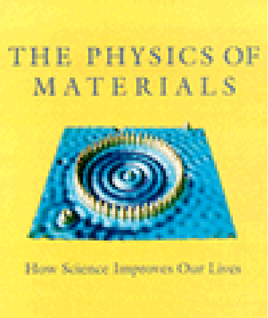

The Physics of Materials: How Science Improves Our Lives

Committee on Condensed-Matter and Materials Physics, Solid State Sciences Committee,Board on Physics and Astronomy,National Research Council

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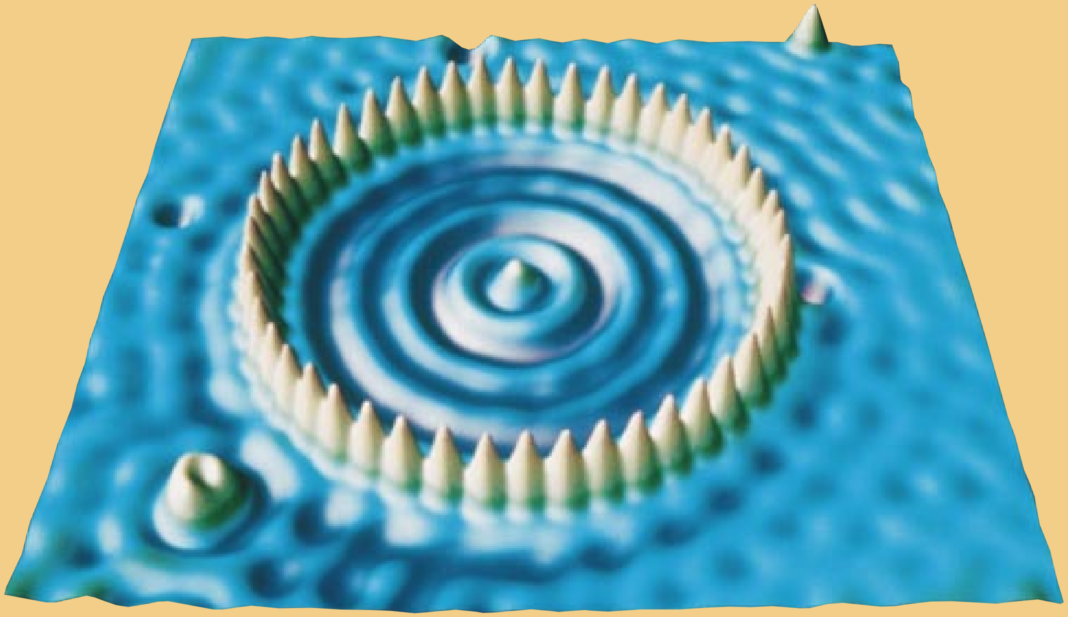
THE PHYSICS OF MATERIALS



How Science Improves Our Lives

The Physics of Materials

How Science Improves Our Lives

❖

Committee on Condensed-Matter and Materials Physics

Solid State Sciences Committee
Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1997

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Front Cover: A scanning tunneling microscope image that shows the wave nature of electrons confined in a "quantum corral" of 48 individually positioned atoms. See page 2. (Courtesy of IBM Research.)

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Preface

In the spring of 1996, the National Research Council's Board on Physics and Astronomy established the Committee on Condensed-Matter and Materials Physics to prepare a scholarly assessment of the field as part of a new decadal physics survey. The work of the committee began with a two-day workshop in Washington in June 1996. This workshop brought together some 60 leading practitioners in the field as well as key policymakers from government, industry, and universities. Since then, the committee has met several times to formulate its report, which is to be completed by June 1998.

This short report, *The Physics of Materials: How Science Improves Our Lives,* is an early output of the ongoing study, intended for a broad audience. Based largely on the presentations at the June 1996 workshop, it highlights some of the fundamental science at the forefront of research in the field and demonstrates, through illustrative examples, the field's impact on our everyday lives.

Even though the highlights presented are primarily physics based, the committee would like to emphasize the importance of links with other fields of science and engineering and the inherent interdisciplinary nature and unity of materials research. Important examples of these multidisciplinary links include fullerenes (physics and chemistry), macromolecules (physics and biology), structural alloys (physics and materials engineering), and silicon technology (physics and electrical engineering).

The committee would like to express its gratitude for the interactions it has had with numerous scientists and policymakers. As it continues its deliberations over the next several months, the committee looks forward to receiving further input from the community. ❖

1 ❖ Introduction

Condensed-matter and materials physics has played a key role in many of the scientific and technological revolutions that have changed our lives so dramatically in the last fifty years. The years ahead will see equally dramatic advances, making this an era of great scientific excitement for research in this field. It is also a time of stress on the institutions that support the field. The goal of this report is to give the reader a sense of what condensed-matter and materials physics is about—of the excitement that scientists feel, the importance of their work, and the challenges they face.

Within our lifetimes, improvements in our understanding of materials have transformed the computer from an exotic tool, used only by scientists, to an essential component of almost every aspect of our lives. Computers enable us to keep track of extraordinarily complex data, from managing financial transactions to forecasting weather. They control automobile production lines and guide aircraft around the world.

Discovery: 1940s

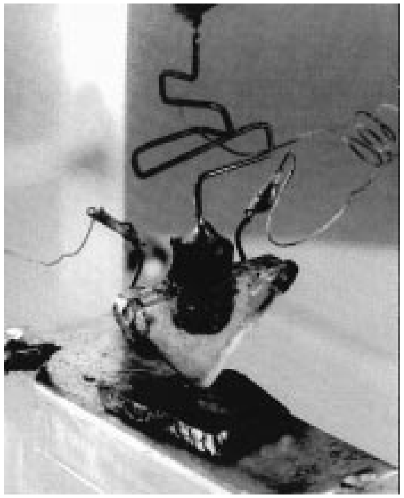


FIGURE 1.1 The world's first transistor, developed in 1947. It was a point-contact device roughly one centimeter across. (Courtesy of Lucent Technologies Bell Laboratories.)

Application: 1990s

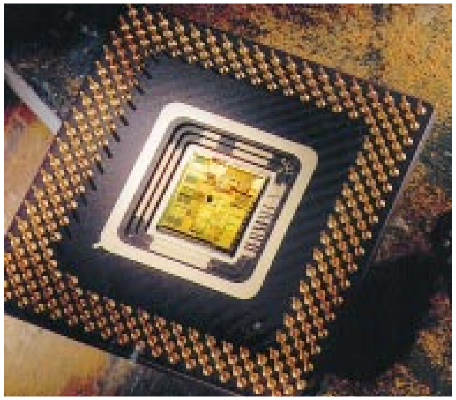


FIGURE 1.2 A Pentium® chip with 3.3 million transistors. Such microprocessors are at the heart of today's personal computers. (Courtesy of Intel Corporation.)

During the same period, telecommunication has evolved from rudimentary telephone conversations to instantaneous simultaneous worldwide transmission of voice, video images, and data. The cellular phone is even unleashing us from telephone wires.

Almost every American can now enjoy, while relaxing in the living room or driving the car or even while jogging, music of a quality that in previous generations was available only to concertgoers.

Just a few generations ago, a trip across the United States was a great adventure. Today, jets whisk us safely across the continent or the oceans in only a few hours.

Making these extraordinary accomplishments possible are a wide variety of polymeric, ceramic, and metallic materials, as well as the transistor, the magnetic disk, the laser, the light-emitting diode, and a host of other solid-state devices. The development of these materials and devices depended on our ability to predict and control the physical properties of matter. That ability is the realm of condensed-matter and materials physics (CMMP), the subject of this report.

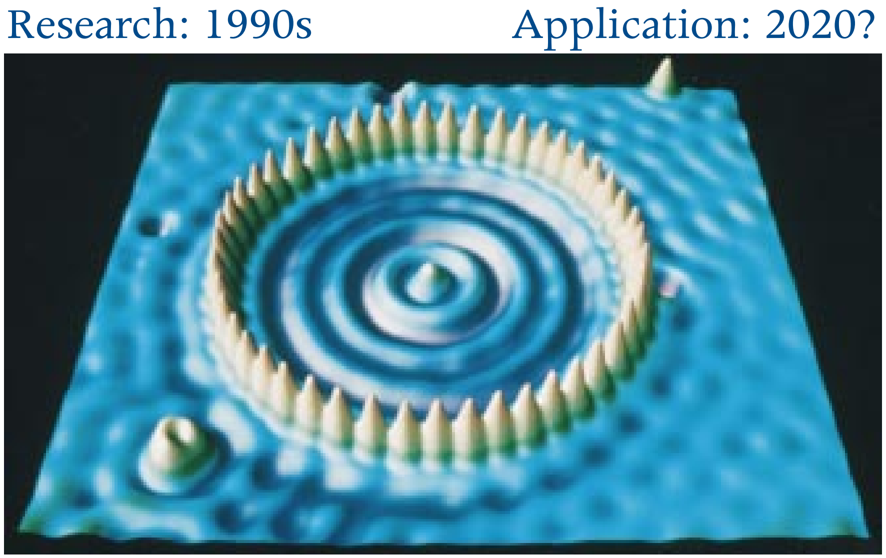


FIGURE 1.3 A scanning tunneling microscope (STM) image that shows the wave nature of electrons confined within a "quantum corral," 14 nanometers in diameter, made up of 48 individually positioned iron atoms on a copper surface. Devices formed by precise positioning of atoms or molecules may one day play an important role in ultrahigh-performance computer chips. (Courtesy of IBM Research.)

Fifty years ago, the major intellectual challenge facing researchers in CMMP was to understand the physical properties of nearly perfect single crystals of elements, simple compounds, and alloys. Today our challenge is to extend that understanding to much more complex forms of matter—high-temperature superconductors, multicomponent magnetic materials, disordered crystals, polymers, glasses—and to more complex phenomena like the fracture of solids and the continuous hardening of glass as it cools. Ever in view in today's CMMP is another scientific revolution, the dramatic change under way in the biological sciences. Great opportunities lie ahead as condensed-matter and materials physicists increasingly work together with biological scientists.

Part 2 of this report illustrates the vital impact of CMMP on our daily lives. It consists of a brief story—a few simple events that happen every day—accompanied by descriptions that highlight a sampling of the scientific and technological advances in CMMP that make those everyday events possible.

Part 3 explores the nature of the CMMP endeavor itself. CMMP is a diverse, evolving, interdisciplinary field linked strongly to other science and engineering disciplines, which benefit from and contribute to its successes. Indeed, CMMP is distinguished by its extraordinary interdependence with other science and engineering fields. Its practitioners include those who make and refine new materials, those who seek to understand such materials at a fundamental level through experiments and theoretical analysis, and those who apply the materials and understanding to make new devices. This work is done in universities, in industry, and in government laboratories.

Part 3 speaks, as well, of a field in transition. New linkages with disciplines such as polymer chemistry and the biological sciences are growing in importance.

The evolution of CMMP is taking place within an evolving national and international context, as described in Part 4. The great industrial laboratories, so prominent over the last half century, have shifted the scale, scope, and emphasis of their R&D investments in CMMP to adjust to changes in the global marketplace. Industry is looking more and more to universities and government laboratories to perform basic research that will lead to the next generation of technology. Yet these very academic and government institutions are themselves facing considerable stresses that limit their abilities to respond to new demands.

Part 4 also discusses issues arising from the growing dependence of CMMP on shared large and medium-size experimental facilities. Increasingly sophisticated equipment has become necessary for scientific innovation, from electron-beam instruments to giant x-ray synchrotrons. These facilities are essential for continued advances in the invention, understanding, and control of increasingly complex materials. They are required for a broad range of scientific and technological endeavors, not only in CMMP but also in many other fields of science and in industry. But funding large facilities strains the resources of the agencies that have traditionally provided research support to universities and government laboratories, even as those institutions are being asked to play a broader role.

CMMP promises to be a dynamic field of research for many years to come. If the challenges currently facing the field can be met, there are enormous opportunities for scientific and technological advances that will improve our lives. ❖

2 ❖ Technology in Daily Life

Here is a brief story about life today in the United States. It is fiction, but millions of episodes like it occur every day. Each event involves familiar technologies whose present state of development—or very existence—would have seemed extraordinary just a generation ago. The capitalized phrases in the story are links to sidebars on the facing pages that provide more information about some of these technologies.

The owner of a small business is driving her car to the airport. Many structural elements of her car and the airplane that she will be boarding are products of research in **MATERIALS SYNTHESIS.** She is on the way to visit a potential customer. As a seasoned business traveler, she has with her all the tools she needs for her normal daily business. She picks up her cellular telephone and dials her son's pager. The communications revolution represented by the telephone and the pager has been greatly enhanced by advances in **COMPOUND SEMICONDUCTOR ELECTRONICS.**

MATERIALS SYNTHESIS

The materials in modern cars and airplanes that make them safer, lighter, and more fuel-efficient than their predecessors result from advances in materials synthesis and processing. Progress in the synthesis of materials takes many forms: research aimed at discovering new materials, development of methods for inexpensive and reliable production of such materials, incorporation of well-known materials in new geometries and environments, and continuous improvement of the production and processing of traditional materials. Each of these activities has firm roots in materials physics and chemistry.

"Nonequilibrium" materials processing involves raising the energy of the starting materals (for example, by heating) and guiding them into the desired final state. Such an approach has allowed the creation of new surface alloys that improve the wear characteristics of artificial joint replacements and machine tools. The opposite approach, operating very near equilibrium, is also useful. For example, it makes possible the growth of large, ultrapure, defect-free crystals of silicon for use in the semiconductor industry.

The production of traditional materials also continues to evolve. An object as simple as an aluminum can is a good example. The raw material these days consists increasingly of recycled cans. Can walls are being made thinner and thinner, an achievement made possible by close control of the alloy composition and of the processing of the aluminum sheet. Optimization of these processes increasingly requires integration of computer-based modeling over a large range of length scales: from atomic bonds, motion of dislocations, and deformation and rotation of individual crystallites, to macroscopic behavior.

Another example is the development of alloys for jet aircraft. Alloys in early jets suffered from fatigue that ultimately led to disintegration. Modern alloys are not only stronger and lighter but also more resistant to stress.

FIGURE 2.1 A futuristic high-performance aluminum car. (Courtesy of Ford Motor Company.)

COMPOUND SEMICONDUCTOR ELECTRONICS

Silicon is the material underlying most electronics, but compound semiconductors composed of more than one element, such as gallium arsenide (GaAs) and silicon germanium (SiGe), have advantages that can lead to devices with intrinsically higher speed and lower noise. The worldwide market for compound semiconductors is estimated to be $750 million in 1996, and it is growing at the rate of 40% per year. Discrete components are now widely used in the low-noise receivers of cellular telephone handsets, in addition to the specialized high-speed microwave applications for which they have long been the materials of choice.

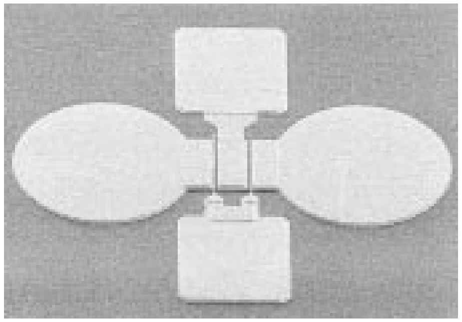
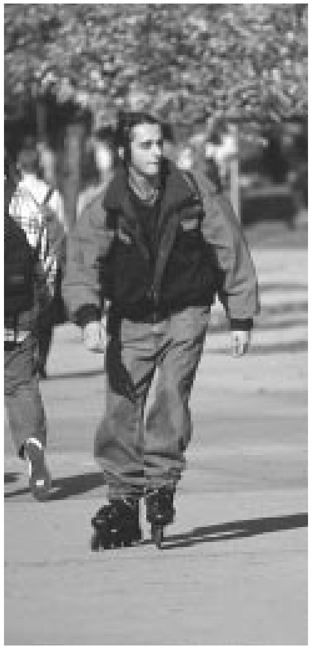


FIGURE 2.2 A high electron-mobility transistor (HEMT) such as those used in cellular telephones. The round bonding pads are 100 microns in diameter, roughly the size of a human hair. The gate of the transistor, just 0.05 microns across, appears as the two narrow lines in the center of this scanning electron micrograph. (Courtesy of Sandia National Laboratories.)

Compound semiconductors such as GaAs, SiGe, and gallium nitride (GaN) are key to the development of the next generation of wireless telephones, which will use higher frequency microwaves in order to transmit more information. GaN transistors, for example, are characterized by high breakdown voltage and great robustness. A potential high-volume application for such transistors is in transmitter power amplifiers for wireless base stations.

Pushing the limits of semiconductor materials technology is essential for increasing the speed of transistors and advancing our ability to modulate lasers for high-speed optical information transmission. Because compound semiconductors are composed of more than one element, they promise a vastly increased range of materials from which to select those with desired electronic properties. This promise can be realized with manufacturing techniques such as molecular beam epitaxy, which allows the repeated, controlled, precise growth of one material on another in single atomic layers, producing compound layered materials not seen in nature. In the future, the use of novel forms of microscopy for fabrication and testing will determine our ability to design and build such structures on the atomic scale—a scale on which the motion of electrons is governed by quantum mechanics.

The woman's son is a college student who, at that moment, is rollerblading across the campus, listening to a compact disk that he has just recorded in his music course. His rollerblades are light and strong and run smoothly because of advances in the physics and chemistry of **POLYMERS.** The compact disk, containing over an hour of high-fidelity music, is a miracle in the development of **OPTICAL STORAGE MATERIALS.** The crucial component of the student's portable CD player is a **SEMICONDUCTOR LASER.**

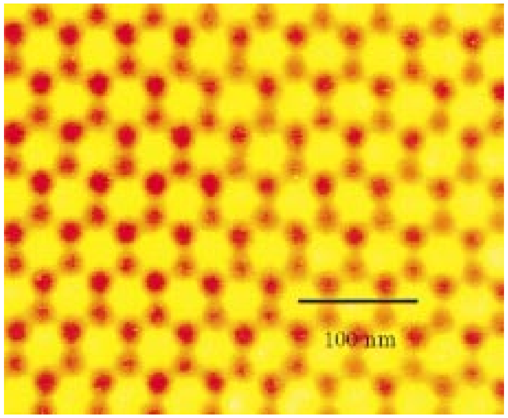


POLYMERS

Polymers permeate our lives, from the new, lightweight materials that improve the fuel efficiency of cars and airplanes to the high-strength components that make possible in-line skates and other sporting equipment. Polymers are molecules composed of many molecular units ("mers") connected together into macromolecules. A single polymer macromolecule may consist of a million or more atoms. Chemists have learned how to make an almost endless variety of highly complex yet well-defined macromolecules that incorporate a wide variety of monomers. Today, significant improvements in chemical synthesis and a growing collaborative effort between polymer chemists and materials scientists have resulted in the availability of extremely well-defined materials with novel properties. Given the sophistication of current polymer synthesis, it is now possible to systematically test hypotheses about how a polymer's properties are related to its structure and to design macromolecules to form specified microstructures and provide desired physical properties.

Some people still think of polymers as weak and flimsy compared with metals and ceramics, but in fact, truly impressive physical properties have been achieved. Some polymers are 1.5 to 2 times stronger than steel, and because their densities are typically only one-fifth that of steel, this means 10 times greater tensile performance per unit weight! The polymer Kevlar is used in bulletproof vests.

FIGURE 2.3 This false-color micrograph shows the structure of a block copolymer. The orange and yellow regions contain disordered chains of small, chemically distinct units (here denoted A and B—many different substances can be used) that are strung together in sequence AAAABBBB. . . . If the B substance (yellow) is chosen to be soft and rubbery while A (orange) is hard and glassy, adjusting the A-to-B ratio permits production of copolymer materials with a wide range of mechanical properties. Such materials are very inexpensive to process, because the array of A and B domains forms naturally. One application is in the soles of high-tech running shoes. The scale bar is 100 nm (10^{-7} m) long. (Courtesy of Cornell University.)



OPTICAL STORAGE MATERIALS

The compact disk in a CD player is the most common example of optical storage, an industry with $8 billion in annual sales. Information is stored on a CD in the form of shallow pits just a few thousand atoms across. These pits are embossed in a polymer surface coated with a thin reflective film, and the digital information, represented by the position and length of the pits, is read optically with a focused laser beam. The same format is also used to store information on a computer—an encyclopedia, for example, or a piece of software—in which case it is called a CD-ROM (compact disk read-only memory).

Many materials challenges had to be surmounted to make this technology possible. The availability of inexpensive semiconductor lasers made it possible to read the disk. Substrate materials had to be invented with the optical, mechanical, and chemical stability to ensure reliability and long life. A manufacturing process had to be developed that could produce high yields of reproducible patterns with small features.

A future challenge is making optical storage erasable so that CDs can be used in the same way that we use memory devices in computers. Two approaches are being studied; both rely on improved materials. One uses light to locally change the direction of a material's magnetization, which can then be read out by detecting its effect on the polarization of another beam of light. The other uses a laser to change the local arrangement of atoms in a material, altering its reflectivity.

FIGURE 2.4 A magneto-optical disk. Information is stored magnetically and read out optically. (Courtesy of IBM Research.)

SEMICONDUCTOR LASERS

Stimulated emission of light, the physical principle that underlies all lasers, was predicted by Albert Einstein in 1917, but it was not until 1960 that the first working laser was developed, using ruby crystals. (A microwave version known as a maser was built in 1953.) Within five years came a variety of other important developments: laser spectroscopy, the use of lasers for telecommunications, the carbon dioxide laser, and the semiconductor laser.

Semiconductor lasers made the photonics revolution possible. For example, they produce the beams of light used for transmitting information and reading compact disks in a CD player. Lasers made of the semiconductor gallium arsenide (GaAs) can emit light particularly efficiently because of GaAs's electronic structure. In addition, it is possible to combine GaAs and related compounds to tailor the optical properties and vary the color of the emitted light. Under favorable circumstances, nearly perfect single-crystal growth (epitaxy) of layered structures of different semiconductors is possible. This allows fabrication of miniature, continuously operating lasers the size of a grain of salt. Such lasers today find wide application in such diverse areas as telecommunications, laser printing, bar code recording, medicine, and video and audio disks. Nearly 50 million semiconductor lasers are now sold annually.

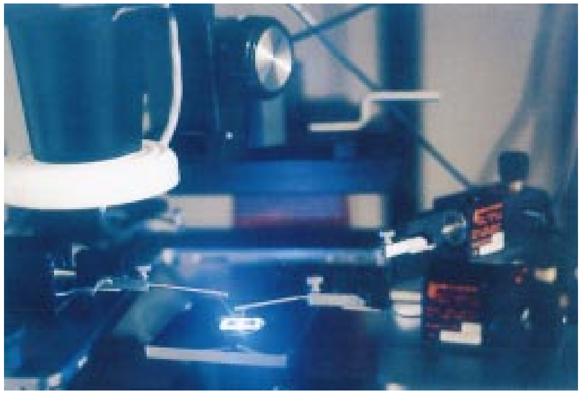


FIGURE 2.5 Blue Light emission from a gallium nitride semiconductor LED. (Courtesy of the University of California, Santa Barbara.)

More than 20 billion closely related light-emitting diodes (LEDs) based on the same materials technology are sold each year—enough for 3 to 5 for every person on Earth! With new materials and careful tailoring of the optical properties using advanced crystal growth techniques, lasers can be produced that span the spectrum from medium infrared wavelengths to visible light, including green and blue. Such advances hold new promise for military and space communications, for optical recording and display, and even for longer-lived, more efficient, and more reliable traffic lights.

Feeling the vibration of his pager, the student turns off his CD player and hurries to his dorm room to return his mother's call. The message is about his grandmother, who has been hospitalized following an accident. A CAT scan has indicated that she needs a hip replacement. Artificial bone replacements are possible because of research in **BIOMATERIALS.**

Fortunately, an additional MRI scan has ruled out any spinal injury. Magnetic resonance imaging (MRI) depends on **SUPERCONDUCTING MAGNETS.**

The attending physician believes that the surgery may be more complex than usual, so he has arranged a video consultation with a specialist in another part of the country before operating. Videoconsultation is an example of today's growing use of **OPTICAL FIBERS** for telecommunication.

The surgery has been successful, and the patient is resting comfortably.

BIOMATERIALS

Special-purpose metal alloys and polymer coatings are used to prevent the body from rejecting prosthetic bone replacements. Many other new materials are also used in medical applications where they must stick to bone, mimic color, flex like natural tissues, and keep their form under extremes of heat and cold. The secret in making an artificial material compatible with living substances is in discovering the ways of "soft condensed matter," the plastic materials that act neither as solids nor liquids, whose properties can be modulated by a combination of chemical synthesis and physical treatment.

The next time you have a front tooth filled, notice the range of colors and textures that the dentist is able to create to match that of your particular tooth. Watch how he or she mixes a sticky putty to fill the space, smooths its surface, and applies ultraviolet light to cure the putty into a lump of just the right flexibility and tenacity. What is going on? A mixture of entangled, space-filling polymers flows nicely into the clean cavity. The ultraviolet light drives chemical reactions between the polymer molecules to harden them into place. The whole operation takes only a few minutes, and the full setting takes only hours. A new material has been created right in your mouth.

It is no surprise that these new procedures are coming into use at the same time that we are learning so much about the physics of polymers—how they flow, how they mix, how they stick, how they pack. These have been subjects of intense study, driven by the physicist's desire to explain surprises not seen in traditional solids and liquids and by the chemist's joy in creating materials with novel properties.

FIGURE 2.6 An artificial hip joint made from a special-purpose surgical alloy and processed by ion implantation to reduce corrosion and wear. Approximately 200,000 hip replacements are performed in the United States each year. (Courtesy of Oak Ridge National Laboratory.)

SUPERCONDUCTING MAGNETS

Nuclear magnetic resonance, the basis of magnetic resonance imaging (MRI), was invented to study the local environment of atoms in matter. With the development of high-speed computers and advances in fundamental mathematics, it is now possible to make high-resolution images using this technique. Making such images requires placing the subject in a strong magnetic field, typically provided by a superconducting magnet.

When certain metals are cooled to low enough temperatures, they pass into a superconducting state in which electrical currents flow with no resistance. A current flowing in a closed loop of superconducting wire will flow literally forever. Many useful scientific instruments, including MRI systems, contain coils of superconducting wire to provide strong and nearly perfect magnetic fields without high power consumption and other problems associated with conventional magnets. The worldwide market for metallic superconductors used for such magnets is currently about $500 million.

Superconductivity was discovered by accident in 1911. The scientists who made this unanticipated discovery were measuring how the electrical resistance of metals changed upon cooling to the temperature of liquid helium, which they had just learned to produce. Despite intensive research, nearly 50 years passed before a theoretical understanding of the effect was developed or before any significant practical equipment was built.

The discovery in the mid-1980s of ceramics that display superconductivity at much higher temperatures than any previously known material—temperatures that can be reached using inexpensive liquid nitrogen—has motivated a wide range of research and development activities over the past decade. Though the mechanism by which high-temperature superconductivity occurs is still not fully understood, progress on practical applications has been impressive, with dramatic improvements in the properties needed for use in wires for magnets and power transmission, filters for microwave and cellular base stations, and magnetic field sensors.

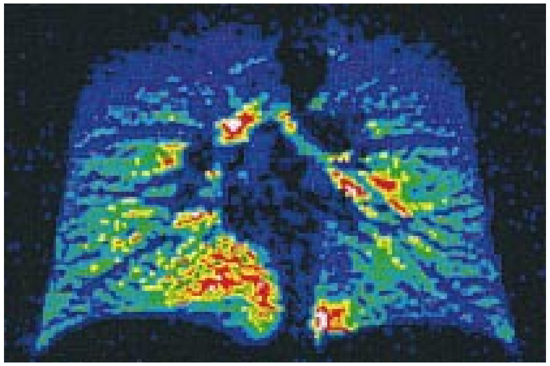


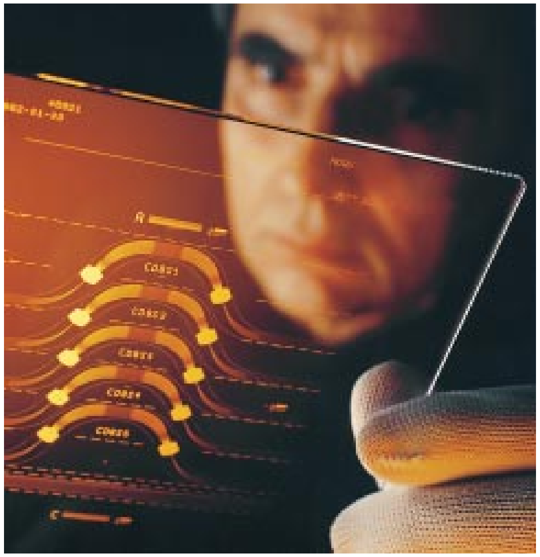
FIGURE 2.7 An MRI image of a human lung filled with minute quantities of inhaled laser-polarized helium-3 gas, using a technique invented in 1995. Such scans will allow unprecedented imaging of the gas space and the movement of gases in the lungs, for diagnosis of ventilation disorders. (Courtesy of Princeton University.)

OPTICAL FIBERS

Videoconsultation is possible because of the recently constructed infrastructure of optical fiber for communication—enough to encircle the world seven times. We are in the midst of a revolution in communications brought about by the introduction of optical networks into the marketplace in the early 1980s. With the emergence of the Internet and rapid growth in video and data transmission, demand for network capacity has increased dramatically over the last decade. The information capacity of fiber is far higher than that of copper wire, the technology fiber replaces. The total annual market for communications is now about $100 billion.

This progress has relied on advances in the physics of optical materials. The major advance that enabled the introduction of optical communication was the development in the 1960s of a fundamental understanding of how light is absorbed and scattered in the glass materials used in optical fibers. Subsequent refinements in materials research have led to a steady reduction of optical transmission losses, by a factor of nearly 10,000 since 1965.

FIGURE 2.8 A researcher holds a lithography mask used to produce integrated photonic circuits for optical communications. Circuits made with this mask will incorporate silicon dioxide waveguides for routing optical signals at eight different wavelengths. This will enable an eightfold increase in transmission capacity compared with present single-wavelength systems. (Courtesy of Lucent Technologies Bell Laboratories.)



The past decade's advances in making fiber components promise to dramatically change the architecture of future optical communications networks and our ability to communicate worldwide. We can now build optical integrated circuits for communications networks, analogous to the electronic integrated circuits used in electronics. Fiber optical amplifiers are just now being installed into optical networks, although the fundamental materials research that enabled this development began 30 years ago.

The woman reaches the airport, parks her car, goes through security to the gate, and boards her flight. Only minutes after takeoff, her airplane is cruising at 500 miles per hour at an altitude of 30,000 feet. It will fly across the continent without refueling.

To achieve such power and efficiency, the turbine blades in modern jet engines must operate at very great speeds and high temperatures. To withstand such extreme conditions, they are made of **SUPERALLOYS.**

Once airborne, the businesswoman opens her laptop computer and reviews the presentation that she plans to make on her arrival. The computer's monitor uses one of the new **LIQUID CRYSTAL DISPLAY MATERIALS.** Like almost every other technology in this story, the computer also depends on **MAGNETIC MATERIALS.**

SUPERALLOYS

Superalloys are special combinations of metals that maintain high strength during prolonged exposure to elevated temperatures. This capability is essential for applications such as the turbine blades in a jet engine. Superalloys consist mostly of nickel, with smaller amounts of aluminum, titanium, chromium, and up to ten other elements. The idea behind the design of these alloys is the creation of stable, hard, small precipitates like Ni_3Al or Ni_3Ti in the nickel matrix to obstruct the motion of dislocations, the atomic-scale cause of undesirable deformation.

The performance of alloys in turbine blades is further improved by eliminating crystal boundaries in each blade; those boundaries are the prime sites for the initiation of fracture. Through the development of a detailed understanding of the solidification process, it is now possible to cast an entire turbine blade, with the very intricate shape shown in Figure 2.9, as a single crystal.

Progress in alloy design and processing has led to a continuing increase in the allowable operating temperature of the turbine blades. The most recent improvements have resulted from the application of ceramic thermal barrier coatings to the outside of the blade. Increases in the operating temperature, together with improvements in the blade design (such as air cooling, through the passages seen in Figure 2.9, made possible by sophisticated casting techniques) have greatly increased the efficiency of jet engines and decreased their weight for a given thrust.

FIGURE 2.9 A turbine blade from a jet engine, cast as a superalloy single crystal. (Courtesy of GE Aircraft Engines.)

LIQUID CRYSTAL DISPLAY MATERIALS

Flat panel displays, such as the liquid crystal display in the laptop computer in our story, will soon be ubiquitous in both the home and the workplace, as the cost of these high-tech products is driven down by the volume market for consumers. Low-power, lighter-weight, thinner displays are already displacing the commonplace cathode-ray tube (CRT) for desktop and especially for portable applications. The portability and compactness of these displays have initiated and driven new applications and markets, such as notebook and palmtop computers, personal digital assistants, large viewing screen video cameras, miniature televisions, and individual televisions for each airline seat. Insatiable demand for lower-cost flat panel displays has created a burgeoning growth of the market from tens of millions of dollars in 1980 to about $11 billion today and to a projected $22 billion by 2001.

FIGURE 2.10 *A high-resolution, active-matrix liquid crystal flat-panel display. (Courtesy of dpiX, Incorporated.)*

Liquid crystals are materials in which the molecules show a preference for alignment with their neighboring molecules even though they can be in a liquid state having no long-range translational order. The molecules in these liquid crystalline phases are easy to orient by the application of an electric field and so can be made to act as a switch for light if they are placed between crossed polarizers and electrodes. Fundamental research on the physics and phase transitions of liquid crystals began in the 1920s, but it was not until the early 1970s that the first liquid crystal displays were developed. Flat-panel liquid crystal displays have only been manufactured in great volume in the last decade. Active-matrix liquid crystal displays used for the highest performance laptops today have high resolution and brightness as well as full color at high speed due to the separate electrical switching elements for each of about 1 million separate picture elements or pixels in the display. Extensive research being carried out today will eventually allow high-performance flexible displays on plastic substrates, with higher resolution and at lower manufacturing cost, which will in turn drive new technology, markets, and applications.

MAGNETIC MATERIALS

From the Ancient Mariner's compass to the automobile starter motor, from refrigerator magnets to the snapshots stored magnetically in the latest digital camera, magnetic materials have grown steadily in their importance and variety of applications. Materials display a host of fascinating magnetic properties, all of scientific interest and many of them useful in technological applications. The accelerating interplay of the science and applications of magnetism is well illustrated by the phenomenon of magnetoresistance, in which a sample exhibits a change in its ability to conduct electricity upon application of a magnetic field.

Beginning in the early 1980s, a decade of work at IBM perfected the use of magnetoresistance in a product with major commercial importance. This application, in the data sensor of the recording head within a hard disk drive, employs a single magnetic film about 200 atoms thick. The film changes resistance as it passes near a small magnetized region of a magnetic disk. Such recording heads are a growing segment of today's $30 billion hard disk drive industry. The time from Lord Kelvin's discovery of magnetoresistance in 1856 to its realization in this commercial product was 135 years.

Another class of magnetic materials, permanent magnets, are essential in a wide variety of electric motors and generators. Research and development leading to stronger magnets has resulted in a steady decrease in the cost, size, and weight of motors in such diverse devices as automobile starters, cordless shavers, hand-held drills, household appliances, toys, and disk drives (again) in laptop computers. The latest of the permanent magnet development spurts, in the late 1980s, illustrates the unpredictable effects of the interplay between politics, economics, research, and development. Samarium cobalt was the magnetic material of choice until the price of the starting materials became prohibitive due to political unrest in Zaire. Intense exploratory research discovered a superior replacement material, neodymium iron boron. The newly introduced magnets are expected to have an annual market of $4 billion within 10 years.

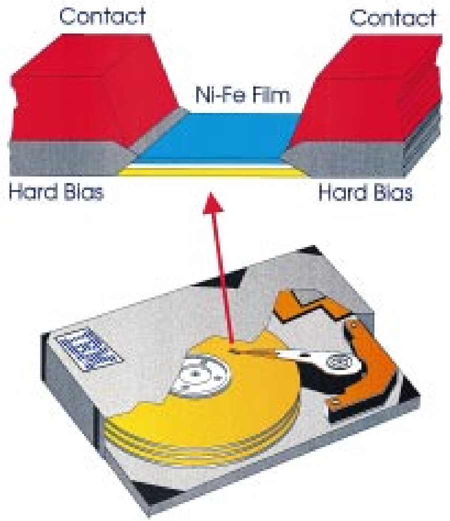


FIGURE 2.11 *A hard disk drive assembly with a magnetoresistive sensor for reading the stored data. (Courtesy of IBM Research.)*

The computer that analyzed the data from the MRI and CAT scans, and the computers that were involved in essentially every aspect of the airplane trip—making the reservations, assuring security at the airport, determining the flight path, and so on—are based on **SILICON TECHNOLOGY.**

Well into her flight and resting briefly before her important meeting, the woman relaxes in her seat and reflects on just how much of what she has taken for granted in the past several hours would have been unthinkable only a few years ago: modern cars and airplanes, telecommunications, modern medicine, the power and portability of computers. Our lives have been changed by CMMP research—and for the better.

She wonders what equally remarkable changes will take place during her son's lifetime. No one really knows, of course, but perhaps one hint can be found in new advances like **INTEGRATED MICROSYSTEMS.** Other ideas will arise from the scientific challenges discussed in Part 3.

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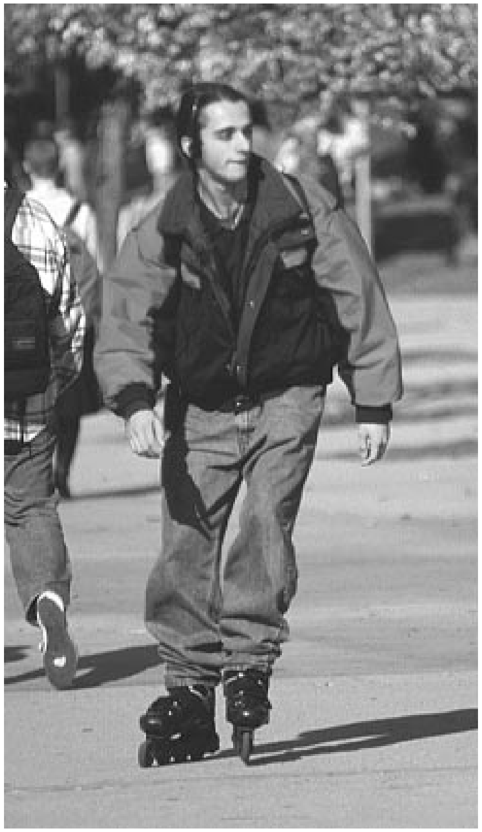



SILICON TECHNOLOGY

Microelectronics based on silicon and its oxides underlies all of today's high-technology industries, from computers to communications to biotechnology. Microelectronics has also become common in our day-to-day lives, in applications ranging from automobiles and banking to control of household appliances.

Although silicon and germanium were used in radar detectors in the early 1940s, very little was known about the physics and materials science of these semiconductors. Scientists at Bell Laboratories soon recognized that a deeper understanding of these materials was necessary for rapid application to communications. Materials research in the mid-1940s ultimately enabled the invention of the transistor in 1947. Extensive, long-term research, along with the unexpected discovery in 1959 that silicon dioxide can passivate (protect) the surface of silicon, led to the invention of metal-oxide-silicon (MOS) transistors. The MOS transistor, combined with the increased understanding of the physics and materials science of semiconductor materials and devices that resulted from almost twenty years of intensive research and development, ultimately led to the invention of the integrated circuit.

Perhaps no other device has had as large an impact on day-to-day life as the silicon-based integrated circuit (IC). Although the IC was based on many years of condensed-matter and materials research at large industrial laboratories, the acceleration of its development and use was driven by government needs. Enabled by stable, long-term research stretching over almost two decades and stimulated by government funding, the discovery of the IC spawned the modern microelectronics industry, which is now a global enterprise. In 1995, IC sales exceeded \$150 billion and supported an electronics industry with sales approaching \$1 trillion. Without transistors and ICs, none of this would be possible.

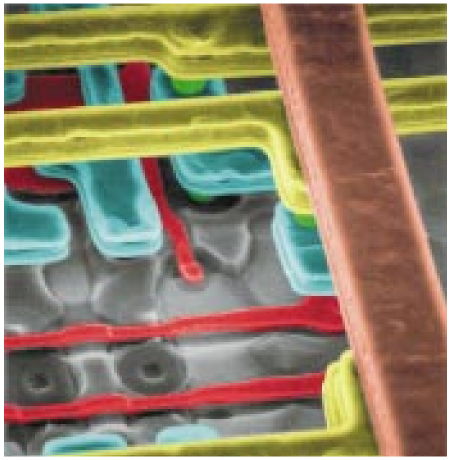


FIGURE 2.12 Intricate layers of aluminum and tungsten wiring on an integrated circuit memory chip are revealed by etching away the interlayer dielectrics and then imaging the chip with a scanning electron microscope. The width of this image is about 10 microns (0.001 cm). A chip can contain as many as 50 million connections like those shown here in an area 1 cm on a side. (Courtesy of Lucent Technologies Bell Laboratories.)

INTEGRATED MICROSYSTEMS

The microelectronics industry has grown explosively over the last forty years. Such phenomenal growth has not been experienced in any other field in history. A key element behind the success of microelectronics has been integration. Integration of electronic functions on ever greater length scales leads to the low cost of production and assembly and high reliability. Miniaturization allowed for integration and simultaneously resulted in increased performance.

In the early 1980s researchers unveiled the first micromachined motor, demonstrating that the tools, facilities, and infrastructure developed to fabricate microelectronic circuits could also be used to build miniature mechanical systems. Though many research problems must be surmounted before microsystems can become as ubiquitous as the integrated circuit, this demonstration raised the hope that complex microsystems that integrate physical and chemical sensing and mechanical response with control and communications electronics can be mass produced at low cost. High-performance microsystems at lower prices would create markets for many products. In transportation, they could be used for position sensing, collision avoidance, navigation, and reliable airbag deployment. Environmental monitoring could be performed in hostile environments with inexpensive, disposable detectors. Microsystems could also be used in areas as diverse as biomedical applications and consumer products. They will probably have a profound effect on our lives and the lives of our children.

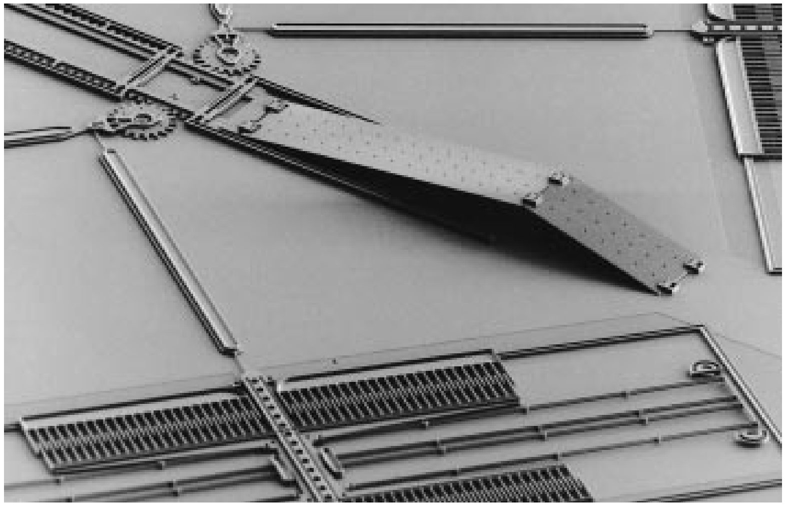


FIGURE 2.13 A prototype micromechanical mirror for use in optical communications systems. Either side of the flat hinged structure in the middle can be used as the mirror. The gears at the upper left are just 50 microns in diameter. (Courtesy of Sandia National Laboratories.)

3 ❖ The Research Endeavor

The brief story told in Part 2 illustrates how much the world has changed in recent years and the enabling role that condensed-matter and materials physics is playing in modern technology. We turn now to a closely related topic, the fundamental scientific challenges of research in this field. Once again, the capitalized words in the main text link to sidebars that provide more information on a few selected topics.

What is "condensed-matter and materials physics"? Fifty years ago, the transistor emerged from this area of physics. High-temperature superconductivity was discovered by condensed-matter physicists, as were the fascinating low-temperature states of superfluid helium. Scientists in this field have long-standing interests in essentially all aspects of magnetism and magnetic materials. They investigate the properties of glasses, polymeric materials, granular materials, and composites in which diverse constituents are combined to produce entirely new substances with novel properties. They are reaching out to researchers in the earth and atmospheric sciences because they share interests in topics such as friction, fracture, and fluid flow. The outreach to biology and the study of biological materials are now beginning in a serious way.

Hardly any other field of science so seamlessly spans the whole range between the most basic research and the most applied. Advances in basic research inspire new ideas for applications, and application-driven technological advances provide tools that enable new fundamental investigations. At the same time, technological problems raise questions that demand new fundamental insights. For example, with new fundamental understanding of **NONEQUILIBRIUM PHENOMENA,** we may soon see a qualitative improvement in our ability to predict and control complex properties of the structural materials used to manufacture everything from airplanes and bridges to electronic devices. Technological advances provide tools such as synchrotrons, neutron sources, electron microscopes, high magnetic field facilities, **COMPUTERS,** and

NONEQUILIBRIUM PHENOMENA

The processes that are used to produce industrial materials—casting alloys for jet engines or fabricating microscopically small features of computer chips—are all exercises in what we call "nonequilibrium physics," the study of systems that are changing their shapes or properties as we exert forces on them, freeze them, or otherwise disturb their states of equilibrium. Predicting and controlling these processes with the precision that will be needed for applications requires fundamental understanding of the nonequilibrium phenomena underlying them and is a challenge for physicists.

For example, snowflakes form by a branching process that is called "dendritic crystal growth." Research in this area has been driven not only by our natural curiosity about snowflakes, but also by the need to understand and control metallurgical microstructures. The interior of a grain of a freshly solidified alloy, when viewed under a microscope, often looks like a collection of overly ambitious snowflakes. Each grain is formed by a dendritic mechanism in which a crystal of the primary composition grows out rapidly in a cascade of branches and side branches, leaving solute-rich melt to solidify more slowly in the interstices. The speed at which the dendrites grow and the regularity and spacing of their side branches determine the observed microstructure, which in turn governs many of the properties of the solidified material such as its mechanical strength and its response to heating and deformation. We cannot yet predict microstructures accurately, but much progress has been made in the last decade. Figure 3.1 shows one of the best new theoretical efforts in this direction.

Much of the most important recent progress in nonequilibrium physics has consisted simply of recognizing that fundamental questions remain unanswered in many familiar situations. The recent growth of interest in fracture and friction, for example, has led us to realize that we need to establish first-principles understanding of the difference between brittleness and ductility, especially in noncrystalline materials. We are learning about the dynamics of granular materials, systems that are like liquids in some respects, like solids in others, and unlike either in many of the most important ways. And we are just beginning to learn which questions to ask in a search for understanding the dynamics of fracture at crack tips, failure at interfaces between different solids, or rupture on earthquake faults.

COMPUTATION IN CMMP

Because of the astonishingly rapid advances in both hardware and software, the small workstations or PCs that sit on almost every scientist's desk these days have the power of machines that we called supercomputers little more than a decade ago. Today's supercomputers can simulate the behavior of hundreds of millions of interacting classical molecules or follow the transitions among comparable numbers of quantum states. This exponential growth in computational power will continue for at least another decade.

Computers play a central role in modern experiments, controlling apparatus, acquiring and storing data, and analyzing data. Theorists also find them essential for solving mathematical problems that once seemed intractable. But the computer is now emerging as much more than just a tool for assisting the work of scientists; it is making a qualitative change in the kinds of research that will be done in the near future. Consider just a few examples.

Starting from little more than the masses and charges of electrons and atomic nuclei, as well as the rules of quantum mechanics, we are approaching the point where we will be able to predict accurately the properties of molecules, of atoms at solid surfaces and interfaces, of defects in solids, and even of larger structures such as the recently discovered fullerenes (see page 21).

In situations that justify neglecting quantum effects, multimillion-molecule simulations are beginning to provide valuable information about complex solid-state phenomena such as fluid flow, fracture, friction, and deformation. The great advantage of such computational investigations is that they can tell us in detail about the behavior of individual molecules. Thus, computer-based studies of this kind have features of both experimental and theoretical research.

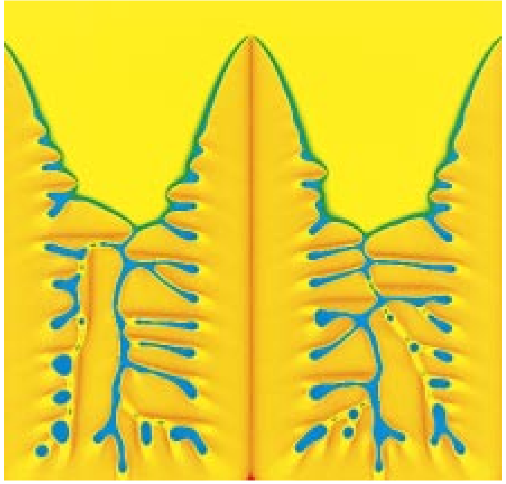


FIGURE 3.1 Computer simulation of dendritic growth in the solidification of a nickel-copper alloy. The colors indicate relative concentration of copper, from low (red) to high (blue). The orange and red regions are solid; the green and blue regions are liquid. (Courtesy of the National Institute of Standards and Technology.)

SCANNING PROBE MICROSCOPES. These tools, in turn, provide unprecedented opportunities to investigate materials on the atomic scale, leading to fundamental discoveries that drive both science and technology. The new physics of **THE FRACTIONAL QUANTUM HALL EFFECT,** for example, was made possible by new materials fabrication technology. The study of **MATTER UNDER EXTREME CONDITIONS** has led both to fundamental and practical breakthroughs.

Several of the most profound conceptual developments in science have occurred in CMMP in the last two decades. The so-called "renormalization-group" theory of critical fluctuations in condensed matter has helped us understand phenomena as varied as phase transformations, the interactions between elementary particles, and the fluctuations of the stock market. Chaos, turbulence, and pattern formation are other core concepts in this field that have had wide-ranging implications across the world of science. The historic role of condensed-matter physicists, ever since the emergence of quantum electronics and the transistor, has been to discover new concepts and phenomena and to develop their new knowledge in ways that are meaningful for fundamental advances in many fields and for practical applications.

SCANNING PROBE MICROSCOPY

Although the atomic picture of the world was formed over a century ago, it is only in the last few decades that compelling visualization of atoms has become possible. Since there are only 92 stable elements, the diverse materials known to us derive their complexity for the most part from the patterns of their atoms' arrangement, in molecules and in solids. Direct atomic-scale visualization of these patterns allows us to develop new materials and better understand old ones. It has been used to look at the action of semiconductor devices, the workings of chemical reactions, and the structure of genes.

Many new visualization tools emerged from condensed-matter and materials physics. One such advance was the invention of scanning probe microscopy. In this class of techniques, a sharp needle-like tip is moved around (scanned) near a surface. A map of the surface is then constructed in real time by measuring some response of the surface to the tip—the force of the surface on the tip, for example, or the electric current that flows between the tip and the surface. Using precision actuators called piezoelectrics, a tip can be moved up and down or sideways by less than the size of an atom. Scanning the tip across the surface in this way while measuring the response allows an atomic-level image to be built up, much as a blind person can acquire a mental picture of an object by feeling its shape.

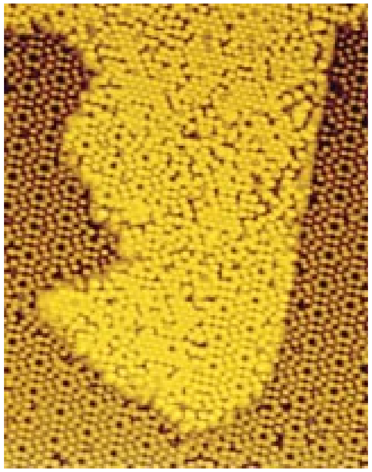


FIGURE 3.2 A scanning tunneling microscope image showing a snapshot of the growth of germanium on a silicon surface. Each bright spot is a single atom. (Courtesy of IBM Research.)

The first suggestion of a super-resolution microscope can be traced back as far as 1928 to the British scientist E.H. Synge, but the first working scanning probe microscope with atomic resolution was not invented until 1981, at IBM's research laboratory in Zurich, Switzerland.

In the decade and a half since then, a wide variety of related visualization techniques have been developed. Scanning probe techniques now exist that allow atomic-scale sensing and mapping of electrical, optical, and magnetic properties, surface forces, and other phenomena.

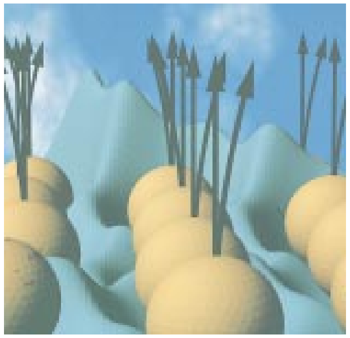
A particularly important recent innovation has been the possibility of using a scanning tip not just to study a sample but also to manipulate atoms actively. The "quantum corral" shown on the front cover and in Figure 1.3 was made in this way. This microscopic atom-by-atom "engraving" makes even microsurgery look like the metaphorical bull in the china shop.

THE FRACTIONAL QUANTUM HALL EFFECT

The fractional quantum Hall effect is an example of beautiful and fundamental new physics made possible by technological advances in the fabrication of artificially structured materials. It takes place in a two-dimensional electron "gas" produced in a transistor-like device subjected to extreme conditions of high magnetic fields and low temperatures. Under these conditions, electron correlations become dominant. The basic observation is a precise quantization of the Hall conductance with the unusual property of being described by a quantum number that is fractional rather than an integer.

The application of a strong magnetic field at low temperature induces large numbers of vortices ("whirlpools") that attach themselves to the electrons to form composite objects, which condense into a special quantum "fluid." This fluid of composite particles has the bizarre property that the low energy excitations consist of a single vortex that binds a fraction of an electron charge. These objects have recently been observed through direct measurement of their fractional charge and by tunneling experiments in which an electron added to the system is seen to break up into three excitations, each with one-third of the charge. Theoretical work on this problem has led to profound and intellectually exciting new concepts and techniques with applications both in other areas of condensed-matter physics and in quantum field theories studied in elementary particle physics. We are familiar with the idea in high-energy physics that certain elementary particles such as protons are actually composite objects made up of fractionally charged quarks. These quarks can be observed in collisions at very high energies (or equivalently, high temperatures) carried out using particle accelerators. In condensed-matter physics, one does the reverse: the analog of the accelerator is the refrigerator. At sufficiently low temperatures, in a strong magnetic field, electrons added to a quantum Hall system break up into fractionally charged elementary vortex excitations. This, then, is a fundamentally new form of conduction in an artificially created, layered material.

FIGURE 3.3 A pictorial representation of the many-particle state that underlies the fractional quantum Hall effect. The height of the green landscape represents the amplitude of the quantum wave of one electron as it travels among its companions (gold balls). The arrows indicate the vortices induced by the magnetic field. These vortices attach themselves to the electrons to form composite particles. (Courtesy of Lucent Technologies Bell Laboratories.)



MATTER UNDER EXTREME CONDITIONS

An important frontier of materials science is in the behavior of condensed matter under extreme conditions: heat and cold, high pressures, mechanical stresses, large magnetic and electric fields, and intense radiation environments. Experiments at this frontier will continue to have a major impact on engineering, where breakdown of component materials in various hostile environments is a significant concern. Topics of major national interest include jet engine technology and weapons. Progress in the physics of materials under extreme conditions has great significance for other areas of science—notably geophysics, where conditions of high heat and pressure are routine, and astrophysics, because extreme conditions routinely occur elsewhere in the universe. Extreme conditions sometimes also occur unexpectedly on the simple laboratory scale and yield novel phenomena such as sonoluminescence, in which flashes of light are emitted from collapsing air bubbles under the influence of sound waves.

Many of the most important breakthroughs in materials physics, ranging from the discovery of superconductivity at the beginning of the century to the discovery of the quantum Hall effect near its end, have occurred as the result of explorations whose goal was simply to find out what happened to known substances under more extreme conditions than they had been exposed to previously. Discoveries found at this frontier can be translated into practically useful technologies either as subsequent advances make the extreme conditions routinely achievable (as for the superconducting magnets in magnetic resonance imaging devices with medical applications), or by inspiring scientists to create new materials that display the newly discovered phenomena under less extreme circumstances. We suspect that throughout the rest of human history, the agenda of this most human of pursuits in materials research—namely to produce the world's highest magnetic fields and pressures or the lowest temperatures, and to be the first to observe what these conditions imply for materials from hydrogen to gallium arsenide—will remain the same, with equally productive outcomes.

FIGURE 3.4 A generator at the National High Magnetic Field Laboratory. This generator serves as a power supply for a high-performance magnet that will provide unprecedented insights into the behavior of matter subjected to extremely strong magnetic fields. (Courtesy of Los Alamos National Laboratory.)

What does the future hold for condensed-matter and materials physics? There must be many surprises in store for us. Consider the fact that essentially none of the most important discoveries in this area made in the last decade were anticipated in the 1986 National Research Council report *Physics Through the 1990s*. And the pace of scientific change, especially when viewed on an international scale, is now accelerating.

A particularly dramatic surprise was the discovery in 1986 of **HIGH-TEMPERATURE SUPERCONDUCTIVITY,** which disproved a consensus then growing among scientists that superconductivity could exist only at temperatures very near absolute zero. Now, just over a decade later, we are beginning to see commercially marketed devices based on superconductivity at easily accessible liquid-nitrogen temperatures, and we can look forward to decades of new developments. Even more important, condensed-matter and materials physicists have learned that chemically complex materials, like the new superconductors, can have extraordinarily interesting properties. The study of such complexity in solids is emerging as a whole new style of inquiry.

HIGH-TEMPERATURE SUPERCONDUCTIVITY

By the mid-1970s it seemed that the limiting temperature for superconducting materials was near 25 K, a temperature still requiring expensive liquid helium cooling. Theoretical calculations based on the mechanism that controlled electron pairs in known superconductors indicated a maximum temperature for superconductivity of less than 40 K. In 1986 a totally unexpected, even shocking, discovery was made. A class of copper oxide ceramic materials was found to become superconducting at temperatures much higher than 25 K. We now have many complex materials that become superconducting at temperatures well above the boiling point of inexpensive liquid nitrogen, 77 K.

The occurrence of superconductivity in a totally unexpected class of materials, and the potential for its practical use above the temperature of liquid nitrogen, have motivated a wide range of research and development efforts over the past decade. Superconductivity has now been observed in specially prepared ceramics at temperatures as high as 135 K.

Despite extensive worldwide efforts, however, an understanding of the mechanism for superconductivity in the new oxide materials is still lacking. For example, physicists cannot reliably predict whether a material could exist that would superconduct at room temperature. These new materials are brittle ceramics, with properties completely different from those of the ordinary metals in which low-temperature superconductivity occurs. Paradoxically, in their pure state, these oxides do not conduct electricity at all—they are magnetic insulators. Even when charge carriers are introduced by chemical doping, they are poor conductors at room temperature.

The superconducting state itself appears to have pairs of electrons orbiting around each other in an unconventional manner. (See Figure 3.5.) The sensitivity of this state to magnetic fields presents technological challenges that must be overcome for certain practical applications; but on the positive side, it has also led to exciting new fundamental scientific ideas.

The discovery of high-temperature superconductivity has focused attention on the enormous variety of complex oxide materials. In addition to superconductivity, many of these materials exhibit other novel magnetic and electrical properties.

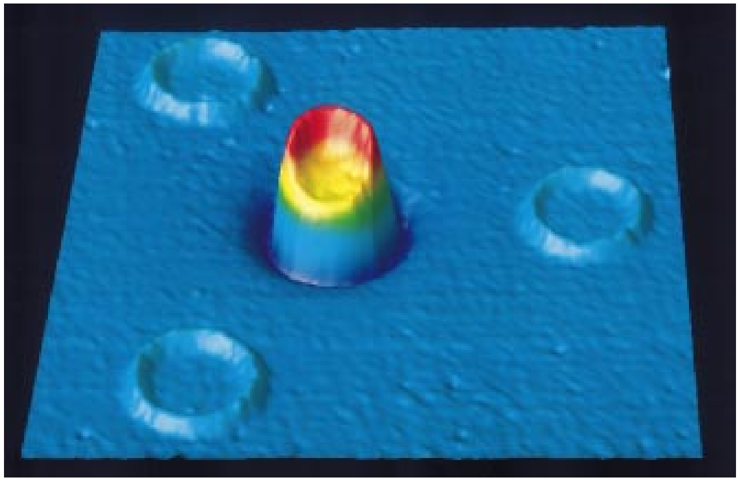


FIGURE 3.5 This magnetic image shows four high-temperature superconducting rings, each 60 microns in diameter, fabricated on a specially prepared multicrystal substrate. The height out of the plane at each point in the image represents the strength of the vertical component of the magnetic field at that point, measured at a constant elevation above the substrate. The volume of each structure thus represents the magnitude of the magnetic flux trapped within that ring. The trapped flux in the center ring is exactly half the normal quantized amount; the other three rings contain no flux. This half-integral flux quantization effect is strong evidence for unconventional electron pairing. (Courtesy of IBM Research.)

A different kind of unanticipated complexity is emerging in **ARTIFICIALLY STRUCTURED MATERIALS,** engineered with features so small that they behave like artificial atoms. These structures are candidates for the next generation of computing elements, but their potential uses in both science and technology go far beyond computing as we know it. As we learn how to assemble increasingly complex structures from more and more complex building blocks, perhaps even from biological molecules, we can anticipate a whole new world of scientific phenomena and practical applications.

Other completely unexpected discoveries of the last decade include **FULLERENES,** and carbon nanotubes—spherical and cylindrical arrangements of carbon atoms that have remarkable chemical and structural properties. Even more glimpses of the future have recently been provided by observations of intrinsically quantum mechanical behavior in systems so large that they had been thought to be outside the realm where such effects could occur. Such macroscopic quantum phenomena include Bose-Einstein condensation of collections of large numbers of atoms and the excitonic laser. Suddenly, deep philosophical questions about the meaning of observations in quantum mechanics are becoming relevant to the development of entirely new kinds of electronic devices, perhaps even the development of ultrafast quantum computation.

ARTIFICIALLY STRUCTURED MATERIALS

Artificially structured materials are structures not available in nature. Often the surfaces and interfaces of these materials dominate their properties. Artificially structured materials are critically dependent on enabling technologies for fabrication and characterization, tying progress in science to advances in relevant technologies. Although the field was born in the 1960s, there has been impressive progress in the last decade. New structures are possible because of increased cleanliness, extreme growth conditions, and substrate modification before growth. Our scientific understanding has increased through atomic-level elucidation of surface and interface structure and defects using the new scanning probe microscopies that have completely changed our thinking about how to study surface phenomena.

Artificially layered structures have enabled the realization of many new devices, including high electron-mobility transistors, semiconductor lasers, giant magnetoresistance materials, and x-ray optics. Some of these devices are now ubiquitous in such consumer electronics as cellular telephones and compact disk players. Others promise major advances in computing and communications. These technological advances have in turn enabled the structures and materials required for many of the accomplishments detailed in other sections of this report, such as the fractional quantum Hall effect.

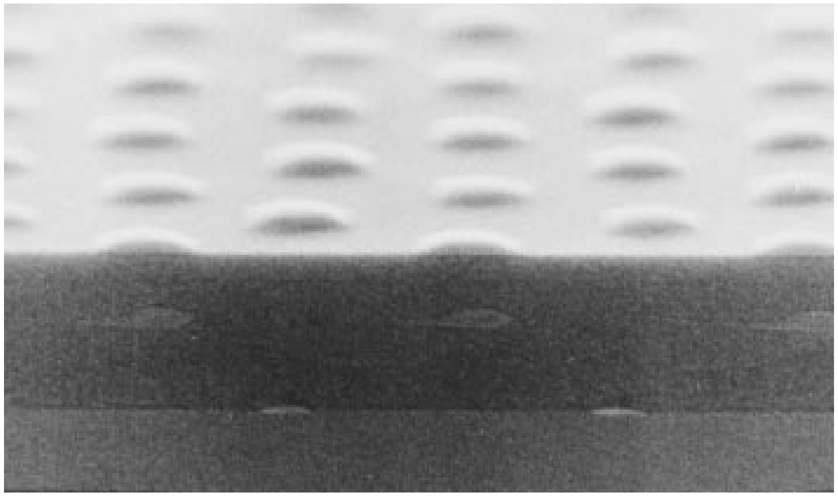


FIGURE 3.6 A self-organized ordered array of InGaAs quantum dots grown in three regular layers on a GaAs substrate. The dots are the bumps on the surface and the light-colored internal structures beneath them. The layers are separated by about 65 nm, and the dots within each layer are about 250 nm apart. (Courtesy of NTT Optoelectronics Laboratories.)

FULLERENES

Solid carbon is well known for its two stable crystalline forms, diamond and graphite. It is also known to exist in a number of other metastable forms, such as coke and glassy carbon. These different forms of carbon are among the most widely used materials because of their remarkable properties, such as the hardness of diamond and the lubricity of graphite. Until recently, no one would have suspected that another large class of carbon structures could be made, with yet more remarkable properties. Yet over the last decade that is exactly what has happened.

In 1985, while working with gaseous carbon like that found in interstellar space, scientists found that under certain conditions (laser ablation of graphite in an atmosphere with a controlled partial pressure of helium) molecular clusters could be made that contained only certain specific "magic numbers" of carbon atoms. The structural motif they proposed for this class of clusters had its inspiration in the geodesic dome designs of the architect Buckminster Fuller. The simplest of these designs is that of C_{60}, which is made of 5- and 6-atom carbon rings fused together into a structure resembling a soccer ball.

Large amounts of fullerene carbon were soon synthesized, allowing a wide variety of experiments to be performed. The proposed structure was dramatically proven correct, and a number of fascinating properties were discovered. One of the most remarkable is that molecular clusters of C_{60} can be doped with electrons by donors such as alkali metals. This makes them into superconductors with critical temperatures surpassed only by the recently discovered copper oxides.

The fullerene forms of carbon are now also known to include capped cylinders, sometimes called buckytubes. These cylinders appear to be one of the promising approaches to the development of nanoscale wires and other electronic components.

For their initiation of fullerene research, Richard Smalley, Harold Kroto, and Robert Curl were awarded the 1996 Nobel Prize for Chemistry.

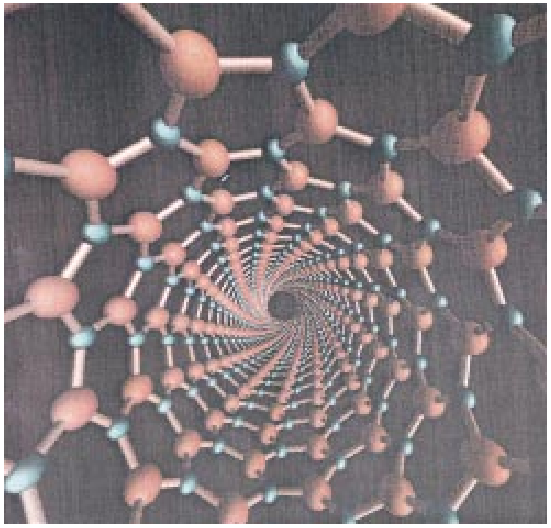


FIGURE 3.7 A computer model of the interior of a carbon nanotube. Such tubes exist in various forms, including this spiral structure. (Courtesy of the University of California, Berkeley.)

Surely one of the most significant developments on the horizon is the movement of condensed-matter and materials physics into the biological and medical sciences. Here, in parallel with advances in materials, communications, and information technologies, is the other scientific revolution that has profoundly changed our world in recent decades. Modern medical techniques such as magnetic resonance imaging and laser surgery were made possible by research in physics, and **THE PHYSICS OF MACROMOLECULES** is a well-established area of research at the intersection of physics, chemistry, and biology. Nevertheless, physics laboratories so far have played only relatively minor roles in mainstream biological research.

THE PHYSICS OF MACROMOLECULES

Progress in molecular biology depends on using a technique called gel electrophoresis to analyze DNA. A sample is placed at one end of a slab of gel, and an electric field is applied. The field pulls DNA molecules of different sizes through the gel at different speeds, separating the components of the sample.

Despite its widespread use, little was known about how DNA molecules actually move through a gel when physicist Pierre-Gilles de Gennes began work on the problem in 1971. Gels are a water-swollen tangle of long chain-like molecules called macromolecules. De Gennes proposed that when other macromolecules such as DNA move through a gel, the tangles force them to slide along their own contours in a snake-like motion called reptation. This theoretical model remained controversial for twenty years, for until recently the motions of individual molecules could not be observed. Optical tweezers can now tug on a single molecule of DNA while its motion is observed through a microscope. The DNA moves along its own contour as predicted.

Recent experiments with simulated gels made from etched silicon have further improved our understanding of the motion of macromolecules. For example, we now know that long molecular chains tend to get caught on post-like obstacles, looping around them like a rope hanging over a pulley. Varying the strength of the applied electric field helps to free the molecules from such obstacles. Theory and experiments in this area are discovering the optimum variation of the applied field for efficient separation of different lengths of DNA.

DNA is not the only important macromolecule; synthetic polymers like polyethylene and nylon are also noteworthy. Predicting the flow properties of molten polymers, whose motion is also dominated by the entanglement of the long molecules with each other, has stimulated new extensions of the reptation model. A better understanding of industrial processes for shaping polymers, such as extrusion and injection molding, should result.

In this way, reptation—a simple idea in condensed-matter and materials physics—has had a major impact on both molecular biology and polymer engineering. Many challenges remain for the future, such as efficiently simulating the motion of macromolecules by computer and following the motion of biological macromolecules on surfaces at high resolution using new scanning probe microscopies. But the reptation idea will continue to provide a starting point for understanding these more difficult problems.

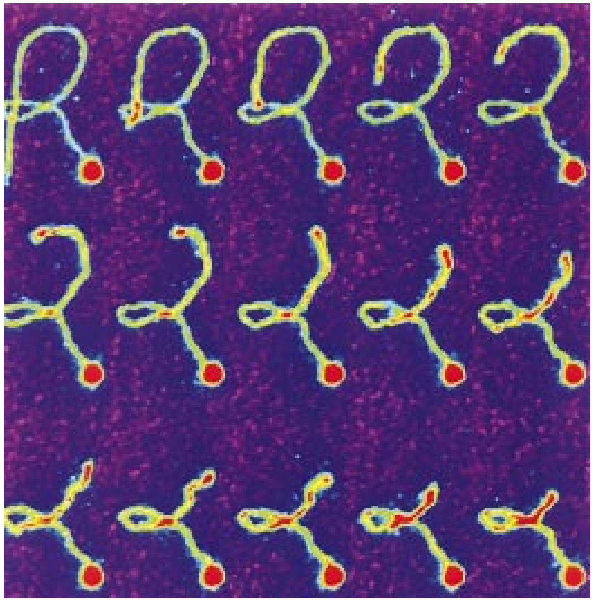


FIGURE 3.8 The motion of a single fluorescently labeled DNA molecule (60 microns in stretched length) in a concentrated solution of unlabeled DNA. In the first image (top left) the molecule has been formed into an R shape by pulling on a small attached sphere (red) with optical tweezers. Subsequent images, taken 8.3 seconds apart, show the molecule moving along its own contour as it unstretches. (Courtesy of Stanford University.)

That situation is about to change. Although we could hardly have imagined such possibilities a decade ago, we now have instruments such as scanning probe microscopes and **OPTICAL TWEEZERS** that allow us actually to see what large molecules are doing inside biological cells and even to measure the forces that they exert on one another. In centers around the world, scientists are just beginning to use these new tools to solve critical problems involving the physics of biological systems. These problems are posing entirely new intellectual challenges; the implications of their solutions are likely to be immense.

As these examples illustrate, condensed-matter and materials physics is a vital field at the very crossroads of the scientific enterprise. It combines the intellectual stimulation of investigations at the frontiers of human knowledge with the satisfaction of providing insights and capabilities that can improve all our lives. ❖

OPTICAL TWEEZERS

Imagine a string that is a ten-millionth of an inch across and a ten-thousandth of an inch long. Suppose you wanted to test its strength, measure its length, or pick it up and move it. How would you hold it? When the string is really a molecule of DNA, you need a pair of molecule-size tweezers.

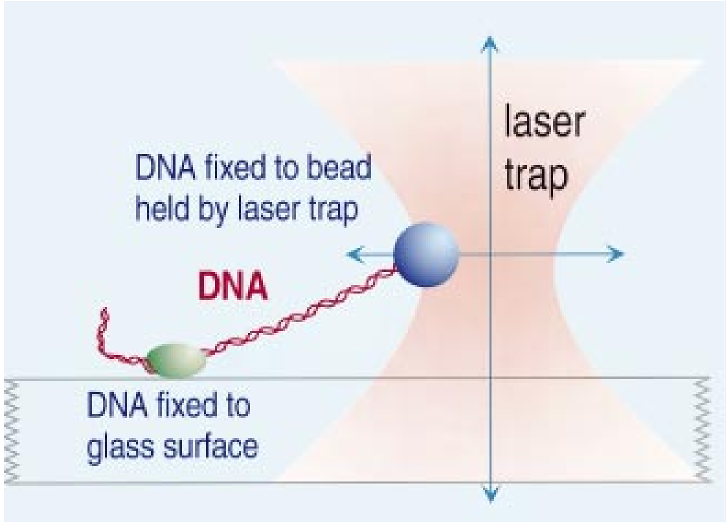
The "optical tweezer" was invented around 1980. It turns out that a tiny bead attached to a strand of DNA can be attracted to the spot of a laser's light. Pick one end of the strand, shine the light, and you can hold the molecule in place. Fix the other end, move the light, and you can stretch the molecule.

In 1995, scientists were able to pull straight the normally crumpled DNA molecule and measure the amount of work it took. The force required was only about a millionth the weight of a drop of water. The researchers showed that DNA first stretches by being straightened; but once it is straight, the "string" itself can stretch. By looking at just one molecule, they were able to test a theory of how DNA acts as a mechanical object.

The entire genetic code for a human being (the human genome) has 4 billion "base pairs" of molecular data. The full set is stored in duplicate in almost every one of the body's roughly 10^{13} cells. Altogether, this amounts to about 20,000,000,000 miles of DNA per human body, enough to stretch around the earth a million times. At the normal rate of cell reproduction, each of us is making new DNA at a rate faster than 10,000 miles per hour.

Only a small part of this DNA is actually used in any single cell. The rest contains the code for making other types of cells in the rest of the body. This means that each cell must find just the right little bit of the DNA crowded into the small space of the cell nucleus. It becomes a big problem to hold all that DNA, pick out the right bit, and open it up to read its message. The physics of DNA stiffness, twisting, and sticking becomes a major factor in understanding how this genetic material works.

FIGURE 3.9 Using "optical tweezers" to stretch a strand of DNA. One end of the strand is attached to a stationary glass surface. A tiny bead attached to the other end is then trapped using laser light. Adjusting the laser trap moves the bead and stretches the DNA molecule. (Courtesy of Princeton University.)



4 ❖ An Era of Change

We live in a world shaken by change. The Cold War has ended. A global economy is emerging. The information technology revolution continues apace. Social and economic systems are struggling to adapt to new ways of doing business. Economic strength is replacing military strength as the barometer of greatness. High technology, once confined to the developed nations, is propagating through the world literally at the speed of light. This era of rapid and pervasive change has profound implications for our future.

Science is also undergoing unprecedented change. The great industrial laboratories—the engines that have driven technology for the past half century—have adjusted to the realities of the new global marketplace and changed both the scale and scope of their long-term R&D investments in the physical sciences. Under pressure to balance the federal budget, the U.S. government is reducing its discretionary expenditures, the category that includes federal support for science. At the same time, many other countries are increasing their investments in long-term R&D. The debate about the appropriate roles in R&D of industry, government laboratories, and the universities is set against this backdrop of constrained resources and increased global economic competition.

In the next century, the United States will need to respond to world tensions arising from economic competition, regional military conflict, competition for energy and other strategic resources, and global environmental issues. These new international challenges differ from those of the Cold War past, and addressing them cost effectively will require continued scientific advances. National issues related to security, the environment, and energy resources will also need to be confronted. Condensed-matter and materials physics will play a pivotal role in ensuring the nation's prosperity in this new world.

This report demonstrates that condensed-matter and materials physics lies at the heart of modern technology. Advances in communications, computing, medicine, transportation, energy, and defense have all been enabled by new materials and materials-related phenomena. Research in condensed-matter and materials physics, pushing forward the frontiers of both science and technology, provides much of the fundamental underpinning for these advances. Its success has been one of the great sagas of the 20th century.

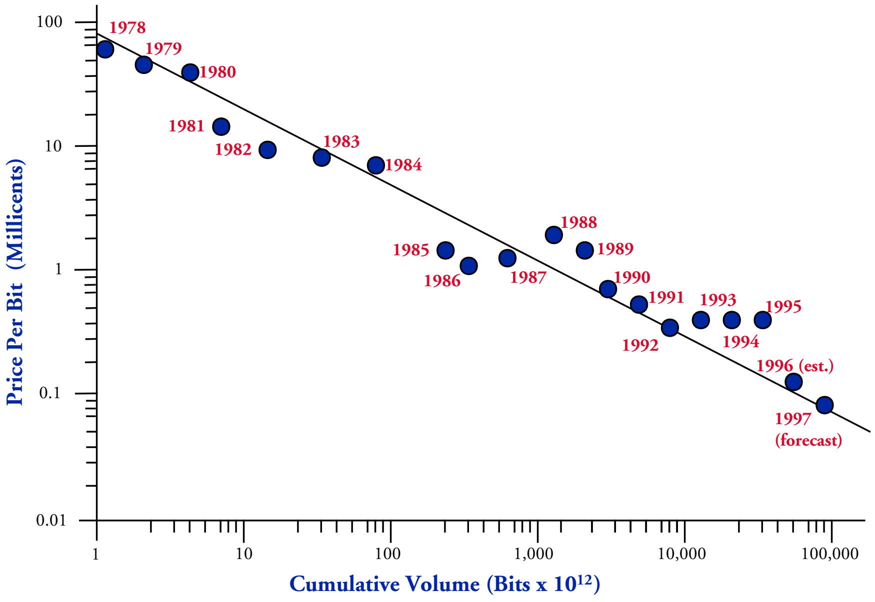


FIGURE 4.1 The price per bit of dynamic random access memories (DRAMs) has been falling steadily by 25–30% per year as the volume produced steadily rises. The capabilities of other electronic components are advancing at similar rates. If aircraft had developed at the same rate, a flight from New York to San Francisco would now take 10 minutes and cost $20. (Courtesy of SEMI/SEMATECH.)

As we enter the new millennium, the field of condensed-matter and materials physics is evolving in several important directions. It is becoming increasingly interdisciplinary, with progress often being made at the interfaces with other disciplines, such as biology, chemistry, engineering, materials science, and atomic and molecular physics. Partnerships across disciplines and among universities, government laboratories, and industry have become essential to assemble the resources and diverse skills necessary to continue advancing our knowledge. The emergence of national facilities, from atomic-resolution microscopes to powerful synchrotron and neutron sources, has transformed both the practice and the substance of the field. These developments foreshadow a condensed-matter and materials physics community more closely connected with industry and with the rest of science, and armed with experimental and computational capabilities that were not even imagined just a few decades ago.

The 21st century will bring significant challenges to condensed-matter and materials physics. Foremost among these challenges is ensuring the future vitality of the field and its continued ability to enhance our quality of life. The shift of the major industrial laboratories away from long-term, funda-

FIGURE 4.2 The Advanced Photon Source at Argonne National Laboratory, commissioned in 1996, is the nation's most powerful synchrotron x-ray facility. It will provide unprecedented research opportunities to thousands of users in the materials, biological, and engineering sciences. (Courtesy of Argonne National Laboratory.)

mental research in the physical sciences leaves a significant gap in the nation's scientific infrastructure and its ability to transform the fruits of research into applications. The economic impact of this shift may not become apparent for decades, because of the time required for fundamental scientific advances to be incorporated into new products. If U.S. industry no longer can support basic research at the levels it once did, then the realities of global economic competition place the burden for support of such research squarely on government. Our nation must move quickly to determine the scale and form of this governmental responsibility.

FIGURE 4.3 Microanalytical facilities such as this transmission electron microscope are essential to continued progress in condensed-matter and materials physics. These facilities often include a wide variety of instrumentation available to both internal and external users. (Courtesy of the University of Illinois at Urbana-Champaign.)

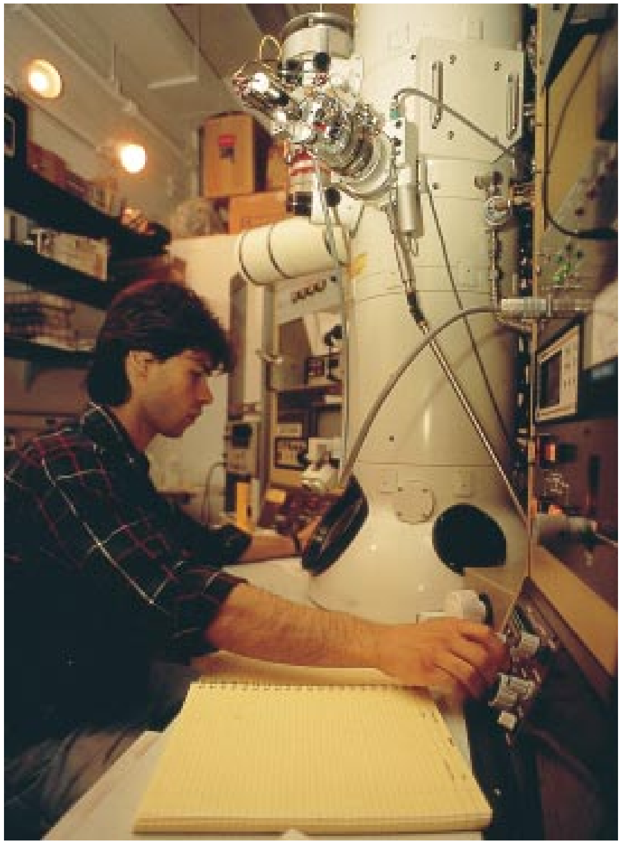


FIGURE 4.4 The High Flux Isotope Reactor provides the nation's most intense steady-state neutron beams for materials research and isotope production. The neutron scattering spectrometer shown here is being configured for an experiment that uses the neutron's unique sensitivity to magnetism. (Courtesy of Oak Ridge National Laboratory.)

Innovation is the key to developing breakthrough technologies. It must continue to flourish despite the resource constraints that are sending shock waves through the R&D system. Constrained resources mean that hard choices must be made, but the system must adapt in a way that preserves the nation's ability to innovate and enables us to meet the challenges of the future.

Progress in condensed-matter and materials physics, as in many other scientific fields, will require continued investment in major facilities for experiments in such areas as neutron scattering and synchrotron radiation. These facilities provide capabilities far beyond those available in individual laboratories. Though they have been developed and supported primarily by the condensed-matter and materials physics community, they also serve thousands of scientists and engineers in other endeavors, such as structural biology and environmental science. The construction and operational costs of large facilities, however, force us to consider carefully their budgets relative to those for other R&D initiatives and to look more closely at the role and impact of the internationalization of science.

Finally, increased cooperation will be required among universities, government laboratories, and industry to leverage existing resources and to ensure the effective integration of science and technology. These interactions will be facilitated by modern communication and information technologies.

We face an era of vast opportunity for condensed-matter and materials physics and the technology it enables. Just as the transistor, the optical fiber, and the solid-state laser have strengthened our economy and changed our lives, new developments in quantum engineering, nonequilibrium phenomena, and biomaterials (to name just a few highlights) hold out the promise of revolutionary breakthroughs in the next century. To fulfill this promise, the condensed-matter and materials physics community will need to build on the unique strengths of universities, government laboratories, and industry, finding new ways to meet the challenges of our changing world. ❖

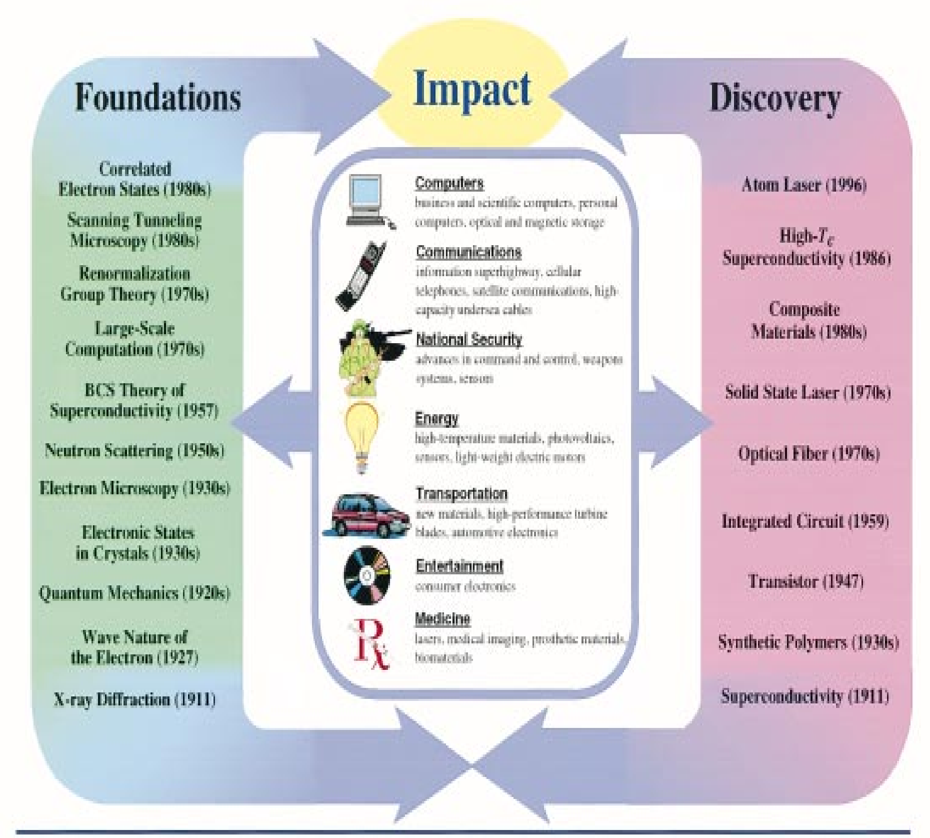


FIGURE 4.5 The incorporation of major scientific advances into new products can take decades and often follows unpredictable paths. Supported by the foundations of condensed-matter and materials physics, the discoveries shown in this figure have enabled breakthrough technologies in virtually every sector of the national economy. The two-way interplay between discovery and foundations is a powerful driving force in this field. The most recent fundamental advances leading to new foundations and discoveries have yet to realize their potential.

The 1996 Nobel prizes for physics and chemistry were both awarded for research in areas discussed in this report. The physics prize (left) was given to David Lee, Douglas Osheroff, and Robert Richardson for their discovery of superfluidity in helium-3. The chemistry prize (right) was given to Harold Kroto, Robert Curl, and Richard Smalley for their discovery of fullerenes, a new form of carbon. (Courtesy of Pressens Bild.)

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