductor-insulator, and ceramic-metal interfaces. Also, the ability to form interfaces with great precision, for example, by ultrahigh vacuum deposition or MBE growth, now offers the possibility of unprecedented control in examining the influence of such factors as impurities and strain. Such factors might play an important role in radiation-induced changes in interface properties. In the case of electronic materials, studies of interfaces will benefit from a close coupling to ongoing programs in which charge trapping and radiation sensitivity of microelectronic devices are under investigation. A core program in this area of radiation-induced interface effects would support materials programs in advanced electronics, optoelectronics, and composites and ensure the radiation integrity of such programs.

RADIATION-ASSISTED DEPOSITION

Thin films, coatings, and artificially structured materials are becoming increasingly important in applications ranging from microelectronic device fabrication to surface modification of parts for resistance to friction, wear, or corrosion. This need has spawned a variety of deposition techniques such as physical vapor deposition, MBE, and chemical vapor deposition (CVD). Nevertheless, there is an increasing need for deposition techniques with better spatial control and selectivity, and with the capability for low-temperature processing. As understanding of radiation effects has increased and as new and better radiation sources have become available, it is clear that selective radiation effects would enhance many deposition methods and produce unique materials properties and structures in the process.

Ion bombardment during deposition produces coatings with increased density and adhesion. Ion irradiation during MBE deposition and doping of semiconductor structures has produced epitaxial semiconductors with dopant incorporation that can exceed the solid solubility limits and produce much more abrupt dopant depth profiles. Direct ion-beam deposition has produced epitaxial films of silicon (Si), germanium (Ge), and gallium arsenide (GaAs) at temperatures much lower than those in conventional methods. The unique benefits of ion bombardment derive from defect production during film growth and the increased kinetic energies imparted. Ion-induced defects produced during film growth can alter nucleation phenomena, surface atom mobilities, and dopant incorporation probabilities. Collision cascades distribute kinetic energy to the surrounding atoms and significantly alter film growth without thermal heating. This field is still in the early stages of understanding and application and, as such, offers significant research opportunities.

The variety of laser powers and energies offers even greater opportunities for selective photon-assisted deposition techniques. Both pyrolytic and photolytic decomposition of molecules during CVD have made it possible to selectively deposit species from the gas phase onto surfaces and to "write" patterns onto surfaces with focused and scanned laser beams. There is enormous potential in this field because of the ability to select photon beams from the x-ray to the infrared portion of the spectrum, to select or "design" gaseous molecules tailored to the bond-breaking selectivity of the laser energy, and to control deposition rates and patterns through optical patterning.

By exploiting photolytic reactions, it is often possible to initiate depositions at much lower substrate temperatures than those associated with thermally activated CVD. This aspect is particularly important for compound-semiconductor materials and their heterostructure combinations. By simple on-off time sequencing of gases and/or lasers, it is possible to fabricate superlattice structures and to control layer thicknesses with monolayer accuracy. The technologies necessary to exploit radiation-assisted deposition (and dry etching) are now available and a plethora of research opportunities exist, given the necessary ingenuity and program focus.

TAILORING SURFACE PROPERTIES

Surface modification and radiation-assisted deposition make it feasible to select a material for its bulk properties and tailor its surface properties for the intended use. New artificially structured materials and low-temperature processing should broaden the fabrication options for microelectronic and optoelectronic devices. Selective bond breaking, spatial specificity, and ability to control film deposition with monolayer precision are opportunities that should lead to exciting discoveries in the future. New materials structures and properties have resulted from early applications of radiation-assisted processing techniques, and further advances are anticipated.

Opportunities for applications of radiation-stimulated, materials-processing techniques are numerous. Extension of practical surface modifications, such as improved friction, wear, and corrosion of metal parts used in naval systems, should continue.

An emerging area of application that could be important is processing of optical materials. Ion implantation, doping, and selective annealing have produced optical wave guides and mixers in lithium niobate ($LiNbO_3$) that are superior to diffusion methods, and ion damage has been used widely to produce waveguide structures. Advances in the fabrication of optical thin-film materials with improved nonlinear properties or of new layered structures with active two-state characteristics may be particularly beneficial for Navy applications.

ULTRAFAST MATERIALS RESPONSES

This research opportunity pertains to situations in which pulsed radiation (photons, electrons, ions, and "dust particles") interacts with solids and leads both to particle emission and to target changes. This happens variously at ambient or ultrahigh temperatures, although always on a very short nanosecond to picosecond time scale. It relates, to give one example, to programs in which pulsed radiation is directed at flying objects such as rockets.

We suppose that high-energy, short-time pulses of radiation interact with solids, as, for example, photon pulses having lengths of 10 ns to 0.1 ps. The materials responses and important questions are discussed in the following sections on particle emission, formation of new phases, and creation of high temperatures.

PARTICLE EMISSION

What are the mechanisms of particle emission? With metals, only thermal processes have ever been identified, and they are well understood, except for a general ignorance of the role of the critical temperature (highest temperature attainable with a condensed phase!). With ceramics such as alumina (Al_2O_3) or silicon carbide (SiC) and polymers such as PMMA (polymethylmethacrylate), nonlinear electronic processes have long been known to dominate, but an understanding of the mechanisms is still lacking. Thus, there is no predictive capability.

High-temperature thermodynamics presents many questions. Metals or metal-like systems such as carbon yield vapor at ultrahigh temperatures, which makes possible the study of both vapor thermodynamics and cluster formation.

How important are near-surface gas-phase collisions? Interactions of pulsed beams with surfaces lead to a unique situation in which the emitted particles collide with each other before going into free flight. A small extent of collision is called "Knudsen-layer formation"; a large extent is an "unsteady, adiabatic expansion." Understanding such collisions is essential for unraveling mechanisms of particle emission but also has a practical application to, for example, steering a satellite. Knudsen-layer formation causes 20 to 30 percent of the emitted particles to return to the emitting surface, which can cause severe contamination.

FORMATION OF NEW PHASES

What are the mechanisms? There is an abundant literature in which pulsed radiation causes phase changes (e.g., amorphization) or mixing. In particular cases, the new phase has interesting chemical, electronic, or mechanical properties. It is significant, however, that the underlying mechanisms are still ill defined, so that there is still inadequate predictive capability.

CREATION OF HIGH TEMPERATURES

Access to critical temperatures and to "phase-change time constants" requires study. All condensed phases have critical temperatures such as those for melting or vaporization. In a simplistic sense, temperatures for these processes are the absolute upper limits to superheating a solid and existence of a liquid, respectively. From another point of view, all phase changes, both equilibrium and critical, have time constants. It is significant here that knowledge for metals is only sporadic and that knowledge of such temperatures for ceramics is effectively nonexistent. Similarly, information on phase-change time constants is effectively lacking for all systems.

Pulsed photon and electron sources require no comment except to note that photon sources are lacking for wavelengths below ~10 nm, and most electron sources are not monoenergetic. Pulsed ion sources, on the other hand, are essentially unknown for the time scale (nanosecond to picosecond) of interest.

NEEDED EXPERIMENTS

In regard to particle emission, a variety of well-known techniques can be used, including time of flight, internal states of diatomics, doppler shift, and angular distributions ($f(\theta)$). For example, if $f(\theta) \propto \cos\theta$, one infers that the emitted particles do not interact, whereas if $f(\theta) \propto \cos^4\theta$, one infers Knudsen-layer formation.

For examination of the target surface, the choices involve real-time features such as reflectivity, deformation, recoil, and pulsed diffraction, as well as delayed-time features such as Rutherford backscattering spectrometry and various electron microscopies.

In comparing linear and nonlinear regimes, it has been assumed that continuous wave ion beams interact with matter either linearly, as for incident Ar^+, or nonlinearly, as for incident I_2^+. However, the use of pulsed radiation makes possible more explicit comparisons, especially with ceramics, by the simple artifice of using energy densities lying below or above the nonlinear threshold.

HIGH-INTENSITY IONIZING TRANSIENTS IN COMPLEX SEMICONDUCTOR DEVICES

Microelectronic systems capable of reliable operation in space and weapons radiation environments are essential for communication, data processing, and other critical functions in Navy systems. The operational capability of these systems can be compromised by high-intensity ionizing transient radiation, such as that produced by cosmic ion interactions or the transient ionizing radiation bursts associated with nuclear detonations. The miniaturization of microelectronic devices brings with it a corresponding decrease in the amount of charge used to represent and process information, and therefore an increased sensitivity to radiation-induced memory and logic upset. Recent advances in the experimental capability to measure charge transport due to fast transients and in computational resources enabling the study of complex structures and processes within microelectronic devices offer the opportunity to explore and understand responses on the temporal and spatial scales typical of transient interactions with complex semiconductor devices. Such an understanding will lead to significant advances in hardening microelectronic systems against worst-case radiation environments.

SITUATIONS AND DEVICES OF INTEREST

Effort must be concentrated on understanding the transient effects due to high densities of electron-hole pairs produced in active device regions by sources of ionizing radiation. Of particular interest are excess carrier concentrations, which greatly exceed the equilibrium mobile carrier concentrations typical of integrated circuit devices. Radiation sources of interest include those that produce both local and global transient perturbations. Local effects may result from single-ion tracks, either from cosmic rays or ion bombardment experiments, and can also be simulated using focused laser sources. Global effects can be simulated using electron or proton beams, or flash x-ray sources. Devices of interest are representative of those used or planned for use in spaceborne systems. Simple silicon or compound-semiconductor structures should be investigated to provide basic understanding and to establish the validity of experimental and computational techniques. The goal of the research effort should be to identify and understand the interaction of transient ionizing radiation with the very complex structures typical of very large-scale integration and ultralarge-scale integration microelectronic devices.

EXPERIMENTAL CHARACTERIZATIONS

Present capabilities for the investigation of ionizing radiation interactions with devices include microbeam and fast transient measurement techniques. In order to achieve the resolution necessary for unambiguous characterization of the transient processes of interest here, these techniques must be extended to provide spatial resolutions in the range of 0.2 to 2.0 microns and temporal resolutions in the range of 10 ps to 10 ns. With such resolution, specific regions within typical advanced microelectronic circuits can be studied, and the influence of circuit variables, especially applied voltages, and circuit environments, such as vulnerable nodes with active resupply, can be quantified.

COMPUTER CHARACTERIZATIONS

Recent advances in computer codes, including the development of fast, efficient algorithms for coupled solutions of Poisson's and continuity equations ("physical-level" codes), and extensions of circuit-level codes to accommodate the complexity of present and future integrated circuit elements and parasitics, provide the opportunity for innovative analyses of transient radiation effects on microelectronics. For simulations of the localized effects of ion-device interactions, physical-level codes in two spatial dimensions confront the fundamental symmetry conditions imposed by the cylindrical nature of the electron-hole-pair distribution produced along the ion track; two-dimensional codes in Cartesian coordinates are inappropriate for these analyses. Three-dimensional codes in either cylindrical or Cartesian coordinates are preferable, but two-dimensional cylindrical codes, with the z-axis along the ion track, are adequate in many cases of interest. Physical-level codes are computationally intensive and therefore are suitable only for the simulation of device regions proximal to ion tracks. In order to incorporate the very important effects of other circuit elements, which may determine the voltages of collecting nodes, circuit-level codes should be integrated with physical-level codes. Ideally, this integration enables circuit regions not directly affected by an ion event to be represented at the device model level. No such simulation capability exists at present. Such an approach focuses the available computational intensity directly on the region where the most complex phenomena occur, and therefore holds the greatest promise for accurate simulation of the complex interactions associated with localized transient phenomena. Considerable effort will be required for accurate definition and incorporation of the effects of materials boundaries and interfaces on the transport processes to be modeled. In addition, present analytical forms for materials parameters, including carrier mobility, diffusion coefficients, and carrier lifetimes, must be revised to include their dependence on electron-hole-pair concentration, high electric fields, and other effects of high carrier density.

For global transient effects, physical-level codes and most circuit-level codes are inappropriate, due to the complexity of the total integrated circuit structures. Recently developed specialized codes for dose-rate response simulations should be adopted for global analyses.

COORDINATION OF ANALYSES AND EXPERIMENTS

An essential aspect of the suggested investigations is the combination of experimental and computer simulations of transient effects on microelectronics structures. Designs for the two types of simulation analyses must be chosen to allow direct comparison of the results of the studies. Iterative approaches to establish congruence between modeled and measured transient responses can be anticipated. The successful conclusion of these efforts to coordinate analytical and experimental understanding of these effects can lead to design solutions that will minimize the deleterious effects of transient radiation on the performance and reliability of microelectronic devices and systems.

RADIATION SENSING AND DETECTION

The detection of a wide spectrum of radiations is an integral part of the Navy program. Increased levels of sophistication anticipated in both electronic and directed energy warfare require advances in radiation sensing capabilities. These same capabilities are also applicable to the broad range of basic and applied physical and chemical processes involving the emission or absorption of radiation. Particular areas that would benefit from improved sensing modalities are diagnostics of plasma processing, fluorescence probing of chemical reactions, and analysis of surface chemistry in ion-solid interactions.

Sensors can be improved in many ways such as spectral response, response time, efficiency, dynamic range, and multielement architectures supported by advanced signal processing. Two recent materials advances--heteroepitaxial semiconductor layers and high T_c superconductors--may be exploited for detector development. Overlying the development of individual detector elements is an opportunity for multiple-element arrays for parallel multiparameter data acquisition.

ENERGY SPECTRUM AND INTENSITY

There are two new developments in materials that offer opportunities for pronounced improvements in detection performance: high T_c superconductors and artificially structured layers and quantum wells in semiconductors. Each of these addresses an area of radiation sensing of interest in both general science and naval needs: layers and quantum wells for infrared detectors and superconductors for broad-band response.

Artificially Structured Semiconductors

The use of MBE and metal-organic MBE allows both the formation of quaternary III-V compounds, such as $Ga_xIn_{1-x}As_ySb_{1-y}$, and multiple quantum well (MQW) superlattices. In quaternary structures where one wants to build lattice-matched structures, there are some composition (or bandgap) regions that are not accessible due to miscibility gaps. These regions of composition (which lie in bandgap regions between 2 to 4 microns for GaInAsSb) might be obtained by use of MBE techniques that allow growth at modest substrate temperatures. One can form metastable (nonequilibrium) epitaxial layers of selected composition and hence selected energy gaps.

In MQWs, there are two concepts that lead to infrared detectors. One is in the lattice-matched AlGaAs/GaAs system, where the superlattice spacing is such that the lowest level, E_1, in the GaAs narrow well is about 0.1 eV from the adjacent AlGaAs. With an applied field, photon-excited carriers from the E_1 level are transported across the structure, giving a response in the 8- to 12-micron region (developments at AT&T Bell Labs). The other concept is to use nonlattice match heterojunction structures--strained layer superlattices (SLS). The InAsSb/InSb system is a type II heterostructure, which means that the transitions can take place between the conduction bands in adjacent wells. In the InAsSb/InSb system, SLS structures have shown good infrared detector response in the 8- to 12-micron region (developments at Sandia National Laboratories).

High T_C Superconductors

The NRL currently has a program dealing with the application of superconductors in particular tunnel junctions as radiation detectors. The advent of high T_C superconductors offers broad research opportunities to characterize these materials as optical detectors. In these applications, epitaxial layers (with smooth rather than matte surfaces) should be investigated.

FAST-RESPONSE DETECTORS

In the development of instrumentation for radiation detection, ultrafast response times are the key to applications involving sensing of fast processes such as thermochemical reactions. For detectors with ultrafast response times, development opportunities exist for GaAs devices in the ballistic transport regime and high T_C superconductors in the tunnel-junction regime.

Conventional, reverse-bias p-n junction detectors have a time response given by the dielectric relaxation time, τ. For 1 ohm-cm Si ($\tau = \rho k$), the response time is about 100 ns. The current NRL program evaluates response times for the study of single-event upsets. To shorten the response time, detectors should be operated in the high-field, velocity-saturated regime or in a tunnel-junction configuration.

Ballistic Transport in Layered Structures

The application of Si p-i-n structures as fast detectors is well documented. With the advent of Si MBE, one can now consider what improvements could be gained by use of thin, high-resistivity (or intrinsic) regions where carrier velocity (for both electrons and holes) approaches 10^7 cm/s. Response times of less than 1 ps should be attainable. Gallium-arsenide structures should also be evaluated to determine if ambipolar transport will be the ultimate limitation.

Superconductor Junctions

The NRL program has already shown the feasibility of obtaining fast response with tunnel junctions on conventional superconductors. There is a research opportunity to explore applications at higher operating temperatures.

SENSOR ARRAYS AND REAL-TIME ACQUISITION AND ANALYSIS

For rapid detection of and response to a radiation threat as well as for process diagnostics and control, sensors that maximize the amount and rate of data collection and spectral and spatial selectivity, and that are supported by real-time computer-based analysis, are needed. Significant capability enhancement will result from research focused on extension of current and forthcoming single-element sensors to ganged arrays and/or to (quasi-) continuous position-sensitive regimes. (Sensor arrays were also noted as an important field for technology development in the report of the Solid State Sciences Committee of the National Research Council, *Photonics: Maintaining Competitiveness in the Information Era*, National Academy Press, Washington, D.C., 1988.)

Depending on the type of radiation and spectral region of interest, these arrays may be formed from low or high T_C superconductors as bolometers or tunnel junctions and from artificially structured (tunable) heteroepitaxial semiconducting detector elements. These probably will require fabrication technologies such as microlithography. Therefore, research on these sensors in the form of two-dimensional, thin-film-layered devices, with associated interconnects and patterning methods, is suggested. Extension to three-dimensional array structures (possibly monolithic) should be studied to exploit penetration as an energy-selective mechanism.

Although arrays per se will yield higher data collection rates and can offer (in conjunction with appropriate input optics) position definition with high spatial resolution, a complete diagnostic capability will require spectral selectivity. We therefore recommend that concomitant research be pursued on spectral filtering algorithms. At long wavelengths, from the infrared to the x-ray region, compatible thin-film overlayers for photons may be developed. In the x-ray through gamma-ray region, use of array elements with differing intrinsic wavelength-dependent sensitivities can be employed and "synthesized" at the analysis stage in the computer.

Immediate applications as diagnostic tools for advanced real-time array sensors can be envisioned in, for example, plasma diagnostics for optimization and control in microelectronic component fabrication, in the study of materials surface response to radiation insults, and in the use of plasmas as photon and charged-particle sources for other beam applications. Laser-induced fluorescence spectroscopy also awaits this type of diagnostic capability.

As particle sensors, arrays with energy-selective elements will be valuable diagnostic tools for ion-scattering studies and the study of radiation-induced particle emission from surfaces.

The array and real-time analysis concepts should also be extended to high-intensity detection needs by exploiting new materials (such as high T_C superconductors with relatively higher specific heat than their low T_C analogs) for use as microcalorimeters.

From the standpoint of threat detection, threat response, and hardening, arrays with spectral, spatial, and real-time analysis offer more definitive threat identification while displaying effectively increased reliability and hardness through built-in redundancy and computer compensation for element-to-element variation.