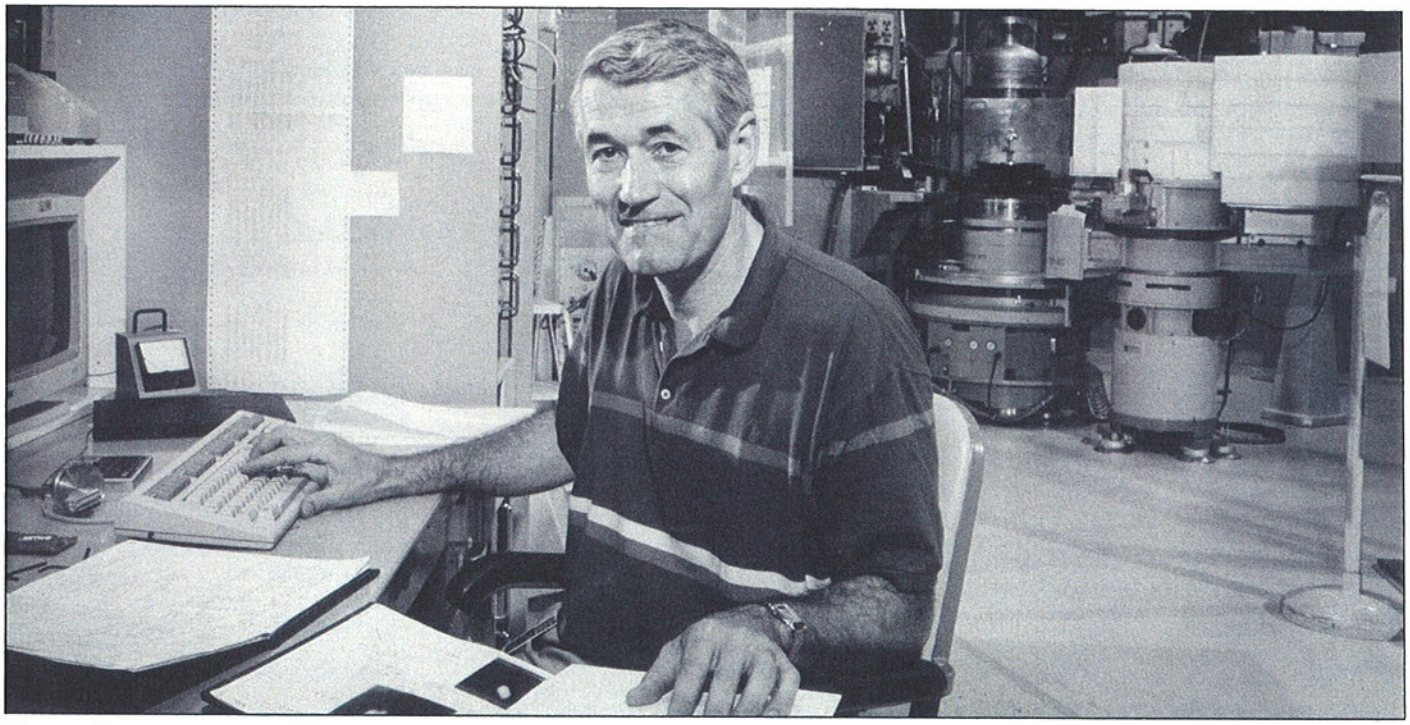
RLE currents

Volume 7, Number 2 • Spring 1994

The Research Laboratory of Electronics at the Massachusetts Institute of Technology

SOLID-STATE SECRETS: Probing the Mysteries of Surface Physics at RLE



Dean Robert J. Birgeneau at the spectrometer controls of the High Flux Beam Reactor at the Brookhaven National Laboratory on Long Island, New York. The reactor employs neutron scattering to characterize the properties of solid-state materials. Dean Birgeneau and his collaborators also use a beam line at Brookhaven's National Synchrotron Light Source to conduct high-resolution x-ray scattering experiments. *(Photo courtesy Brookhaven National Laboratory)*

Since the development of the scientific method in the 17th and 18th centuries, investigations into the properties of matter have not only answered many questions, they have also revealed even more deeply puzzling phenomena. How can some materials emit light energy without shining light on them? Why are the semiconductors silicon and germanium highly sensitive to impurities while other materials are not? Is it possible to change the atomic binding energies that keep solids together in order to create different materials? Can we create solids without their usual crystalline lattice and instead obtain the atomic structure of a liquid? These questions illustrate the many complicated and fascinating issues addressed in the study of solid-state matter—a multidisciplinary field that involves both experimentalists and theo-

Director's Message

Modern integrated circuits are fabricated by means of several processing steps that interact with the surface of a semiconductor wafer. It's not surprising, then, that the understanding of such surfaces and how they behave is central to the production of accurately controlled devices at today's submicron dimensions. Within RLE, there is a coordinated research thrust in both experimental and theoretical surface studies, and remarkable progress has been made in characterizing a variety of surface configurations for many materials using several crystal orientations of the underlying substrate.

From a theoretical perspective, techniques have been developed to predict atomic-level surface structure using minimum energy calculations that exploit the best performance modern supercomputers can offer. Experimentally, intense x-ray beams have been used to study the structure of semiconductor surfaces, as well as several atomic layers beneath them, over a wide range of temperatures. Here again, the most advanced laboratory facilities are used to probe surface behavior, in this case, a large synchrotron and related instrumentation. These studies have led to an important, new understanding of how surface steps and facets form and move during processing. This understanding, in turn, will facilitate new growth techniques for the production of extremely precise semiconductor structures.

Professor Jonathan Allen, Director Research Laboratory of Electronics

As the critical dimensions of integrated circuits continue to decrease, these new perspectives will be vital for continued progress and the consequent complex, high-performance circuits that will be possible in the future.

SURFACE PHYSICS AT RLE
(continued)

reticians in physics, chemistry, chemical engineering, materials science, and electrical engineering.

At RLE, research has focused on the solid state of matter, particularly on phenomena associated with solid-state surfaces and interfaces. In order to increase our knowledge about matter and its various properties, scientists need to model its fundamental structures and parameters. *Surfaces* are the outer faces or boundaries of a solid material and present an abrupt termination of its regular structure. Surface atoms exhibit different properties from atoms contained within a solid material. For example, they are considered to be highly ordered since they cannot move far before meeting the material's rigid atomic structure. Because they come into direct contact with a material's external environment, they exhibit processes and phenomena not associated with what is called the material's bulk. Studies are carried out to investigate surface *adsorption,* where external atoms become bonded to but do not penetrate a solid's surface. *Interfaces* are areas within a material where there is a junction or change in the nature of the solid's internal structure. They may occur naturally or be artificially created.

Of particular interest is the phenomenon known as *surface reconstruction,* which involves freshly cleaved semiconductor surfaces. Semiconductors are the focus of this research because of their extensive surface reconstruction when compared with metals. Generally, atoms arrange themselves in positions of equilibrium that correspond to the atomic forces and internal energy of a material. Once a new surface is formed, the atoms move to establish a new equilibrium. In rearranging themselves, surface symmetry is spontaneously reduced and surface energy is minimized. There is an extraordinarily large number of potential surface reconstructions because of the various geometric orientations that are possible on a solid's surface. Investigations continue to try to understand the nature of reconstruction and its consequences since it changes not only a solid's geometric properties, but its electronic properties as well.

RLE currents

RLE currents is a biannual publication of the Research Laboratory of Electronics at the Massachusetts Institute of Technology.

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The staff of ***currents*** would like to thank Dean Robert J. Birgeneau and the faculty and staff of RLE's Surface and Interfaces Group for their contributions to this issue.

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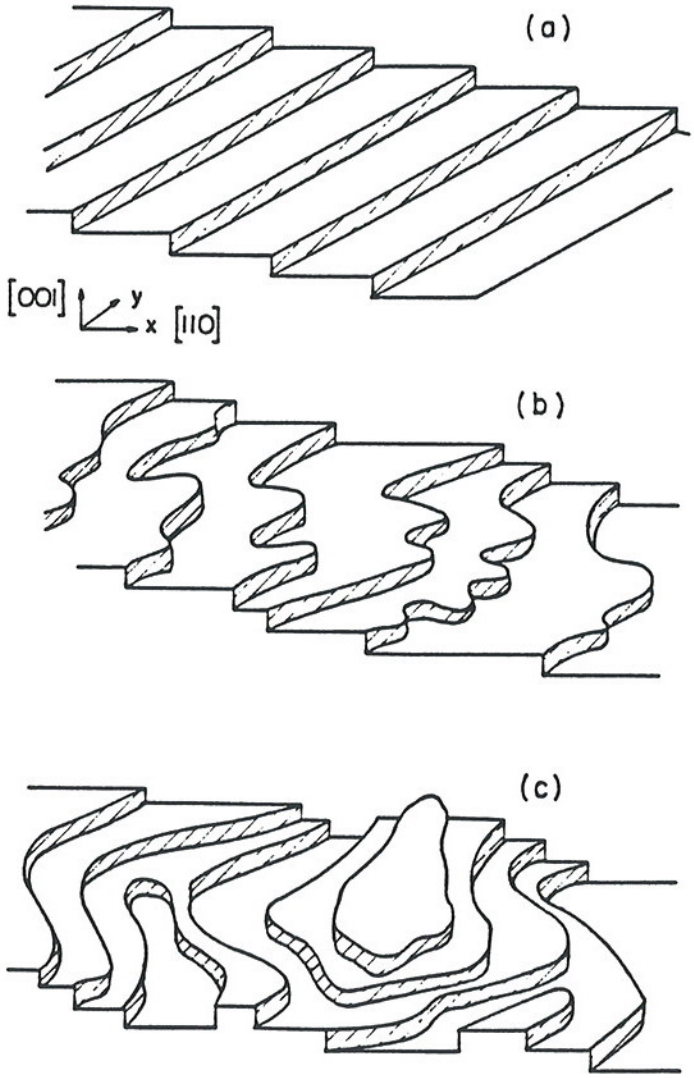
(ISSN 1040-2012)

The study of solid-state surfaces is essential to the operation, fabrication, and interconnection of microelectronic devices. Developments in experimental techniques, such as improved synchrotron light sources and new molecular beam surface scattering techniques, have made possible observations of a surface's microstructure and its dynamics with extremely high resolution. In addition, the theoretical computation and simulation of real solids has been aided by advances in supercomputer technology as well as an increased understanding of the quantum theory of many-particle systems. The goal of this research is to theoretically predict a solid's electronic, geometric, and mechanical properties by using only the identity of the solid's atoms as experimental input.

The Solid State of Matter

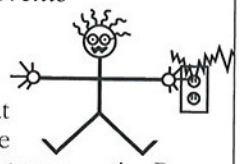
Based on pioneering work in the science of crystallography in the 17th and 18th centuries, several historic milestones emerged in the 19th century. It was only at the beginning of this century that the actual structure of solids was confirmed. Until that time, it was believed that a solid's content determined its characteristics and that by changing its content, its basic substance could be altered. Scientists discovered that the properties of solids were actually determined by their structure, how a material's individual atoms were configured, and the way in which they were put together. Most solids were found to be crystalline in structure, and by the end of the 19th century, modern atomic theory showed that crystals were made of specific atomic arrangements. This emphasis on structure witnessed an important shift in how humans interacted with materials—from simply using the materials at hand to exploiting their properties. One example is the scientific investigation into the structure of radioactive uranium. The results of these studies had an irrevocable effect on world affairs in the 20th century.

While the constituent atoms of a particular element may remain the same, its atomic arrangement may vary. For example, carbon may take the form of noncrystalline soot; then, when squeezed under tremendous pressure, carbon forms graphite; and with more pressure, diamonds. Although both graphite and



Various configurations of stepped (11m) surfaces with increasing temperature that are under study in Dean Robert J. Birgeneau's research group. The illustrations show (a) an ordered phase, (b) a rough phase with meandering steps, and (c) a rough phase above T_R (001) with nested islands.

SHORT CIRCUITS



The staff of ***currents*** would like to clarify the caption of the 1991 photo that appeared in the "History of Electromagnetics Research at RLE" on page 19 in the fall 1993 issue. The model aircraft displayed in the photo is a conceptual representation of future vehicles that might benefit from the aircraft navigation systems currently being investigated in RLE's Electromagnetics Group. Professor Jin Au Kong's research includes the study of electromagnetic interference as it relates to these potential aircraft navigation systems, such as the Instrument Landing System, the Microwave Landing System, the Global Positioning System, and synthetic vision systems.

diamonds are essentially carbon, it is interesting to note that graphite is a good electrical conductor while diamonds are not. This fact demonstrates the importance of bonding and geometric coordination in a material. Elemental materials can also assume various forms. For example, when the water in an ice cube absorbs heat energy, it melts into water. Further thermal energy may cause the water to evaporate. Ice in the form of a solid, water in the form of a liquid, and water vapor as a gas exhibit three common states of matter. The basic chemical composition of the water molecules remains unchanged during these state changes, only the physical properties are altered. The different possible homogeneous atomic arrangements in these different states of matter are called phases. *Phase transitions* occur when a material changes its structure, sometimes as a result of external temperature or pressure variations.

Another condition that characterizes matter is the *equilibrium state,* in which a material is in thermal and mechanical equilibrium with its surroundings. In nonequilibrium states, a material is not allowed to relax in equilibrium with its surroundings. Usually this occurs during the processing of a material, such as in casting or melting. Scientists face many difficulties in predicting the criteria for relaxation that are needed for equilibrium. Since traditional statistical mechanics can only address equilibrium, new theories and techniques have been developed to model nonequilibrium processes. Another challenge is to model the nonequilibrium amorphous, or noncrystalline, states of matter.

The discovery of x-rays in 1895 by German physicist Wilhelm C. Roentgen led to their application by Munich professor Max von Laue in 1912 to examine the structure of atoms in solids. Similar to light diffracting when it shines through a prism, when x-rays encounter atoms in a solid's crystalline structure, the resulting diffraction forms symmetrical patterns that characterize a crystal's atomic structure. X-ray diffraction methods enabled scientists to finally probe the structure of atoms and molecules in matter. They also influenced the work of English scientists William Henry Bragg and William Lawrence Bragg, a father and son team who developed the first mathematical formula to calculate how crystalline structures interact with and reflect x-rays. The Braggs' calculations made it possible to measure the crystalline layers and the distances between atoms in a solid. Their work provided a simple geometric basis for the analysis of crystal structures.

Crystalline and Noncrystalline Solids

All solid materials with a crystalline structure have atoms that are configured in a uniform pattern. The degree of order in crystalline solids is highly regular and *periodic,* that is, they are constructed by repeating a specific atomic arrangement. The internal order and external symmetry of crystals, as revealed by x-ray and electron diffraction techniques, indicate not only their physical nature but their chemical nature as well. A crystal is the most ordered atomic array with binding forces called *bonds.* The bonds themselves are somewhat elastic and the atoms can vibrate within their positions in the crystal lattice. External symmetry arises from this internal order of atoms and molecules which, in turn, determines a crystal's unique properties. The geometric orientation of a crystal lattice must be known in order to carry out diffraction experiments and to understand the behavior of electrons and properties in crystals. The analysis and classification of atomic arrangements in crystal structures are carried out in both two- and three-dimensional systems. Special notation is used to describe the various faces and the orientation or direction of their intersections in crystals. Miller indices, developed in 1839 by English crystallographer William H. Miller, provide a numbering system used to identify a crystal's various planes and axes.

The close-packed layers of atoms in the crystalline lattices of solids often contain imperfections or defects. These result from lattice vibrations that cause disorder in the crystalline array, atom vacancies or interstitial atoms in the lattice's framework, and dislocations that

Professor John D. Joannopoulos provides an animated explanation of how the tip of a scanning tunneling microscope can affect the structural properties of the surface it is measuring. He uses models of crystal lattices to help describe the atomic structure of the solid's surface. Professor Joannopoulos' research efforts in the field of theoretical condensed matter physics has resulted in the development of several calculational schemes and techniques used to study complex solid systems. (Photo by John F. Cook)

cause shifts or mismatches in the crystal's uniform pattern. Single crystals that are free of defects can serve as the starting material in microelectronic devices and integrated circuits. Efforts to produce defect-free crystals are aimed at raising the state of the art in this technology because the high electron mobility found in defect-free semiconductor materials would result in integrated circuits with extremely high operational speeds. Studies of crystal defects will enable scientists to artificially grow defect-free crystals and to design new synthetic crystalline materials.

Some materials that may appear to be hard and rigid, such as glass, wood, and plastic, are actually thick liquids because they lack a crystalline structure and have no set melting temperature. These amorphous solids have no long-range periodic structure, but they do exhibit short-range interatomic order. Another class of solids is called *quasi-crystalline*. Although they possess long-range orientational order, which indicates that they are not amorphous or glassy, their symmetry has no translational periodicity and is not consistent with accepted crystal symmetries. For example, polymers and liquid crystals may have quasi-crystalline properties. Unique quasi-crystals with five-fold symmetry were discovered in the early 1980s that promise a deeper understanding of different atomic arrangements in solids.

Physical and Electronic Properties of Matter

The various geometric properties of a material are directly related to its constituent atoms and the material's behavior is determined by how these atoms are held together. Thus, the electronic structure of a surface is closely tied to its atomic structure. In addition, a material's surface exhibits different properties than those observed elsewhere in the material. In studying surface phenomena, it is important to note that as a material gets smaller, the percentage of surface atoms increases, and the more its surface accounts for a material's overall behavior. As microelectronic devices become increasingly smaller, more of a device's atoms become surface atoms, and the device's behavior will depend increasingly on their structure. In the future, microelectronic devices that simply utilize a single surface layer measuring one molecule thick, a *monolayer,* may be possible. The work of theorists and experimentalists in surface physics is vital to the understanding and realization of these futuristic devices because it contributes to the knowledge of improved crystal growth and microfabrication techniques for semiconductors and metals.

Bonds and Bands

The way in which an atom will interact with another atom depends on its arrangement of electrons. The outermost, or *valence,* electrons govern these interactions. Bonding is based on the electrical attraction between one atom's total positive charge and another's negatively charged electrons. Atoms prefer to have closed electron shells, where all their electron orbits are filled up. In most cases, when an atom has a single electron in its outer shell, it wants to donate that electron to another atom. Conversely, when an atom has an outer shell that is almost full, it wants to attract an electron from another atom to complete that shell. Although there are several types of bonding, and more than one type can occur in a single crystal, *covalent bonding* is our focus here.

Covalent bonding, or electron-pair bonding, forms the crystal lattice in a crystalline solid and involves the rapid exchange of shared valence electrons between two nearest-neighbor atoms. Because these electrons are located in the outermost shell, they are more weakly attached to the nucleus and can be excited into the *conduction band,* which is the range of energies that freely moving electrons have within the structure of a solid. Electrons are no longer seen as occupying precise orbits, as they did in Bohr's model of the atom. The different electron shells are now considered to occupy discrete energy levels, as dictated by the *Pauli exclusion principle,* which states that no two electrons can simultaneously occupy the same energy level or quantum state within a system. Electrons can move from high- to low-energy bands to free up quantum energy, and from low- to high-energy bands to absorb energy. They can leave the atom entirely if they reach the highest energy levels in the atom. Each electron has a specific energy value that can be calculated by using quantum statistical wave equations. Between conduction bands are the energy regions where electrons are not allowed, known as *forbidden bands* or *energy gaps*.

Metallic bonding is an extension of covalent bonding where all the valence or outermost electrons are shared by all the constituent atoms of a material. In contrast to ordinary covalent bonding, where electron pairs are shared between atoms, the bonds between metal atoms generally involve less than two electrons; in effect, clouds of free electrons exist throughout the material. These free electrons possess the characteristics of both waves and particles, so they are not restricted to the quantum limits placed on them by an atom's quantum structure. Because the conduction band of a metal extends into its valence band, no energy gap exists, thus only a small amount of energy is needed to excite the electrons into the conduction band where they can easily move around and wander freely from atom to atom. These high-energy free electrons shared by all the atoms in a particular material account for the excellent conductivity characteristics of metals.

How a material will react to electrical forces is determined by how the material's atoms are arranged. In a solid, when external electrical energy is applied, it is transmitted to all the atoms locked tightly together in the material, and the entire object reacts. In liquids, the atoms are closely packed but they do not require the action of others to react. In gases, where the atoms are spread out, there is only occasional interaction between them. When atoms are arranged to form a particular solid, liquid, or gas, the arrangement of their electrons depends on their short-range interatomic forces that can be calculated using quantum theory techniques. These forces determine if electrons are free to move around in response to external electrical forces, thus enabling an electrical current to flow through the material.

A material's proficiency in conducting electrical charges is determined by the free electrical charges it is able to possess and the polarity of these charges. In metals, conduction electrons are not bound to individual atoms and can move freely through the material. Insulators have the electrons closely bound to their atoms, thus the material is not capable of carrying electrical current. They have all their valence bands filled with electrons, and for those elec-

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NEW EYE ON THE WORLD

Decked out in cardboard 3-D glasses, the audience looked ready for a showing of that 1950s Hollywood classic, *House of Wax,* with its hideous wax figures leaping out of the screen. But instead of Vincent Price, the leading man was a sinister oxygen atom that had invaded a quiet silicon neighborhood and thrown the local electrons into a tizzy. The theater was a room at the March 1992 meeting of the American Physical Society in Indianapolis; the "flick"—actually a series of slides—was "The Enchanting Properties of Oxygen Atoms in Silicon," produced and directed by MIT Professor of Physics John D. Joannopoulos. The very fact that such a documentary could be made is extraordinary. After all, none of science's powerful microscopes or other tools have the ability to peer into a solid piece of silicon, watch as an oxygen atom settles in, and record the reactions of the neighboring electrons. It's simply not possible.

Professor Joannopoulos' success is based on the discovery of the power of what is being called the *third branch of science:* computer simulation of reality. With simulations so accurate that they can take their place alongside experimental data as an object of scientific study, this "computer experimentation" is giving physicists a new eye on the world.

One of the most important and fundamental problems that has plagued device technology for the past 30 years has been the lack of a microscopic understanding of the role of oxygen in influencing and impeding the electrical properties of devices based on silicon wafers. To overcome this one needs to obtain a detailed understanding of oxygen as a substitutional and interstitial impurity in silicon and determine its migration and diffusion properties. This then can lead to a microscopic understanding of the aggregation properties of oxygen and the initial stages of oxidation.

Professor Joannopoulos and his collaborators have made enormous strides in bringing about a fundamental understanding of the role of oxygen in silicon. Their approach has been to perform theoretical experiments on a supercomputer using a quantum mechanical formalism they have developed where only the fundamental constants and the atomic numbers of silicon and oxygen are taken as input. In effect, they are using a *theoretical microscope* to probe into the workings of silicon on a subatomic length scale. Professor Joannopoulos says, "What I wanted to do is attack this problem by developing a technique that would really give me the sense that I was in the material—to imagine that I was an electron in the material."

Together with Robert Wolfe, a visualization expert at IBM, Joannopoulos and his collaborators devised a scheme for making sense out of the huge amount of data generated by these computer experiments. The result: a volumetric rendering technique using color, brightness and translucency that generates clearly resolved three-dimensional images of the electron density in the material. "Your eye immediately detects what's going on as the oxygen atoms move around in silicon," says Professor Joannopoulos. In a typical computer experiment a single oxygen atom is inserted into a periodic array of blocks of 64 silicon atoms and the fundamental quantum mechanical equations of the system take over. The computer then traces out the movement of the oxygen atom inside the silicon, monitoring the changes in the charge density, offering insight into how the intruder begins the oxidation process that can degrade the silicon used in integrated circuit chips. Already, Professor Joannopoulos and his colleagues have discovered that oxygen atoms migrate differently than previously supposed and that oxidation does not start in the ways that earlier theory proposed—a finding that could lead to improved processing of silicon.

The recent introduction of massively parallel supercomputer architectures into the mainstream of supercomputer technology paves the way for "theoretical microscope" studies of systems of unprecedented complexity. It is in this vein that Professor Joannopoulos and his colleagues have successfully completed a series of calculations to understand the atomic properties of one of the most controversial and widely studied surfaces of a solid. This is the 7 x 7 reconstruction of one of the faces of a silicon crystal. This extremely complicated structure has defied all realistic theoretical modeling in the past. While all comparable earlier efforts peaked at systems with periodic arrays of blocks containing about 100 atoms, the MIT group upped this figure to an unprecedented 700 atoms—enough to reproduce the full complexity of the silicon surface.

Modeling on this scale could eventually offer new insights into how defects and changes in composition alter the atomic structure of solids and hence their properties. "The excitement here is that you can now do *ab initio* calculations on real materials," Joannopoulos says, "and beyond that lies the possibility of theoretically designing and discovering completely new materials."

contributed by John D. Joannopoulos

(continued from page 5)

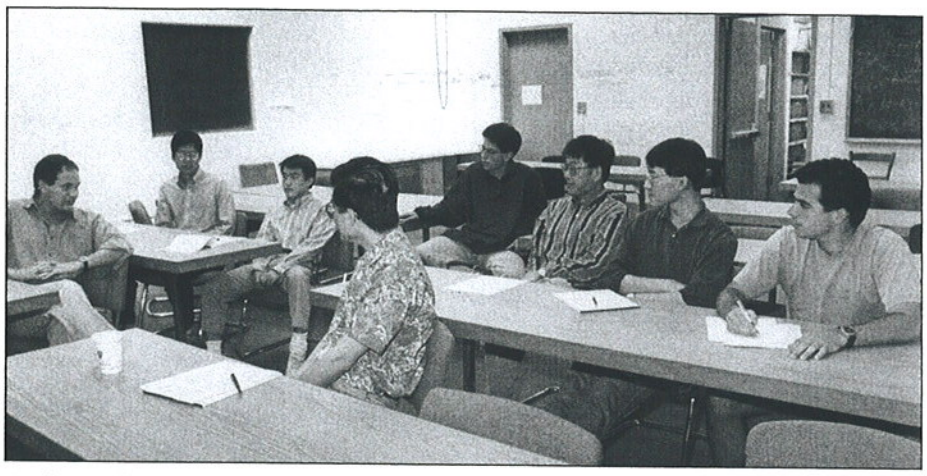
trons to move in a nonconducting crystal, they would have to cross the forbidden energy or band gap that separates the energy bands. In these materials, when external electrical forces are applied, the forces usually are not strong enough to free the bound electrons from their atoms. If a high enough voltage is applied, it can ultimately tear electrons away from their atoms. This is seen in nature, when electrical charges in a thunder cloud produce the plasma we know as a lightning bolt.

Semiconductors

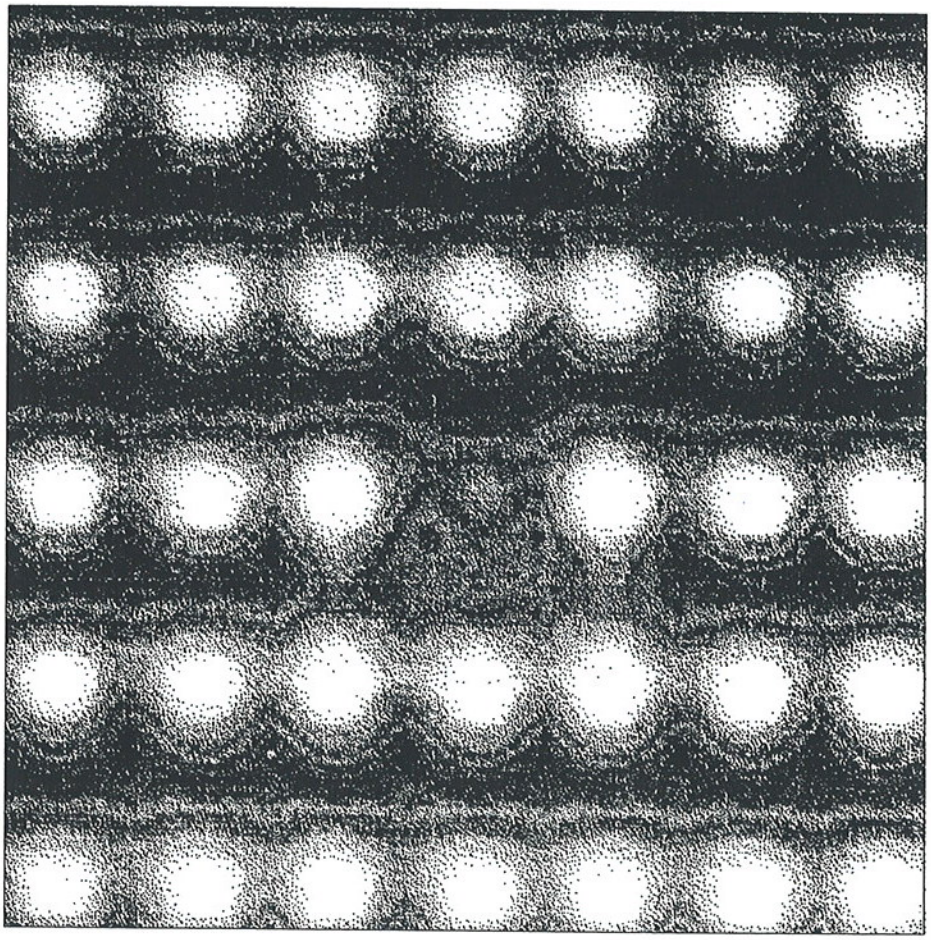
The understanding of crystalline structure and its properties is the keystone for the entire solid-state electronics industry, which was launched with the discovery of the transistor in 1947. William Shockley, a theoretical scientist at Bell Telephone Laboratories, predicted how an electrical force could control the flow of electrons through a semiconductor crystal. With help from fellow research team members John Bardeen and Walter H. Brattain, they produced the first solid-state transistor. Solid-state electronics has directly led to the burgeoning industry of integrated circuit microelectronics. Since 1960, the number of integrated circuit components on a chip has increased exponentially, and today an entire electronic system can be fabricated on a microchip substrate.

Solid-state electronics relies on the properties of quasi-metallic elements such as silicon and germanium. These two elements, the most common examples of semiconductor materials, are basic to the integrated circuit devices found in microelectronics. In pure form, these materials are insulators and only begin to conduct electricity when they are heated because of their narrow band gaps. When thermal energy is communicated to the valence electrons within these materials, some will gain enough energy to cross the forbidden energy gap and produce both negative electrons and positive holes that can move under the influence of an applied field to produce current. This is known as *intrinsic semiconductivity.*

Semiconductivity is also produced by the influence of specific impurity atoms such as phosphorus or arsenic. These impurity atoms, or *dopants,* have one more electron than is required for covalent bonding. The extra valence



Professor John D. Joannopoulos meets with several members of his research team to compare notes on some of the complex problems associated with accurate theoretical predictions of surface geometries and behavior. From left: Professor Joannopoulos; Research Assistants Jerry C. Chen and Shanhui Fan; Postdoctoral Fellow Kyeongjae Cho; undergraduate Joshua N. Winn; Visiting Scientist Hunhwa Lim; and Research Assistants Ickjin Park and Rodrigo B. Capaz. (Photo by John F. Cook)



In calculating the electronic structure of the clean and doped gallium arsenide (110) cleaved surface, Professor John D. Joannopoulos and his colleagues use theoretical cross-sectional scanning tunneling microscopy to investigate the initial stages of gallium arsenide heteroepitaxy on silicon. This positive-bias X-STM image shows the gallium arsenide (110) surface with a silicon impurity. What appears to be the missing gallium atom is actually the signature of the silicon atom.

electron has a relatively small binding energy and can be ripped away from its atom, thus being allowed to respond to an electric field. This material is called *donor* or *n-type* because conductivity is carried out by the electrons, which are negative charge carriers. In other cases, impurities are supplied by dopants, such as boron, that are deficient of a valence electron. If such a dopant atom can attract or accept an electron from another atom, it will produce a hole that will result in conduction. These are known as acceptor impurities, and conductivity will be produced by the positive holes, thus it is known as a *p-type* semiconductor.

Investigations into the nature of semiconductivity in various materials, as well as the nature of materials in non-semiconducting states, has become a focus for research in modern condensed matter physics. Although silicon is the dominant material used in semiconductors, research is ongoing to develop III-V semiconductor compounds, such as gallium arsenide (III and V represent the columns where these materials are located in the periodic table of elements).

Mastering the Probabilities in Quantum and Statistical Mechanics

In the early part of the 20th century, the conceptual evolution of several atomic models, coupled with controversies surrounding various wave-particle theories, served to encourage the development of mathematical techniques used in modern quantum mechanics. No less than five atom models were proposed, beginning in 1898 with Englishman J.J. Thomson's model and continuing through 1913 with Danish physicist Niels Bohr's model of the hydrogen atom. Bohr's model pictured the hydrogen atom as an electron circling a nucleus in a specific orbit. His widely accepted model assumed that matter consisted of discrete particles, but it did not take into account that matter also exhibited wave-like properties. Although many modern electronic devices would not have been possible without Bohr's atomic model and the simple particles and exact electron orbits that were part of physics earlier this century, a new perspective with a less specific interpretation of a material's properties was needed to permit a deeper look into this basic physical science.

Following Albert Einstein's 1905 paper on the photoelectric effect (in which light behaves like particles), other scientists contributed their views to the controversy surrounding particle-wave theories. What was needed was a set of laws that could account for both particle and wave behavior to explain both diffraction (where light and electrons behave as waves) and photoelectricity (where they are treated as particles) and how these phenomena could be calculated. In 1923, French physicist Louis de Broglie proposed that light was made of wavelike particles and that electrons were wave particles. Viennese physicist Erwin Schrödinger developed his mathematical equation for wave phenomena in 1926, based on Einstein's and de Broglie's assumptions. This was quickly followed in 1927 by Bell Labs' C.J. Davisson and L.H. Germer, who discovered that electrons diffracted from a crystal's surface in the same manner as x-rays, and similarly as light diffracted from a diffraction grating. That same year, Werner K. Heisenberg proposed the *uncertainty principle,* an essential concept of quantum theory that states it is impossible to determine both the position and speed of an object at one specific moment in time. In addition, the smaller an object, the more influence the uncertainty principle has on it, and the very tools used to measure or locate an object can actually distort the measurements an observer is seeking to obtain.

Heisenberg's principle provided the impetus for the investigation of other questions in physics, not only the determination of the exact position and momentum of atomic particles. Waves of matter were now seen as having probabilities. Conceptual visualizations could now be made of the rising and falling probabilities that particles will occupy a specific space, such as the wave peaks that surround an atom's nucleus which exactly match the most probable positions in an electron's path.

New mathematical techniques were developed in modern quantum mechanics, where fundamental, statistical laws of nature are characterized by complex equations. The equations represent probabilities and predict what is likely to be the average, not what the actual results will be. Quantum statistical descriptions, called *wave equations,* are used to predict the behavior of objects such as electrons. Wave equations indicate the likely position of an electron or quantum, for example, where packets of quanta may be located when the diffraction of light is performed. The ability to predict the pattern of electrons, when they are recorded as waves, is based on the individual research of Louis de Broglie and C.J. Davisson. de Broglie developed equations that not only treated waves as particles, but also particles as waves. He concluded that electrons exhibited this dual behavior and that solid matter, such as electrons, could behave as waves. As a result, an electron may behave like a billiard ball when it is a particle, or a sound wave when it is a quantum wave, or both. The laws of quantum mechanics can characterize all these behaviors, and quantum statistics is used to quantify the various energy states of atoms in motion and other phenomena.

Advances in theoretical understanding of materials and their properties and the development of accurate numerical simulations have changed the nature of surface science. Simulations of complex situations at several levels of length scales are used to describe electronic and crystalline structure at microscopic or atomic lengths, microstructures at the intermediate length, and on macroscopic scales related to bulk material properties. Modern computer systems with their unprecedented speed and capacity can quickly and correctly solve complex mathematical problems and produce highly detailed data analysis and measurements.

One quantum mechanical method used to predict the structure of a solid (assuming zero-temperature ground state and a regular crystalline atom array) involves calculating the total energy of the solid as well as a configuration that minimizes its total energy. This is accomplished by determining the position of the atoms, using self-consistent density-functional and pseudopotential methods to determine the electronic ground state energy, and computing the total energy and comparing it to other configurations to find the equilibrium state of the entire system.

New microscopic theories of quantum systems may help scientists in the future to theoretically design materials with specific electronic or mechanical properties. Studies that investigate the behavior of materials could simulate chemical reactions, radiation, or other conditions within or on the surface of a material, even under conditions not available in the laboratory.

Probing Techniques: More to the Surface Than Meets the Eye

Studies in surface physics involve the quantitative measurements of a material's electrical, optical, thermal, and magnetic characteristics. These measurements also focus on the behavior of a material's response to externally applied electrical fields and temperature gradients. The first methods used to probe the structure and composition of solids included the light microscope, x-ray diffraction, and infrared and ultraviolet spectroscopy. The science of spectroscopy was originally used to determine the chemical composition of materials and new techniques were developed to detect structural properties as well.

The advanced instrumentation that has been developed to probe the mysteries of matter and its properties provides high-intensity sources of radiation for increased sensitivity and resolution. National laboratory facilities were established in the 1940s by the Atomic Energy Commission as major research centers for nuclear development and high-energy physics. Under the Department of Energy, these centers were built around large, expensive apparatus such as nuclear reactors, accelerators, and synchrotron light sources that provided energy systems and materials development for defense and civilian purposes. High-intensity electron or proton storage rings, originally built for reactor development, are now used for neutron scattering. High-intensity photon beam reactors, originally used as high-energy physics machines, are now used as synchrotron radiation sources.

Synchrotron light consists of a continuous spectrum of electromagnetic radiation, ranging from infrared to x-rays. When electrons are accelerated in a synchrotron, they radiate coherent energy in the form of electromagnetic waves. The light produced has several advantages in terms of using the synchrotron as a research tool. Synchrotron beam intensity is many orders of magnitude greater than conventional beams that are generated in a laboratory. The beams are highly polarized and forward directed and can be used to analyze very small or highly diluted samples. Either the full synchrotron spectrum or specific spectrum energies may be selected when carrying out specific experiments.

The National Synchrotron Light Source (NSLS) at the Brookhaven National Laboratory on Long Island is currently the nation's largest experimental facility dedicated solely to the production of synchrotron light. At the NSLS, light is produced by accelerating bunches of electrons in two closed-orbit storage rings. The vacuum ultraviolet ring stores electrons at 750 million electron volts of energy to produce infrared, visible, and ultraviolet light. The other ring is an x-ray ring that stores electrons at 2500 million electron volts and extends capabilities into the higher energy x-ray region. Seven storage ring insertion devices, very powerful magnets called *wigglers* and *undulators*, increase the range and intensity of the synchrotron light. Seventeen beam ports on the vacuum ultraviolet ring and 30 ports on the x-ray ring support a total of 83 beam lines where research is conducted. Scientists from university, industrial, and government laboratories from the U.S. and abroad perform basic and applied research in a variety of disciplines at the NSLS. Researchers study the absorption and scattering of light to determine the properties of matter such as crystalline structure, bonding energies of molecules, details of chemical and physical phase transformations, electronic structure, and magnetic properties. The properties of synchrotron light are well matched to surface studies that lead to a better understanding of surfaces on the atomic level.

A variety of other experimental methods that involve diffraction, microscopy, and spectroscopy are used to probe the surface of solids:

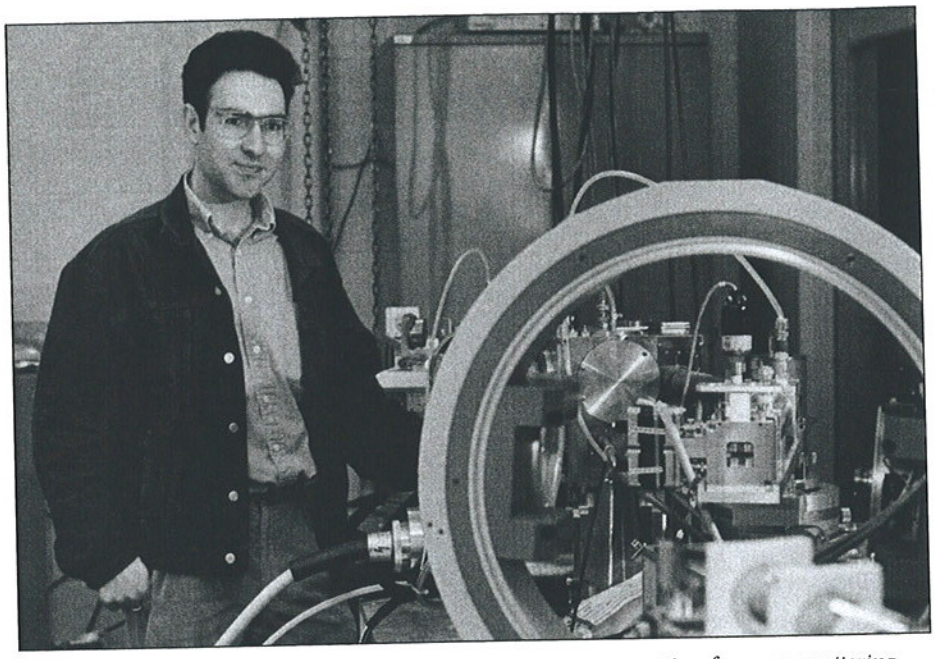
Scanning and electron microscopies are used to probe geometric structure. The scanning tunneling microscope (STM), developed in 1981 by Nobel laureates Gerd Binnig and Heinrich Rohrer, can produce a *micrograph* (microscope photograph) of individual atoms. It exploits a quantum mechanical phenomenon—the tunneling of electrons below the tops of energy barriers—in order to collect highly accurate information about individual surface atoms. A stylus probe is held near the surface of a material and generates an electric current into the material's surface. By making several passes over the surface, the location of the electron clouds can be determined, and the rate at which electrons tunnel quantum mechanically from the surface to the probe is measured. With this information, a picture of individual atoms can be formed. The STM can even detect reconstructed surfaces, defects, edge steps, and dangling atomic bonds. Since STM is limited to the study of metal surfaces, atomic force microscopy (AFM) can be used on both nonmetallic and metallic surfaces. AFM employs interatomic forces to record surface images on an atomic scale.

Electron microscopy can obtain nearly atomic resolution of a material's atomic arrangement and chemical composition. This technique requires a clean sample that meets ultrahigh-vacuum standards in order to provide surface characterizations such as reconstruction and phase transitions. Scanning transmission electron microscopy (STEM) has made possible new imaging techniques by using inelastically scattered electrons, emitted x-rays, and other forms of an elastically scattered beam. Low-energy electron microscopy reveals defect structures on surfaces by using a field emission source that creates a bright beam collimated at high energy and is then decelerated before being back-diffracted from the sample. The beam is magnified and forms an image of the sample. Low-energy diffraction increases the surface resolution and diffraction intensity. Low-energy electron diffraction (LEED) techniques were developed by L.H. Germer (of Davisson-Germer fame) as a display system in surface chambers. LEED measures the actual translational symmetry of a surface, but does not indicate the nature of surface reconstructions. New techniques have been developed to enable the observation of diffuse low-energy scattering from surfaces.

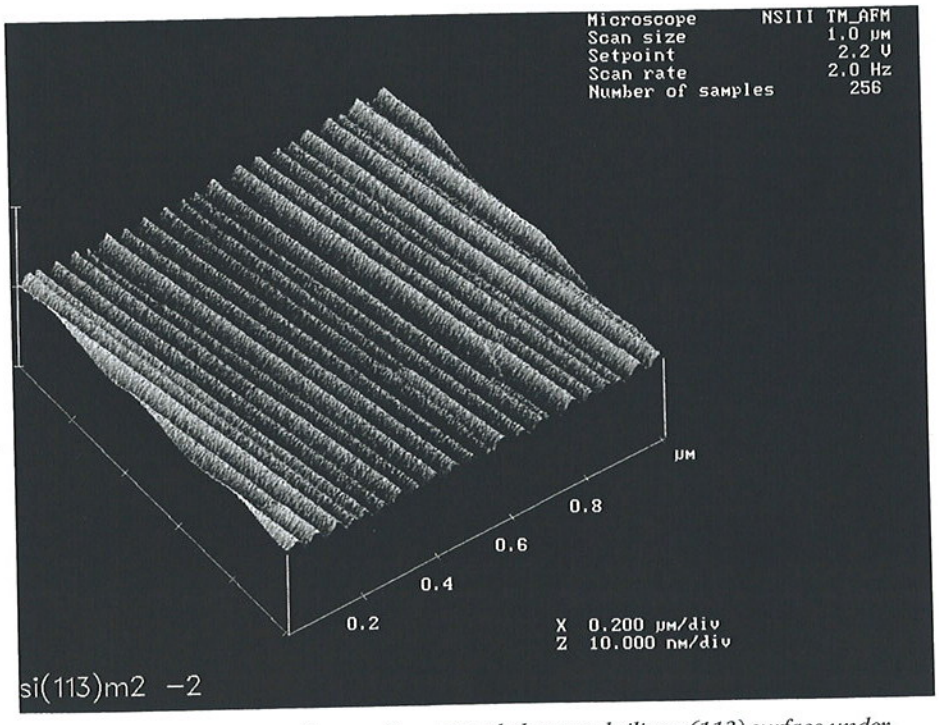
Surface vibration spectroscopies probe the atomic motion at the surface. These methods include: High-resolution electron loss spectroscopy, where monoenergetic electrons are inelastically scattered from a surface, and its energy is analyzed to measure the vibration of molecules adsorbed on the surface or phonon modes of clean surfaces; inelastic atomic scattering that measures surface phonon dispersion; and surface infrared spectroscopy that measures the differences between two states of a surface in terms of its chemical, geometric, and electronic properties.

Research in RLE's Surfaces and Interfaces Group

Professor Robert J. Birgeneau investigates the properties of surface structures and their transitions. The objective of his



Professor Simon G.J. Mochrie adjusts a diffractometer in preparation for x-ray scattering studies of surface structure. The phase behavior, structure, and stability of both metal and semiconductor surfaces are the focus of Professor Mochrie's research. He is currently participating in the development of a new six billion-electron-volt synchrotron radiation facility at the Argonne National Laboratory. The Advanced Photon Source will be used for x-ray correlation spectroscopy to study the dynamics of condensed matter at atomic-length scales. (Photo by John F. Cook)



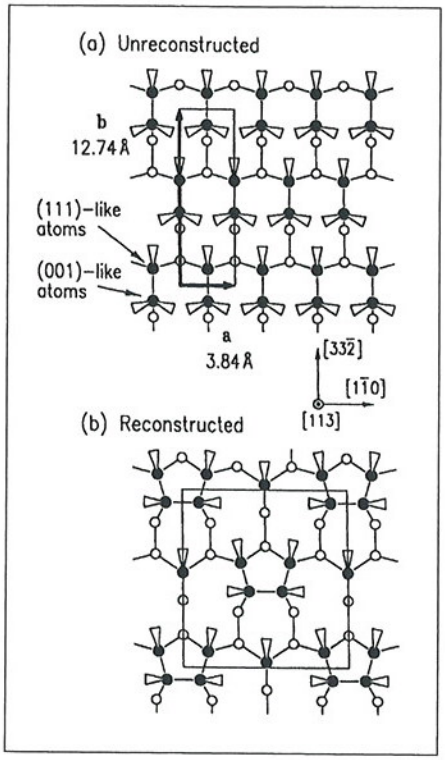
An atomic force microscopy image of an annealed, stepped silicon (113) surface under study in Professor Simon G.J. Mochrie's research group. This sample was prepared by heating it in an ultrahigh vacuum, then slowly cooling it to room temperature. Below 1134 K, steps on the silicon (113) surface condense to form large (114) facets. The resulting surface, a hill-and-valley structure composed of atomically smooth (113) and (114) facets, is caused by a thermodynamic faceting transformation. The average facet size is about 200 to 300 angstroms.

research is to understand the morphologies and microscopic structures of simple semiconductor and metallic surfaces at high temperatures. Using modern x-ray scattering techniques, Professor Birgeneau and his colleagues study structures and phase transitions in thin films and on surfaces. Their work is carried out at two principal facilities. At MIT, four high-resolution computer-controlled x-ray spectrometers are used in their experiments. At the National Synchrotron Light Source at Brookhaven National Laboratory, three fully instrumented beam lines are employed for high-resolution x-ray scattering experiments. Scanning tunneling microscopy is also used to provide information on local surface structure. In collaboration with Professor Simon G.J. Mochrie, a second-generation x-ray surface facility was recently built that allows a wide range of surface scattering experiments. Several surface phenomena continue to be investigated including roughening, reconstruction, melting, amorphization, and dilution.

Using high-resolution x-ray diffraction, Professor Birgeneau has studied the surface structures and morphologies of silver and gold, two noble metals. For silver, his studies found that increasing temperature causes roughening phenomena at 450° C, which is below the metal's bulk melting temperature of 962° C. This process was found to be completely reversible. In the case of gold, which melts at 1065° C, both roughening and deconstruction of the surface was observed at 485° C. This unusual behavior exhibited by gold, which is contrary to current theoretical ideas, is still being investigated.

Other studies include research on *vicinal* (stepped) semiconductor surfaces, where x-ray and optical diffraction techniques are used to probe novel nonequilibrium phenomena. Understanding the factors that control the morphology and perfection of vicinal semiconductor surfaces may lead to improved electronic device processing and semiconductor device performance. In collaboration with Professor Mochrie, detailed x-ray scattering studies are also being carried out to probe the microscopic symmetry of the three-dimensional-to-disordered phase transformation of the Si(113) surface, which has exhibited a new two-dimensional universality class. Finally, studies have been conducted on the melting transition of near-monolayer xenon adsorbed into

the basal planes of single-crystal graphite. Xenon on graphite is widely regarded as a model system for two-dimensional melting in the presence of a weak orientational ordering field. Professor Birgeneau's investigations have confirmed that, at 140 K, there is a continuous evolution of length scale of positional fluctuations that corresponds to the transition of a finite-sized, limited two-dimensional solid to a well-correlated, orientationally ordered two-dimensional liquid.



Professor Simon G.J. Mochrie's group has carried out x-ray diffraction measurements to determine the three-dimensional structure of the Si(113) surface. A top view of the (Si)113 surface is shown in (a), where the centered unit cell is outlined. Solid circles illustrate the silicon atoms in the surface layer and open circles indicate atoms in the lower layers. The solid lines show bonds between neighboring atoms and triangles represent dangling bonds. A top view of the Si(113) (3 x 1) reconstruction is shown in (b) with the centered unit cell outlined. The (3 x 1) structure is formed from the unreconstructed surface by removing every third (001)-like atom in the (1 -1 0) direction, dimerizing the two remaining (001)-like atoms, and rebonding the (111)-like atom that neighbors the vacancy to the layer below. This work constitutes the first definitive determination of the (3 x 1) structure of the Si(113) surface.

Advances in ultrahigh vacuum technology have made microscopic studies of surface systems possible. Understanding the aspects of the phenomenon known as *faceting* (how atoms move in order to reduce surface energy, the number of atom layers involved in this process and the resulting electronic and vibrational states, and the final symmetry of the surface layer) will help to explain the nature of clean surfaces, chemisorption processes, and the initial stages of interface formation. Professor John D. Joannopoulos and his group are at the forefront of solving the complex theoretical problems associated with these issues. Their efforts are focused on developing new techniques for calculating the total ground-state energy of a surface from *ab initio* or "first principles." *Ab initio* calculations do not use semiempirical models, preconceived ideas, or experimental interpretations to produce results, although they are used in combination with experimental observations. The theoretical techniques previously developed by his group enabled the first microscopic model of heteroepitaxial growth to be developed. These techniques are applied to various phenomena such as surface growth and reconstruction, structural phase transitions, and chemisorption in order to obtain accurate theoretical predictions of surface geometries and behavior.

Using *ab initio* simulations, Professor Joannopoulos has carried out an in-depth investigation of gallium arsenide (GaAs) grown on silicon (Si) substrates. The resulting *ab initio* calculations have revealed that conventional two-dimensional epitaxial growth is not possible on terraced regions of a silicon surface. Two-dimensional growth on these regions stops after only a few monolayers and three-dimensional growth proceeds at double-layer steps. Investigations continue into the initial stages of heteroepitaxy of gallium arsenide on silicon using cross-sectional scanning tunneling microscopy. In other research, scanning tunneling microscopy was used to show the presence of numerous dimer, or atom pair, vacancies of the Si(100) surface. *Ab initio* total energy calculations of over twenty defect complexes were combined with statistical mechanical and kinetic arguments to construct a realistic theory of this system and its intrinsic defects.

The goal of Professor Simon G.J. Mochrie's research program is to obtain a detailed description of the structure, phase behavior, and morphology of semiconductor surfaces, particularly silicon. The results of these studies are essential to theoretical efforts aimed at understanding the energetics of the silicon surface. Professor Mochrie and his colleagues employ high-resolution x-ray scattering for surface x-ray diffraction studies of step structures on semiconductor surfaces, which are carried out using an ultrahigh vacuum apparatus at Brookhaven Laboratory's National Synchrotron Light Source. These studies help to determine the atomic positions of the steps and how temperature affects their behavior. Often, semiconductor surfaces can be stepped, and unless a wafer of the material is cut and polished absolutely parallel to its crystalline planes, the surface will consist of flat terraces separated by steps. In molecular beam epitaxy (MBE), a flat surface prevents monolayer growth because it lacks a center for nucleation. Thus, most wafers are miscut to create these surface steps. The ability to understand these step structures is important because of the increased used of MBE to create electronic structures and devices.

Professor Mochrie has recently completed a comprehensive x-ray scattering study of the Si(113) surface structure. Current crystallographic techniques make it possible to determine the full three-dimensional atomic structure of a surface with high accuracy. Knowledge of the atomic structure is critical for evaluating the calculations of surface energetics. X-ray diffraction measurements carried out by Professor Mochrie on the Si(113) surface was the first definitive description of its full three-dimensional atomic structure. Faceting transitions, surface roughening, and surface reconstruction are some of the related physical issues that he has investigated to further the understanding of step structures on semiconductor surfaces.

Other surface science investigations at RLE include the dynamics of chemical reactions at surfaces and the statistical mechanics of constrained electronic systems and semiconductor surfaces. *RLE Progress Report Number 136* provides a highly detailed report on the latest findings of the research described in this article.

by Dorothy A. Fleischer

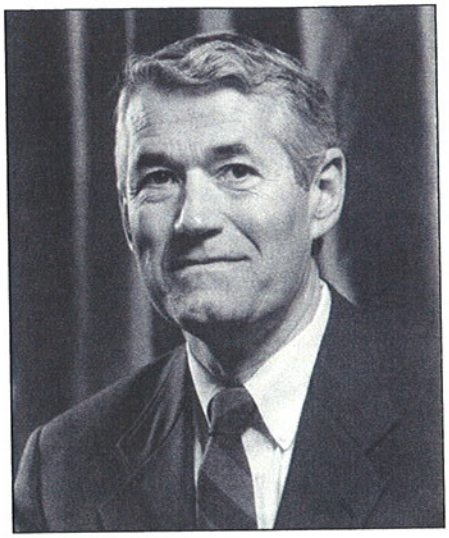
FACULTY PROFILE:

Robert J. Birgeneau

In 1975, Dean Robert J. Birgeneau came to the MIT physics faculty from AT&T Bell Laboratories. The Toronto native, a graduate of the University of Toronto (BSc '63) and Yale University (PhD '66), pursued research in the field of experimental neutron scattering early in his career and became widely recognized as an outstanding solid-state spectroscopist. He joined RLE as a principal investigator in 1976.

Dean Birgeneau and his colleagues investigate phases and phase transition behavior of novel states of matter and have pioneered the use of x-ray synchrotron radiation for high-resolution studies. In recognition of their work in studies of two-dimensional phases and phase transitions by diffraction methods, Dean Birgeneau and Dr. Paul Horn received the Bertram Eugene Warren Award of the American Crystallographic Association in 1988. Dean Birgeneau also received the American Physical Society's Oliver Buckley Prize in 1987 and the U.S. Department of Energy's Materials Science Outstanding Accomplishment Award in 1988. The American Association of Physics Teachers named him the 48th Richtmyer Memorial Lecturer in 1989.

In 1982, he was appointed Cecil and Ida Green Professor of Physics and served as RLE's Associate Director from 1983 to 1986. Following a three-year tenure as head of the Physics Department, he was appointed Dean of MIT's School of Science in 1991. Dean Birgeneau is a Fellow of the American Academy of Arts and Sciences, the American Association for the Advancement of Science, and the American Physical Society. He has served on the advisory committee and boards of many government agencies and professional organizations, including the Boston Museum of Science and the Argonne National Laboratory.



Dean Robert J. Birgeneau
(Photo by John F. Cook)

• What motivated you to work in the field of solid-state physics?

In 1963, I had just finished as an undergraduate in mathematics at the University of Toronto. My first thoughts were to go to MIT to attend the Sloan School and do operations research under Professor Jay Forrester. That summer, I had a job at Chalk River Labs in northern Ontario, Canada, where what became known as the field of neutron scattering was pioneered. The group at Chalk River was interested in studies of lattice dynamics or acoustic vibrations in metals. I worked with another student, John Cordes, who is now a professor at Dalhousie University studying quantum optics theory. The lab wanted to begin a program on transition metals, so it was a good project for the two of us. As circumstances would have it, the scientists in charge had to go away for most of the summer. John and I spent the first month reading a graduate-level textbook and teaching ourselves solid-state physics. We spent the rest of the summer measuring the lattice dynamics in nickel metal. We performed and completed all the experiments correctly and did most of the analysis ourselves. When our mentor Gerald Dolling returned, he congratulated us on our efforts, and then we produced a draft of a paper that was subsequently published in the *Physical Review*. I think it's still my most referenced paper! That job essentially taught me solid-state physics, which I thought was rather exciting research with a good combination of experiment and theory, and I learned to do experiments. It also made me realize that I enjoyed doing research and I might even have a talent for it. Based on that, I decided to go to graduate school in physics at Yale.

There was a person from my summer job, Dave Woods, who explained something quite interesting to me. At that time, the dichotomy between experimentalists and theorists was much larger than it is today. The experimentalists were very apparatus oriented and the theorists provided a conceptual framework for physics. Dave said that physics research was going to change, and there was going to be an enhanced role for people who could not only understand deep theoretical issues, but could also do the experiments to address those issues. He also said that the nature of experimental science was going to change because of the advances in computers. This would make certain kinds of experiments much easier and much more effective. In turn, this meant that there was going to be a new kind of career for someone with theoretical depth who could do such experiments to influence the fundamental issues. Dave thought I would be good in such a role and told me that I should not become a theorist, which is what I thought I would do, because in those days if you majored in math and got good grades—that's what you did. His advice greatly influenced me.

• What was the nature of your work with Professor Werner Wolf at Yale?

Very little solid-state physics was going on at Yale at the time of my graduate studies. I was grateful that Werner had just arrived from Oxford to set up a new research program in magnetics. We used electron spin resonance spectroscopy to look at the properties of magnetic ion pairs in solids. It was useful to learn about local behavior in solids, but the rest of the field was beginning to address more fundamental issues, so I did not stay with that work. Werner is a wonderful person and has been a friend ever since our work at Yale. He thinks deeply about physics,

and as my graduate advisor, he was my role model in the sense of how I would try to pattern my own life as a professor. He treated the students in his lab like professionals, not like serfs.

After I graduated from Yale in 1966, I stayed on as an instructor in the School of Engineering for one year. Then, Peter Wolff at Bell Labs in Murray Hill, New Jersey, hired me and agreed that I could go to Oxford for a year as a postdoc before I joined Bell. During my stay at Oxford, Bell decided to diversify their basic research. Several people who were just hired (including myself) would be allowed to choose a research area and do whatever they wanted. Since I was basically given a ticket to go in any direction, I thought more about what I wanted to do. Also at that time, the High Flux Beam Reactor at Brookhaven National Laboratory on Long Island was commissioned and research was just starting. When I read the first research papers that came out of there, I realized this was a tremendous opportunity to work at a new facility with capabilities far beyond anything that existed in the world. We were excited about this, since it was a capability Bell wanted but did not have.

• ***Could you describe the various spectroscopy techniques used in your research?***

There are three basic objects that we can scatter in order to understand matter—electrons, photons, and neutrons. It's difficult to have a research effort that utilizes all three; that's part of the constraint. Which one we choose depends on what we're trying to understand. We must also decide what kind of information we want in order to determine which probe would be best to use. For example, if I wanted to work exclusively on surface problems, I would use a combination of photons in the x-ray range and electrons.

Many beautiful experiments are done with visible photons from lasers, but we need to understand matter at a microscopic level. The basic problem is that the wavelength of laser light is typically a few thousand angstroms, so we cannot use optical photons to probe microscopically. In the type of physics we do, we start at the atomic level and try to build up to the macroscopic level, using a probe that starts at the size of an atom and connects to the macroscopic world. Since we need an angstrom-level probe, we could use electrons, but they do not penetrate far enough and they interact strongly with matter, making it hard to interpret the results.

That leaves x-ray photons and neutrons to consider. Although both have disadvantages as probes, they both take measurements at the angstrom level and interact weakly with matter, so we can interpret scattering patterns quantitatively. Neutrons are neutral and can penetrate any material; a neutron beam can pass through an inch of aluminum without hardly being diminished. The neutron is like a tiny dipole refrigerator magnet, and it can see other magnets inside of materials. The neutron also detects vibrations of the nuclei. So we use neutrons to study the microscopic magnetic and structural properties of materials.

Generally speaking, neutrons and x-rays are complementary. X-rays couple to charge, so we use them to see electronic charge. Neutrons cannot detect charge, they see only mass and spin. X-rays can see charge because the electric field of the x-ray photon couples to charge in materials, enabling us to detect the electron charge distribution. In recent research, x-rays were found to detect spin, but with a cross section a million times weaker than that of neutrons. X-ray techniques are more difficult to use, but when they work, they work wonderfully. So, we use neutrons or x-rays, depending on whether we're looking for mass, spin, or charge fluctuations.

• ***How has increased x-ray beam intensity had an impact on the success of your experiments?***

It's been revolutionary, and we've been lucky in terms of its timing in history. We were able to play an important role in developing the utilization of a first-generation synchrotron source whose beams could provide a spatial resolution somewhere between 100 and 1000 times better than that obtained using beams from a normal x-ray machine. This has opened up new areas of research that can only be accomplished by using synchrotron sources, one of which is the work that Professor Simon Mochrie and I have done on semiconductor and metal surfaces. The source we use for our current experiments is primarily the National Synchrotron Light Source at Brookhaven, where we have several x-ray beam lines in partnership with IBM.

• ***Could you describe Brookhaven's synchrotron facility?***

It has two rings, one operates in the ultraviolet range and the other ring operates in the x-ray one-angstrom range, which is where I do my experiments. There are 30 different ports, and each port has two or three spectrometers with a total of about 75 spectrometers. When the facility is fully operational, there are experiments being conducted on every one. People come from around the world to work there, and the facility is heavily oversubscribed. What's really exciting about this research is that it's basically a young person's field. When you walk into the synchrotron facility at Brookhaven at one in the morning, probably 50 people, with an average age of about 26, will be working on their experiments. We've never before had a facility that operated 24 hours a day with 50 to 75 experiments going on simultaneously. People are there all the time, talking to each other and exchanging ideas—industrial people, university people, government people, graduate students, postdocs, professors, and even a few administrators.

What's really exciting about this research is that it's basically a young person's field.

We've been fortunate to obtain funding to use the new Advanced Photon Source (APS) that will be commissioned at the Argonne National Laboratory in Chicago in 1996. This third-generation light source will give us another factor of 1000 in beam brightness and will enable a variety of experiments that

are currently not possible. Some of the experiments that we plan to do at this source use light beating spectroscopy techniques. This is analogous to what can already be done with lasers in the visible wavelength range. Using x-rays, we will be able to look at the dynamics of objects on the time scale of a millisecond to thousands of seconds at the angstrom distance level.

• *What brought you to MIT?*

Although I had worked at Bell for almost eight years and really enjoyed it, I was interested in education and working with graduate students. At Bell, if you had "human" talents, there was tremendous pressure to go into management. If I stayed, I'd ultimately be pursuing an administrative career. That was the last thing I wanted to do at that time, even though I had just become the research head of the Scattering and Low Energy Physics Department. I wanted to do undirected basic research as long as I could, and I knew it would be easier to do so in a university environment. One possible option seemed to be Harvard. I discussed this with Werner Wolf at Yale, and he said, "When you think about where you want to end up, remember one thing: at MIT, science and engineering will always matter." Fortunately, Peter Wolff, who had hired me at Bell, was now on the MIT faculty and responsible for building up an effort in solid-state physics. Since he had hired me before, and I wasn't a total failure, he hired me again at MIT. I must say that my expectations, in terms of the graduate students at MIT, have been surpassed. I have had many outstanding students here who have gone on to very successful careers in universities, industry, and national laboratories.

• *What has been the progress of your work in RLE?*

When I came to MIT in 1975, I wanted a lab where the students could do preliminary experiments, and then at some point, go off to do experiments at national facilities, such as those at Brookhaven. I decided to try something new in order to diversify my research, so I planned a program in x-ray scattering. Previously, there had been x-ray diffraction research for its own sake at MIT. Professor Bert Warren was a leader in this field, but our approach was rather different. We were less interested in characterizing x-rays and their interactions with matter and more focused on using them as tools to elucidate new kinds of physics.

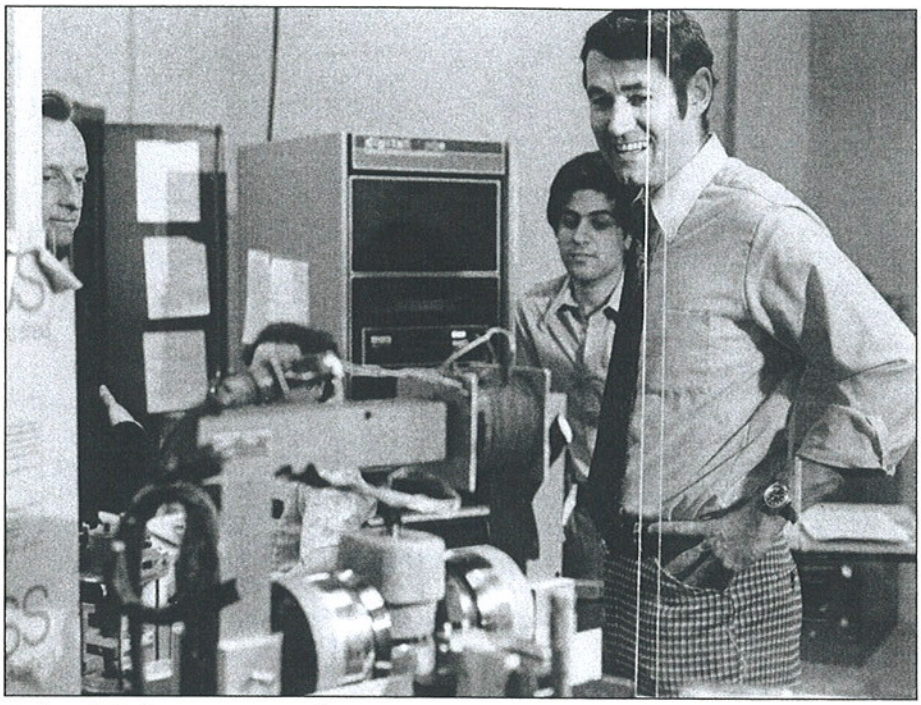
We've been fortunate to obtain funding to use the new Advanced Photon Source that will be commissioned at the Argonne National Laboratory in Chicago in 1996. . . Using x-rays, we will be able to look at the dynamics of objects on the time scale of a millisecond to thousands of seconds at the angstrom distance level.

In some ways, my RLE research has probably been the most creative work that I've done at MIT. It was about 1970 when Dave Litster started a research program in liquid crystals. Few experiments had been done in that field using x-ray techniques, and it seemed that the experiments could be done much better than what had appeared in the literature. Dave came to me with some very creative ideas on using x-rays to study liquid crystals. I quickly educated myself on the science of liquid crystals, and we began a new research direction in RLE. We were joined by an outstanding Danish physicist, Jens Als-Nielsen, and the three of us launched a program using x-rays to study liquid crystal materials. By synthesizing and integrating information from our individual experiments (x-ray information from our own liquid crystal experiments together with information from Dave's light scattering experiments and heat capacity data from Carl Garland of the chemistry department), we were able to make significant progress in understanding the nature of liquid crystals and their phases.

Our next major research program with x-rays, which has probably had the most long-standing impact, was our work that started in 1978 with Paul Horn. Paul was then with the University of Chicago and had come here on sabbatical. At that time, people at Brookhaven were using neutrons to characterize the properties of single layers of rare gas atoms on exfoliated graphite. I studied that work and realized that x-rays could do a better job. Under the sponsorship of the Joint Services Electronics Program in RLE, we looked at the physics of monolayers of rare gases adsorbed onto both turbostratic and single-crystal graphite. It turned out to be a novel and rich area of research that contained much of the basic physics important in a variety of surface problems.

In the course of those studies, Paul and I talked with David Moncton of Bell Labs, who was an MIT graduate. Dave realized that we could do much better by using x-rays emitted by large particle physics machines. We worked together at the Stanford Synchrotron Radiation Laboratory, exploring the use of synchrotron radiation to study condensed matter and emphasizing the physics of single layers of rare gas atoms adsorbed on graphite. It turned out that the synchrotron's geometrical characteristics were quite favorably matched to study surface physics as well as other problems such as thin films of liquid crystals. The wave-vector resolution was orders of magnitude higher than what had been available in previous experiments, and we obtained better information on the phases that occur on surfaces as well as very precise line shape information. We were able to analyze the data quantitatively in a way that is still not possible with traditional surface probes.

Horn, Moncton, and I got to play a seminal role in developing synchrotron radiation techniques for high-resolution condensed matter studies. These techniques eventually made possible research we hadn't even anticipated. Today, this field is a multibillion-dollar worldwide endeavor that had its roots in the early experiments carried out at Stanford by our group and, of course, many others. In terms of its impact on science, our early role in helping to develop the field of high-resolution synchrotron x-ray scattering may well be the single most important achievement



In this 1980 photo, Visiting Professor Jens Als-Nielsen, graduate student Cyrus R. Safinya, and Professor Robert J. Birgeneau discuss the x-ray scattering methods used in their investigations of the structure and dynamics of liquid crystals. (Photo by John F. Cook)

in all three of our careers. For this and related work, I received the American Physical Society's Buckley Prize, Paul and I were corecipients of the American Crystallographic Association's 1988 Warren Prize, and Dave received the Department of Energy's Lawrence Award. Paul is now head of IBM's Almaden lab and is responsible for next-generation storage devices. Dave is associate director of the Argonne National Lab and is responsible for the billion-dollar Advanced Photon Source that will be commissioned in 1996.

• ***Why did you shift the focus of your studies from model systems to more practical systems?***

It was a conscious choice, and in retrospect, I regret that I did not do it a few years earlier because it would have more of an impact on our work today. We initially studied model systems partly because we wanted to address fundamental issues concerned with the nature of phases on surfaces. We did an elegant family of experiments on rare gases on graphite. By the mid-'80s, we were beginning to experience diminishing returns, although we were still discovering new phenomena. We decided to switch to metal and semiconductor surfaces, which are of practical importance and more in the mainstream of surface science. Our first research involved the noble metal silver, looking for a phenomenon known as surface roughening.

• ***What is surface roughening?***

You might think that in a quiescent state, any surface, such as the ocean for example, would be perfectly flat. However, at any nonzero temperature, there will always be waves, simply due to natural thermal effects. If the ocean was infinite in its extent, the amplitude of the surface fluctuations would actually be infinite, albeit varying logarithmically with the size of the ocean. You do not sense this when you are in a bathtub full of water because the amplitude of the surface fluctuations is truncated by the tub's size. We might ask if this roughening phenomenon also happens on the surface of a crystal. At low temperatures, the answer is no, because there is a difference between the lattice structure of a solid and the continuum of a liquid. However, as we heat the crystal up, its surface structure becomes increasingly disordered, and at some stage, its surface starts to fluctuate wildly.

The concept of roughening is sufficiently counterintuitive that many people have been reluctant to accept it—the idea that a surface could have infinite height fluctuations. Roughening was predicted theoretically and perceived inferentially, but there was never any unambiguous, direct evidence. Proving it is a very delicate matter. We must show that the surface has entered a unique phase of matter with divergent height fluctuations. This turns out to be technically quite difficult. Among other things, one must prove that any anomalous behavior is an intrinsic property of the surface and not a result of impurities condensing down onto the surface. In the case of silver, it's more devious because impurities come from inside the silver. However, we believe that we have demonstrated roughening on the (110) surface of silver quite convincingly. Simon Mochrie has recently done a magnificent experiment that demonstrates roughening on a platinum metal surface at high temperatures.

• ***Could you characterize your work on semiconductor surfaces?***

Prior to our silicon work, we did some experiments on tungsten surfaces, but those studies were unsatisfactory. Specifically, in order to answer the questions at hand, we needed perfectly clean surfaces, and we could not keep tungsten clean long enough in order to do the physics we wanted to do properly. That left me a little jaded about our ability to do high-quality synchrotron x-ray studies on chemically active surfaces. I felt it might not be possible to investigate properly the deep issues that we wanted to address in surface physics. Then, just because I thought we ought to try a semiconductor anyway, we started with silicon. To my total shock, semiconductor surface problems turned out to be relatively simple and technically much easier than transition or noble metals. Our semiconductor surface experiments with silicon and germanium in an ultrahigh vacuum environment were no more difficult than the rare gas

on graphite experiments we had done many years before.

Since we started to study semiconductor surfaces relatively later than others, we feared that all of the important problems might well have been solved. That was actually far from the truth since there was still a cornucopia of unanswered questions when we started this work in 1988. Of course, there's been an explosion in the last several years, primarily because of the profusion of technical developments with a variety of probes. The scanning tunneling microscope was discovered in 1981, and it has become an essential tool. There's also been a tremendous improvement in electron microscopy techniques. Suddenly, a lot of new information on surface structure and dynamics is available as a result of these technical developments. It is truly a very exciting time right now in the field of semiconductor surface physics.

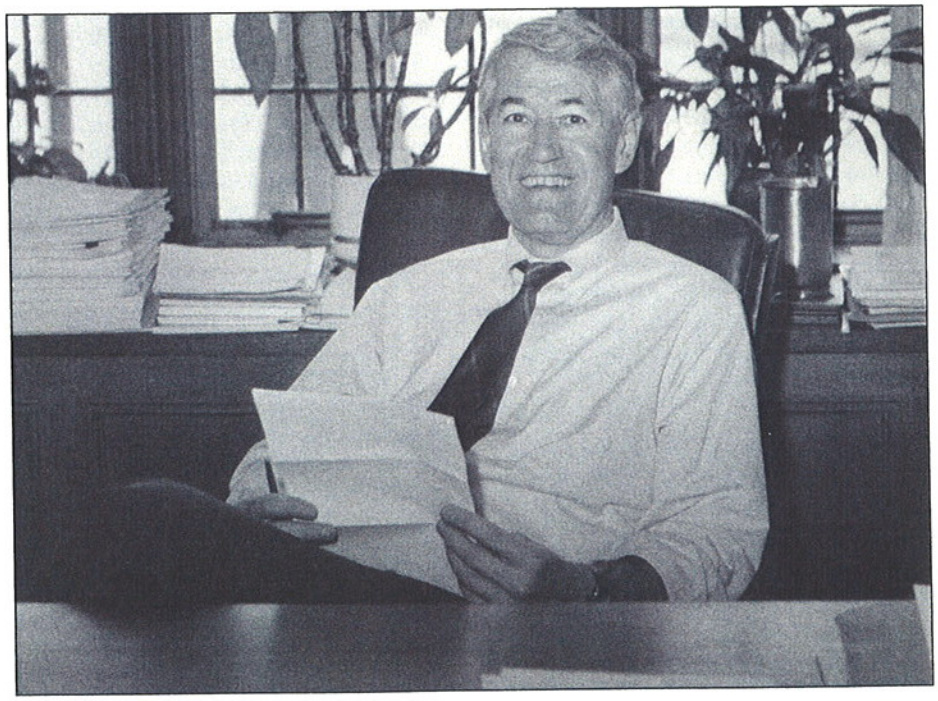
The concept of roughening is sufficiently counterintuitive that many people have been reluctant to accept it—the idea that a surface could have infinite height fluctuations. . . Proving it is a very delicate matter.

• ***How does your work on stepped surfaces combine the basic theoretical issues with the practical importance of device fabrication?***

The statistical mechanics of stepped surfaces is by itself interesting and sophisticated. Among other questions, it involves the issue of roughening. Suppose you draw a straight line in two dimensions at zero temperature. As you warm it up, the line will undulate with thermal vibrations that grow indefinitely in amplitude. The relative amplitude is certainly much greater than that of capillary waves on a surface. Thus the line will wander indefinitely as a result of the thermal vibrations. A stepped surface corresponds to a bunch of such lines; thus the steps on a surface will start to wander and collide with each other due to thermal fluctuations, no matter what we do. It costs a lot of energy when two steps come together. One can readily imagine the new physics that this phenomenon could produce.

One of the first things we studied quantitatively on the silicon surface is a phase transition on stepped silicon (111). At about 1100 K, the flat surface reconstructs with a very elaborate pattern known as the 7 x 7 reconstruction. This has been predicted very beautifully by John Joannopoulos. However, on a stepped silicon (111) surface, as the flat regions reconstruct, they do not like having the steps around because they interfere with the surface's new symmetry. Nature deals with this by pushing all of the steps apart so that they agglomerate in high step density regions separated by large flat (111) terraces. For example, if the steps are 100 angstroms apart above the transition, the terraces below the transition will be perfectly flat over distances exceeding a micron. Our measurements were the first to show large-scale step wandering, and we were also the first to make high-quality stepped surfaces that were perfectly flat over distances exceeding a micron in the phase-separated region. An amazing feature of this transition is that it is completely reversible. If we warm the crystal above 1100 K again, the steps, which had phase separated, suddenly return and form a completely uniform system with steps at every 100 angstroms. Graduate student Monte Ramstad has recently found that we can control the stepped surface morphology in a nonequilibrium way using electric fields.

Many semiconductor devices are grown on stepped surfaces. By varying the temperature or by growing the device either just below, above, or at the separation transition, we can control the surface morphology, which in turn can greatly influence device fabrication and longevity. Our interest is primarily in the



When asked about his vision for MIT's School of Science, Dean Birgeneau responds, "The dean of science has a special responsibility to ensure that MIT maintains its excellence in basic science . . . to be aware of emerging fundamental issues in science and to make certain that the school is organized in such a way that it can have a significant impact. The frontiers of science are constantly evolving, and we must make certain that we stay at the cutting edge." (Photo by John F. Cook)

basic science of this phenomenon. We are now also anxious to apply these techniques to interfaces as well as surfaces. A nice feature of x-rays is that one can just as easily look at interfaces as surfaces. Ken Evans-Lutterodt, one of my former students who is now at AT&T Bell Labs, did a beautiful family of experiments in which he used these techniques to look at the structure of silicon-silicon dioxide buried interfaces, which are the basis of most practical semiconductor devices. He demonstrated how we can relate the roughness of the interface, which influences device quality, to growth conditions.

• ***Is there a project that you're excited about?***

We accidentally discovered in some of our experiments that, at high temperatures, the structures and phase transitions of silicon surfaces depend on how we heat them. At first, we found this to be an annoyance, but we now realize there is some important and deep physics happening here. Under the Joint Services Electronics Program in RLE, we are probing the nonequilibrium behavior of semiconductor surfaces at high temperatures. It may potentially have great practical importance because, by properly combining electric field and temperature conditions, we can manipulate the morphology of the surface at both the microscopic and macroscopic levels, determine what the surface looks like, and then, by quenching, we can retain that structure at room temperature.

• ***What has been the most challenging problem in your field?***

The most difficult physics problem that I continue to work on, in addition to the surface issues I have mentioned, is to understand the basic microscopic physics of high-temperature superconductors. It has been an extraordinarily deep and difficult problem whose immensity Marc Kastner and I really could not have imagined when we started our collaboration in 1987. At that time, I thought it would be a two- or three-year research program, and that was clearly a gross underestimation. It turns out that two-dimensional physics dominates the materials in ways that we have not yet determined, and there are some basic science issues connected with *correlations,* which generically are poorly understood. High-temperature superconductivity is a deep phenomenon that, when solved, will probably have an impact that goes far beyond the copper oxide materials themselves.

• ***What is the most important issue in your field of research?***

The physics of highly correlated electronic systems is the deepest and most difficult unsolved problem in solid-state physics. Basically, we understand the physics of conventional semiconductors and metals quite well. The standard one-electron theory assumes that we can take one electron and then take into account its surroundings by their average effect. That theory, which describes ordinary semiconductors and metals, is well developed and remarkably successful. However, those systems are only a subset of the materials that exist in nature. In highly correlated electronic systems, an electron's behavior depends in detail on what the other electrons around it are doing. So, we cannot treat them on average like we would with conventional semiconductors and metals. If we use standard techniques in which only the averaged environs are included, we obtain qualitatively wrong results. This is a great problem in science, and we do not know what to do about it yet.

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On a separate tack, as our work on semiconductor surfaces is revealing, we do not understand yet the nonequilibrium behavior of complex systems. That field of research is still entirely open. Our original work on surfaces was focused on trying to understand equilibrium properties. Only recently did we discover the dramatic, metastable history-dependent phenomena that occur on stepped silicon, which I mentioned earlier. We hardly know how to begin to understand these effects. In the next 25 to 50 years, I think we will see a huge research effort on nonequilibrium properties.

• ***What is needed for continued progress in your field?***

We need to develop experimental techniques continually. On the x-ray side, we're looking forward to the new Advanced Photon Source at Argonne. I've also been involved with a group at Stanford that has an idea about making a true x-ray laser, and this looks possible. Continued development in x-ray techniques would contribute another large factor in resolution and may open up a whole new field of x-ray imaging. On the neutron side, the U.S. faces a dilemma because the research reactors in this country were built in the '50s and '60s, and all of them may die by the end of this century. If we do not commit to a next-generation neutron source, the U.S. will be left out of this entire field of research in the future. This is in contrast to western Europe and Japan, both of which are making huge investments in neutron beam facilities. The caveat is that a next-generation neutron source to meet our current needs could cost more than two billion dollars. It's crucial for our scientific leaders and the federal government to continue to have the courage to invest in these pioneering research facilities.

• ***What are your thoughts on university-industry collaborations?***

We take pride in this area, particularly since we've had such a successful, long-term connection with IBM. One of the

The establishment of MIT's Center for Learning and Memory was announced in May 1994 at the site of the recently completed biology building. Dean Birgeneau congratulates Nobel laureate Professor Susumu Tonegawa of MIT's Biology Department, who was named director of the new center. (Photo by Donna Coveney)

major uses of our beam lines at Brookhaven is by a group from IBM Almaden that is looking at magnetic recording heads and related surface morphology problems. IBM has also done a lot of work on *in situ* electrochemistry, specifically looking at the science of organic materials on metal surfaces. They're also interested in the physics of silicon with applications in semiconductor devices. Although they're going through a difficult period, IBM has nevertheless made a commitment of several scientists as well as equipment funds in order to join us and McGill University in our x-ray beam line project at Argonne. We are also exploring other possible industrial connections. More generally, in this era, I believe that university groups such as mine must fill in the gaps in "strategic" basic research that currently is being curtailed by industry. Hopefully, in turn, our technologically sophisticated industries will also support us in that endeavor.

• ***Do you have a vision for the School of Science?***

Yes and no. No, simply because I do not know what will be the most important issue in the year 2010. The yes has several aspects to it. The dean of science has a special responsibility to ensure that MIT maintains its excellence in basic science research and education. At the end of World War II, MIT was an outstanding institution in engineering, but it was not yet a leader in science. Our science leadership has built up progressively over the last 50 years. Indeed, we are now probably the leading school of science in the United States, at least according to *U.S. News and World Report*. It's the dean's responsibility to be aware of emerging fundamental issues in science and to make certain that the school is organized in such a way that it can have a significant impact. The frontiers of science are constantly evolving, and we must make certain that we stay at the cutting edge.

Similarly, science is at the core of the educational process at MIT. As dean, I have tried to impress upon the department heads and the faculty the importance of education, both undergraduate and graduate, in the classroom and in the laboratory. I have made certain that excellence in education is recognized in both our salary structure and promotion process. Also, we are continuously encouraging experimentation in education. Our salient achievement in undergraduate education has been the introduction of biology into the core curriculum this year.

In terms of a vision, there are so many important issues, and because of the size of the School of Science, we have many opportunities to make a major impact. As Dean of Science, the major initiative that I've been involved in is bringing the neurosciences to the School of Science. The Department of Brain and Cognitive Sciences has moved into the school, and in May we announced the formation of the new Center for Learning and Memory. I am very proud of that. Eventually, I hope to see MIT evolve from a university that does valuable work in brain and cognitive science to the leading center of neuroscience research in the U.S. It's an emerging field with remarkable opportunities, and I believe that MIT is well placed for the next several decades in this exciting arena.

We have also tried to create a nurturing environment for young people on our faculty so they can do great things. As head of the physics department and then as dean, I've put a lot of energy into attracting and supporting outstanding young scientists. Ninety percent of the faculty we hire are beginning assistant professors. In my first year as dean, I changed the salary structure in the School of Science so that our junior faculty are now the second highest paid in the country. We also provide young people with generous start-up packages that enable them to establish their research programs quickly. As part of this, we are trying very hard to increase the diversity of our faculty so that they properly reflect the makeup of the student body and the nation that we serve.

Under the combined leadership of President Charles Vest and Dean Joel Moses, the School of Engineering is considering a change of course away from its traditional base of engineering science towards engineering design and manufacturing. Traditionally, applied science had been done in the School of Engineering rather than in the School of Science. If the School of Engineering makes this shift away from applied science, our responsibilities in the School

of Science may change, and we will have to reexamine our goals.

• *Do you have a secret to your success?*

To the extent that I've had success, there are probably three things in addition to simply working very hard. First, I truly enjoy what I'm doing. Second, I've always kept my eyes firmly fixed on fundamental issues in science. And third, I've tried hard to be impeccably honest in my research and not to be swayed by this year's fashion.

Do not do basic science as a means to an end, do it because you really love it. There are easier ways to make a living that are less competitive and less difficult. If you choose a career in science, choose it almost like you'd choose a religion.

• *Do you have advice for young people?*

Do not do basic science as a means to an end, do it because you really love it. There are easier ways to make a living that are less competitive and less difficult. If you choose a career in science, choose it almost like you'd choose a religion. Also, be prepared to work extremely hard. Science isn't a nine-to-five job. In terms of what our junior faculty members achieve, I clearly see the difference between those who work on weekends and those who do not. When you enter a university environment, you should come not only because of the research, but also because you want to play a role in educating the next generation. At MIT, education matters. Finally, one must always have the courage to try completely new and outrageous things. They are inevitably the most exciting and have the biggest reward.

Collegium

The RLE Collegium was established in 1987 to promote innovative relationships between the laboratory and business organizations through research projects and special partnerships. Its goal is to increase interaction and communication between RLE researchers and outside professionals in electronics and related fields. Collegium members have the opportunity to develop close affiliations with the laboratory's faculty, research staff, and students and can quickly access emerging results and scientific directions. This kind of professional interaction provides RLE Collegium members with the most up-to-date technical information, often in areas not fully addressed by business and industry.

Collegium benefits include access to a wide range of RLE publications, personalized seminars and laboratory visits, and other opportunities for technology transfer. RLE also hosts visiting scientists from collegium companies. Individual research projects and special partnerships may develop with mutual technical interests and the appropriate external sponsorship.

The RLE Collegium membership fee is $20,000 annually. Members of MIT's Industrial Liaison Program can elect to transfer 25 percent of their ILP membership fee to the RLE Collegium. Collegium fees will encourage new research initiatives within RLE.

RLE welcomes inquiries regarding the laboratory's research. To request an ***RLE Progress Report,*** an ***RLE Collegium Prospectus,*** or for more information on other RLE publications, please contact:

Research Laboratory of Electronics
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139-4307
Collegium: (617) 253-2509/2510
Publications: (617) 253-2566
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Publications

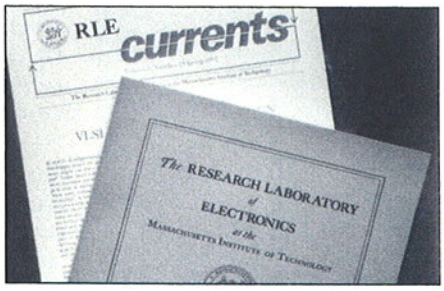
The following new RLE technical reports can be ordered from Document Services, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307; telephone: (617) 253-5668; fax: (617) 253-1690; email: docs@mit.edu. Please contact Document Services for prices and other information.

Analysis and Synthesis of Self-Synchronizing Chaotic Systems, by Kevin M. Cuomo. RLE TR No. 582. 1994. 228 pp.

Estimation and Detection with Chaotic Systems, by Michael D. Richard. RLE TR No. 581. 1994. 214 pp.

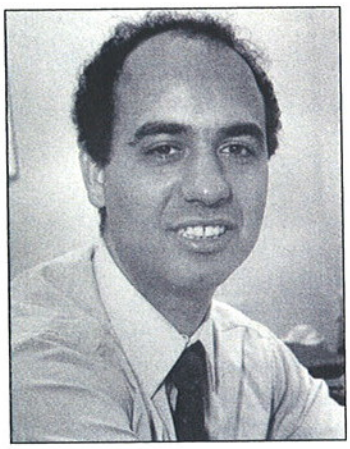
Optimal Feedback Control Formulation of the Active Noise Cancellation Problem: Pointwise and Distributed, by Kambiz C. Zangi. RLE TR No. 583. 1994. 157 pp.

Signal Enhancement for Automatic Recognition of Noisy Speech, by Shawn M. Verbout. RLE TR No. 584. 1994. 84 pp.

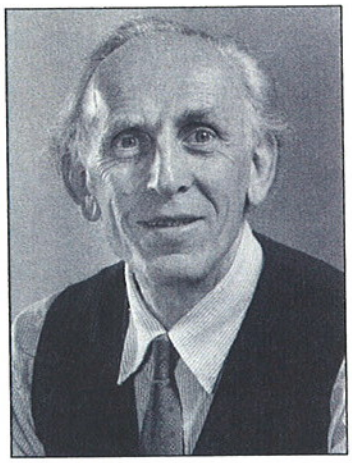


Available from the RLE Communications Group at no charge is ***RLE Progress Report Number 136.*** The ***Progress Report,*** which covers the period January through December 1993, provides extensive information about the research objectives, projects, and publications of RLE's research groups. It also lists faculty, staff, and students who participated in each research project, in addition to current RLE personnel, and identifies funding sources.

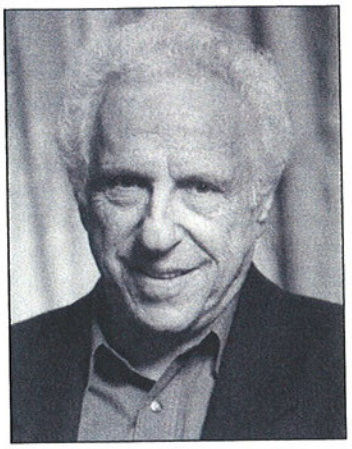
circuit breakers



Dr. Raymond C. Ashoori, Assistant Professor of Physics in RLE's Quantum-Effect Devices Group, received a David and Lucile Packard Foundation fellowship to continue his work on single-electron capacitance spectroscopy (SECS) for artificial atoms. Last fall, Professor Ashoori was among 20 university faculty members in the United States who won the award, which is intended to further the work of promising young scientists and engineers and to encourage talented graduate students to pursue university research. The SECS technique is a valuable diagnostic tool used to study electronic states in solids and surfaces. It enables the detailed measurement of energy levels in nanoscale structures such as artificial atoms. In the future, SECS may make it possible to measure electronic properties in semiconductors with unsurpassed resolution. *(Photo by John F. Cook)*



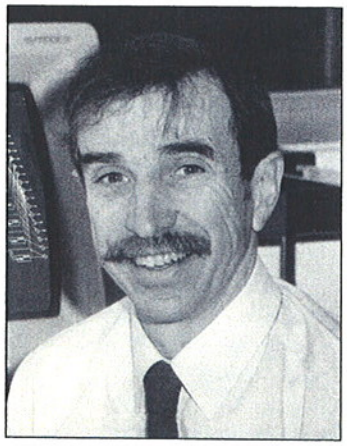
Dr. George Bekefi, Professor of Physics in RLE's Plasma Physics Group, was awarded the Gold Honorary Medal for Merits in the field of Physical Sciences by the Academy of Sciences of the Czech Republic. Professor Bekefi, a native of Prague, was cited for his significant scientific contributions in the field of plasma physics, particularly in the area of powerful microwave generators and free-electron lasers. His research has furthered the understanding of cyclotron emissions from plasmas and magnetic insulation. Recently, his studies have focused on the physics of free-electron lasers that are used to heat fusion plasmas, novel particle accelerators, and communications. The award was presented to Professor Bekefi on the occasion of the 35th anniversary of the Institute of Plasma Physics, which was celebrated at the International Conference on High-Power Particle Beams (BEAMS '94), held June 20-24, 1994, in San Diego, California. *(Photo by John F. Cook)*



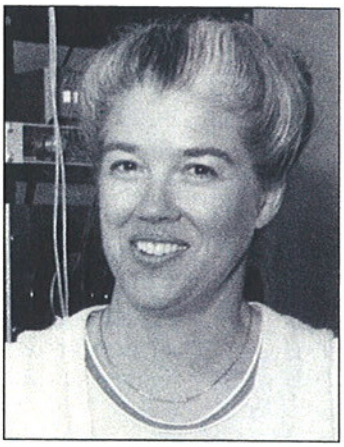
Mr. Nathaniel I. Durlach, Senior Research Scientist in RLE's Sensory Communication Group, received the Acoustical Society of America's (ASA) Silver Medal in Psychological and Physiological Acoustics at the society's annual meeting at MIT on June 8, 1994. The Silver Medal is awarded for contributions to the advancement of science, engineering, or human welfare through the application of acoustic principles or through research accomplishments in acoustics. Mr. Durlach was recognized for his pioneering contributions to research concerning binaural hearing, intensity perception, hearing aids, tactile aids, and virtual reality. His wide range of research includes the development of the Equalization-Cancellation model of binaural detection and a dual-mode model of auditory memory that accounts for stimulus range and interstimulus time. In addition, he has investigated the intelligibility of clear speech versus conversational speech, multimicrophone hearing aids, and tactile aids for the deaf and blind. Mr. Durlach's current work addresses issues in human sensory communication that are associated with the development of virtual environments and teleoperator systems (see ***currents,*** Spring 1993). *(Photo by John F. Cook)*

Dr. James G. Fujimoto (SB '79, SM '81, PhD '84) was promoted to Professor of Electrical Engineering and Computer Science, effective July 1, 1994. Professor Fujimoto, a principal investigator in RLE's Optics and Devices Group, joined the MIT faculty in 1985 as an assistant professor and became an associate professor in 1988. His research on femtosecond optics and its applications to quantum electronics and laser medicine have resulted in the production of laser pulses as short as a few wavelengths of light. The pulses then are used to investigate ultrafast dynamics in optoelectronic materials and devices. In 1990, he received the National Academy of Sciences Award for Initiatives in Research. Professor Fujimoto was recently elected as a fellow of the Optical Society of America and is a member of the American Association for the Advancement of Science and the American Physical Society. *(Photo by John F. Cook)*

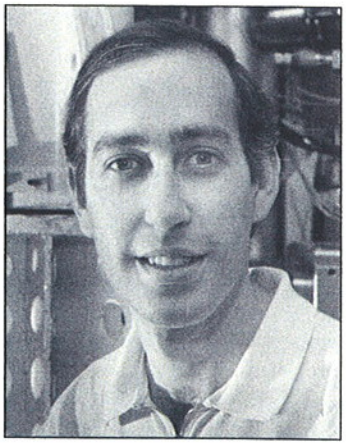
Dr. Hermann A. Haus (ScD '54), Institute Professor and principal investigator in RLE's Optics and Devices Group, was named recipient of the 1994 Frederic Ives Medal of the Optical Society of America, the society's highest award for overall distinction in optics. Professor Haus was cited for his fundamental and seminal contribution to the understanding of quantum noise in optical systems and for a lifetime of dedication to science and engineering education. The medal will be presented at the society's annual meeting in Dallas, Texas, to be held October 2-7, 1994. Over his forty-year career, Professor Haus has made prolific contributions to numerous emerging technologies in the field of optics: quantum noise theory, waveguide devices, all-optical switching, soliton systems, squeezed state generation, and ultrashort pulse lasers. Among his many honors, he has received the 1987 Charles Hard Townes Award of the Optical Society of America and the 1984 Award of the IEEE Quantum Electronics and Applications Society. In 1991, he received the Education Medal from the IEEE for his creative contributions to education in electromagnetic fields and waves, and quantum electronics. Professor Haus is a member of the National Academy of Engineering and the National Academy of Sciences, and a fellow of the American Academy of Arts and Sciences, the IEEE, the American Physical Society, and the Optical Society of America. *(Photo by John F. Cook)*



Dr. Alan V. Oppenheim (SB/SM '61, ScD '64), Distinguished Professor of Electrical Engineering, was awarded the Everett Moore Baker Memorial Award for Excellence in Undergraduate Teaching by MIT in May 1994. The award is given to faculty members in recognition of exceptional interest and ability in the instruction of undergraduates. Since joining the MIT faculty in 1964, Professor Oppenheim has received several awards for his outstanding research and teaching, including the 1988 IEEE Education Medal, the 1984 IEEE Centennial Award, and the 1980 Society and Technical Achievement Awards of the IEEE Society on Acoustics, Speech, and Signal Processing. As a principal investigator in RLE's Digital Signal Processing Group, his research focuses on speech, image, and geophysical signal processing. Professor Oppenheim is the author and editor of several widely used signal processing textbooks. He is a member of the National Academy of Engineering and a fellow of the IEEE. *(Photo by John F. Cook)*

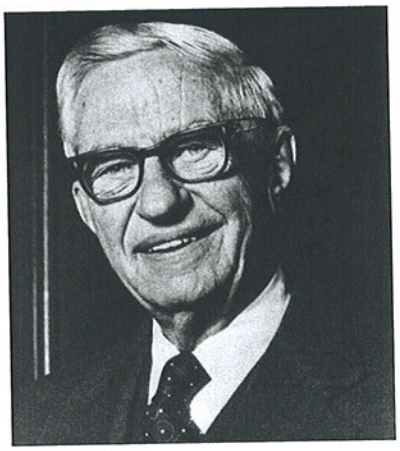


Dr. Stefanie Shattuck-Hufnagel, Research Scientist in RLE's Speech Communications Group, received the Claude Pepper Award from the National Institute of Deafness and Other Communication Disorders on December 1, 1993. The seven-year research award is the highest honor bestowed on a grant recipient and recognizes outstanding contributions in the field of communication sciences and disorders. Dr. Shattuck-Hufnagel investigates the cognitive structures and processes used in speech production planning, particularly at the level of speech sound sequencing. Her work with speech error patterns and the acoustic analyses of prosody contributes to the development of cognitive models of speech production and to phonological theory and also has applications to speech recognition and synthesis. *(Photo by John F. Cook)*



Mr. Scott E. Silverman was appointed Research Engineer in RLE's Quantum-Effect Devices Group and Nanostructures Laboratory, effective October 12, 1993. A graduate of Rensselaer Polytechnic Institute (BSEE '87), he was previously a lithography engineer with Hampshire Instruments of Marlborough, Massachusetts, and a semiconductor research engineer with both Varian Associates of Palo Alto, California, and Sanders Associates of Nashua, New Hampshire. In his current position, Mr. Silverman will maintain the laboratory's scanning electron-beam lithography system and will develop spatial phaselocking techniques used with the system. *(Photo by John F. Cook)*

IN MEMORIAM



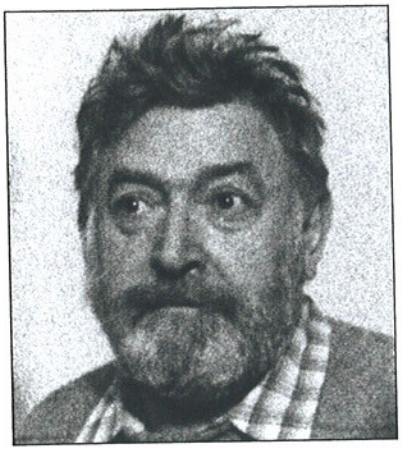
Dr. Lee A. DuBridge, 93, died January 23, 1994, in Pasadena, California. Among his many accomplishments as a nuclear physicist and educator, Dr. DuBridge guided MIT's wartime Radiation Laboratory as its director from 1940 to 1945, and served as president of the California Institute of Technology from 1946 to 1969.

A native of Terre Haute, Indiana, Dr. DuBridge attended Cornell College (AB '22) and the University of Wisconsin (AM '24, PhD '26). He was a member of the physics faculties at Washington University (1928-1934) and the University of Rochester (1934-1946). In 1940, taking a leave of absence from his post as the head of the Physics Department at Rochester, Dr. DuBridge was appointed director of the MIT Radiation Laboratory by the National Defense Research Committee (NDRC). From the Radiation Laboratory's inception in 1940, through its five years of vital wartime research, and final disbanding in 1945, Dr. DuBridge implemented technical policies mandated by the NDRC's Microwave Committee. He was responsible for overseeing the laboratory's nearly 4,000 employees who helped to create over 100 different radar systems and to construct $1.5 million worth of radar equipment—almost half of the radar deployed during World War II. Although Dr. DuBridge was not affiliated with RLE, he guided the Radiation Laboratory, which served as the prototype for RLE when it was established in 1946.

Following his tenure at the Radiation Laboratory, Dr. DuBridge was appointed president of the California Institute of Technology in Pasadena, California. He directed the school through 23 years of growth, doubling the size of its faculty and tripling the institute's physical space. In 1970, he became president emeritus. From 1969 to 1970, he was a science advisor to President Richard M. Nixon. Dr. DuBridge was also active on the advisory boards of numerous government agencies, business organizations, and educational foundations.

As a researcher, his interests included biophysics, nuclear disintegration, photoelectric and thermionic emission, DC amplification, the energy distribution of photoelectrons, the theory of photoelectric effects, and radar. Dr. DuBridge contributed to many scientific and educational publications and was the author of *Photoelectric Phenomena* (with Arthur L. Hughes), *New Theories of Photoelectric Effect*, and *Introduction to Space*. In addition to the many honorary degrees bestowed upon him from colleges and universities across the country, Dr. DuBridge was awarded the Research Corporation Award (1947), the U.S. Medal for Merit (1948), Great Britain's King's Medal for Service in the Cause of Freedom (1948), and the Gold Medal Award of the American College of Cardiology (1966). He was a fellow and past president of the American Physical Society and a member of the National Academy of Sciences and the Association for the Advancement of Arts and Sciences.

(Photo courtesy MIT Museum)



Iñaki Garabieta, 67, died May 22, 1994, in Cambridge after a long illness. Mr. Garabieta, a widely acclaimed craftsman and designer, served as an instructor in MIT's Department of Architecture from 1973 to 1983 and as a research engineer in the Artificial Intelligence Laboratory from 1983 until his retirement in 1992. Starting in 1974, he was affiliated with RLE's Communication Biophysics Group.

Mr. Garabieta was a highly skilled guitar maker, model maker, craftsman, and designer. His expertise was well known in a wide range of fields including acoustics; sculpture; product, machine, and building system design; electronics; and architectural model making. In addition to teaching at the school of architecture, he designed and manufactured laboratory equipment and established the department's woodworking and metalworking shops. His deep knowledge of the materials used in woodworking, metalworking, and plastics, combined with his novel methods of building models, enabled him to design his own tools for many of his projects.

Dr. Joseph S. Perkell, senior research scientist in RLE's Speech Communication Group, fondly remembers Mr. Garabieta: "He collaborated with us for ten years on the development of a system for transducing speech articulatory move-

ments. A crucial part of this system was its unique mechanical components which had to be designed and manufactured with great thought, care, and precision. Iñaki produced devices that far exceeded our expectations in terms of functionality, performance, gracefulness of design, and beauty of form and finish. Virtually everything he made reflected a deep intelligence, the highest possible standards, and an extraordinary understanding of exactly how things should work. At the same time, it was also a real work of art."

Mr. Garabieta was born in Balbao, Spain (Euzcadi), and was a 30-year resident of Lexington. He is survived by his wife Maria Pilar Garabieta, three sons, a daughter, and six grandchildren. Donations may be made in Mr. Garabieta's memory to the Center for Cancer Research, E17-110, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139. *(Photo by John F. Cook)*

MIT President Emeritus Julius Adams Stratton (EE'23, SM'26), 93, died June 22, 1994, in a Boston nursing home after suffering from pneumonia. Dr. Stratton had served as RLE's first director from 1946 to 1949, part of a meritorious research and administrative career at MIT that spanned more than seven decades.

Dr. Stratton was born in Seattle, Washington, in 1901. He traveled widely as a boy and with his strong interest in radio, became a ship's radio operator at the end of World War I. He studied for one year at the University of Washington and then transferred to MIT, graduating in 1923. Following graduation, his interest in the humanities prompted him to enroll at the University of Grenoble and the University of Toulouse, but he returned to MIT for graduate study in electrical engineering. He completed his master's degree in 1926. He studied mathematics and physics at the Swiss Federal Institute of Technology on an MIT traveling fellowship in mathematics

Dr. Julius Adams Stratton

and physics and received his doctorate in 1928. He returned to MIT later that year as an assistant professor of electrical engineering.

During the late 1920s, his research at MIT's Round Hill program in South Dartmouth, Massachusetts, involved the propagation of short waves in radio transmissions. His studies proved to be the forerunner of later efforts to develop radar. In 1930, he transferred to the Department of Physics, where he became an associate professor in 1935 and a full professor in 1941. As a member of a committee in the Department of Electrical Engineering, Dr. Stratton was responsible for innovative changes in the department's curriculum in 1933. He became a staff member at the MIT Radiation Laboratory in 1940 and worked on the development of LORAN in the theory group. In 1942, he was called to Washington as an expert consultant to the secretary of war and was subsequently awarded the Medal for Merit for his services.

Dr. Stratton's efforts to continue the tradition of research that started at the wartime Radiation Laboratory were vital to the establishment of RLE as MIT's first interdisciplinary laboratory. In 1946, Dr. Stratton was named head of MIT's Basic Research Division, which provided the organizational transition from the Radiation Laboratory to RLE, and then was appointed as the first director of RLE. Following his tenure as RLE director from 1946 to 1949, Professor Stratton served in several administrative roles at MIT. He became MIT's first provost in 1949, vice president (1951-1955), chancellor (1955-1957), acting president (1957-1959), and president (1959-1966). Over the years, he intiated important academic and research policies in his various administrative capacities.

In his role as a distinguished educator and physicist, Dr. Stratton was the author of several books and many technical papers. His books include the widely acclaimed *Electromagnetic Theory* (1941) and *Science and the Educated Man* (1966). A life member of the MIT Corporation, he also served as the director, chairman, and trustee of several corporations, including the Ford Foundation (1966-1971), and participated on the boards and committees of many government agencies as well as educational and cultural institutions. He was awarded numerous professional and humanitarian honors, most recently the 1984 IEEE Centennial Medal, and held 17 honorary degrees from institutions around the world. Dr. Stratton was a member of the National Academy of Science (serving as its vice president from 1961 to 1965) and a founding member of the National Academy of Engineering. He was a fellow of the American Academy of Arts and Sciences, the American Association for the Advancement of Science, the American Physical Society, and the IEEE.

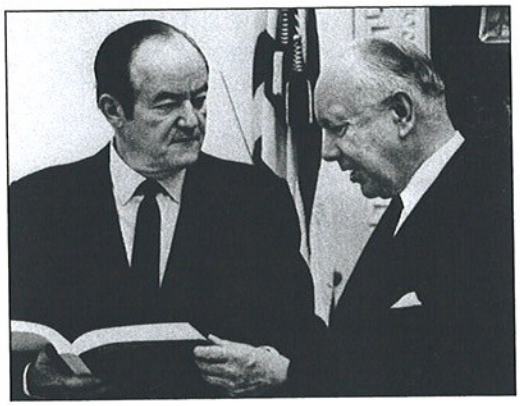
Dr. Stratton is survived by his wife, Catherine N. (Coffman) Stratton of Cambridge, Massachusetts; three daughters, Catherine Nelson Stratton of London, England, Ann Cary Boyd of Newbury, Massachusetts, and Laura Thoresby of London, England; and one granddaughter. Private funeral services and burial were held for Dr. Stratton at Mount Auburn Cemetery in Cambridge and a memorial service at MIT is planned for the fall. A scholarship fund will be established in Dr. Stratton's memory, and donations can be made to the MIT Treasurer's Office, 238 Main Street, Cambridge, MA 02142. *(RLE file photo)*

RLE currents presents this photographic tribute in celebration of the life of Dr. Julius A. Stratton, RLE's first director. He enriched the fabric of MIT's educational and cultural experience for students, faculty, and staff alike. Photos are provided by the MIT Museum.

MIT's newly appointed president celebrates at his 1959 inauguration dinner with Chairman of the Corporation James R. Killian and MIT first lady Catherine N. Stratton. (Photo courtesy MIT Museum)

Julius A. Stratton • 1901-1994

Secretary of War Robert P. Patterson presents Dr. Stratton with the Medal for Merit in 1946. (Photo courtesy U.S. Army)



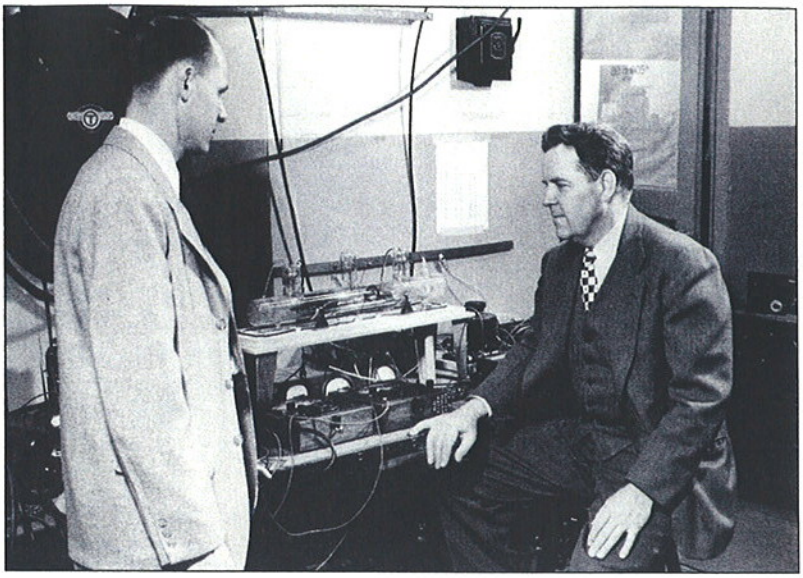
As chairman of the Commission on Marine Science, Engineering, and Resources, he provides Vice President Hubert H. Humphrey with a final report in 1969. (Photo courtesy MIT Museum)

At his MIT retirement party in 1966, he is presented with a telescope by Dr. William P. Allis, his long-time friend. (Photo courtesy MIT Museum) *(Inset): As young MIT faculty members, they return aboard the SS* Santa Barbara *from a 1933 expedition to Ecuador.* (Photo courtesy Grace Lines)

In 1973, he speaks at the dedication of RLE's new home, the Sherman Fairchild Electrical Engineering and Electronics Complex. (Photo by Margo Foote)

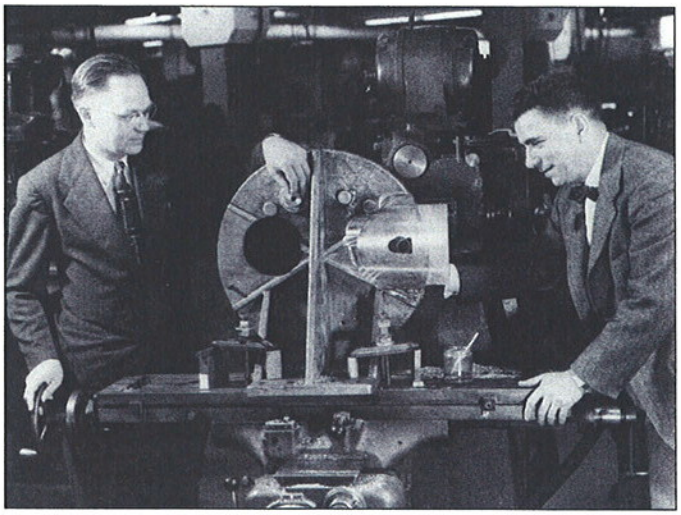
Dr. Stratton celebrates with current RLE Director Dr. Jonathan Allen at the laboratory's 40th anniversary festivities in 1986. (Photo by John F. Cook)

History of Surface Physics Research at RLE



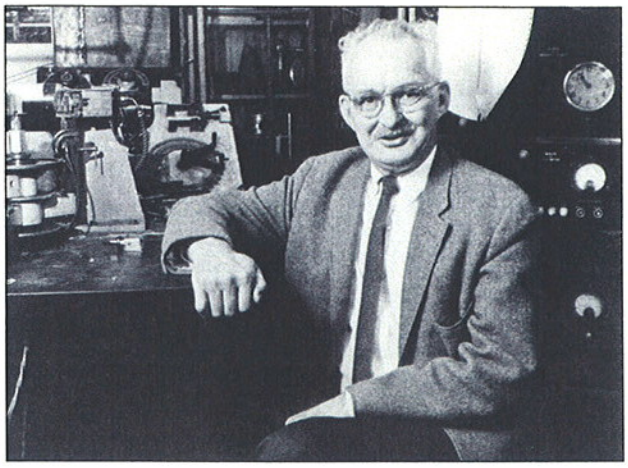
1958

Graduate student Robert M. Steinberg (left) and Professor Wayne B. Nottingham inspect an experimental high-vacuum tube used to study conduction through cesium vapor. Before World War II, Professor Nottingham's physical electronics research involved thermionic, photoelectric, and field emissions and the properties of cathodes and phosphors. His work continued in MIT's Radiation Laboratory, and his research program moved into RLE when it was established in 1946. Professor Nottingham's group investigated electron emission problems, which are closely related to the study of surface phenomena. Rigorous methods were used to maintain desired surface conditions throughout their experiments and detailed, quantitative techniques were developed to produce and measure ultrahigh vacuum environments. *(RLE file photo)*



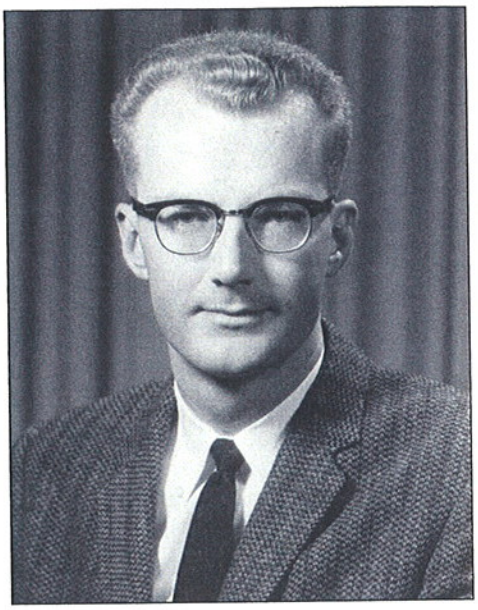
early 1960s

Professor George G. Harvey (left) and Visiting Scientist Dr. Emanuel R. Piore examine a soft x-ray spectrograph being fabricated in RLE's machine shop. This equipment was used in Professor Harvey's solid-state physics group to study the structure of electron conduction bands in the alkalis and transition metals in order to more fully understand their properties.
(RLE file photo)



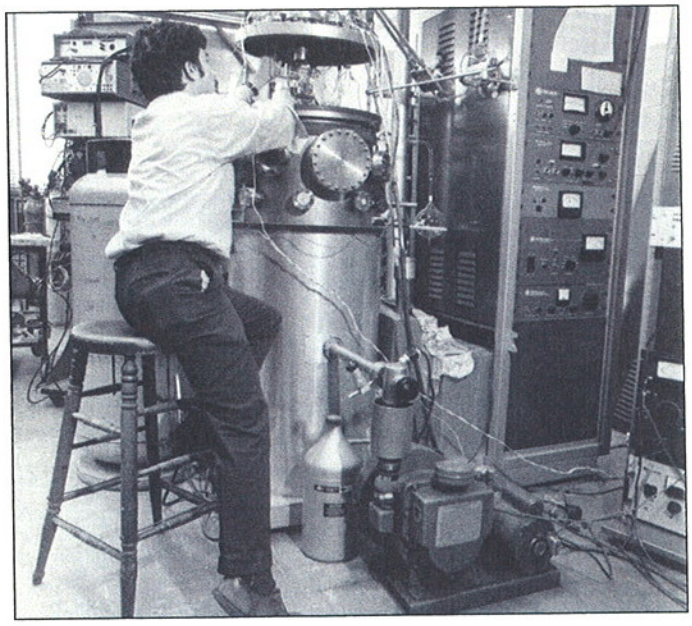
mid-1960s

Professor Bertram E. Warren established a research laboratory where x-ray diffraction methods were used to probe the structures of both crystalline and amorphous matter in solid-state physics. An MIT graduate, Professor Warren (SB'23, ScD'29) was an internationally renowned expert in determining the structure of matter by means of x-rays. His work at RLE included the development of a method to eliminate the Compton-Debye effect in x-ray diffraction experiments involving amorphous substances.
(Photo courtesy MIT Museum)



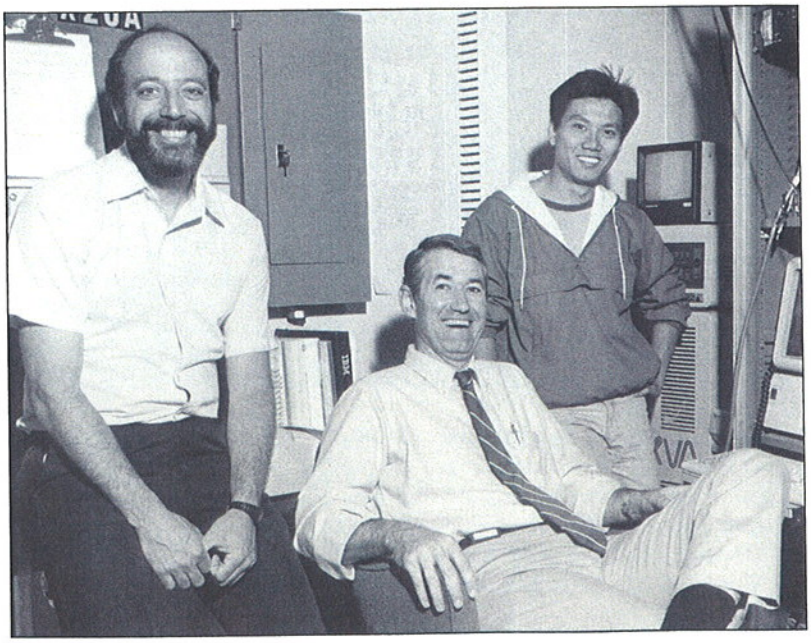
1966

Professor Robert E. Stickney studied the kinetics and thermodynamics of adsorption and desorption processes, evaporation processes, catalytic reactions, and gas molecule reactions with solid surfaces. In 1971, his group was first to successfully observe helium atoms diffracting from a clean metal surface. The group also developed equipment that enabled more detailed experiments, including an Auger electron spectrometer that determined the chemical composition of a solid surface over a wider range of temperatures than previously possible and an ultrahigh vacuum system that measured velocity distributions of molecules desorbed from solid surfaces.
(Photo courtesy MIT Museum)



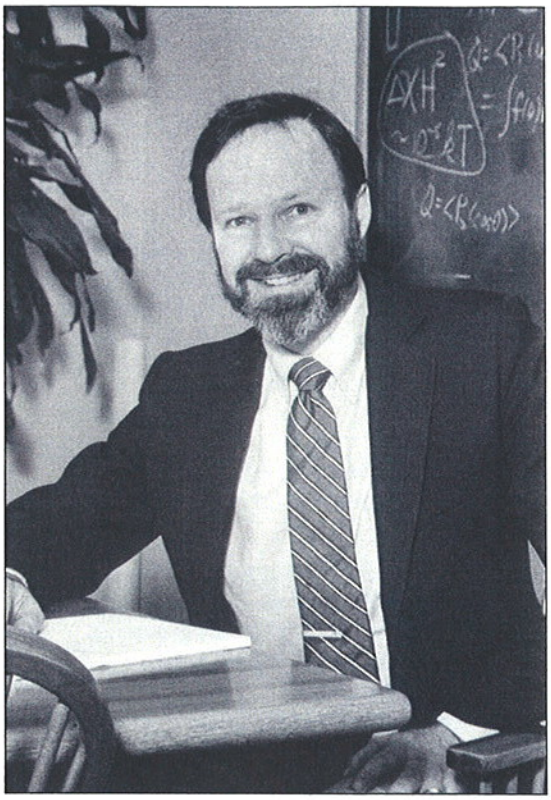
1970

Ali E. Dabiri, a graduate student in Professor Robert E. Stickney's surface physics group, calibrates the equipment used to measure the spatial and speed distributions of desorbed hydrogen molecules from a polycrystalline nickel surface. *(Photo by John F. Cook)*



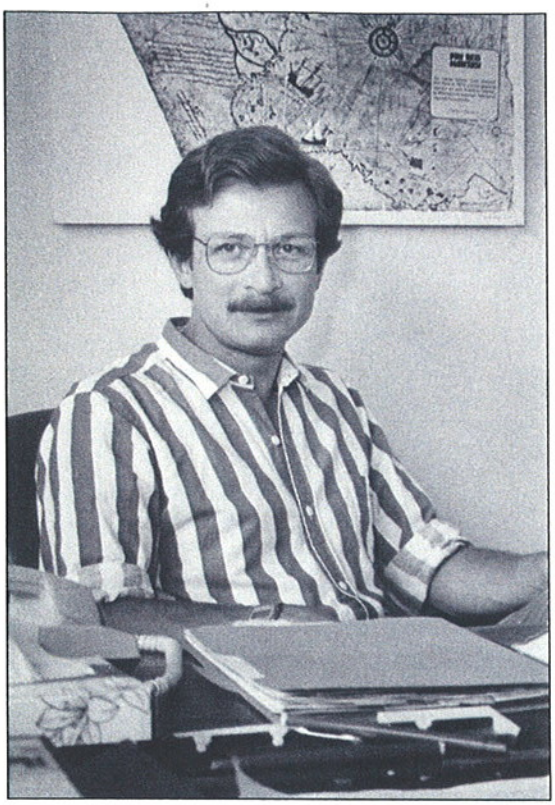
1986

Dr. Paul Horn of IBM, Professor Robert J. Birgeneau, and graduate student Alan Y. Mak pioneered the study of surface monolayer phases and two-dimensional phase transitions using high-resolution x-ray scattering techniques in experiments conducted on the MIT/IBM spectrometer system at Brookhaven National Laboratory. Dr. Horn and Professor Birgeneau received the 1988 Bertram Eugene Warren Award of the American Crystallographic Association for this research. *(Photo courtesy Brookhaven National Laboratory)*



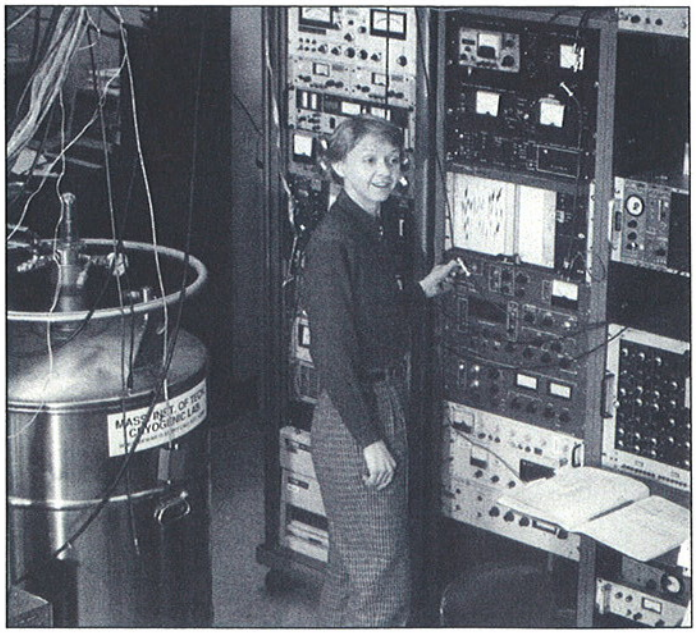
1986

Professor J. David Litster, in collaboration with Professor Robert J. Birgeneau, conducted experiments at the Brookhaven synchrotron facility to analyze the hexatic phase in liquid crystal materials. Using a beam line that supplied an extremely intense monochromatic x-ray beam, they conducted studies on the development of crystalline axes and positional order. These studies demonstrated that transitions in hexatic states are both continuous and reversible. (Photo by John F. Cook)



1986

Professor A. Nihat Berker uses renormalization-group theory to study the finite temperature properties of semiconductor surfaces and of two-dimensional quantum systems. By combining his renormalization-group statistical mechanic techniques with Professor John D. Joannopoulos' electronic energy calculations, a theoretical picture of semiconductor surfaces and interfaces was created, and finite-temperature theories that were truly ab initio *were obtained for the first time.* (Photo by John F. Cook)



1990

Molecular beam surface scattering experiments conducted by Professor Sylvia T. Ceyer probe the chemical reactions that occur when accelerated streams of neutral species impinge on a semiconductor surface and have shown that silicon can be etched without plasmas. Her methods to study molecular reactions with surfaces make it possible to see in detail how a molecule dissociates as it is adsorbed. Professor Ceyer's research has provided far-reaching correlations between the observed dynamics and the potential energy surfaces on which molecule-surface interactions occur. (Photo by John F. Cook)

THE LEGACY OF NORBERT WIENER: A Centennial Symposium at MIT • October 8-14, 1994

Dr. Norbert Wiener (RLE file photo)

A symposium to honor the 100th anniversary of the birth of Norbert Wiener will take place at MIT from Saturday to Friday, October 8-14, 1994. Norbert Wiener was one of the major figures in mathematics in this century, and his interests extended far beyond its traditional boundaries. Dr. Wiener was well known for his remarkable ability to find deep connections between mathematics and other fields. His life's work demonstrated the importance of advanced mathematics in practical applications and vice versa.

An important goal of the symposium will be to raise awareness in the mathematical, scientific, and engineering communities of new opportunities for interactions between mathematics and other disciplines. The symposium will begin with talks on current research in the areas of Dr. Wiener's fundamental contributions to mathematics—harmonic analysis, integration in function space, and potential theory. Physics, electrical engineering, economics, and biology all have strong and growing relationships to mathematics. Speakers from each of these disciplines will discuss the role of mathematics and Dr. Wiener's influence in their respective fields.

Throughout the week, talks will also be devoted to Dr. Wiener's intellectual development and his profound personal influence on colleagues here at MIT and elsewhere. An historical program is planned for Saturday, October 15 at Tufts University in Medford, Massachusetts, where Dr. Wiener received his bachelor's degree in 1909.

Symposium sessions at MIT are scheduled as:

- ***Mathematics,*** October 8-10;
- ***Statistical Physics,*** October 11;
- ***Electrical Engineering & Computer Science,*** October 12;
- ***Financial Economics,*** October 13; and
- ***Neurobiology,*** October 14.

The symposium is supported by Henry Singleton (SB/SM '40, ScD '50), the Massachusetts Institute of Technology, the Sloan Foundation, and the National Science Foundation. Proceedings will be published by the American Mathematical Society.

For further program and housing information, please contact Professor David Jerison, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Room 2-180, Cambridge, MA 02139-4307; telephone: 617-253-2685.

Dr. Norbert Wiener served at MIT from 1919 to 1964 and was a faculty member in the Department of Mathematics. For those of you who had the privilege of knowing him, the staff of ***RLE currents*** would appreciate your writing to us with your reminiscences or anecdotes. We hope that you will allow us to share your memories with others on the occasion of Dr. Wiener's centennial symposium in October. Please write to: ***RLE currents,*** 36-413, Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307.

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