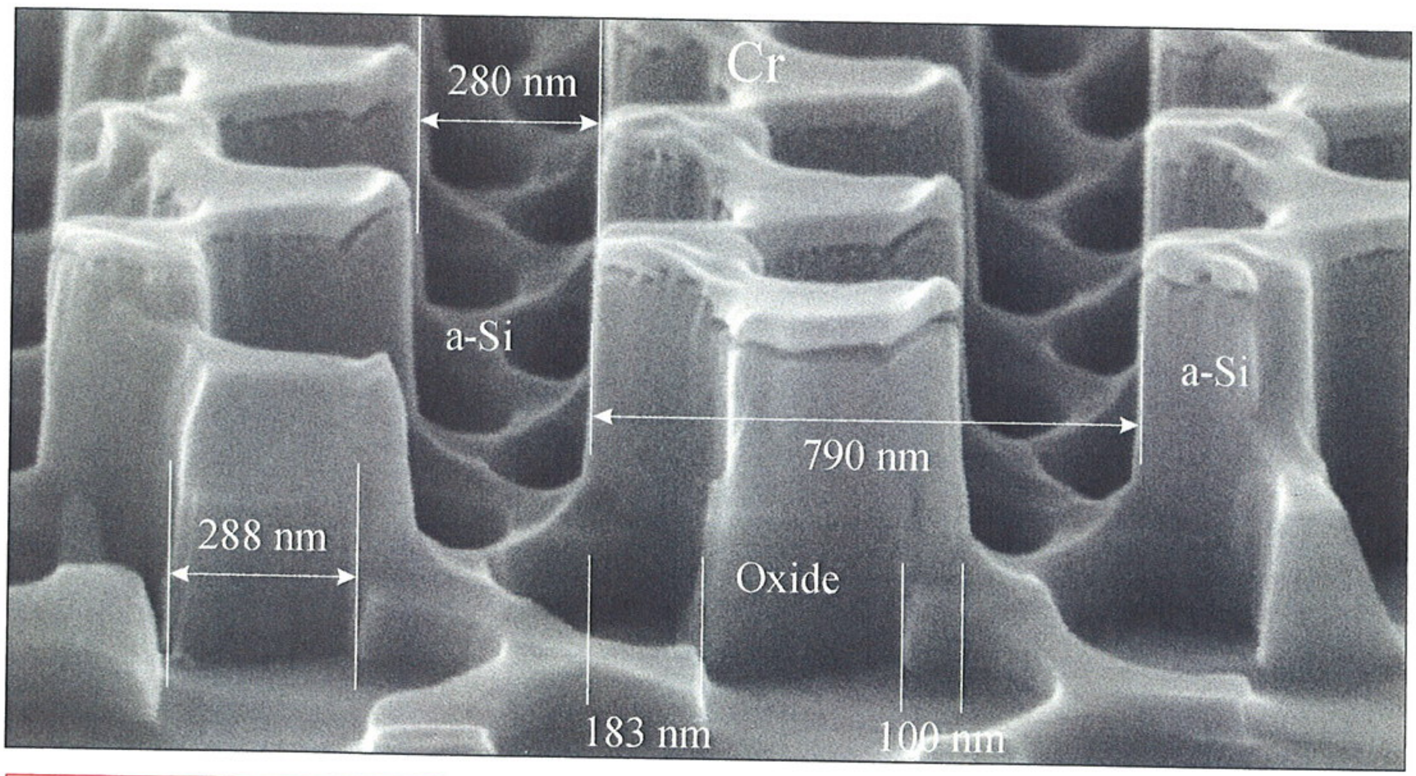
RLE currents

Volume 10, Number 2 • Fall 1998

The Research Laboratory of Electronics at the Massachusetts Institute of Technology

THE FOUNDATIONS OF NEXT-GENERATION ELECTRONICS: Condensed-Matter Physics at RLE



This scanning-electron micrograph shows an early stage in the fabrication of a three-dimensional photonic bandgap structure for the 1.5-micron wavelength. Photonic bandgap "crystals" are periodic lattices comprised of materials with very different dielectric constants. They can be used to manipulate and control light in much the same way that electronic crystals can control electrons. By adding defects to a photonic crystal, light can be confined to dimensions on the order of a wavelength. In this micrograph, the interleaved, complex pattern of the silicon-silicon dioxide structure is seen after formation of the second layer. Chromium is used for masking during a reactive-ion-etching step. The design, which enables planar nanofabrication technology to be used, was developed in Professor John D. Joannopoulos' group. Fabrication was performed at RLE's NanoStructures Laboratory under the direction of Professor Henry I. Smith. The creation of photonic bandgap materials has been made possible by a multidisciplinary research collaboration among several RLE physicists and electrical engineers (see articles on pages 14 and 18).

Inside This Issue

The microelectronics age, now fifty years old, has evolved with the ever-shrinking size of transistors and their interconnections. Momentous discoveries, such as the transistor in 1947 and the integrated circuit in 1959, heralded the information age and microelectronic technology. In 1965, Gordon E. Moore (now Chairman of Intel Corporation) predicted the power of integrated circuits would double every eighteen months with proportional reductions in cost. His prediction, known as Moore's Law, is an axiom in today's microelectronics industry.

The need for smaller and faster electronic devices has created the new field of nanotechnology, where microelectronics is now being eclipsed by the promise of quantum-effect devices. The underlying principles for nanoscale devices are remarkably different because the systems are so small that quantum effects govern their behavior. Nanotechnology involves the study of functional structures in the 1- to 1000-nanometer range. (One nanometer is one-billionth of a meter.) Recent developments in surface microscopy, silicon fabrication, physical chemistry, and computational engineering have come together to help scientists better understand, fabricate, and manipulate structures at this level. The ability to construct matter and molecules one atom at a time, coupled with new methods to fabricate novel materials and devices, has made the field of nanoscience the next biggest challenge for both scientists and engineers.

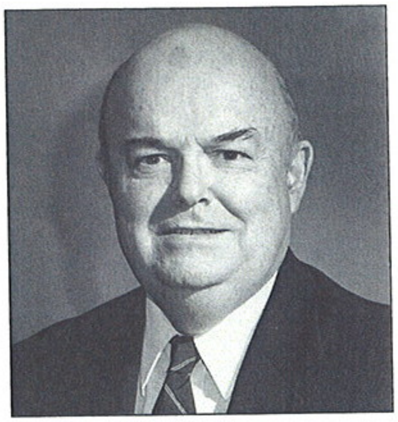
Top-Down or Bottom-Up: The Condensed-Matter Approach

How small can electronic devices be made before the classical laws of physics prohibit them from operating? This question brings together several scientific disciplines in the nanoscience field: condensed-matter physics, solid-state electronics, chemistry, materials science, and electrical engineering. Some observers have described the various approaches to nanotechnology as top-down by the engineering disciplines and bottom-up by the physical disciplines. That is, people working from the bottom up are attempting to create a new understanding and structure from the dynamics of the basic materials and their molecules. Those working from the top down seek to improve existing devices, such as transistors, and to make them smaller.

Specifically, condensed-matter physics addresses the various properties that describe solid and liquid substances, including their thermal, elastic, electrical, chemical, magnetic, and optical characteristics. In terms of solid matter, theoret-

Director's Message

It is easy to imagine that we will continue to enjoy the benefits of increasingly smaller electronic devices in contemporary technology for the indefinite future. We are, however, rapidly entering an era where new materials, structures, and devices are leading to novel electronic and optical technologies based largely on quantum-mechanical principles. The basic understanding for these new systems is being created in RLE by a productive combination of condensed-matter physicists and electrical engineers. From fundamental physical properties to fabricated devices, these investigators are forging the basic ingredients of future electronic and optical technologies, capable of extracting optimal performance from ultra-small-scale components. Research in this area looks for new physical phenomena that can form the basis for switching and interconnect at electronic or optical speeds. Some of these devices may also be very useful as sensors, and micron-scale optical interconnect holds the promise of unifying electronic and optical fabrication on a single integrated chip. These new technologies will undoubtedly require design methodologies radically different from those used today, thus leading to a set of circuit elements and their laws of interaction, that form a strong departure from the familiar lumped circuit elements that constitute today's circuit abstractions. In this issue of ***RLE currents,*** we sense the excitement of these discoveries, as well as the technologies that will surely follow from their use.



Jonathan Allen, Director, Research Laboratory of Electronics

RLE **currents**

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

Jonathan Allen .... Editor-in-Chief
Joseph F. Connolly .... Managing Editor
John F. Cook .... Photography
Everett Design .... Design
Dorothy A. Fleischer .... Editor and Staff Writer
Barbara Passero .... Production and Circulation
Jonah Sacks .... Editorial and Graphics Assistance

The staff of ***currents*** would like to thank the faculty, staff, and students in RLE's Quantum-Effect Devices group, Optics and Devices group, and Surfaces and Interfaces group for their contributions to this issue.

Inquiries may be addressed to:
RLE currents, Room 36-412,
Research Laboratory of Electronics,
Massachusetts Institute of Technology,
77 Massachusetts Avenue, Cambridge, MA 02139-4307.

Previous issues of ***currents*** are contained in the laboratory's World Wide Web pages: http://rleweb.mit.edu/

(ISSN 1040-2012)

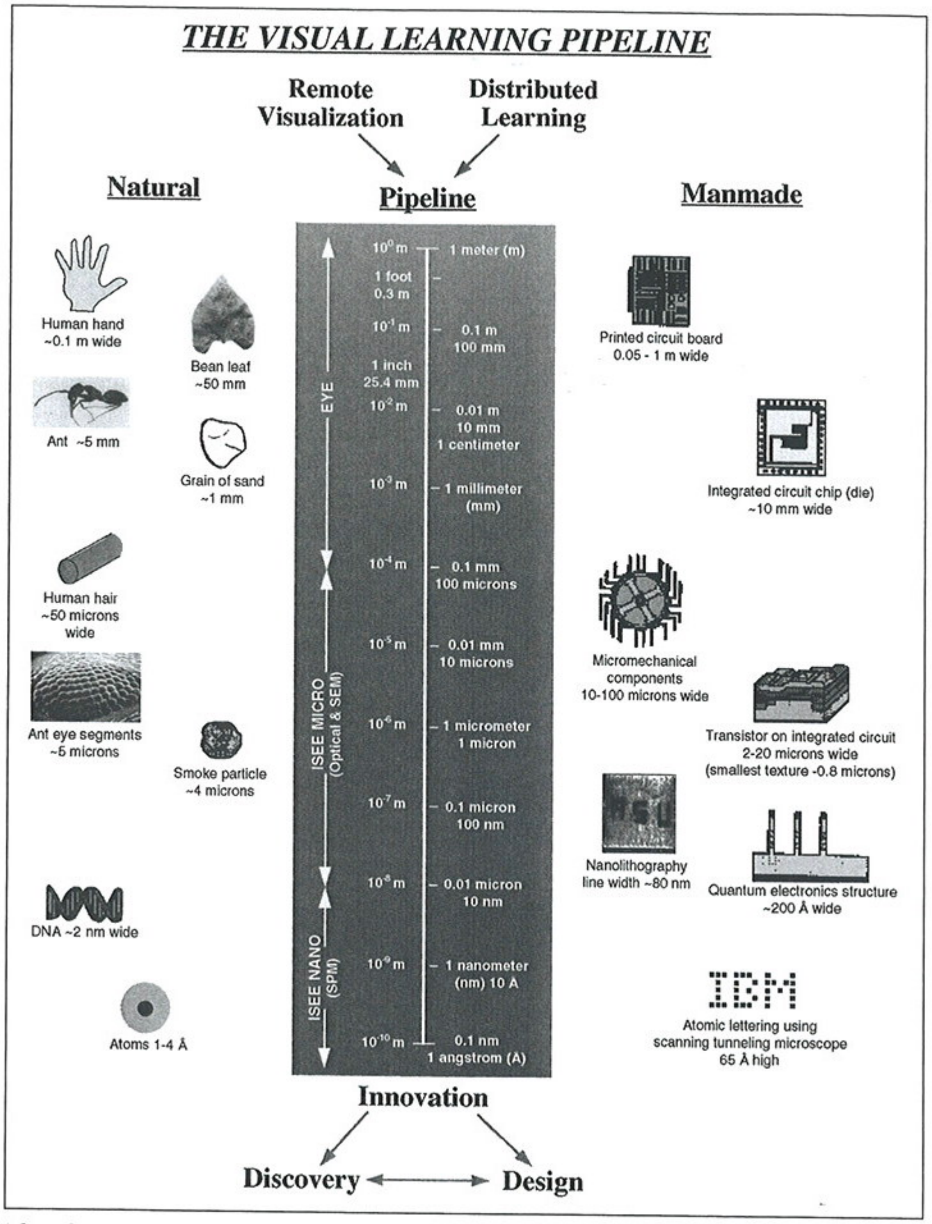
ical advances have been made in recent years to study crystalline materials whose simple repetitive geometric arrays of atoms are multiparticle systems. These systems are described in terms of quantum mechanics. However, because atoms in solids are coordinated over large distances, the theory must extend beyond the atomic and molecular levels. In addition, conductors such as metals contain free electrons that govern the electrical conductivity of the whole material, which is a property of the entire solid rather than its individual atoms. Crystalline and amorphous semiconductors and insulators, as well as properties of the liquid state of matter (liquid crystals and quantum liquids, for example) are also studied in condensed-matter physics. The macroscopic quantum phenomena observed in quantum liquids, such as superfluidity, is also seen in certain metallic and ceramic materials as superconductivity.

Mesoscopic Physics: The New Proving Ground

The phenomenon known as chaos was first discovered and investigated in classical systems. Classical physical systems are often so complex that it is impossible to predict their properties by applying the classical laws of physics. When describing these systems, quantum probability replaces classical predictability. Moreover, when chaos and quantum mechanics converge, a surprising degree of universality can result. In these instances, the field of mesoscopic physics has become a natural focal point where issues related to both chaos and quantum mechanics can be addressed. Theoretically, mesoscopic physics has been described at the level between phenomenology and mechanics.

Investigators are trying to understand the physical properties of mesoscopic systems, which are not as small as a single atom, but small enough so that properties are dramatically different from those in a larger piece of a material. When electrons become confined in the mesoscopic regime, they display quantum-mechanical behavior. That is, nanoscale electronic components are governed by the quantum-mechanical behavior of their electrons. The mutual Coulomb repulsion of the electrons affects the entire integrated circuit. However, this apparently unwanted behavior can also be exploited to design new types of devices such as the *single-electron transistor*. In addition, at low temperatures, quantum phenomena and the Coulomb blockade that dominate electron transport can also be used to develop new sensor technology.

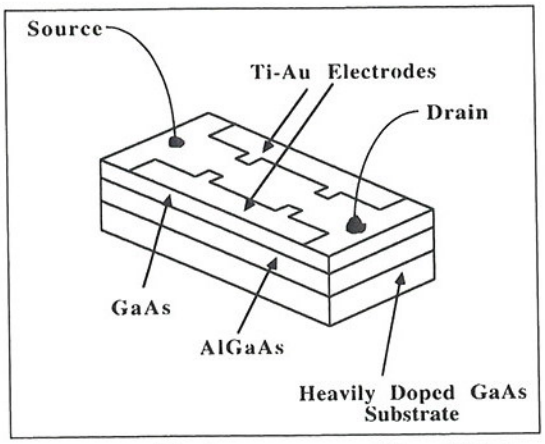
Physicists now work with electronic circuits as small as 10 nanometers. These nanostructure devices are expected to be an important part of the next generation of electronic technology. Devices on this scale are so small that they can only be observed with electron microscopes. After fabricating one of these microscopic circuits, investigators can then characterize its behavior using some of the newest experimental techniques. The fabrication of novel devices sensitive to the effects of quantum coherence has also provided a type of laboratory where the foundations of quantum chaos are investigated and applied. Recently, the study of these new devices, from a circuit perspective,



This chart illustrates the comparative measurements of various natural and human-made objects on several length scales. One nanometer is found between the .01 micron and 1 angstrom measurements on the scale. From "Interactive Nano-Visualization in Science and Engineering Education (IN-VSEE)," http://enpc.1644.eas.asu.edu/. Graphic rendering by S. Selkirk. Concept by V. Pizziconi and B.L. Ramakrishna. © Arizona State University, 1997. Reprinted by permission.

Harnessing the Energy of a Single Electron

As the physical laws related to today's computer memory and processor fabrication reach their limits, new approaches such as single-electron technology are being explored. Single-electron devices are the potential successors to the conventional technology employed to make metal-oxide semiconductor field-effect transistors (MOSFETs). This is because they make use of the electron—the smallest unit of electrical charge—to represent bits of information. While electron tunneling in MOSFETs limits their smallest integration scale, this same behavior in single-electron devices may prove to be the ultimate solution.



A schematic of the device structure of the artificial atom studied in Professor Marc A. Kastner's group. It consists of an inverted heterostructure of a degenerately doped substrate upon which is grown a layer of aluminum gallium arsenide and a layer of undoped gallium arsenide.

When electrons are confined to a small particle of metal or a small region of a semiconductor, both the energy and charge of the system are quantized. In this way, such nanometer-sized systems behave like artificial atoms. While artificial atoms can be constructed using metals and semiconductors in various geometries, the physics of these devices remains the same.

Considered one of the simplest types of artificial atoms, the metallic single-electron transistor (SET) is a nanoscale device that was developed in 1987. A metallic SET consists of a metal particle isolated from its leads by two tunnel junctions (which are similar to diodes) and capacitively coupled to a common gate electrode. The tunnel junctions create what is known as a Coulomb island, which the electrons can enter only by tunneling through one of the insulators. Coulomb repulsion prohibits more than one extra electron at a time on the island (near the gate). Thus, electronic circuits can be made to pump or count electrons one at a time. Because an SET's electrical resistance is highly sensitive to the electrical fields from nearby charges, it can easily detect not only single electrons, but also charges as small as 1 percent of an electron's electrical field. The current as a function of bias across the tunnel barriers can also be measured in order to observe the so-called *Coulomb staircase,* a stepwise increase of current as electrons are added to the metal particle.

At RLE, Professor Marc A. Kastner's group pioneered the first semiconductor SET device, which consists of a semiconductor quantum dot sandwiched between two metallic leads. In their ongoing work on single-electron devices, they continue to investigate a phenomenon called the Kondo effect in semiconductor SETs. Here, a quantum dot interacts with nearby metallic leads much like a single magnetic impurity interacts with a surrounding metallic substance. Professor Kastner's research program is described in detail on page 11 and in the "Faculty Profile" (page 22).

Because SETs exhibit extremely low power consumption, reduced device dimensions, excellent current control, and low noise, they promise to reveal new physics and innovative electronic devices. These features hold the potential for using SETs in specialized metric-scale applications, such as in current standards and precision electrometers. Also, possible design applications that exploit the SET's reduced dimensions and use a minimum number of devices may result in the creation of high-density neural networks. However, their use in high-density computer memory and data-processing systems must overcome problems associated with quantum charge fluctuations and the SET's sensitivity to microwave radiation.

has included a characterization of quantum-mechanical resistance and capacitance with mesoscopic transport theory.

Building to Smaller Dimensions

A classic example of a nanostructure is the single-electron transistor (SET). It consists of a metal island, a few hundred nanometers across, coupled to two metal leads via tunnel barriers. At temperatures below 1 K, no current can pass through the island for low-voltage biases. This effect is known as the Coulomb blockade, which is the result of the repulsive electron-electron interactions on the island. Most importantly, the current through the island can be accurately controlled down to a single electron. SETs are also realized in semiconductor devices, where their behavior is characterized as a quantum dot. (For a more in-depth description of SETs, see article above.) Quantum dots are nanometer-sized human-made boxes that control the flow of atoms by selectively holding or releasing them. The concepts underlying quantum dots and their applications are discussed in this issue's "Faculty Profile" with Professor Marc A. Kastner (see page 22).

Building Itself from Scratch: Self-Assembly

Nature uses self-assembling materials for nanostructures as the components for living cells. Examples of these—such as bones and shells—demonstrate how nature can assemble different materials into a variety of useful composites at the cellular level. However, human attempts at similar structures are limited to building self-assembling nanoscale materials a few atoms or molecules at a time. The process of self-assembly is a coordinated action of independent entities under distributed control that produces a larger structure or achieves a group effect. Earlier this century, scientists successfully coaxed simple materials to self-assemble into microscopic structures such as layered films and liquid-crystal phases. Unfortunately, these structures lacked the complexity of the natural composites.

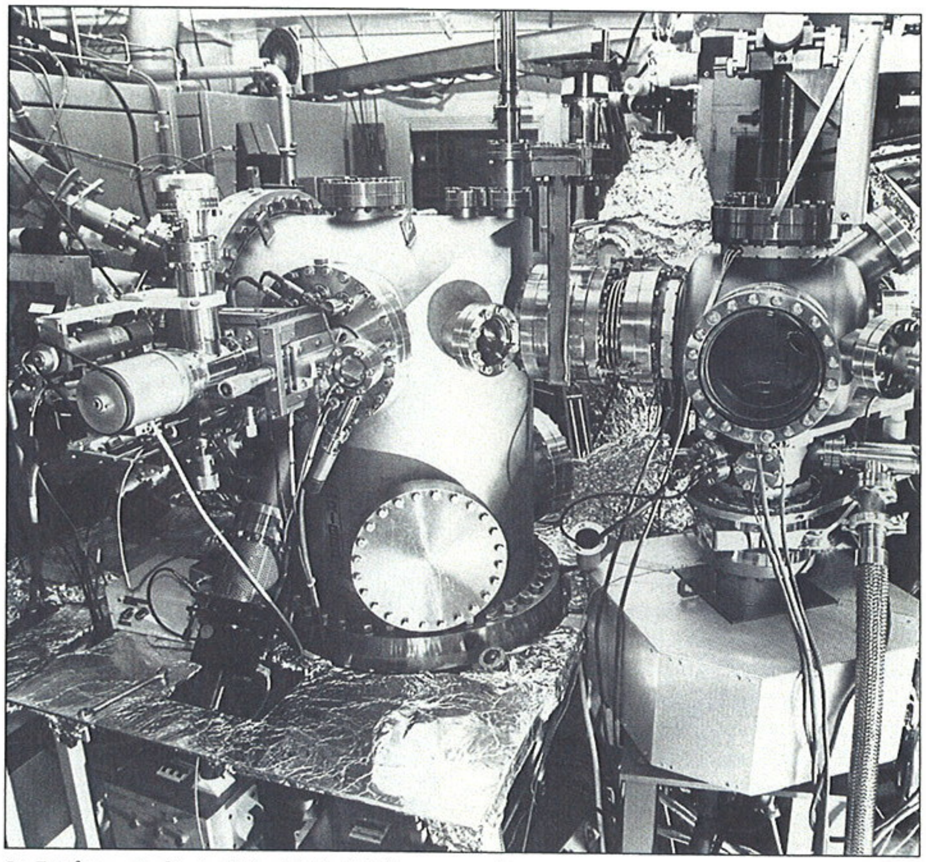
Various examples of self-assembly can be observed in biology, in the fields of embryology and morphogenesis; in chemistry, where groups of molecules form more loosely bound supramolecular structures; and in robotics, where some efforts are aimed at producing and programming robots capable of self-assembly. In building nanostructures and nanoelectronic devices, chemical self-assembly has become an important factor in building supramolecular nanostructures with useful electrical properties. One example is in the field of x-ray nanolithography, which is well suited for generating patterns on the submicron scale. However, it is not the best method for accurately manipulating structures that are less than approximately 30 nanometers wide. Hence, new self-assembly techniques hold promise for going beyond the limits of this technology. The challenge now is for scientists to uncover the secrets of the self-assembly process—how it is achieved, how it can be controlled, and how it can be effectively applied to strategies for nanofabrication.

TOOLS OF THE NANOTECHNOLOGY TRADE

The nanotechnology frontier is becoming accessible for the first time with powerful fabrication and probing techniques. Some of these same methods are employed in condensed-matter physics studies, where quantitative measurements probe the electrical, optical, thermal, and magnetic properties of a material. These measurements also focus on a material's response to externally applied electrical fields and temperature gradients. Earlier methods used to probe the structure and composition of solids included the light microscope, x-ray diffraction, and infrared and ultraviolet spectroscopy. In fact, spectroscopy was originally used to determine the chemical composition of materials and new techniques were added to detect structural characteristics. The development of new tools and techniques for nanostructure research has become a science in itself, particularly in the field of materials science and its applications to nanotechnology.

Much of the advanced instrumentation designed to probe the mysteries of matter and its underlying properties provides high-intensity sources of radiation for increased sensitivity and resolution. On the atomic level, synchrotron light, a continuous spectrum of electromagnetic radiation ranging from infrared to x-rays, is well suited to surface studies. However, various other experimental methods have been developed that involve diffraction, microscopy, and spectroscopy. These enable scientists to get an even closer and more precise look at materials and their properties. Methods (such as atomic layer epitaxy, molecular-beam epitaxy, and the Langmuir-Blodgett technique) have been developed to fabricate thin, two-dimensional nanostructures with an accuracy of a single atomic layer. However, the challenge comes when scientists attempt to create structures less than 100 nanometers in two or three dimensions.

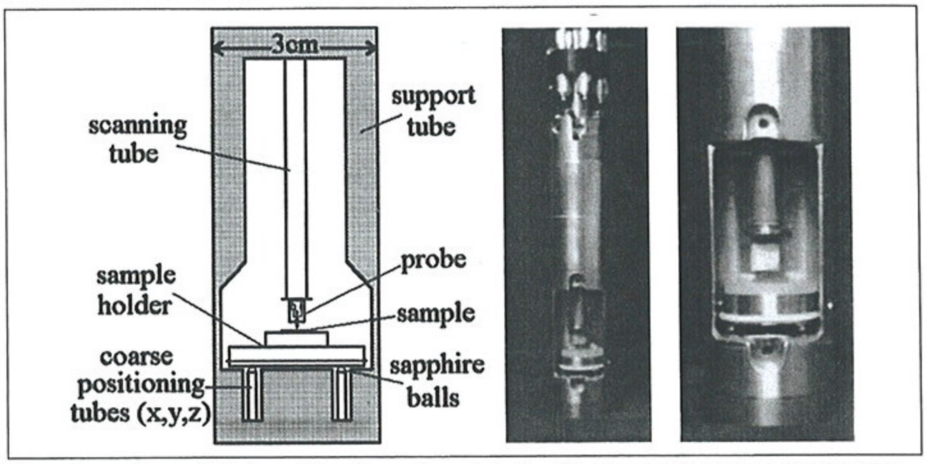
To efficiently emit or detect photons, it is often necessary to constrain fabrication processes to very thin semi-



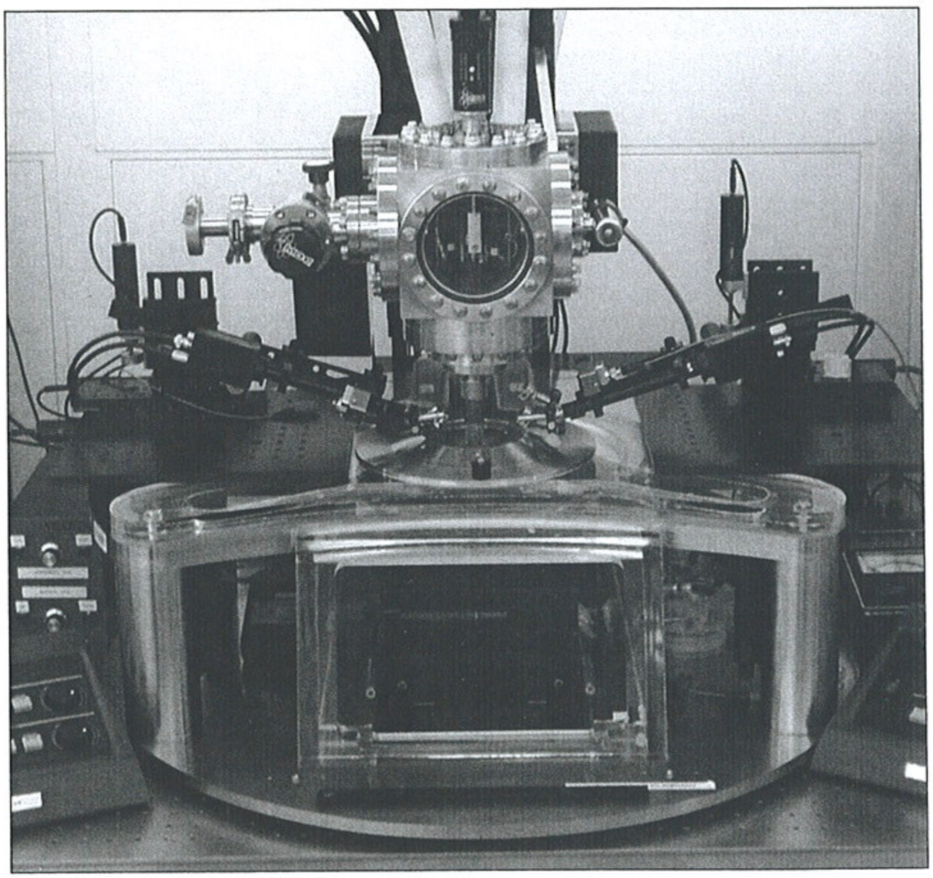
In Professor Leslie A. Kolodziejksi's laboratory, this gas source molecular-beam epitaxy system is used for the deposition of III-V compound semiconductor materials that contain arsenic and phosphorus. (Photo by John F. Cook) conductor layers. These thin layers, grown on top of bulk semiconductor wafers, are called epitaxial layers. Their crystalline properties match that of the substrate, although the composition of materials may be different. For example, gallium aluminum arsenide may be grown on a gallium arsenide substrate. The layers that form (which are measured in angstroms) are called a heterostructure. Sandwiching very thin layers of a semiconductor material between layers of a different composition enables scientists to control the heterostructure's bandgap. Bandgap engineering is applied to III-V compound semiconductors as well as elemental semiconductors such as silicon and germanium. It allows the creation of semiconductor materials with novel properties.

Epitaxial layers are normally grown on flat surfaces, but methods are being explored to grow layers on nonplanar structures in order to accommodate features, such as ridges or channels, etched into the surface of semiconducting devices. However, a better understanding of these surfaces is needed in order to develop the nonplanar epitaxial techniques required to produce future monolithic integrated optical devices that contain all-photonic switches and logic elements. The understanding and control of surfaces are critical, particularly in the production of silicon-based electronics, as feature sizes continue to shrink and quantum effects influence the operation of these devices.

The most precise method to grow epitaxial layers on a semiconducting substrate is molecular-beam epitaxy. This technique uses a beam of atoms or molecules emitted from a common source. After traveling across a vacuum, the beam strikes a heated crystal surface and forms an epitaxial layer with the same crystal structure as the substrate. Another deposition method is atomic layer epitaxy (ALE), which is a digitally controlled layer-by-layer technique used to produce thin material layers with atomic accuracy. Each layer that is formed is the result of a saturating surface reaction. The thin films are virtually free of defects and have near-perfect step coverage, which is required in submicron semiconductor technology. The surface control achieved in ALE produces thin films with bulk density and excellent uniformity on large area substrates. In the future, ALE may be a valuable tool for nanotechnology, especially when combined with appropriate pat-



The schematic and photographs above show details of the innovative probe used in the scanning tunneling microscope designed by Professor Raymond C. Ashoori's group. The high-range piezoelectric scanning head, which sits inside a helium-3 cryostat so it can operate at 0.3 K, incorporates a sharp tip into an extremely sensitive "bridge-on-a-chip" detector. By mounting the probe on the end of a piezoelectric element, the tip can scan over a material's surface. The resulting signal produces a two-dimensional image of a material's capacitance. The microscope can also operate as a conventional STM.



An x-ray lithography alignment/exposure system used in RLE's NanoStructures Laboratory. Features as fine as 20 nanometers are readily exposed in resist by using an x-ray wavelength of 1.32 nanometers. The mask alignment scheme, which was developed in the NanoStructures Laboratory, is called interferometric broadband imaging. It is capable of detecting sub-1-nanometer misalignment between mask and substrate. Substrates as large as 20 centimeters in diameter and as small as 1 centimeter can be accommodated. This system is employed for sub-100-nanometer-channel silicon devices as well as optoelectronic devices. (Photo by Euclid E. Moon) terning and micromachining techniques.

Both scanning and electron microscopies are used to probe geometric structure. Scanning tunneling microscopy (STM) can determine the distance between the probe and the surface under study by exploiting the quantum tunneling effect—the tunneling of electrons below the tops of energy barriers. Held near the surface of a material, the STM's stylus probe generates an electric current into the 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. Moving the probe up and down over the surface produces a three-dimensional image. STM allows both the topographical and electrical properties of a material to be studied. STM also permits the manipulation of atoms on the material's surface.

In another type of three-dimensional atomic resolution microscopy, the atomic force microscope (AFM) exploits various interatomic forces that occur when two objects are brought within nanometers of each other. AFMs operate when its sharp silicon-tip probe contacts the surface, which causes a repulsive force, or when the probe is a few nanometers away, which results in an attractive force. Similar in operation to the STM, it also creates three-dimensional images. Both STMs and AFMs can be used in resist-based lithographic processes. However, STM is limited to the study of metal surfaces while AFM can be used on both nonmetallic and metallic surfaces. AFM techniques are also used to fabricate microelectromechanical systems (MEMS) in order to build an array of many AFM tips on a single chip.

In the early 1980s, scanning probe microscopes (SPMs) produced the first real-space images of the silicon surface. As an offshoot of the STM, the SPM is used to study the surface properties of materials from the atomic to the micron level. It can also be used in the three-dimensional imaging of structures, where it has a large dynamic range that encompasses the domains of both the optical and electron microscopes. The SPM's probe is atomically sharp, and it typically scans a material's surface at a distance of a few angstroms or nanometers. Not only does it allow probing under various conditions (such as air, gas, liquid, and vacuum), but it also permits the selective manipulation of single atoms on a solid surface. Thus, it has the ability to measure many physical properties. By combining the methods of ultrasensitive charge sensing with low-temperature SPM, Professor Raymond C. Ashoori in RLE has developed *subsurface charge accumulation imaging* (SCA), a new approach to observing behavior under the surface of semiconductor materials (see page 10).

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 electron microscopy (SEM) is performed by scanning a focused probe across the surface of the material. Secondary electrons emitted from the sample are typically detected by a photomultiplier system, the output of which is used to modulate the brightness of a monitor synchronized with the electron-beam scan. The more electrons a particular region emits, the brighter its image. 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. In STEM, the electron beam is rasterized across the surface of a sample in a similar manner to SEM, however, the sample is a thin section and the diffraction contrast image is collected on a solid-state detector.

Electron beams have played a significant role in semiconductor technology for more than twenty years. Early electron-beam machines used a raster-scanned beam spot to write patterns onto electron-sensitive polymer resist materials. Today, electron-beam lithography (EBL) is employed to make the smallest components on silicon substrates and is the most effective method of creating patterns on substrates such as photomasks and x-ray masks. In RLE's NanoStructures Laboratory, a scanning-electron-beam lithography system is used to direct-write onto device substrates, to make photomasks and x-ray masks, and to develop a new technique called spatial-phase-locked electron-beam lithography, which will improve the writing precision of the current EBL system.

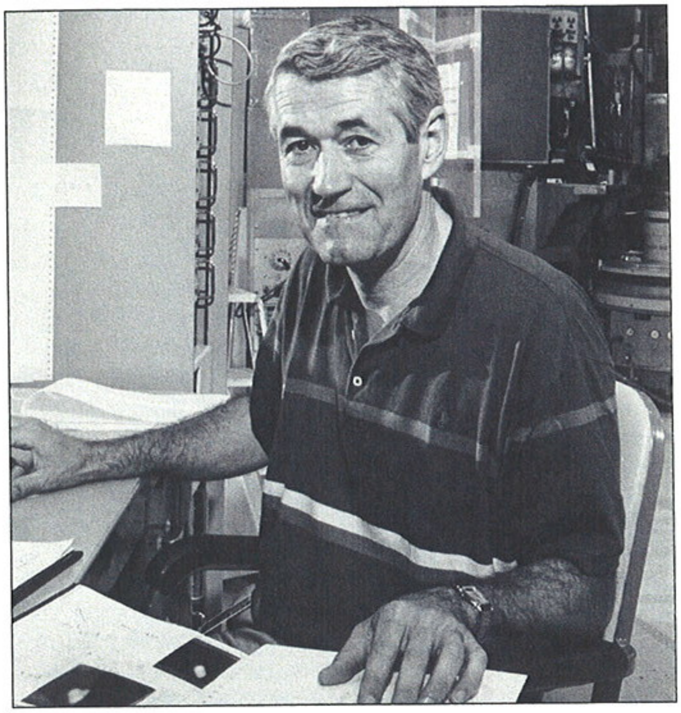
EVOLUTION OF CONDENSED-MATTER PHYSICS IN RLE

Since the invention of the transistor in 1947, RLE has continued to make a strong investment in solid-state electronics and condensed-matter physics. In the laboratory's early days, interest focused on basic device physics, circuit modeling, and the use of evolving solid-state technology. Following the invention of the integrated circuit in 1959, there were profound changes in electronic system implementation and increased possibilities for highly complex designs at the circuit and system levels.

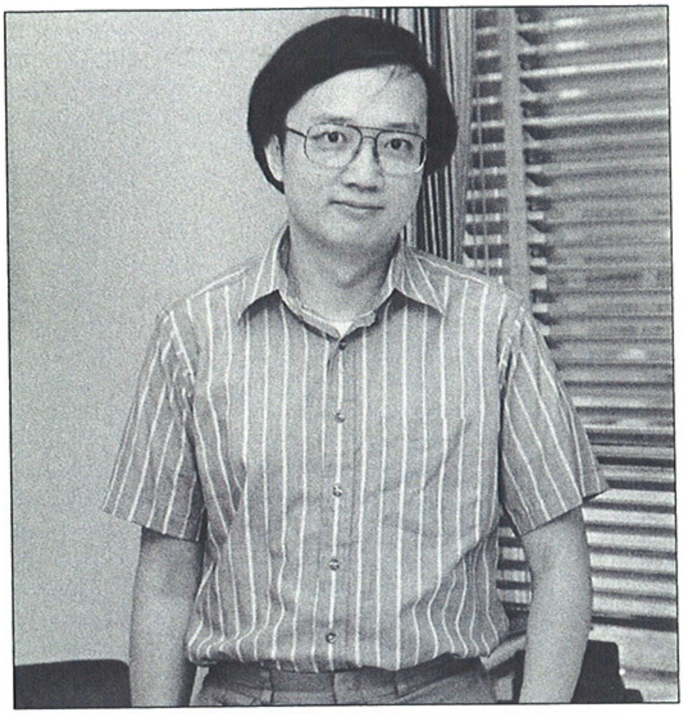
Maintaining its broad interpretation of electronics, RLE was supported in its efforts through the sponsorship of the Joint Services Electronics Program (JSEP), which was the laboratory's initial sponsor in 1946. After fifty years of sponsorship, during which time RLE investigators were able to explore the electronics of the future, JSEP was discontinued. However, RLE continues this tradition of basic research in future electronics by investigating the physics of quantum structure in restricted dimensional systems and quantum optics in nonlinear media. These areas are crucial to developing nanoscale devices that can operate in the quantum world and to merging electronics with photonics to create optical circuits.

Today, RLE's broad scope of electronic disciplines encompasses materials and fabrication, surfaces and interfaces, devices, circuits, and systems. These areas provide a comprehensive base from which new strategies for circuit and system design are evolving. Investigators in RLE have continually sought to provide the necessary scientific tools and methods for advances in ultrasmall and ultrafast device technology.

The properties of surfaces and interfaces have also been extensively studied and characterized, theoretically and experimentally. This has led to richly detailed views of surface reconstruction and epitaxy. In addition, novel solid-state devices have been developed with compatible electronic system interfaces. New insights have also been obtained for many diverse phenomena with very small dimensions in crystal growth, surface adsorption, phase transitions, and fundamental transport in ultrasmall devices that exhibit quantum effects.



Since coming to the MIT faculty in 1975, Professor Robert J. Birgeneau has investigated phases and phase transition behavior of novel states of matter. He and his colleagues have played a seminal role in developing synchrotron radiation techniques for high-resolution condensed-matter studies and carrying out an extensive series of x-ray diffraction studies of surface phase transitions and reconstructions. In collaboration with Professor Simon G.J. Mochrie, who joined RLE in 1992, he has studied surface morphology and growth patterns using high-resolution x-ray diffuse scattering techniques. His collaborations with Professor Marc A. Kastner have also provided a deeper understanding of the interrelationship of antiferromagnetism and superconductivity. Today, as MIT's dean of science, Professor Birgeneau continues his work in the Department of Physics by studying the large, reversible changes in semiconductor surface morphology caused by current flow in certain temperature regions. He also continues his efforts to better understand the basic microscopic physics of high-temperature superconductors. *(RLE file photo by John F. Cook)*



Professor Patrick A. Lee focuses on the physics of small devices including conductance fluctuations, transport through quantum dots, the quantum Hall effect in confined regions, and the theory of high-temperature superconductors. He has close theoretical collaborations with Professors Marc A. Kastner and Raymond C. Ashoori in developing new transport models for phenomena revealed in their experiments. Professor Lee was instrumental in establishing a theory to explain the unusual temperature dependence of conductance peaks in single-electron transistors as a function of gate voltage and accounted for their behavior in strong magnetic fields. His recent studies involve the coupling of quantum dots and wires to realize devices that are more complex. He has also addressed transport phenomena and the Kondo effect in quasi-one-dimensional metals, which may be realized in a quantum dot coupled to narrow source and drain leads. By contributing to Professor Ashoori's experimental research on electrons tunneling into a quantum dot, Professor Lee has extended the understanding of electron behavior in integer or fractional quantum Hall states. *(RLE file photo by John F. Cook)*

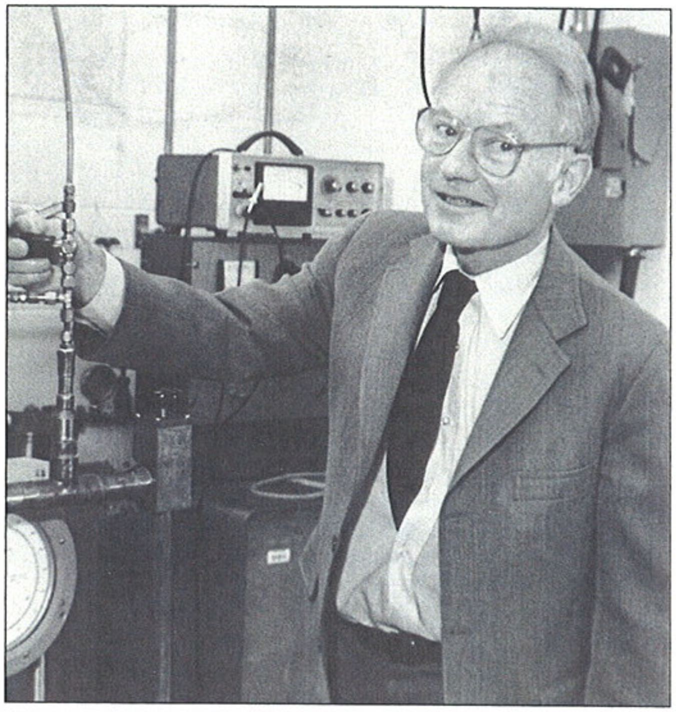
In the early 1970s, several condensed-matter physicists joined the Physics Department faculty. Professors Marc A. Kastner, John D. Joannopoulos, and Robert J. Birgeneau became the core of a new condensed-matter physics effort at MIT. These faculty members joined RLE after Professor Peter A. Wolff was appointed laboratory director in 1976. They contributed not only to new directions in RLE's Joint Services Electronics Program, but also to an emerging emphasis on the basic theory of and experimentation with electronic devices.

CURRENT RLE RESEARCH IN NANOSCIENCE

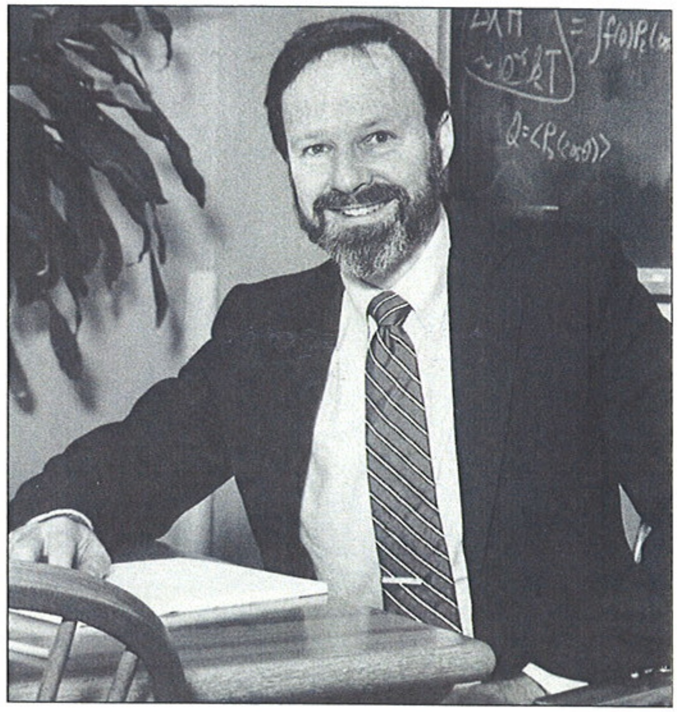
As the critical dimensions of integrated circuits continue to decrease, the new insights developed at RLE in condensed-matter physics will be vital to the complex, high-performance circuits anticipated for the future. Ongoing research in this area is carried out in RLE's Quantum-Effect Devices group and its Surfaces and Interfaces group.

Quantum-Effect Devices

New quantum effects in nanostructures can now be found at low temperatures and in high magnetic fields, but as the size of these structures decreases, quantum effects will become important in environments that are more normal. Ongoing studies of novel states of matter in semiconductor materials such as silicon and gallium arsenide seek to provide a new and fundamental understanding of basic processes in these materials at more normal magnetic fields and temperatures. Research in this area



Professor Emeritus Peter A. Wolff began his career at Bell Labs and came to the MIT faculty in 1970 as the Department of Physics Division Head for Solid-State and Atomic Physics. During his tenure as RLE director, from 1976 to 1981, Professor Wolff was instrumental in building a solid-state physics presence in RLE. His own research in RLE involved a broad range of interests in solid-state physics. His investigations have included experiments in magnetism, local moments, semimetals, semiconductors, solid-state plasmas, and light scattering in solids. More recently, his research has focused on the nonlinear optics of semiconductors for use in optical signal processing and picosecond electron kinetics. In studying free carriers in semiconductors, he demonstrated that optical nonlinearities are caused when properties of electron states vary with energy. After serving as director of MIT's Francis Bitter National Magnet Laboratory (from 1981 to 1986), he retired in 1989 and joined the NEC Research Institute in Princeton, New Jersey. Professor Wolff returned to MIT in 1994 and currently assists the MIT Physics Department in its efforts to work together with industry. *(RLE file photo by John F. Cook)*



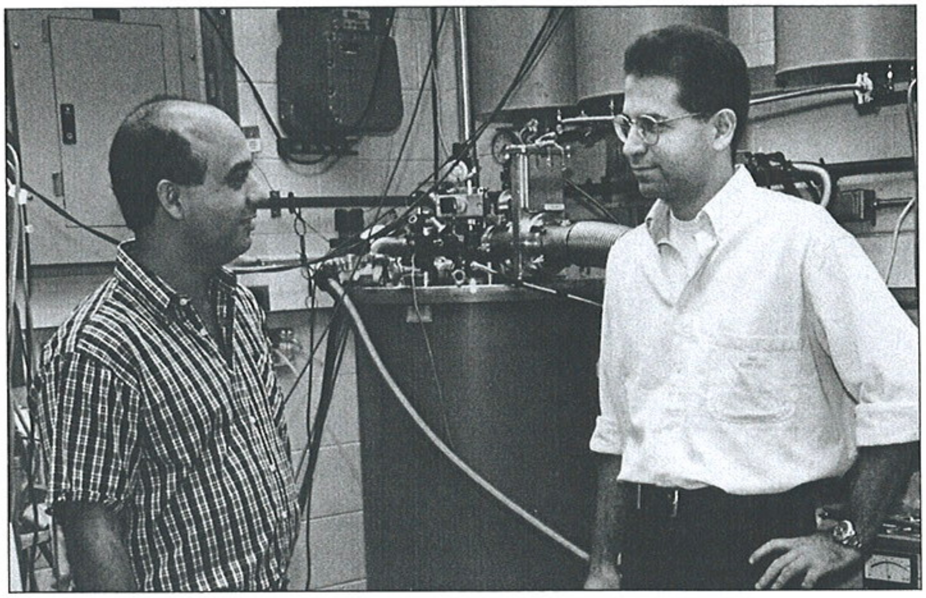
In the late 1970s, Professor J. David Litster collaborated with Professor Robert J. Birgeneau and began a new research direction in RLE using x-rays to study the nature of liquid-crystal materials and their phases. One of their results provided the first experimental verification that a one-dimensional density wave system is realized in nature in the form of a smectic liquid crystal. In later collaborations, they analyzed the hexatic phase in liquid-crystal materials using the MIT/IBM beam lines at the National Synchrotron Light Source at the Brookhaven National Laboratory. Their extensive studies on the development of crystalline axes and positional order demonstrated that transitions in hexatic states are continuous and reversible. Currently, Professor Litster is MIT's Vice President for Research and Dean for Graduate Education. He continues his experiments in the Physics Department on novel liquid-crystal phases and transitions with an emphasis on two- and three-dimensional behavior. *(RLE file photo by John F. Cook)*

of nanoscience often focuses on single atoms and single charge carriers that are characterized with high precision. This work holds the promise for the development of new devices that will rely on the motion or presence of a single carrier. Investigators anticipate the ability to design at this level of precision by developing novel fabrication technologies and circuit techniques adapted to these new quantum-effect devices. RLE's Quantum-Effect Devices group combines both theoretical and experimental studies of these devices.

Ultrasensitive Capacitance Spectroscopy of Semiconductors

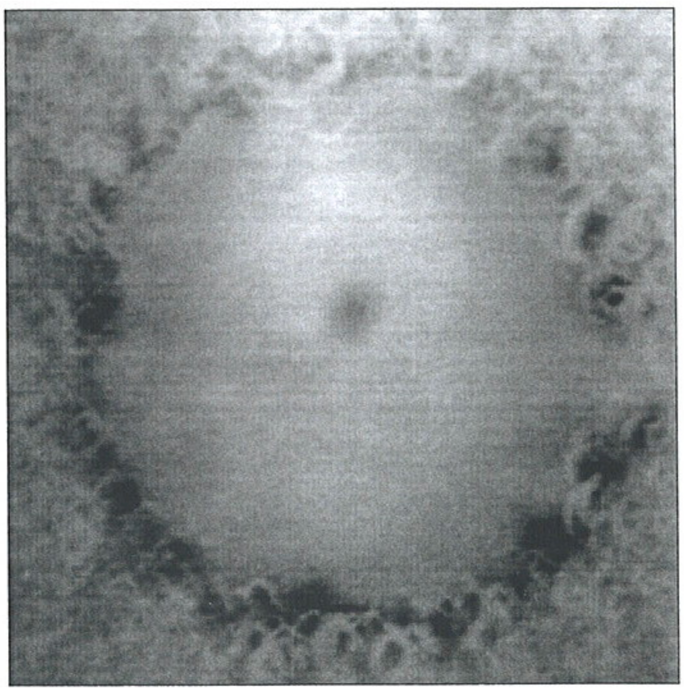
Professor Raymond C. Ashoori's group is focused on new methods of charge sensing to study semiconducting samples. Experiments are conducted using ultrasensitive high-capacitance measurement apparatus to investigate the physics of electronic processes inside materials. In Professor Ashoori's earlier research, he carried out experiments in which a single electron tunneled on and off a quantum dot, mapping the energy level structure of the first several tunneling electrons. By exploiting this ability to tunnel electrons onto a quantum dot, he was able to produce artificial atoms. This demonstration of electrometry allowed his group to observe the motion of single electrons moving into single traps inside a semiconductor. These traps can consist of individual impurities, random potential fluctuations, or structures such as artificial atoms. Professor Ashoori and his colleagues have been working to further exploit these experimental techniques.

By combining the methods of ultra-

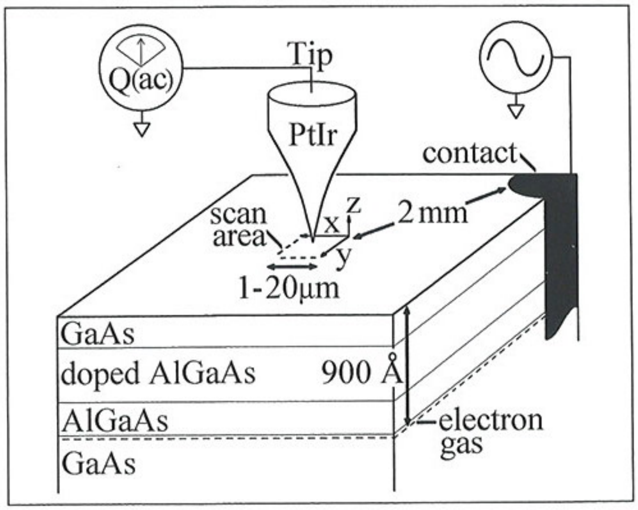


Professor Raymond C. Ashoori (left) and Research Assistant Paul I. Glicofridis discuss ongoing quantum Hall imaging experiments using the subsurface charge accumulation imaging methods developed in their group. (Photo by John F. Cook)

sensitive charge sensing with low-temperature scanning probe microscopy, Professor Ashoori and his group have developed a new method to directly observe charge distributions under the surface of semiconductor materials. This new tool, called *subsurface charge accumulation imaging* (SCA) is used to directly image nanoscale structures in the quantum Hall electronic liquid. The quantum Hall effect occurs in a two-dimensional electron gas (2DEG). A most impressive consequence is that electrical currents with no resistance can exist at the edges of a semiconducting sample. The structure of these electronic states has long been a mystery, and Professor Ashoori's group is using SCA as a powerful means for their study. SCA's spatial resolution is approximately 1000 times finer than previous images of



A subsurface charge accumulation image (SCA) of the two-dimensional electron gas (2DEG) in the quantum Hall regime. The sample was prepared so that the maximum density of electrons is at the center of the image, and decreases smoothly and radially outward. Electron density is approximately 10 percent higher at the center of the image than at the edges. A 3.07-tesla magnetic field is applied perpendicularly to the sample's plane. This magnetic field causes electronic energy levels in the 2DEG to become quantized into states known as Landau levels, and their subsequent filling depends on the local electron density. Regions of completely filled levels cannot accommodate more electrons in response to the applied ac excitation. This causes dark areas to appear, which correspond to low charge accumulation in the 2DEG. Such regions are electrically insulating and are called incompressible. Brighter areas result from partially filled levels, which are conducting and compressible. The observation of a ring-shaped incompressible strip demonstrates the capability of subsurface charge accumulation imaging to probe electronic structures in the quantum Hall fluid.



This schematic shows the sample and measurement configuration of a two-dimensional electron gas (2DEG) between aluminum gallium arsenide (AlGaAs) and gallium arsenide (GaAs) layers, 900 angstroms beneath the surface of a semiconductor material. An ac excitation is applied to the 2DEG, causing charge to flow in and out of this layer. A sharp metal tip is positioned 50 angstroms above the sample surface and scanned at a constant height. The technique, called subsurface charge accumulation imaging (SCA), produces an image of the charge accumulating in the 2DEG by detecting the charge induced on the tip from the layer.

the quantum Hall system. It has allowed his group to observe the behavior of a strongly interacting quantum-mechanical fluid of electrons. In an effort to understand the images observed with SCA and how these microscopic structures might lead to the quantum Hall effect, experiments are being prepared to study systems in which the scan probe will image the entire Hall bar. Future investigations will focus on several intriguing features in the quantum Hall effect, such as edge states and the fractional quantum Hall effect.

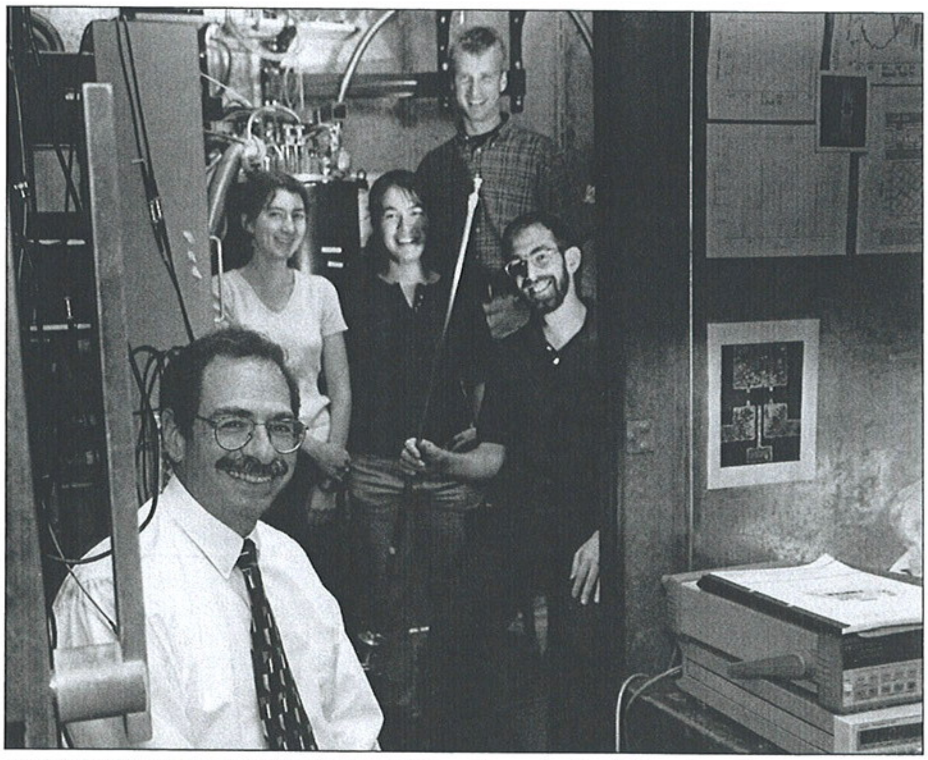
The SCA microscope developed in Professor Ashoori's group has many other practical and scientific applications. For example, scientists can now look beneath the silicon and silicon dioxide interface, where most transistors perform digital logic operations by modulating conduction. SCA can also create images of distributions as well as different types of semiconductor defects and impurities. This enables researchers to observe the mechanisms that affect device performance. Professor Ashoori believes this new type of microscopy will prove extremely powerful in understanding the many physics problems that are related to electrical conduction inside materials.

Single-Electron Electronics

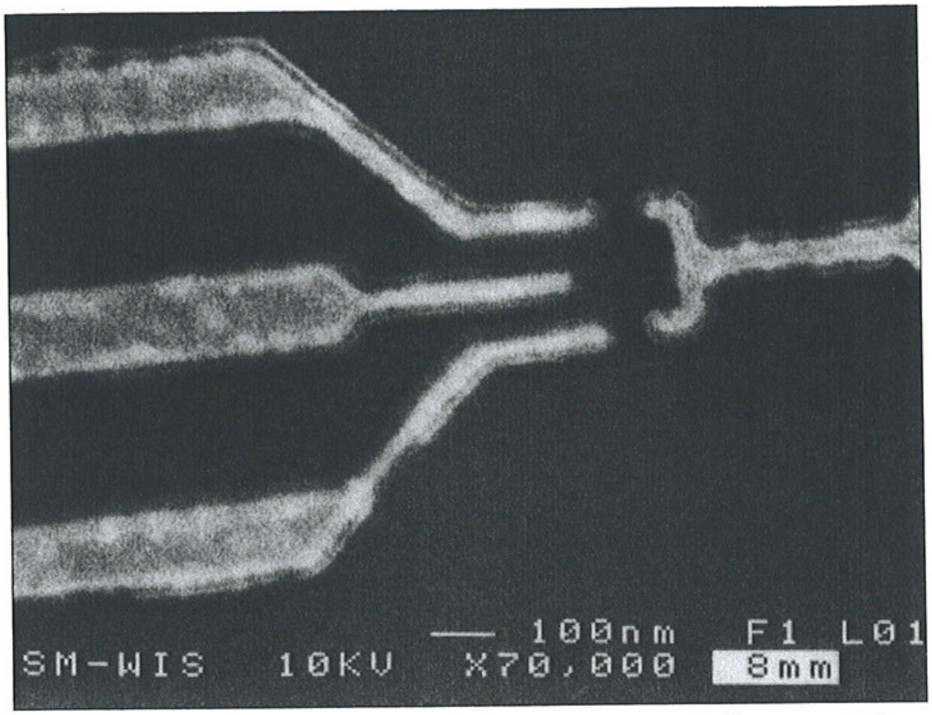
Professor Marc A. Kastner's early research in RLE centered on the electronic structure of amorphous semiconductors, specifically the relationship between chemical bonding and the electronic structure of defects in glasses. Today, Professor Kastner's group is focused on the study of few-electron systems such as artificial atoms or quantum dots. These systems are so small that the addition of a single electron scientists can observe, as well as how that addition affects the distribution of other electrons in the system. By carrying out low-temperature measurements (50 mK to 50 K) of electron current in these devices as a function of applied voltage, chemical potential, and magnetic field, Professor Kastner's group can gain important insight into the nature of their electronic states. A better understanding of the physical phenomena that is critical in submicron regimes will contribute to the development of new and smaller electronic devices.

In addition, his group's investigations into very small field-effect transistors (FETs) that are separated from their source and drain by tunnel junctions has enabled the study of Coulomb blockade effects in these structures. This work has led to the realization of a semiconductor *single-electron transistor* (SET), a device that is turned on and off by the addition of a single electron (see article on page 4). His group's experiments in this area are aimed at understanding the quantum transport and novel device action observed in SETs. One goal is to raise the energy scale of SETs so that they can be used at practical operating temperatures. Ongoing experiments seek to improve the design of SETs in gallium arsenide, and the group is also working to fabricate these devices in silicon, which is the material of choice for higher operating temperatures. To overcome the difficulties in controlling individual SETs, Professor Kastner's group is also investigating two- and three-dimensional arrays of self-assembled artificial atoms and their applications. Since a small capacitive coupling between two artificial atoms drastically alters their properties, novel configurations for these devices are possible. One potential application for complex SET arrays may be neural networks or cellular automata for computation. However, this research relies on the availability of devices that can operate above liquid nitrogen temperatures.

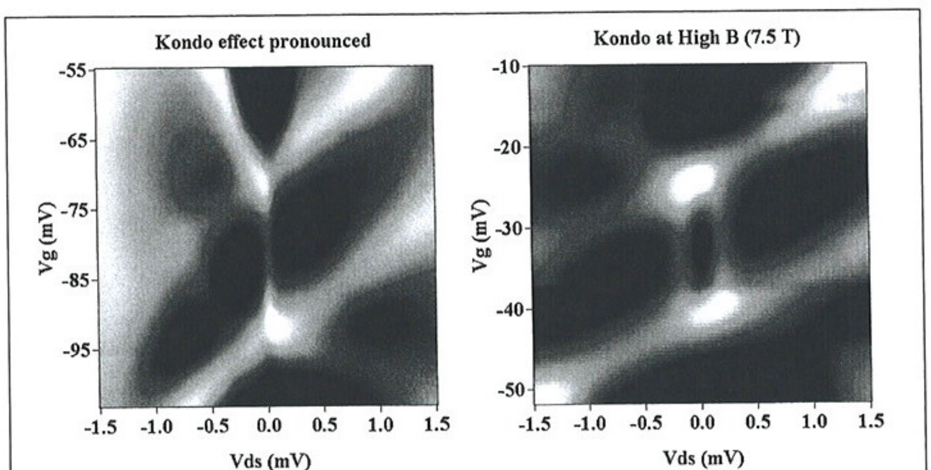
In collaboration with Professor Kastner, Professor Ashoori has introduced SETs to improve the sensitivity of his spectroscopic measurements. Methods have been developed to use single-electron transistors for charge sensing on semiconducting samples. In terms of charge sensitivity, SET devices give an approximately 100-fold improvement over other methods. By measuring the electron addition spectrum of quantum dots as a function of gate voltage, Professor Ashoori can determine the voltage at which single electrons can be added to an artificial atom. In this way, Professor Kastner can use this information in his experiments to learn more about coupling quantum states of the artificial atom to the leads. In addition, the combined research of Professors Kastner and Ashoori is used to test the theoretical predictions made by Professor Patrick A. Lee. (For a more



In the shielded room used for their experiments on single-electron transistors are (from left): Professor Marc A. Kastner, Research Assistants K. Jessica Thomas, Nicole Y. Morgan, Jörn Göres, and David J. Goldhaber-Gordon, who wields the probe and sample holder. (Photo by John F. Cook)



Metal electrodes on the surface of an aluminum gallium arsenide/gallium arsenide heterostructure that create a single-electron transistor. When grown, the heterostructure contains a two-dimensional electron gas everywhere, except where there are electrodes. The electrodes are biased negatively to create an isolated droplet of electrons separated by tunnel junctions. The tunnel junctions are caused by the two narrow constrictions. The regions outside the constrictions act as source and drain leads. When the voltage on the narrow middle electrode (the gate) is increased, the transistor turns on and off once for every electron added. Research on single-electron transistors is carried out in Professor Marc A. Kastner's group.



The differential conductance is plotted using a color scale for the single-electron transistor as a function of both gate voltage (vertical) and source-drain voltage (horizontal). The bright, broad diagonal bands are where the combination of gate and source-drain voltage provide the energy for electrons to tunnel onto and off of the confined droplet. With no magnetic field (left), there is a single narrow line at zero source-drain voltage. This is the extra conductance from the Kondo effect. In a magnetic field (right), the narrow line splits because the magnetic moment of the unpaired electron on the droplet can be either parallel or perpendicular to the magnetic field. Kondo behavior was observed in an artificially created quantum dot by Professor Marc A. Kastner's group and the Weizmann Institute of Science in Rehovot, Israel. This study found Kondo physics in a system that allows quantitative exploration of the phenomena in a controlled way.

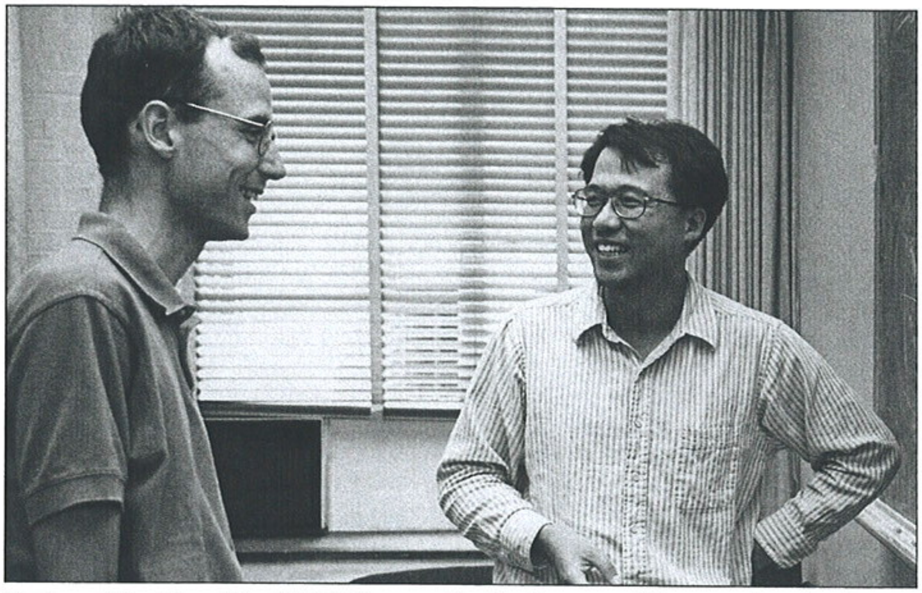
in-depth look at Professor Kastner's research, see the "Faculty Profile" on page 22.)

Quantum Circuit Theory

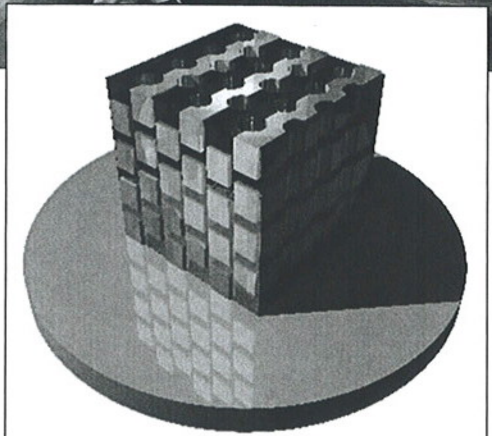
By developing theoretical models of quantum dots and quantum wires, Professor Xiao-Gang Wen is working towards a novel circuit theory for quantum-effect devices. His work addresses issues involved with the ever-decreasing dimensions of the integrated circuit, which is soon expected to approach one-tenth micron. However, because the properties of wires and transistors in an integrated circuit change at this quantum level, they can no longer be characterized by classical electronic circuit theory. Quantum effects, such as the quantization of electronic charge and the interfering wave properties of electrons as they propagate through wires and transistors, become critical. In order to understand the properties of integrated circuits on such a small scale, a rigorous theory is needed for quantum wires, quantum transistors, quantum resistors, and other circuit elements.

In his study of the dynamical theory of quantum dots, Professor Wen is investigating possible modifications to the equation of motion for the density matrix, which is linear for an isolated dot. A preliminary study has demonstrated how the density matrix of the dot can be manipulated through its coupling to the environment. It is anticipated that a nonlinear density matrix equation will enable investigators to explore conditions where quantum dots will have useful properties, such as those similar to a memory element or oscillator. Professor Wen's studies will also guide experimentalists in creating real quantum dots that possess certain novel properties.

Using models obtained from the experimental results of Professors Ashoori's and Kastner's work, Professor Wen is also examining how quantum dots can affect voltage on the leads. In efforts to establish a quantum theory for resistors, his group is developing new models for lead-dot contacts. These models will enable the study of nonlinear quantum dynamics of coupled dots and wires so that quantum electronic circuits can be designed with desired properties. This work will also contribute to a new understanding of the behavior of systems that border on the classical and quantum regimes.



Professor Xiao-Gang Wen (right) discusses the development of theoretical models for quantum dots and wires with Research Assistant Sven Heemeyer. (Photo by John F. Cook)



From left: Professor John D. Joannopoulos; Research Assistant Ickjin Park; physics graduate students Maksim A. Skorobogatiy, Evan J. Reed, and Joshua S. Weitz; Research Assistant Steven G. Johnson; Research Scientist Dr. Pierre R. Villeneuve; Visiting Scholar Nikolaj Moll; and Research Assistants Tairan Wang and Attila Mekis. (Photo by John F. Cook)

A three-dimensional periodic photonic crystal has been proposed by Professor John D. Joannopoulos' group. This complicated structure, with a full bandgap in three dimensions, is a challenge to fabricate at submicron length scales. It is to be fabricated in layers using two dielectric materials, such as silicon and silicon dioxide. Staggered channels of the lower-dielectric material pass through the high-dielectric substrate, and a triangular air-hole lattice is etched perpendicular to the channels throughout the entire crystal.

Surfaces and Interfaces

Modern integrated circuits are fabricated by means of several processing steps that interact with the surface of a semiconductor wafer. Thus, understanding these surfaces and their behavior is central to the production of accurately controlled devices at nanoscale dimensions. In addition, because many of today's nanoelectronic fabrication techniques are concerned with surface phenomena, it is necessary to obtain a detailed atomic-level understanding of equilibrium and growth conditions for realistic and practical surface systems.

In RLE's Surfaces and Interfaces group, there is a coordinated research effort in both experimental and theoretical surface studies. From a theoretical perspective, new techniques have been developed to predict atomic-level surface structure using minimum energy calculations. Experimentally, new tools and methods have been created to study the structure of semiconductor surfaces and several atomic layers beneath them, over a wide range of temperatures. One result is a new understanding of how semiconductor surface steps and facets form and move during processing. Ultimately, this understanding will enable new growth techniques to produce extremely precise semiconductor structures.

Semiconductor Surface Studies

Professor John D. Joannopoulos' research efforts span a wide range of topics in theoretical condensed-matter physics and are responsible for the development of numerous calculational schemes and techniques used to study complex solid systems. These powerful theoretical tools have improved the understanding of various surface conditions such as equilibrium phases and

Photonic Bandgap Engineering: Lighting the Way to Quantum Circuits

Since the suggestion in 1987 that the creation of a periodicity in dielectric materials could prevent the propagation of electromagnetic waves with certain frequencies, much theoretical and experimental work has been performed. For example, a photonic crystal is a periodic dielectric structure that prohibits the propagation of photons in all directions within a certain range of frequencies. This forbidden band of frequencies is called a photonic bandgap (PBG) and is similar to an electronic bandgap in a semiconductor crystal. The absence of electromagnetic modes inside a photonic bandgap can lead to unusual physical phenomena. By exploiting its properties, scientists can easily control light and create effects that are not possible with conventional optics.

In a photonic crystal, light can be localized and trapped in a defect within the structure by introducing a point defect or resonant cavity. It is now possible for that defect to pull a light mode into the bandgap and, since such a state is forbidden to propagate in the bulk crystal, the mode becomes trapped. This enables investigators to adjust frequency, symmetry, and other properties related to the resonant cavity. Photonic crystals not only hold promise for various applications in lasers, antennas, millimeter-wave devices, but also present interesting new physics such as cavity electrodynamics, localization, disorder, and photon-number-state squeezing.

Professor John D. Joannopoulos' group in RLE is involved in predicting and explaining the behavior of photonic crystals, and is investigating new phenomena and devices based on these structures. Working closely with other investigators in RLE and in the departments of Physics, Electrical Engineering and Computer Science, and Materials Science and Engineering, his group has been able to fabricate and optically characterize their designs (see article on page 18). Several directions are now being explored in this wide-ranging research project.

A one-dimensional periodic photonic crystal is created by introducing periodic structure to a conventional waveguide. The one-dimensional PBG devices studied in RLE are called monorail and air-bridge microcavity devices. In monorail microcavity devices, the photonic crystal is a gallium arsenide waveguide with an array of periodically spaced holes etched through its structure. A defect is created by introducing additional space in the middle of the array. The crystal itself rests on a layer of aluminum oxide, which has a much lower refractive index than gallium arsenide. In air-bridge microcavity devices, the crystal is suspended in the air, which results in a higher refractive index contrast between the crystal and its environment. The monorail and air-bridge devices are designed to operate at the 1.55-micron wavelength, which is crucial to optoelectronic applications. To facilitate optical characterization, both devices have waveguides coupled into and out of them.

A one-dimensional photonic crystal works by confining a specific wavelength of light along the direction of its waveguide. Light is also confined in the other two directions by total internal reflection. The confined wavelength is determined by the dimension and spacing of the holes in the crystal. This yields a low-modal volume, high-quality factor resonant microcavity. Because this type of microcavity can alter the spontaneous emission rate of an active region in the microcavity, it promises to improve the performance of optoelectronic devices.

A two-dimensional photonic bandgap device inhibits the propagation of light within a range of frequencies in any direction within a plane. In the device currently being investigated at RLE, the two-dimensional photonic bandgap effect is used to improve the extraction efficiency of a light-emitting diode (LED). The device consists of an LED structure with a periodic array of air holes. This periodic array forms a triangular lattice and results in a photonic bandgap in the plane of the active layer that inhibits the layer's guided modes. When light is generated in the active layer from carrier recombination, the only modes allowed for the light to couple into are the designed radiation modes. Consequently, a higher flux of radiation is emitted in the vertical directions. Simulations have shown greatly improved extraction efficiency of an LED using this technique compared to a conventional LED.

Professor Joannopoulos' group has also proposed a three-dimensional periodic photonic crystal. Since this complicated structure with a full bandgap in three dimensions is a challenge to fabricate at submicron dimensions, the group's proposed design (see illustration on page 13) is to be fabricated in layers using two dielectric materials, such as silicon and silicon dioxide. Staggered channels of the lower-dielectric material pass through the high-dielectric substrate, and triangular air-hole lattice is etched perpendicular to the channels throughout the entire crystal.

The group is also investigating the introduction of waveguide bends in photonic crystals. This work seeks to overcome problems inherent when creating integrated optical circuits with conventional waveguides. A linear defect is created in the crystal that supports a mode in the bandgap. This mode is forbidden to propagate in the bulk crystal because of the bandgap, making it impossible for light to escape when a bend is created in the waveguide. Possible reflection problems are addressed in the same way one-dimensional resonant tunneling is analyzed in quantum mechanics. Thus, it is possible to create waveguides with photonic crystals that allow full transmission with 90-degree bends. This work was recently published in *Science* (S-Y. Lin, E. Chow, V. Hietala, P.R. Villeneuve, and J. D. Joannopoulos, "Experimental Demonstration of Guiding and Bending of Electromagnetic Waves in a Photonic Crystal," October 9, 1998, vol. 282, no. 5387, pp. 274-76).

An overview of this group's research in photonic crystals can be seen on the Web at http://jdj.mit.edu/photons/index.html.

growth patterns in realistic and practical surface systems. Research topics include the electronic and vibrational structure of crystalline and amorphous bulk solids, their surfaces, interfaces, and defects; localization in disordered systems; phase transitions and other phenomena in quantum systems; and most recently, the theory of photonic bandgap crystals.

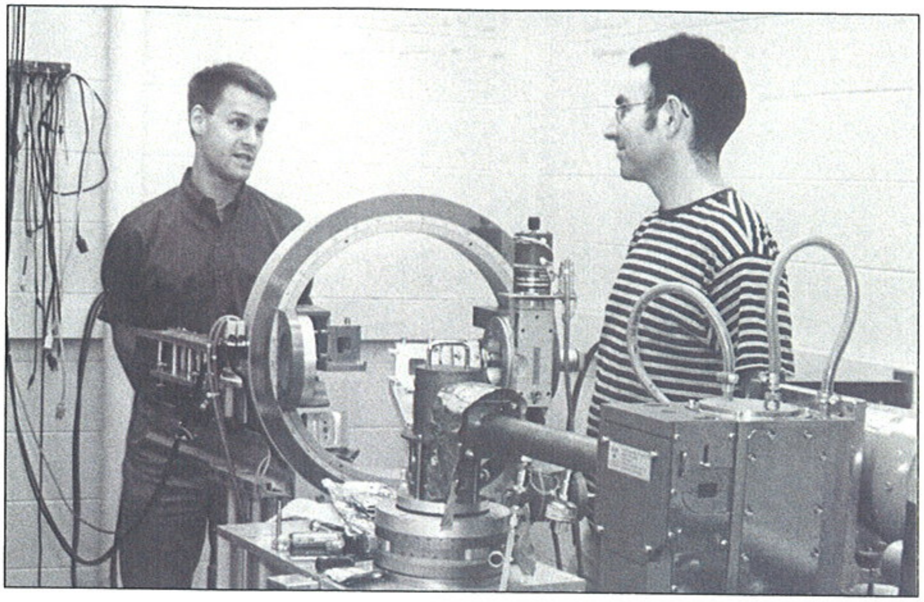
The development of new techniques to calculate the total ground-state energy of a surface *ab initio* or from "first principles" is a major focus of Professor Joannopoulos' group. *Ab initio* calculations do not use semi-empirical models, preconceived ideas, or experimental interpretations to achieve results. However, they are used in combination with experimental observations. In calculating the total energy of a solid, they employ a combination of density functional theory, pseudopotential theory, and iterative minimization techniques. These techniques are applied to various phenomena such as surface growth and reconstruction, structural phase transitions, and chemisorption. In this way, accurate theoretical predictions of surface geometries and behavior can be obtained.

One aspect of *ab initio* investigation is its potential to lead to the realization of new materials designed to meet desired specifications. Recent *ab initio* calculations carried out in Professor Joannopoulos' group introduce a new class of semiconductor compound materials designed for the optimal heteroepitaxial growth of monolithic optoelectronic components. One goal is to design a new optical material operating in the optoelectronic wavelength of 1.5 microns that could replace indium gallium arsenide phosphide. The realization of a new material would resolve long-standing problems related to the polarity and lattice mismatch with silicon.

In a wide-ranging project that involves the theory and design of photonic crystal structures, Professor Joannopoulos has collaborated with other investigators to carry out various components of this research (see related articles pages 14 and 18).

Step Structures and Epitaxy on Semiconductor Surfaces

One important aspect of Professor Simon G.J. Mochrie's research program seeks to characterize the structure, phase behavior, and morphology of semiconductor surfaces, particularly silicon. These studies are essential to the theoretical efforts aimed at understanding the dynamics of the silicon surface. Professor Mochrie and his colleagues use high-resolution x-ray scattering to carry out surface x-ray diffraction studies of stepped, or vicinal, semiconductor surfaces. These studies help to determine the atomic positions of the steps and how temperature affects their behavior.



Professor Simon G.J. Mochrie (right) and Research Assistant Dirk Lumma take time out from their spectroscopy experiments in the rotating anode x-ray scattering laboratory. (Photo by John F. Cook)

Semiconductor surfaces are often stepped, and, unless a wafer of the material is cut and polished 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 since it lacks a center for nucleation. Therefore, wafers are typically miscut to create surface steps. An increased understanding of these step structures is vital since MBE is used increasingly to create electronic structures and devices.

Professor Mochrie's studies also include the faceting of semiconductor surfaces. In this phenomenon, a crystal surface increases its area in order to decrease free energy. The dynamics related to faceting include how atoms move to reduce surface energy, the number of atom layers involved in faceting and the resulting electronic and vibrational states, and the final symmetry of the surface layer. A better understanding of these dynamics contributes to knowledge about the nature of clean surfaces, chemisorption processes, and the initial stages of interface formation.

In recent investigations, Professor Mochrie has explored how semiconductor surfaces self-assemble into ordered patterns. Scientists have demonstrated that nanoscale structures on certain semiconductor surfaces may spontaneously self-assemble into somewhat ordered patterns. Two examples are certain types of silicon surfaces that spontaneously form a periodic nanoscale groove structure and the growth of germanium quantum dots on the silicon (001) surface. Using *in situ* x-ray scattering and *ex situ* atomic force microscopy, Professor Mochrie has addressed this phenomenon. He has demonstrated that quantum-sized objects (quantum dots of germanium) can be built by nanostructure self-assembly during strained heteroepitaxial growth on a flat silicon substrate. By studying the methods of self-assembly, he seeks to achieve a microscopic and predictive understanding of factors that determine the nanostructures of quantum dots and wires and how they may be controlled and exploited to create novel nanoscale surface structures.

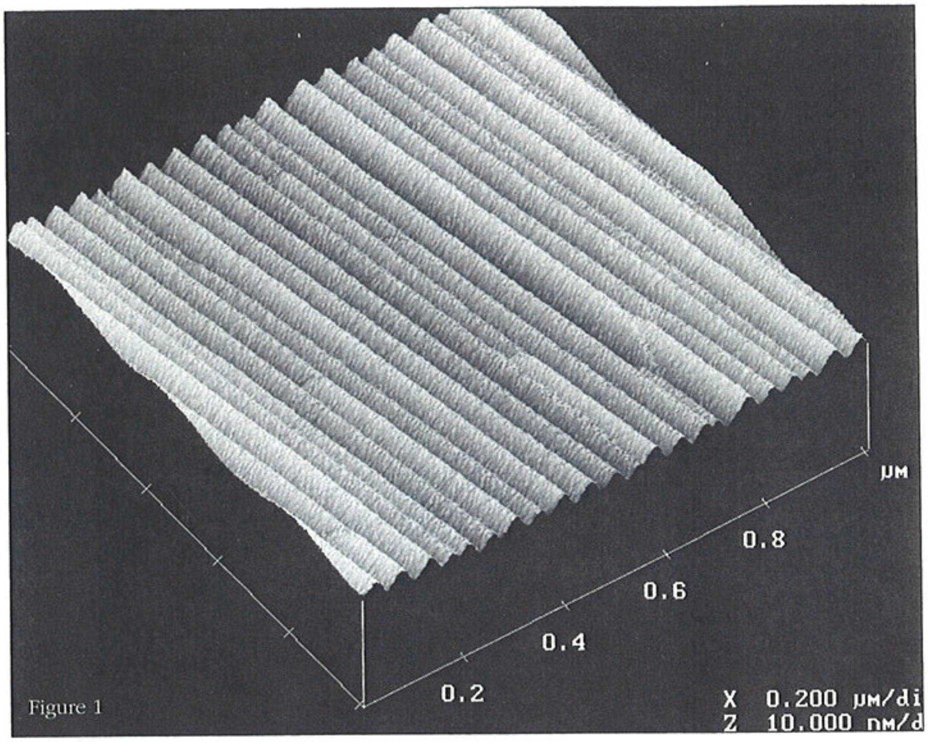


Figure 1

Three atomic force microscopy images produced in Professor Simon G.J. Mochrie's group:

Figure 1 (at left) is a 10000x10000Å² area of a self-assembled grating on a stepped silicon (113) surface. One side of each groove is step-free; the other side is densely stepped.

Figure 2 (below left) shows germanium quantum dots on silicon (001).

Figure 3 (below right) is the surface morphology of a stepped silicon (113) surface tilted towards (110) and quenched from 900 K.

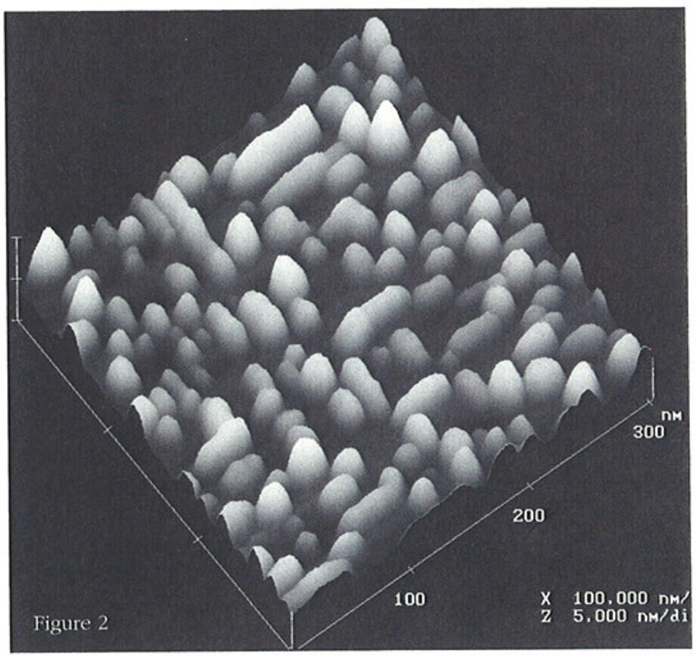


Figure 2

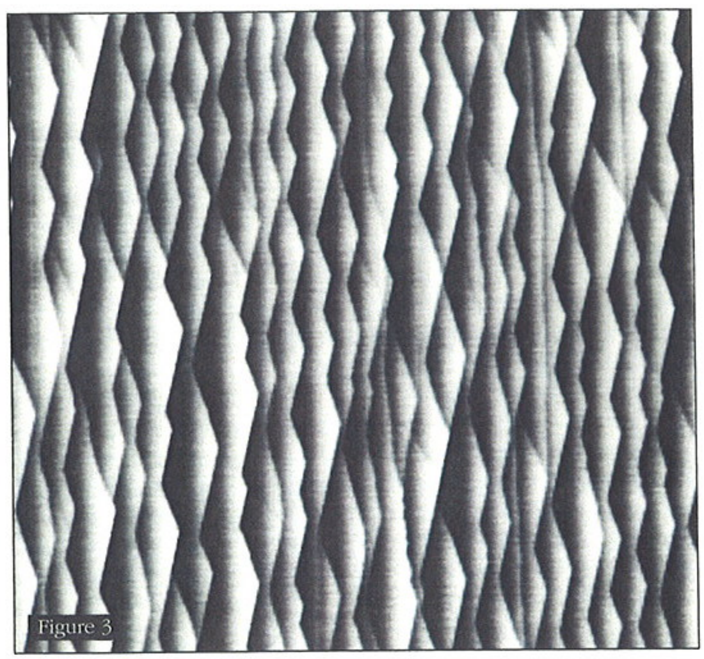
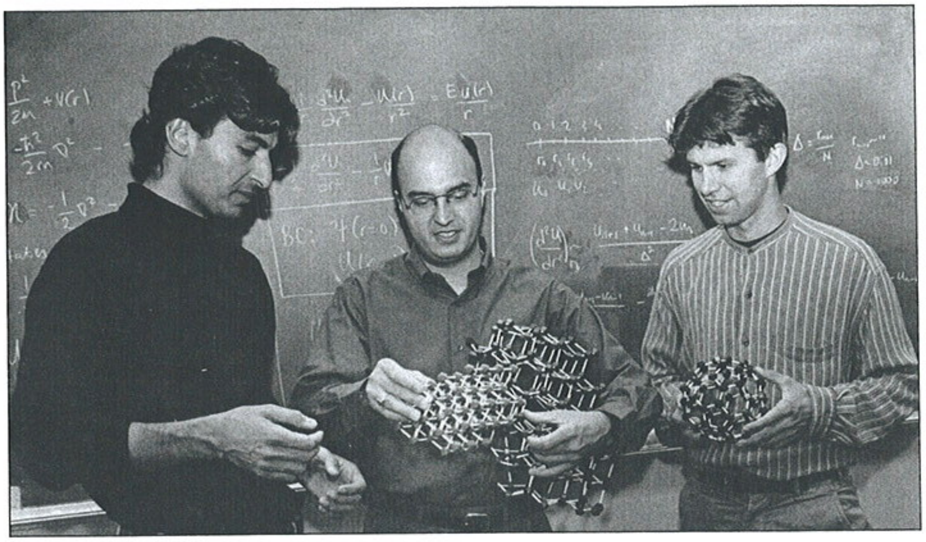


Figure 3

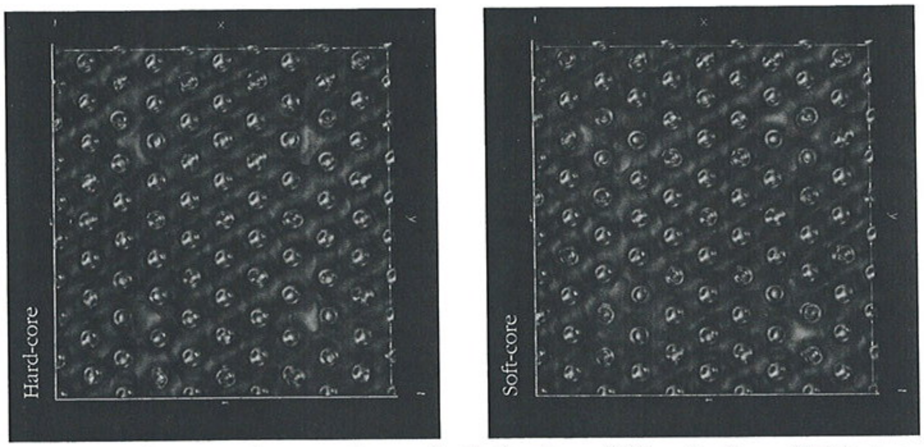
Understanding Metals under Extreme Conditions

Using *ab initio* methods, Professor Tomás A. Arias is developing connections between the quantum-mechanical descriptions of materials and their practical behavior. By predicting the mechanical properties of materials from the behavior of their basic constituents from first principles, Professor Arias seeks to connect the modern quantum world of atoms, nuclei, and electrons to the classical Newtonian world of macroscopic materials properties. His quantum-mechanical calculations are carried out at the atomic level using only fundamental constants of nature as input and the methods of density functional theory (for which physicist Walter Kohn shared the Nobel Prize in Chemistry this year). In this area, his focus is the exploitation of theoretical techniques and supercomputer architectures to perform large-scale quantum calculations, and the development of new theoretical techniques to link *ab initio* calculations of complex solid and liquid systems with phenomena on larger scales.

One direction of Professor Arias' work is aimed at understanding how



Professor Tomás A. Arias (center) discusses with Research Assistants Sohrab Ismail-Beigi (left) and Torkel D. Engeness how a single equation, detailed on the blackboard, can describe the rich variety of structures of covalently bonded materials found in nature. (Photo by John F. Cook)



Results of Professor Tomás A. Arias' group for the hard-core (left) and soft-core (right) structures of the molybdenum (111) screw dislocation. The figures show four nearby dislocations in both structures, which are linear defects in the crystalline order. The dislocation lines run perpendicular so that the distortions in the crystal appear localized at the center of the four quadrants in each figure. Three contours of constant electron density are shown. The high-density contour (light color) highlights the cube-like symmetry of d electrons in the material, which stay most bound to the atoms. The medium-density contour (medium color) marks conduction electrons, which tend to spread throughout the metal. Finally, the low-density contour (dark color) indicates unusual low-density voids in the sea of conduction electrons associated with distortions in the crystalline order. The energies calculated from these electron densities have enabled Professor Arias' group to show that previous theories of the behavior of these defects were incomplete.

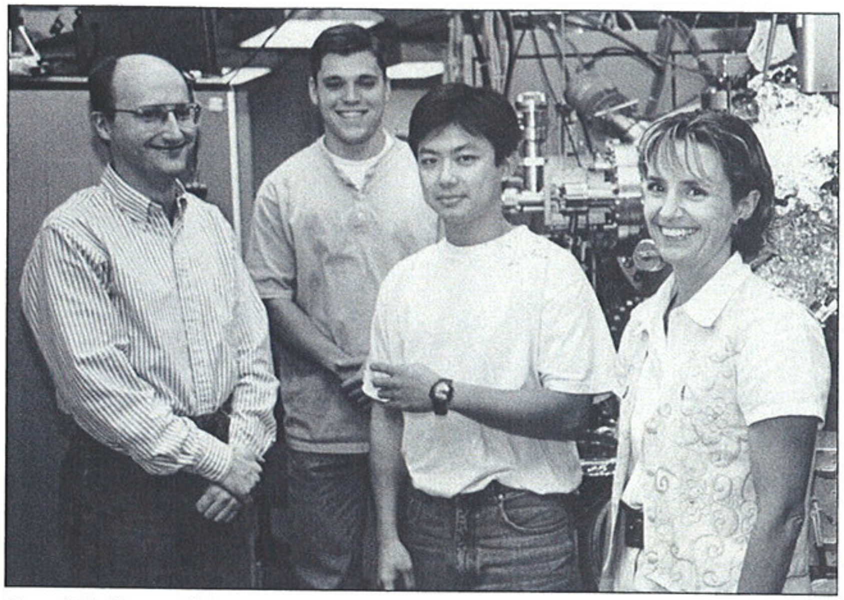
body-centered cubic (bcc) metals behave under extreme conditions, particularly how these materials bend and distort under extreme mechanical stress. The focus of the study is on two bcc metals with different responses to stress: tantalum, a ductile material that tends to "bend" (undergo plastic flow), and molybdenum, which is brittle and tends to fracture. In order to connect these macroscopic behaviors to the quantum-mechanical behavior of countless atoms in a macroscopic sample, Professor Arias' group applies a mechanical analog of another famous theory—Fermi liquid theory—which Russian physicist Lev D. Landau originally developed to understand the behavior of electrons in metals. Essentially, in order to understand the behavior of a complex system that consists of many particles, one need focus only on the behavior of the system's lowest energy excitations, which are called *elementary excitations*. In the context of mechanical properties, elementary excitations are known as *grain boundaries* and *dislocations*, which are departures from the perfect crystalline structure that occur along a plane or a line in the material, respectively.

Professor Arias has demonstrated that results from previous models, which ignored quantum-mechanical effects, were misleading in terms of the most basic excitation controlling plastic flow: the (111) screw dislocation. A screw dislocation occurs along certain lines in a crystal's periodic structure where atomic planes form a spiral-shaped ramp that winds around the line of the dislocation. Previous models indicated two possible structures for this defect: "hard-core" and "easy-core." These two structures were so far apart in energy that only the easy-core structure should be found in nature. It was thought that the motion of the easy-core dislocation controlled the material's tendency to undergo plastic flow. However, Professor Arias' more accurate quantum-mechanical calculations in molybdenum have established that the energy difference between the two structures is three times smaller than previously expected. Thus, a new range of previously unconsidered processes associated with the hard-core structure contributes to how molybdenum responds to applied stress, and changes the fundamental view of how the material behaves. Further calculations are now underway to explore the physics of the hard-core structure in molybdenum and to establish which structures play a role in tantalum.

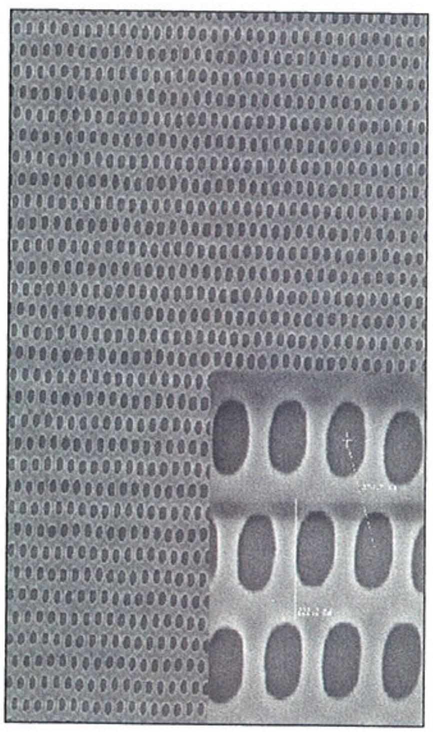
By studying systems smaller than those fabricated by conventional technologies, the theorists and experimentalists involved in condensed-matter physics are pioneering developments in the basic field of nanoscience. In this way, physicists will be able to anticipate and exploit newly discovered phenomena as engineers and technologists move toward the ultimate in nanometer dimensions for electronic applications. At RLE, the efforts of both physicists and engineers are converging to meet the challenge of nanotechnology and its future applications.

by Dorothy Fleischer

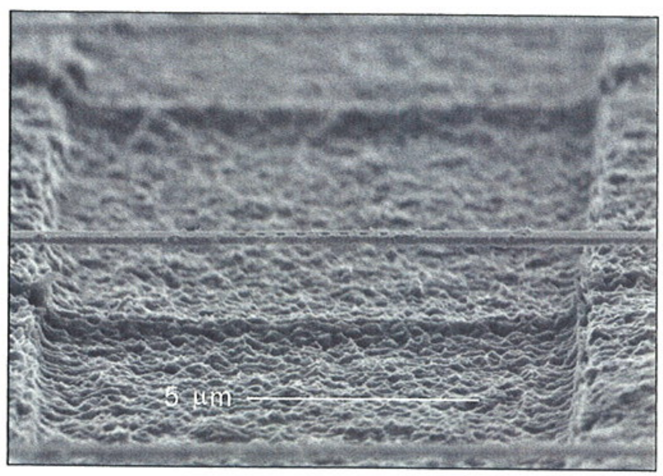
The fabrication of state-of-the-art optoelectronic devices requires the ability to deposit ultrathin layers of semiconductor materials and the ability to process the resulting structures. Employing gas source molecular-beam epitaxy systems, Professor Leslie A. Kolodziejski and her colleagues fabricate optoelectronic devices using compound semiconductors. These devices include optical emitters and filters, photonic microcavities, and optical detectors. Her group's gaseous source molecular-beam epitaxy facility is capable of growing both II-VI and III-V compound semiconductors. Collaborative research with Professor John D. Joannopoulos on PGB structures focuses on materials deposition and integration, characterization of the materials, and device fabrication. Here, the goal is to demonstrate control of electromagnetic radiation in the optical frequency range using PBG crystals. Efforts are now underway to fabricate a complex three-dimensional structure.



From left: Research Scientist Dr. Gale S. Petrich, Research Assistants Alexei A. Erchak and Kuo-Yi Lim, and Professor Leslie A. Kolodziejski. In the background is the gas source molecular-beam epitaxy system used to fabricate the III-V semiconductor photonic bandgap structures designed by Professor John D. Joannopoulos' group. (Photo by John F. Cook)

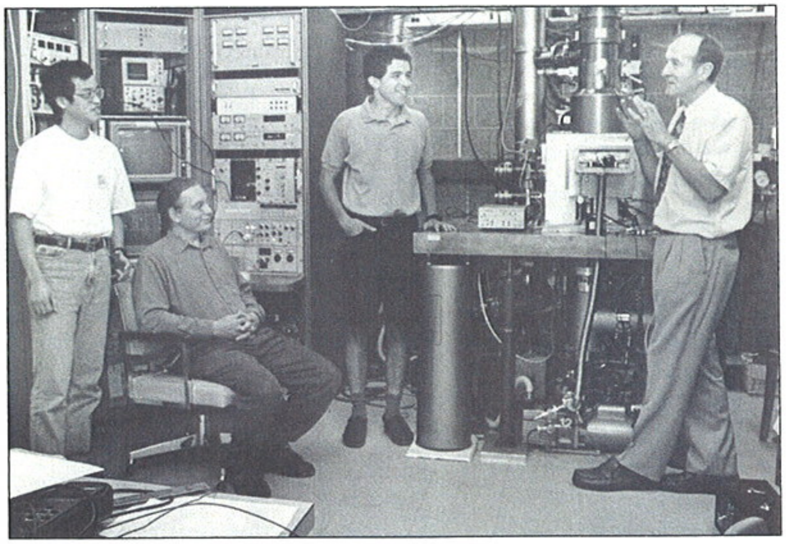


A triangular lattice of holes in $In_{.51}Ga_{.49}P$ *forms the surface layer of a light-emitting diode (LED). The inset shows hole spacing and diameter designed to open a photonic bandgap near the 980-nanometer emission wavelength of the LED. The two-dimensional photonic bandgap effect is used to enhance the LED's extraction efficiency.*



The one-dimensional photonic bandgap air-bridge microcavity in this scanning-electron micrograph is designed to operate at the optical communication wavelength of 1.55 microns. The one-dimensional photonic crystal is defined by an eight-hole periodic array in the gallium arsenide air-bridge. A defect region is created in the photonic crystal by increasing the distance between two holes in the center of the array. The minimum feature size in the structure is approximately 0.2 micron and requires the use of direct-write electron-beam lithography. The air-bridge structure is suspended by the sacrificial etch of Al_xO_y*, which is formed by the thermal oxidation of* $Al_{0.9}Ga_{0.1}As$.

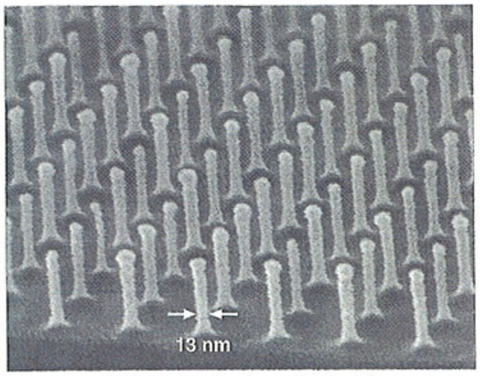
As electronic devices become increasingly faster, fundamental limits are quickly being approached. In many cases, photons are now replacing electrons in a new world of optoelectronics (see article on page 14). The photonic bandgap (PBG) structures project in RLE is a multidisciplinary effort involving several groups in the laboratory. Professor John D. Joannopoulos' group designs the structures and theoretically calculates their optical properties. Using compound semiconductor technologies, Professor Leslie A. Kolodziejski's group fabricates the various devices that exhibit photonic bandgap structures in one, two, and three dimensions. Nanoscale lithography and fabrication are then provided by Professor Henry I. Smith's group. Finally, the devices are optically characterized by Professor Erich P. Ippen's group, and applications are developed by Professor Hermann A. Haus' group. Because of the complex design, fabrication, and properties of these structures, close interaction is necessary between all the groups involved. Related research in novel semiconductor lasers and quantum-effect devices is conducted by Professors Rajeev J. Ram and Qing Hu.



Professor Henry I. Smith (right) discusses the finer points of scanning-electron-beam lithography for nanofabrication with Research Assistant Minghao Qi, Research Specialist Mark K. Mondol, and Research Assistant Juan Ferrera. *(Photo by John F. Cook)*

RLE's NanoStructures Laboratory, under the direction of Professor Henry I. Smith, provides a foundation of fabrication and metrological technologies that are crucial to photonic, quantum-effect, and deep sub-100-nanometer devices. Professor Smith and his colleagues have developed several deep sub-100-nanometer lithographic, processing, and metrological techniques that enable the fabrication of highly innovative structures and devices. The group's focus on developing fabrication techniques capable of sub-100-nanometer placement accuracy and long-range spatial-phase coherence is unique and critical to emerging classes of new devices. Their lithographic capabilities include spatial-phase-locked electron-beam, point-source x-ray nanolithography, interferometric and achromatic-interferometric methods, and zone-plate-array lithography, as well as more conventional methods. In addition to their work with Professor John D. Joannopoulos on PBG structures, their unique fabrication capabilities are also applied to collaborative research on quantum-effect, short-channel, and optical devices that involves Professors Raymond C. Ashoori, Dimitri A. Antoniadis, Hermann A. Haus, Erich P. Ippen, and Leslie A. Kolodziejski.

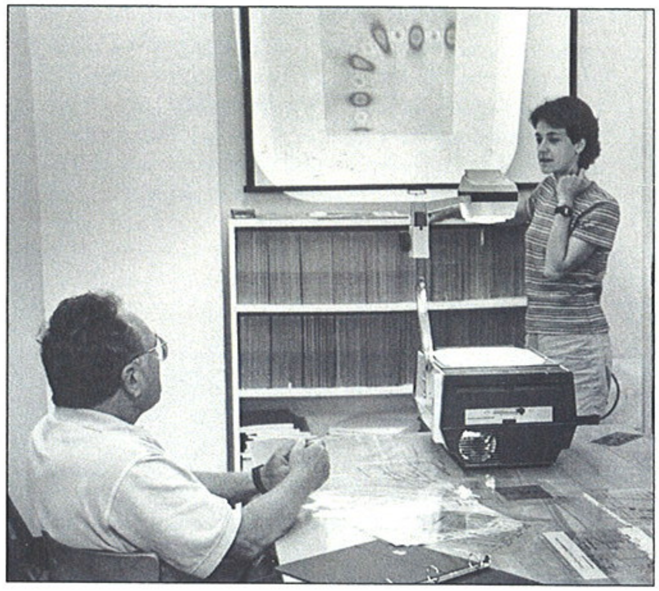
Achromatic Interferometric Lithography



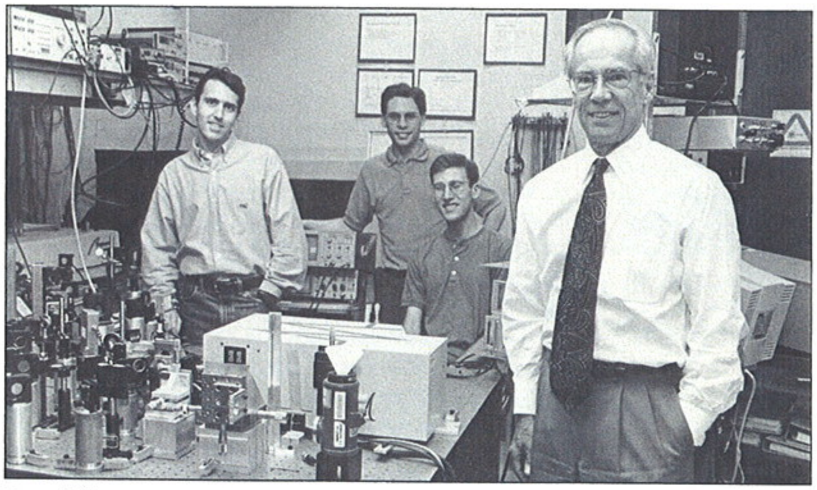
100nm-period posts in Si

This scanning-electron micrograph shows a grid of 13-nanometer-diameter posts on 100-nanometer centers that have been etched into silicon following achromatic-interferometric lithography. These posts will be used to investigate light emission from silicon. Light emission from nanostructured silicon may have applications in optical communications, displays, and various other uses. This research is conducted at RLE's NanoStructures Laboratory.

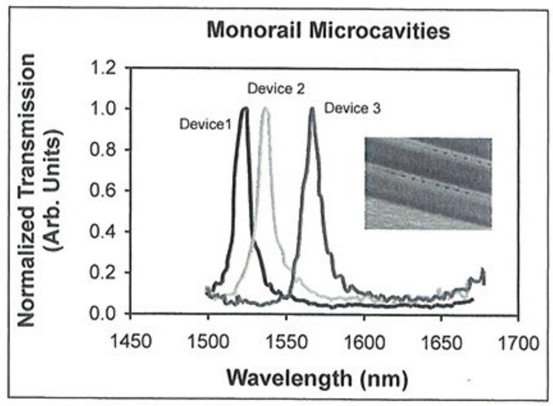
Investigating methods to generate ultrashort pulses of light and developing their applications to various scientific and engineering studies is a joint program carried out in RLE's ultrafast optics group. Current activities include the basic study of ultrafast phenomena in materials, applications of ultrashort pulses to medicine, investigations of ultrafast properties of optoelectronic device structures, and demonstrations of ultrafast switching and signal processing in optical fibers. Using femtosecond pump-probe techniques, the group studies fundamental carrier dynamics in semiconductor thin films, heterostructure interfaces, metals, and superconductors. The optical techniques employed in Professors Hermann A. Haus' and Erich P. Ippen's laboratories have been used to investigate the characteristics of novel structures created in the PBG project.

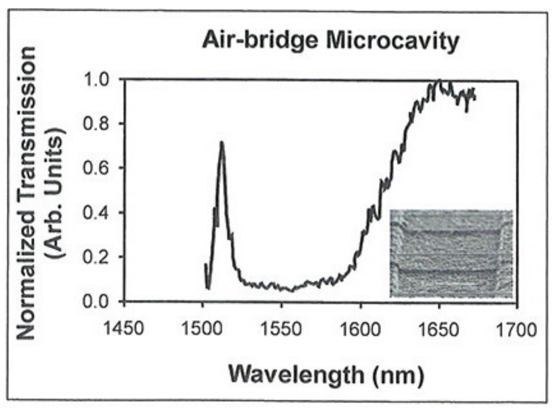


Professor Hermann A. Haus and Research Assistant Christina Manolatou analyze the results of their investigations into waveguide bends in photonic crystals as part of the photonic bandgap (PBG) structures project. The projected image shows an electric field amplitude calculated numerically in a 90-degree high-index waveguide bend. The corner was modified in a low-Q resonator, thus allowing almost full transmission with very low reflection and radiation loss in a wide bandwidth near the resonance frequency. (Photo by John F. Cook)

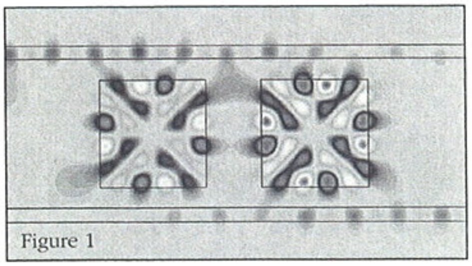


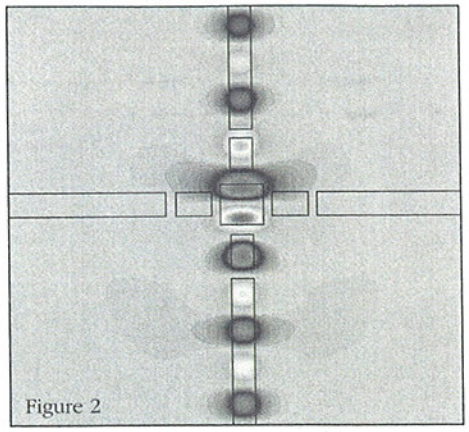
From left: Visiting Scientist Dr. Patrick Langlois, Research Assistants Erik R. Thoen and Daniel J. Ripin, and Professor Erich P. Ippen use this experimental set-up to characterize photonic bandgap crystals at optical communication wavelengths. (Photo by John F. Cook)





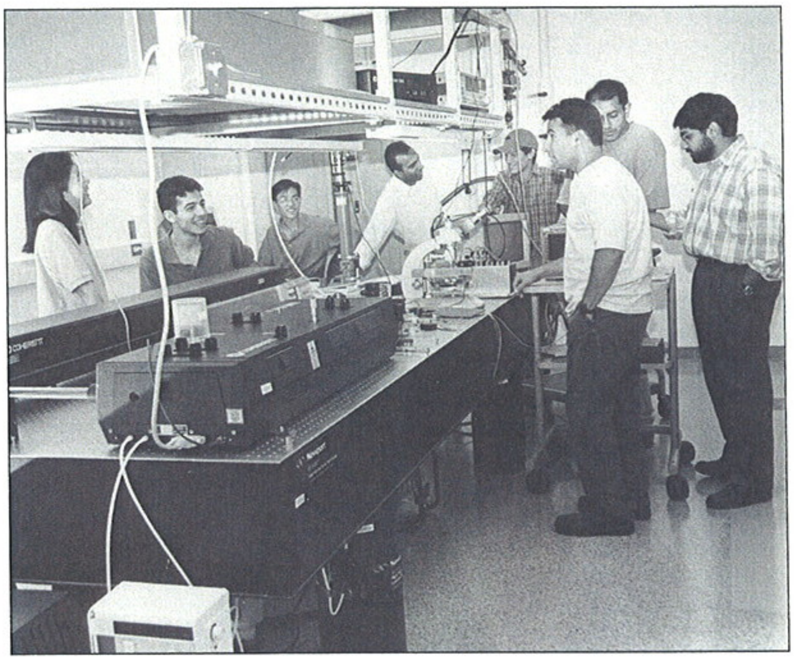
In results obtained from Professor Erich P. Ippen's group, these plots illustrate transmission spectra through a one-dimensional photonic bandgap air-bridge microcavity (top) and a one-dimensional photonic bandgap monorail microcavity (bottom). Both of these structures were fabricated in Professor Leslie A. Kolodziejski's laboratory. The insets in each plot are scanning-electron micrographs of a typical air-bridge microcavity and a one-dimensional photonic air-bridge microcavity, respectively. In these microcavities, the periodic array of holes creates a photonic bandgap and, by changing the space between the two middle holes, a resonator is created. At the resonance wavelength, there is a peak in the relative transmission through the structures. In the air-bridge plot, the beginning of the long wavelength band-edge is seen to the right of the resonance peak. In the monorail plot, three different peak locations are observed for three different defect widths.





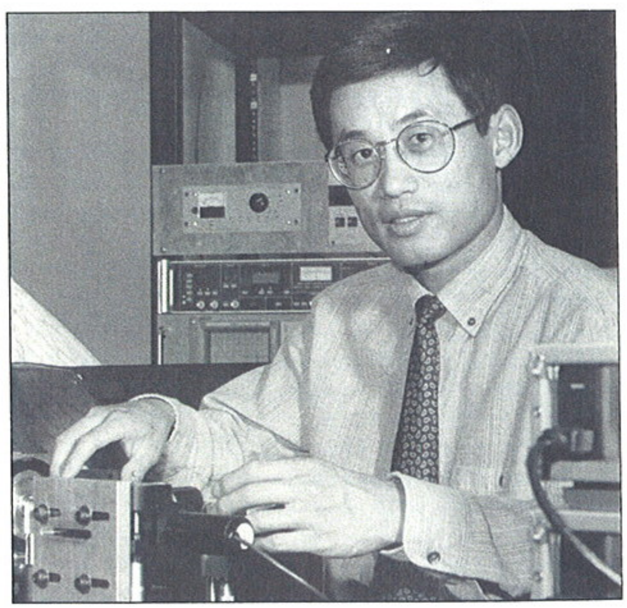
Research results from Professor Hermann A. Haus' group on the design and modeling of optical resonant structures. Figure 1 shows a channel-dropping filter that uses a pair of coupled square resonators between two waveguides. Figure 2 illustrates a low-crosstalk waveguide that employs a resonant cavity at the intersection. Shading in both figures indicates the distribution of the electric field amplitude.

Professor Rajeev J. Ram's research involves the design, fabrication, and testing of novel semiconductor lasers to improve the performance of high-speed optical communication systems. In collaboration with Professor Henry I. Smith, his group explores the bandgap engineering of distributed Bragg reflectors, which are fabricated in Professor Leslie A. Kolodziejski's chemical-beam epitaxy laboratory. This work involves the design of vertical cavity surface-emitting lasers, whose novel properties give them an advantage over conventional edge-emitting laser diodes. Working with Professors Kolodziejski and Smith, his group also develops distributed feedback and distributed Bragg reflector lasers capable of high-speed modulation and low noise.



From left: Undergraduate students Margaret Wang, Mehmet F. Yanik, and Erwin K. Lau; graduate student Mathew Abraham; Research Assistant Harry Lee; graduate student Farhan Rana; Research Assistant Steven G. Patterson; and Professor Rajeev J. Ram use this equipment to perform ultrafast spectroscopy of semiconductor microcavities. (Photo by John F. Cook)

High-frequency studies of quantum-effect devices are the focus of Professor Qing Hu's research. These include terahertz (THz) electronic devices, such as superconducting and semiconducting quantum devices, and THz solid-state lasers. His group's experiments involve photon-assisted quantum transport in quantum devices and nonlinear dynamics. Semiconductor quantum-effect devices, such as vertically grown quantum-well structures and laterally confined mesoscopic devices, are quantum-mechanical systems in which energy levels can be selected by changing the device size. Professor Hu's group develops ultrahigh-frequency devices (such as radiation detectors and mixers) and THz lasers that exploit the intersubband transitions in these devices. Devices with THz frequency characteristics promise picosecond-speed responses, thus easing the electronic bottleneck in current fiberoptic communication systems.



Professor Qing Hu and his colleagues in RLE's Optics and Devices group the develop ultrahigh-frequency devices in the millimeter-wave and far-infrared frequency ranges. (Photo by John F. Cook)

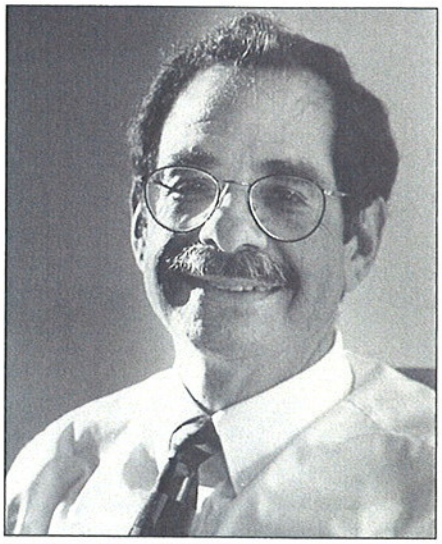
FACULTY PROFILE:

Marc A. Kastner

Dr. Marc A. Kastner joined the faculty in MIT's Department of Physics in 1973, following a year as a Harvard research fellow. A graduate of the University of Chicago (SB '67, MS '69, PhD '72), he rose through the ranks in the department and served as head of its Division of Atomic, Condensed Matter, and Plasma Physics from 1983 to 1987. From 1989 to 1992, Professor Kastner was associate director of MIT's Consortium for Superconducting Electronics; a collaborative program designed to advance the technology of thin-film superconducting electronics. He became director of MIT's Center for Materials Science and Engineering in 1993. Named Donner Professor of Science in 1989, he was appointed head of MIT's Department of Physics in February 1998.

Professor Kastner's initial research at MIT involved the electronic structure of amorphous semiconductors, especially the relationship between chemical bonding and the electronic structure of defects in glasses. In recent years, his interests have focused on the electronic properties of nanometer-size semiconductor structures and on the physics of high-temperature (high-T_c) superconductivity. His collaborations with Professor Robert J. Birgeneau and researchers at Brookhaven National Laboratory and Tohoku University in Japan on high-T_c superconductors have provided a deeper understanding of the electronic properties of these materials, in which electronic correlations play a central role.

In his latest research, Professor Kastner and his colleagues have pioneered a semiconductor single-electron transistor (SET) that turns on and off once for every electron added to it. Not only do these devices have significant technological potential, but they also provide new insight into the behavior of electrons confined to small areas and contribute to our knowledge of the quantum-mechanical processes in semiconductor devices. Using the SET they've developed, his group continues to investigate the Kondo effect, a phenomenon theoretically predicted to occur in semiconductor nanostructures by Professor Patrick A. Lee and his coworkers.



Professor Marc A. Kastner
(Photo by John F. Cook)

In 1988, Professor Kastner received the Outstanding Scientific Accomplishment Award from the U.S. Department of Energy's Division of Materials Science. He was elected to the Council of the American Physical Society (APS) in 1990 and served two years on its executive board. A fellow of the APS and the American Association for the Advancement of Science, Professor Kastner received the APS David Adler Lectureship Award in 1995.

• ***What attracted you to study physics?***
In high school, I was planning to be a lawyer and had little interest in physics or science, but my father convinced me that it would be good to have a bachelor's degree in science. Then I could do patent law if I wanted to, and if I decided not to go to law school, I could still find a job. Of all my science classes in high school, I had done best in chemistry, so I majored in it at the University of Chicago. As I learned more, I found what interested me about chemistry was the physics.

When I started to think about graduate school, my father and I talked about what kind of physics might be good to study. Biophysics was attractive, and I had an offer to study biochemistry at UC San Diego, but I had the feeling it really wasn't a field yet. So, I thought I'd study solid-state physics and go into biophysics later. I was attracted to physics that had the potential for electronic applications. Not that I wanted to build practical devices, but I was fascinated by semiconductors and how they worked. I applied to graduate schools in solid-state physics, but had difficulty getting in because of my undergraduate degree in chemistry. Fortunately, I got into the University of Chicago, where the people already knew me. I was lucky to have a thesis advisor who was supportive and let me take credit for the work we had done jointly. Afterwards, I had an offer to do basic research at IBM, but I really wanted to be a faculty member. So, I decided I would need to do a postdoc if I were going to obtain a university appointment.

• ***What brought you to MIT and RLE?***
In the late '50s and early '60s, there was a view in the MIT Department of Physics that solid-state physics was basically solved, so it should be studied by engineers. MIT had several good solid-state physicists in its Electrical Engineering and Computer Science Department, including Millie Dresselhaus, David Adler, and Steve Senturia. However, the Physics Department's visiting committee believed we couldn't have a top-notch department without solid-state physics.

In 1970, the department brought Peter Wolff from Bell Labs to head the Division of Atomic, Condensed Matter and Plasma Physics and build up solid-state physics in the department. Peter brought me in for an interview in 1973 after my postdoc at Harvard. As soon as I met him, I wanted to work at MIT. With Peter's leadership, I felt that it would be a good place to be.

He hired three assistant professors—John Joannopoulos, Bruce Patton, and me. About two years later, Peter hired Bob Birgeneau as senior faculty member, whom he had hired previously when they were both at Bell Labs. Shortly after that he hired Toyo Tanaka. Also, before I came to MIT, Peter had seen Dave Litster and Tom Greytak through to tenure. It took about eight years or so for Peter to build up this strong effort spanning all areas of condensed-matter physics. He created a core of young, active faculty and he had a strong influence on all of us.

When Peter became director of RLE in 1976, he was enthusiastic about my work on glasses, especially silicon dioxide. He thought the Joint Services Electronics Program (JSEP), one of RLE's sponsors, would be interested too. That's when I came to RLE.

• ***What was the significance of your early work in amorphous semiconductors?***

When I was a graduate student, there had been enormous excitement about possible applications of amorphous semiconductors because they were cheap to make and attractive for applications where lots of material was needed. Today, flat-panel displays, using thin-film transistors, and solar cells are made from amorphous semiconductors. In terms of my research then, there were many fundamental questions about what determined the electronic properties of these materials. Standard theory said we couldn't have a semiconductor if it was amorphous. So, the fact that they existed—well, not great ones, but not terrible ones either—was somewhat amazing. Much of what John Joannopoulos and I did in those days was to understand how electrons moved in those materials.

• ***When did you begin to study high-temperature (high-T_c) superconductors?***

When we first studied amorphous semiconductors in the late '60s, it seemed that the theorists would be able to make predictions that we could test quantitatively. However, as work progressed, it became less and less possible to do that. We could do *qualitative* experiments, but we couldn't quantitatively test the most important predictions. The materials were understood and characterized well, and we could use them, but we ran into brick walls trying to quantitatively understand the fundamental issues.

Then, high-T_c superconductivity was discovered in 1986. Instantly, Bob Birgeneau, Patrick Lee and I, like thousands of other physicists, knew it was

When people talk about great physics problems, they mention the origin of dark matter in the universe or why quarks have the masses they do. High-T_c superconductivity is also one of these great problems. It's extraordinarily mysterious and we still don't understand it.

the greatest condensed-matter physics problem of our time. When people talk about great physics problems, they mention the origin of dark matter in the universe or why quarks have the masses they do. High-T_c superconductivity is also one of these great problems. It's extraordinarily mysterious and we still don't understand it. Most superconductors, when they're warm, are conventional metals. When we cool them, they become superconductors. However, the high-T_c materials are actually semiconductors that become superconductors once we dope them.

Soon after the high-T_c superconductivity phenomenon was discovered, Bob Birgeneau and I realized we had to work on it. Ken Smith (then vice president of research) gave money to Dave Litster (then director of the Center for Materials Science and Engineering) to support crystal growth so we could begin experiments. That fast infusion of funds, plus a great postdoc who worked in our crystal growth facility, quickly resulted in a crystal that allowed us to get a foothold in the field. Disorder in the materials played an important role, and my background in disordered semiconductors was great training. Their magnetic properties were extremely important, and Bob's background in magnetism was critical. Between us, we knew a lot about the basic issues in this area.

• ***How did single-electron transistors (SETs) come into the picture?***

Our nanostructure work actually began before we got into high-T_c superconductivity, and it's an interesting RLE story. In the late '70s, Peter Wolff was instrumental in bringing Hank Smith to RLE from Lincoln Lab. Peter generously helped in building Hank's lab because he believed the capability to make nanostructures on campus was important. Our condensed-matter group in Building 13 went to lunch almost every day and Peter often joined us. One day, Peter mentioned Hank's fantastic submicron facility and said we should think of something good to do with it. I was reading a fascinating paper by the theorist David Thouless. He predicted that if metal wires were made narrow enough or long enough, they would become insulating. Everyone thought this was amazing, and people quickly started to make one-dimensional metal wires. I thought that if we could make a narrow field-effect transistor, then we would have a wire in which the number of electrons could be changed. I suggested this to Peter and he provided funds from JSEP to get us started.

John Melngailis, who was in Hank's lab at that time, collaborated with me. In our initial experiment, we made one of the first narrow silicon field-effect transistors. The results were complicated because the electrons were very sensitive to random charges at the surface of the silicon. Patrick Lee had an interest in mesoscopic systems and helped us understand what was going on. For a while after that, my students and I met every week with Hank, Dimitri Antoniadis, and Terry Orlando to discuss new ways to make narrow field-effect transistors. Dimitri thought of using a double-gate structure to help us make narrower wires.

When one of my students made the first of these devices and measured them, he discovered something very surprising. In a conventional transistor, the conductance increases smoothly as the number of electrons is increased. In the new devices, the conductance was going up and down periodically. In our earlier narrow transistors, we had seen only random fluctuations around a smooth increase. It took six months before we were ready to publish these results because they looked so crazy. This was actually the first SET in a semiconductor, but we just didn't know it. Soon we realized that we could do a better job in gallium arsenide instead of silicon and by using electron-beam instead of x-ray lithography. We had already started work in gallium arsenide for other reasons, so now we could do this quickly. We began to work with IBM and, within a year or so, we made the first controlled SETs.

A group at Bell Labs had already shown the single-electron effect in metallic systems. They made a tiny particle of metal with two electrodes close enough that the electrons could tunnel from one electrode onto the particle and off on the other side. They then created another electrode to change the potential of the particle without any tunneling. Increasing the voltage on the third electrode turned the tunneling current on and off for every electron added to the particle. When our group did this with semiconductors, we didn't know there was a relationship to what the group at Bell Labs had done. In fact, no one we talked to seemed to understand what we were seeing. When a famous physicist visited our lab, he said, "If I saw that, I would think my amplifier was oscillating." I came up with an explanation, which eventually turned out to be wrong, but we published it, and people started to take our measurements seriously. Patrick Lee worked on this project with several postdocs, and we came to a deeper understanding of what was going on. We began to understand that the electrons confined to the particle in a metal SET, or confined to a small region of space by electrodes inside a semiconductor SET, behave like an artificial atom: both their charge and energy are quantized.

The advantage of semiconductors for SETs, from a physics point of view, is that an artificial atom in a semiconductor SET has so few electrons—typically, only 30 or 40. On the other hand, if you make a particle of metal and add electrons to it, you're starting out with billions of electrons and just adding more. As a result, we can see the effects of energy quantization more easily. Many of the interesting quantum-mechanical effects can only be seen when we use semiconductors.

• ***How is the behavior of an artificial atom different from that of a natural atom?***
We use the term "artificial atom" whenever we confine electrons in a small space. This causes their energy and their number to become quantized. The nice thing about an artificial atom is that the nucleus doesn't determine its charge; an outside electrical field does. Since the field is controlled by the voltage on an electrode, we can change the number of electrons at will. Therefore, an artificial atom is tunable and, in some ways, it's nicer than a natural atom. However, as Dan Kleppner has said, we may be making atoms, but we don't make very good ones. He said that because a natural atom is perfectly symmetric. It's perfectly spherical because its nucleus attracts the electrons, and elegant features result from this symmetry. Artificial atoms, on the other hand, are ugly. The electrons are held in a potential well, which is not perfectly symmetric, and the energy levels don't have nice patterns. However, we can make artificial atoms interact with the outside world by passing electrons through them, whereas with a natural atom that isn't possible.

• ***Quantum dots and their behavior have also been called artificial atoms.***
Quantum dots are just a different way to confine the electrons, and there are many ways to do it. Moungi Bawendi of MIT's Chemistry Department does it by growing cadmium selenide particles. Ray Ashoori takes a layer of gallium arsenide and cuts away everything except a tiny disc. Usually, Ray makes contact to a dot with two leads, one from above and one from below. However, if we want to make a transistor, then we need three terminals. We need to have the electrons go in on one side and come out the other, and we need another electrode to act as a switch. People have done many interesting things with different varieties of quantum dots where the fundamental physics is the same, but certain properties are revealed more easily depending on how the dots are made.

We use the term "artificial atom" whenever we confine electrons in a small space. This causes their energy and their number to become quantized.

• ***What would happen if you made arrays of artificial atoms or two- and three-dimensional structures?***
People are doing all kinds of fancy things. They're putting together two quantum dots or two artificial atoms to make an artificial molecule. Then, they can see the effects of the electrons as they jump back and forth. I'm more excited about making a huge array. We've started work on that with Moungi Bawendi by studying films of many quantum dots in order to understand their collective behavior. If we're to make large numbers of artificial atoms, we want each one to be very small and all of them to be close together. However, there are many problems, such as how do we bring the electrons in and out, and how do we make contact.

• ***How do you use the SET developed by your group to study the Kondo effect?***
One way to think about electrons is that they're like a liquid and they interact with each other. A natural atom is out in free space and its electrons would never leave it. That could happen, however, if we put the atom on a metal surface. The electrons could tunnel into the metal surface, but because the charge on the atom left behind is positive, they would be pulled back. Similarly, in an artificial atom, we know the electrons can tunnel into the leads, otherwise we wouldn't

see any current. However, if they can tunnel into the lead, then they can tunnel back again. If you think of them jumping back and forth, it's similar to the electrons hopping back and forth between two atoms in a chemical bond. Except now the bond is between an atom and a metal instead of two atoms. That's the Kondo effect. It's the first example where we've seen strong effects of electron-electron correlations. It's a chemical bond between the unpaired electron on an artificial atom and the electrons in the metal. We saw the Kondo effect because my student, David Goldhaber-Gordon, was able to make artificial atoms smaller than before. People associate the Kondo effect with him rather than with me, and that's rightly so because he made it work. We recently submitted a paper to *Physical Review Letters* that's the first quantitative test of certain features of the Kondo effect, which no one was able to test before these devices were made.

• ***When describing the Kondo effect, you use the term "electron droplet."***
It's a bunch of electrons confined in some small region. In gallium arsenide heterostructures, the electrons can move in two dimensions. We create nanometer-size electrodes on the surface. This causes the electrons to be confined in an isolated region. In order to move in and out of this region, the electrons must tunnel through the potential barriers created by the electrodes. Think of it as a bowl that holds about 50 electrons. We refer to the electrons in that bowl as a droplet.

• ***How do you tune the properties of a SET to study the Kondo effect?***
In a chemical bond, there are unpaired electrons on each atom that pair up to form a bond. The bonds are strongest when electrons on the two atoms have the same energies. If we move the energies apart, the coupling becomes weaker because the electrons can't jump back and forth as easily. When we study the Kondo effect, an important factor is the difference between the energy of the electron in the artificial atom and the energy when the electron is in the metal. If those energies are very different, then the bond will be weak, and we won't see the Kondo effect. So, we want the ability to adjust that energy up and down. We change that the same way we add electrons, by raising and lowering the energy of the artificial atom. Another critical parameter is the tunneling rate between the artificial atom and the leads. We make that energy as big as possible because it creates a stronger chemical bond, and the stronger it is, the easier it is to see the Kondo effect. We can adjust the tunneling rate by changing the voltages on the electrodes that do the confinement. If we confine the electrons a little less, they can tunnel more easily. In some ways, we now have a handle on all these crucial properties to study the Kondo effect.

• ***What are the limitations involved with these experiments?***
As we make things smaller, all energy scales increase. Two basic energy scales are the charging or Coulomb energy and the quantum-mechanical confinement energy. The smaller we make things, the closer the electrons are together and the higher the Coulomb energy. When we confine things in smaller spaces, the wave nature of the particles causes their energy to increase. So, both the quantum-mechanical confinement energy and the Coulomb energy increase as we confine electrons in smaller spaces. The tunneling rate multiplied by Planck's constant is an energy that can never be larger than the Coulomb and confinement energy. So, if we want a large Kondo energy, we have to make artificial atoms very small.

> . . . it's similar to the electrons hopping back and forth between two atoms in a chemical bond. Except now the bond is between an atom and a metal instead of two atoms. That's the Kondo effect.

However, in all our experiments, the limiting factor is temperature. We try to bring it as close as possible to absolute zero, but that's limited by how much heat we can remove from the semiconductor. For any phenomena that we'd like to observe, we want the energy scales to be much bigger than the temperature at which we're working. Otherwise, the temperature will wash everything out. So, we lower the temperature and increase the energy scales as much as we can in order to see things as clearly as possible. In addition, if you're making a device for applications, you want the energy scales to be as big as possible so you can raise the temperature and still see the effect.

• ***What are the issues involved in your work to fabricate devices using silicon and silicon germanium?***
In both silicon and silicon germanium materials, there are interesting physics issues that we might be able to study which we can't study in gallium arsenide. One phenomenon is valley degeneracy. That is, in gallium arsenide, there are only two kinds of electrons: either spin up or down. However, in silicon, there are four kinds of electrons because there are two valleys as well as two spins. In germanium, there are even more valleys. So, in principle, each additional degree of freedom could give us new kinds of Kondo effects.

My student David Abusch-Magder did some work in silicon and was able to achieve very small structures. The problem was disorder at the interface, which seemed to dominate everything. We were never able to see the simple physics that we could see with gallium arsenide. We anticipate that one benefit of silicon germanium is that it might be a compromise between silicon and gallium arsenide, but we haven't done much work on it yet. We're hoping that Gene Fitzgerald's capability to grow silicon germanium in the Department of Materials Science and Engineering will let us continue our work. We've just been working flat out on the Kondo effect in gallium arsenide.

• How do you decide which materials to use?
I always try to use silicon because it's so much easier to exploit standard semiconductor technology. However, gallium arsenide is a cleaner material. Its electrons move below the surface of the material and they don't scatter as strongly. So, gallium arsenide is generally chosen for fundamental scientific explorations.

. . . much of what we do is showing that what we've observed agrees with the principles we already know. However, we always hope to find something that doesn't agree, and then new principles will be needed.

• I understand you're investigating self-assembly techniques and measuring the nanostructures developed by chemists.
Moungi Bawendi is one of the best in the world at making very small particles. Because we want to make things as small as possible, people ask us why we don't use Bawendi's quantum dots. His dots measure 15 angstroms across compared to our artificial atoms, which are 800 angstroms across. Although the energy scales would be huge, and everything would be much easier, it's difficult to put electrodes on these dots. Somehow, we must attach electrodes to the dot in order to make a tunnel junction. We can't make anything unless the electrons can tunnel on and off. The electrodes must be made by lithography, and the smallest dimensions are currently in the range of 300 to 500 angstroms. Bawendi can easily make dots that are 15 angstroms, but when they reach a few hundred angstroms, he can no longer make them bigger. So, there's a gap between the size he can make the quantum dots and the size we can make the electrodes. It's not clear if anyone knows how to bridge that gap and that's a big technological hurdle.

• What is the future for self-assembly?
Many exciting ideas have been proposed for self-assembly, but making them work is difficult because there are still too many fundamental physics questions that must be answered. People have proposed novel circuits using SETs and completely new architectures that use quantum-dot arrays for associative memories.

• Do you use any special equipment in your research?
What we do that's unique, at least at MIT, is very low-temperature measurements of conductance. Ray Ashoori has similar capabilities. We're about to install a new dilution refrigerator that will make things colder than before and will have higher magnetic fields. However, the unique part of any of our experiments is the device itself. People can buy the refrigerators and equipment they need, but the devices are special. Our limitation is that we don't have the facilities like they had at IBM when we worked there on the first controlled SETs, or what they have now at the Weizmann Institute in Israel, where we made the smallest artificial atoms. At Weizmann, they make very high-quality gallium arsenide and do unbelievably good electron-beam lithography, all in the same laboratory. However, this equipment is enormously expensive to purchase and maintain.

• How would you describe your approach to research?
I want to study phenomena in which we have a chance to discover fundamentally new principles. That's what physics is about—understanding nature in terms of first principles. Of course, much of what we do is showing that what we've observed agrees with the principles we already know. However, we always hope to find something that doesn't agree, and then new principles will be needed. Many phenomena are beautiful and elegant, but their principles are well understood. In some ways, our early work on artificial atoms was in that category. We knew that confining electrons in a box would make the number of electrons quantized. Demonstrating it was pretty, but it wasn't fundamentally new.

On the other hand, when we discuss how electrons interact with each other, then the theory is not as developed, especially in the materials where electrons interact. That's what makes high-T_c superconductivity an interesting problem. Within a broad class of materials related to the high-T_c superconductors, electrons are strongly correlated. That means if any electron moves, all the other electrons respond. That's quite different from a conventional semiconductor. In silicon, for example, the electrons ignore each other. However, in high-T_c materials, the electrons interact strongly, so they're strongly correlated. Those kinds of problems fascinate me, and I'm excited about similar problems in mesoscopic systems. The problems I like best are not only the ones that have a chance to reveal new fundamental physics issues, but also the ones that might have a technological application in the end.

• What is the balance of theory and experiment in your group?
We don't do theory, although I like to make simple models so I can think about what to do next. The condensed-matter theory group in the Physics Department is probably the best in the world. For mesoscopic systems and high-T_c issues, people like Patrick Lee, Leonid Levitov, and Xiao-Gang Wen are wonderful to talk to. John Joannopoulos, Mehran Kardar, Nihat Berker and Tomás Arias are outstanding physicists that work on very different kinds of problems. If we have an interesting problem and if we characterize it experimentally well, one of them will help us understand things in a quantitative way.

• Does your research depend on new technologies?
All exciting research depends on new technology. Great science is done when scientists need something new to do an experiment because they want to learn some science. In doing that, they develop technologies that may become

commercially valuable. The scanning tunneling microscope is a good example and it's become a valuable technological tool.

• ***What is the most critical issue facing your research?***
We have a big problem in the United States: the investment in the physics of electronic materials and systems has declined terribly. The fact that we had to go to Israel for our Kondo effect experiment is very telling. There was just no place in the United States where we could have done it. Israel has set up a lab at the Weizmann Institute with a permanent technical staff that's eager to push this technology. Some of this work is now going on at Lucent Technologies, and one of my former students, David Abusch-Magder, is there. However, because overall support of universities isn't what it should be, we have to think about doing less expensive research. I'm also skeptical about university-industry partnerships because the time horizon for industry is short.

• ***How would you characterize RLE's interdisciplinary environment?***
It's been very good. The tragedy was the end of the Joint Service Electronics Program because it allowed the director of RLE to stimulate collaborative activity. That will be harder to do now. Over the years, Patrick Lee, Hank Smith, and I—all of us did research at RLE that we couldn't have done elsewhere. That's because one of MIT's great strengths is the interdisciplinary labs like RLE, which bring people together to do research so more will happen.

• ***What's the most challenging part of your work?***
Since I became an administrator five years ago, I've discovered a new set of challenges. How do you make everyone feel as though they're getting what they deserve? When times are easy, you can give everyone what they want and everyone is happy. When times are tough, you have to make tough decisions and you make everyone angry. The human aspects are always challenging.

On the research side, I've always had problems that I've wanted to work on. Usually, I have an idea of what I want to study and then I start doing experiments with my students. Many times, we find something completely different from what we expected. It's challenging to figure out what's going on while we're facing the unexpected. It can also be nerve wracking and terrifying, but that's what's exciting about being an experimentalist.

Also, in the last few years, the funding situation has been painful and long-range basic research has been beaten up. There are signs it's improving as the budget deficit goes away, but we'll still have ups and downs. It adds another degree of uncertainty that's hard to handle while we deal with the uncertainty of understanding nature, which is a healthy part of what doing research is all about.

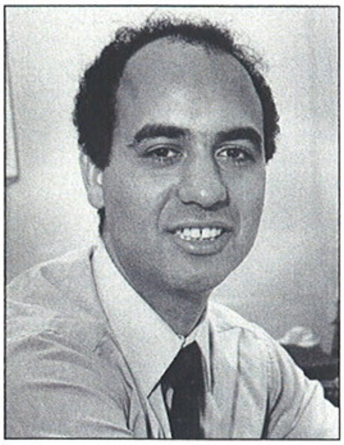
• ***Do you have advice for students?***
Research can be very hard and very challenging. It isn't something you can do unless you are so deeply committed that you can't think of doing anything else. However, it's one of the most rewarding human activities.

Despite funding problems, we're now at a time of enormous opportunities in physics. In every area, new tools and techniques are being invented that will allow us to learn more about nature.

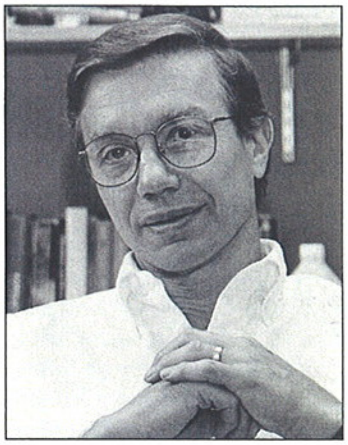
• ***What is your vision for the Physics Department?***
Despite funding problems, we're now at a time of enormous opportunities in physics. In every area, new tools and techniques are being invented that will allow us to learn more about nature. In solid-state physics, we have new microscopes like Ray Ashoori's capacitance microscope. Simon Mochrie is building beam lines at Argonne to do x-ray scattering in ways we couldn't before. We also have new facilities to grow new kinds of crystals. In atomic physics, trapping atoms with lasers and magnetic fields is mind boggling. Because of these new techniques, MIT is the only institution in the world with two kinds of Bose condensates, discovered by Wolfgang Ketterle, Dan Kleppner and Tom Greytak. Moving to higher energies, a new accelerator at Brookhaven will collide heavy ions and make regions of space as hot as it was a fraction of a second after the Big Bang. Sam Ting's experiment went up in the Space Shuttle to measure antimatter particles from outer space. There's the new Magellan telescope project that MIT is part of in Chile. There's the x-ray observatory that's about to go into space, which Claude Canizares has been building for the last decade. It will allow us to look at x-rays from stars that we could never see before. The challenge is finding high-caliber people to exploit these new tools and to support them properly.

• ***What's the most rewarding aspect of your job?***
I love to interact with students—both graduate and undergraduate. Working with graduate students has been the most thrilling part of my job because they're very hardworking and they can teach you so much. It's wonderful to see them start out intelligent and with a lot of general knowledge, but not very much involved in research; but then they go from that stage to where they're teaching me more than I'm teaching them.

As a faculty member, there's a great degree of intellectual freedom that you don't have in other areas of society. You have to get money to do research, but if you have a good idea and can find the funding, no one will tell you what to do. Being a faculty member, especially at a place like MIT, is a sacred trust. We're given such an unusual privilege—support from the Institute, the best students in the world, and the chance to do whatever we want to do. It's an amazing situation and I don't think we value it as much as we should.



Dr. Raymond C. Ashoori, assistant professor of physics, was promoted to associate professor, effective July 1, 1998. A graduate of the University of California at San Diego (BA'84) and Cornell University (PhD'91), Professor Ashoori joined the MIT faculty in 1993, after serving as a postdoctoral member of the technical staff at AT&T Bell Laboratories. His research in semiconductor technology focuses on investigations into the behavior of artificial atoms and the development of new spectroscopic probes to observe their unusual characteristics. His earlier efforts in this area yielded the development of a technique known as single-electron capacitance spectroscopy, which allows single electrons to be detected and manipulated in artificial atoms. Currently, Professor Ashoori and his colleagues in RLE's Quantum-Effect Devices group continue to develop a novel technique called subsurface charge accumulation imaging, which can directly observe charge distributions underneath the surface of semiconductor materials (see page 9). *(Photo by John F. Cook)*



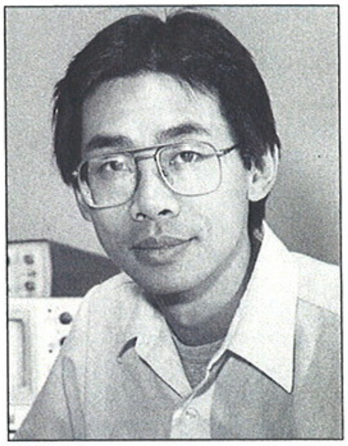
Dr. Thomas J. Greytak (SB'62, SM'63, PhD'67), professor of physics, and Professor Daniel Kleppner, associate director of RLE, have established a new direction in RLE's Atomic, Molecular, and Optical Physics (AMO) group that will explore the properties of cold hydrogen. Professor Greytak, who serves as the Physics Department's associate head for education, conducts research in experimental solid-state physics, spin-polarized hydrogen, superfluid helium, high-resolution spectroscopy with light and x-rays, and cryogenics. His recent collaborations with Professors Wolfgang Ketterle and Daniel Kleppner in the AMO group include pioneering work that contributed to the demonstration of the first atom laser and experiments involving Bose-Einstein condensation of atomic hydrogen for optical clocks. Professor Greytak was awarded the 1994 School of Science Teaching Prize for Excellence in Education. He has served as an MIT MacVicar Faculty Fellow and is a fellow of the American Association for the Advancement of Science. *(Photo by John F. Cook)*

Dr. Bertrand A.R. Delgutte (SM'76, PhD'81), research scientist in RLE's Auditory Physiology group, was promoted to principal research scientist, effective July 1, 1998. Dr. Delgutte joined RLE in 1984, after serving as a research engineer at France's Center National d'Etude des Télécommunications. His early investigations involved stimulus coding in the auditory nerve to better understand the neural signal-processing mechanisms that underlie various psychoacoustic phenomena. This research, which combined techniques used in neurophysiology, mathematical computation, and psychology, focused on speech perception, noise masking, pitch perception, and binaural hearing. Recently, he has used these methods to study the neural coding of acoustic stimuli in the inferior colliculus, which is the principal auditory center of the midbrain. Dr. Delgutte also conducts studies with electric stimuli to determine auditory nerve activity produced by cochlear implant devices. This work seeks to improve the design of new hearing aids and implantable auditory prostheses. A research associate at the Massachusetts Eye and Ear Infirmary, Dr. Delgutte is also an associate professor in Harvard's Department of Otology and Laryngology at and teaches at the Harvard-MIT Division of Health Sciences and Technology. *(Photo by John F. Cook)*

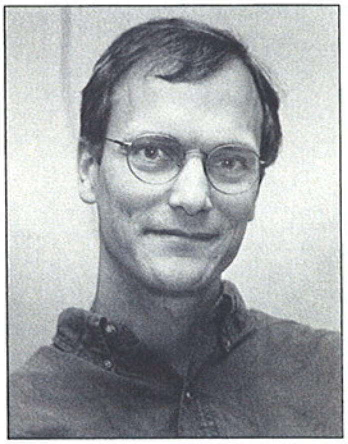
Dr. Qing Hu, associate professor of electrical engineering and computer science, was awarded tenure, effective July 1, 1998. Professor Hu, a graduate of China's Lanzhow University (BS'82) and Harvard University (MA'83, PhD'87), was a postdoctoral fellow at the University of California at Berkeley before coming to MIT in 1990 as an assistant professor. From 1991 to 1993, he held the KDD Career Development Professorship and was promoted to associate professor in 1995. Professor Hu's research in RLE's Optics and Devices group has focused on the response of solid-state devices to high-frequency radiation, which involves photon-assisted quantum transport in the millimeter-wave, terahertz, and infrared frequency ranges. His accomplishments include the development of the first millimeter-wave focal plane sensor arrays by using silicon micromachining techniques and the first achievement of terahertz spontaneous emission from a multiple quantum-well structure. He continues to investigate the development of superconducting electronic devices, semiconductor quantum-effect devices, and solid-state infrared lasers, which have applications to space-to-ground communications and high-frequency, high-speed signal processing. *(Photo by John F. Cook)*

Dr. Wolfgang Ketterle, professor of physics, was named the winner in the Emerging Technology category of *Discover* magazine's Ninth Annual Awards for Technological Innovation. Professor Ketterle, an investigator in RLE's Atomic, Molecular, and Optical Physics group was cited for the realization of the first atom laser. This novel device, demonstrated by Professor Ketterle's group in November 1996, emits atoms with properties closely analogous to the photons emitted from a laser. This achievement was a result of the group's ongoing investigations into the properties of ultracold atomic matter and their observation of the Bose-Einstein condensate in 1995. The *Discover* magazine awards, sponsored by the Christopher Columbus Fellowship Foundation, were presented at the Epcot Walt Disney World Resort on June 6, 1998. The winners and four finalists in nine award categories were featured in the July 1998 issue of *Discover*. Professor Ketterle and his colleagues continue to study the Bose condensate and to work towards the development of a practical, more powerful atom laser. Potential applications for the device include atom interferometry, precision measurements, new atomic clocks, and the creation of microscopic structures by direct-write lithography. *(Photo by John F. Cook)*

Dr. Stefanie Shattuck-Hufnagel (PhD'75), research scientist in RLE's Speech Communication group, was promoted to principal research scientist, effective July 1, 1998. In 1976, Dr. Shattuck-Hufnagel came to RLE as a research affiliate and was awarded a postdoctoral fellowship from the National Institute of Mental Health. In 1980, she was appointed as a research scientist in RLE. As a psycholinguist, her research seeks to provide connections between measurable acoustic-phonetic phenomena, psycholinguistic models of speech processing, and linguistic theories of language structure. Her investigations focus on the speech production planning process, where the models used are based on the prosody (or structure) of spoken utterances and their error patterns. She and her colleagues continue to develop the MIT Digitized Speech Error Database, which will enable the analysis of prosodic constraints on speech error occurrence, detection, and correction. A graduate of Wellesley College (AB'65), Dr. Shattuck-Hufnagel has taught at Cornell and Northeastern universities, and serves as an advisory editor for the *Journal of Phonetics*. *(Photo by John F. Cook)*

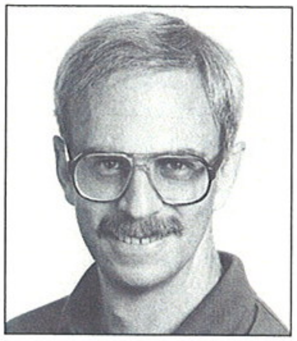


Dr. Ngai Chuen "Franco" Wong, research scientist in RLE's Optical Communications group, was promoted to principal research scientist, effective July 1, 1998. Dr. Wong joined RLE in 1986 as a research scientist. He conducts fundamental studies to characterize nonlinear optical devices and applies their unique phase and amplitude properties to quantum optics, optical frequency metrology, and optical communication networks. Dr. Wong's accomplishments in this area include a novel scheme to implement an optical-to-microwave frequency chain, the demonstration of optical frequency division by two and three optical divider stages, the development of multi-terahertz-span optical frequency comb generation, and the production of twin beams with strongly correlated noise properties. He holds three patents for the development of his optical devices and systems. A graduate of the University of Rochester (BS/BA'77) and Stanford University (MS'79, PhD'83), Dr. Wong is a topical editor for *Optics Letters* and is a member of the Optical Society of America, Phi Betta Kappa, and Tau Beta Pi. *(Photo by John F. Cook)*



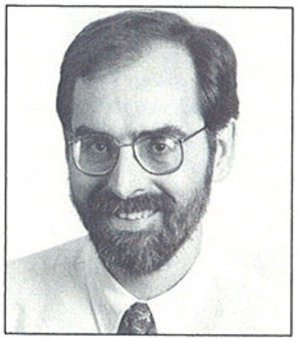
Dr. Gregory W. Wornell (SM'87, PhD'91), associate professor of electrical engineering and computer science, was awarded tenure, effective July 1, 1998. As a principal investigator in RLE's Digital Signal Processing group, Professor Wornell's research in signal processing includes multiuser broadband and wireless communications and the application of fractal geometry and nonlinear dynamics to these technologies. He and his colleagues have developed a variety of new signal-processing techniques that may have future applications to code-division multiple-access and packet-switched mobile radio networks, indoor spread-spectrum personal wireless systems, and digital audio and television broadcast systems. A graduate of the University of British Columbia (BASc'85), Professor Wornell joined the MIT faculty in 1991 and recently held the Cecil and Ida Green Career Development chair in that department. *(Photo by John F. Cook)*

MIT's Department of Electrical Engineering and Computer Science has announced the appointment of three new department heads. ***Professor John V. Guttag,*** who has served as associate department head of computer science and engineering since 1993, was chosen as the new department head, effective in January 1999. Professor Guttag also leads the Software Devices and Systems group in MIT's Laboratory for Computer Science, which studies topics in computer networks, computer and communication security, and advanced wireless communication systems. In addition, ***Professor L. Rafael Reif*** was selected as associate department head for electrical science and engineering and ***Professor Tomás Lozano-Pérez*** (SB'73, SM'77, PhD'80) was named associate department head for computer science and engineering. Since 1990, Professor Reif has served as director of MIT's Microsystems Technology Laboratories, where his research involves the low-temperature epitaxial growth of semiconductor thin films. His appointment will become effective in January 1999. Professor Lozano-Pérez is the Cecil H. Green Professor of Computer Science and Engineering. He serves on the faculty at MIT's Artificial Intelligence Laboratory, where his research interests include robotics, computational geometry and chemistry, and artificial intelligence. His appointment was effective September 1, 1998. Professors Paul L. Penfield, Jr. (ScD'60), and Jeffrey H. Shapiro (SB'67, SM'68, EE'69, PhD'70), who have served as department head and associate head of electrical science and engineering, respectively, since 1993, will return to teaching and research in the department. *(Photos by Mark Ostow)*



Professor John V. Guttag

Professor L. Rafael Reif



Professor Tomás Lozano-Pérez

RLE's Fiscal group, under the direction of Senior Fiscal Officer William H. Smith, handles all proposal generation, budget preparation, and contract monitoring in RLE. The group, which is active in developing new computer-based products and fiscal services for all RLE investigators, recently announced a promotion and a new staff appointment:

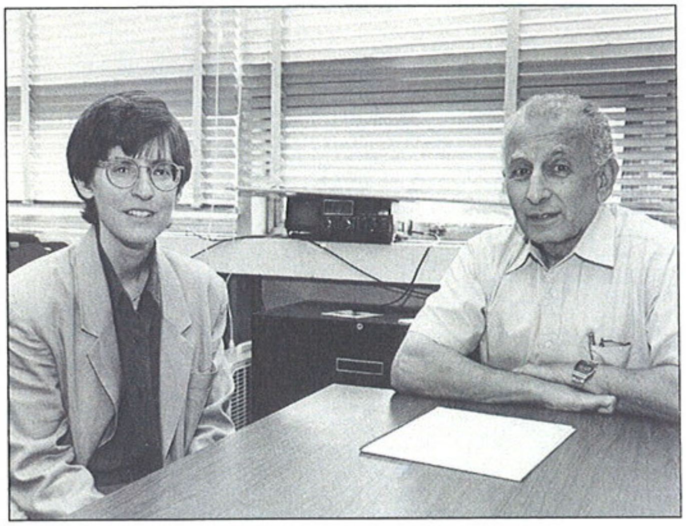
Mary E. Young was promoted to fiscal officer in RLE's Fiscal Group, effective June 1, 1998. Ms. Young joined RLE in 1994 as assistant fiscal officer and was promoted to associate fiscal officer in 1996. Since 1981, when she first came to MIT, Ms. Young has worked with the Program in Science, Technology, and Society; the Department of Political Science; the Division of Toxicology; and the Plasma Science and Fusion Center. She received a certificate in bookkeeping from Bunker Hill Community College in 1981 and a BSBA from Emmanuel College in May 1998. *(Photo by John F. Cook)*

Mary E. Young

Rose M. Rizzo

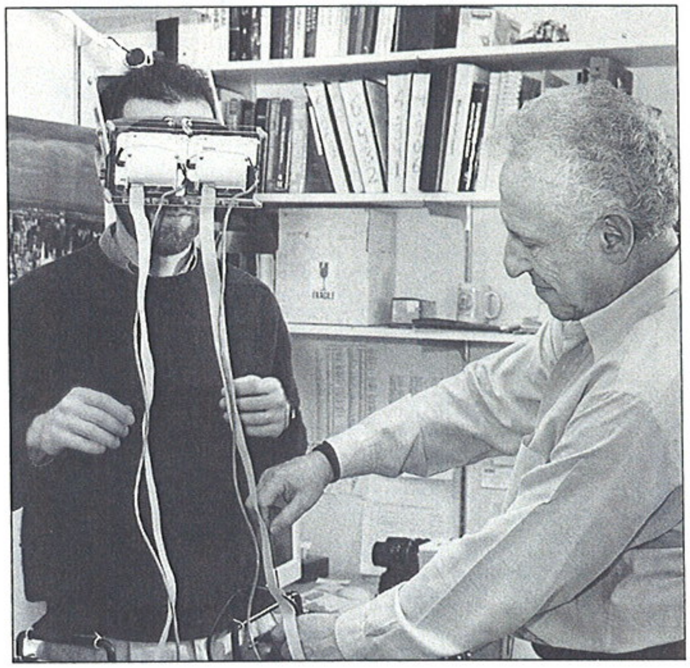
Rose M. Rizzo was appointed financial administrator in RLE's Fiscal Group, effective May 25, 1998. Before joining RLE, Ms. Rizzo worked with MIT's Personnel Department; the Department of Earth, Atmospheric, and Planetary Sciences; the Plasma Science and Fusion Center; and the Center for Cancer Research. She also worked with TAD Technical Services in Cambridge, Massachusetts, before coming to MIT in 1985. Ms. Rizzo holds a BS in elementary education from Boston University and received a certificate in human resources management from Bentley College. *(Photo by John F. Cook)*

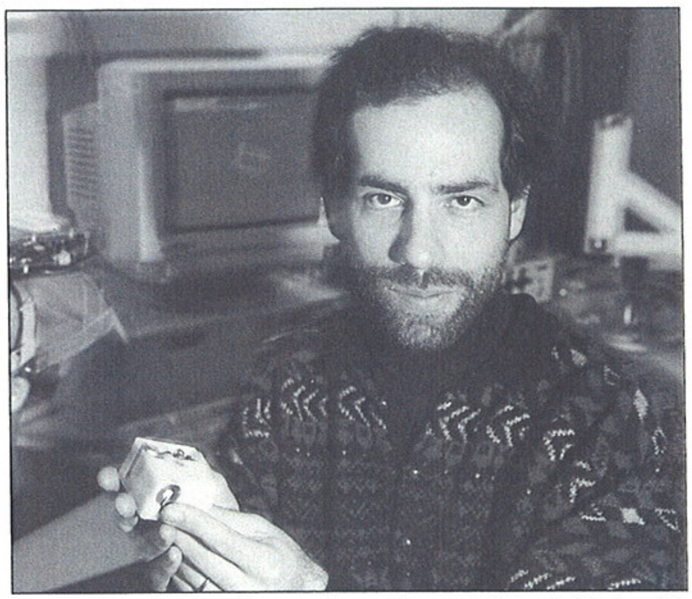
The staff of ***RLE currents*** would like to note that the "RLE Connections" photo caption describing Professor Alan V. Oppenheim's research group on page 12 of the spring 1998 issue mistakenly identified Research Assistant Huan Yao as graduate student Lee Li.



While pursuing her bachelor's degree at Wellesley College, Dr. Prentiss (left) joined RLE in 1980 as a thesis student and assisted MIT Professor Shaoul Ezekiel in various laser experiments. She continued to work with his group as a research assistant while completing her doctorate degree at MIT. Since 1992, she has maintained a research affiliation with RLE, working with Professor Ezekiel in the Atomic, Molecular, and Optical Physics group on atom interferometry for nanolithography applications. (Photo by John F. Cook)

Mara G. Prentiss (PhD'86), professor of physics at Harvard University, is investigating atom lithography, an alternative technique to conventional optical lithography. Although state-of-the-art optical lithography is instrumental in producing the nanosized circuits contained in modern silicon computer chips, it is limited by the laws of diffraction and cannot achieve feature sizes less than 100 nanometers. The novel atom lithography method developed by Dr. Prentiss and her colleagues at Harvard uses a mask made of light to transfer a beam pattern composed of atoms onto a substrate. It is described in detail in the August 1998 issue of *Physics World*. Although it is too early to predict if atom lithography will be practical for computer chip manufacturing, particularly for the precision needed to produce complex electronic circuit devices below 100 nanometers, Dr. Prentiss and her team at Harvard continue to explore this promising approach.



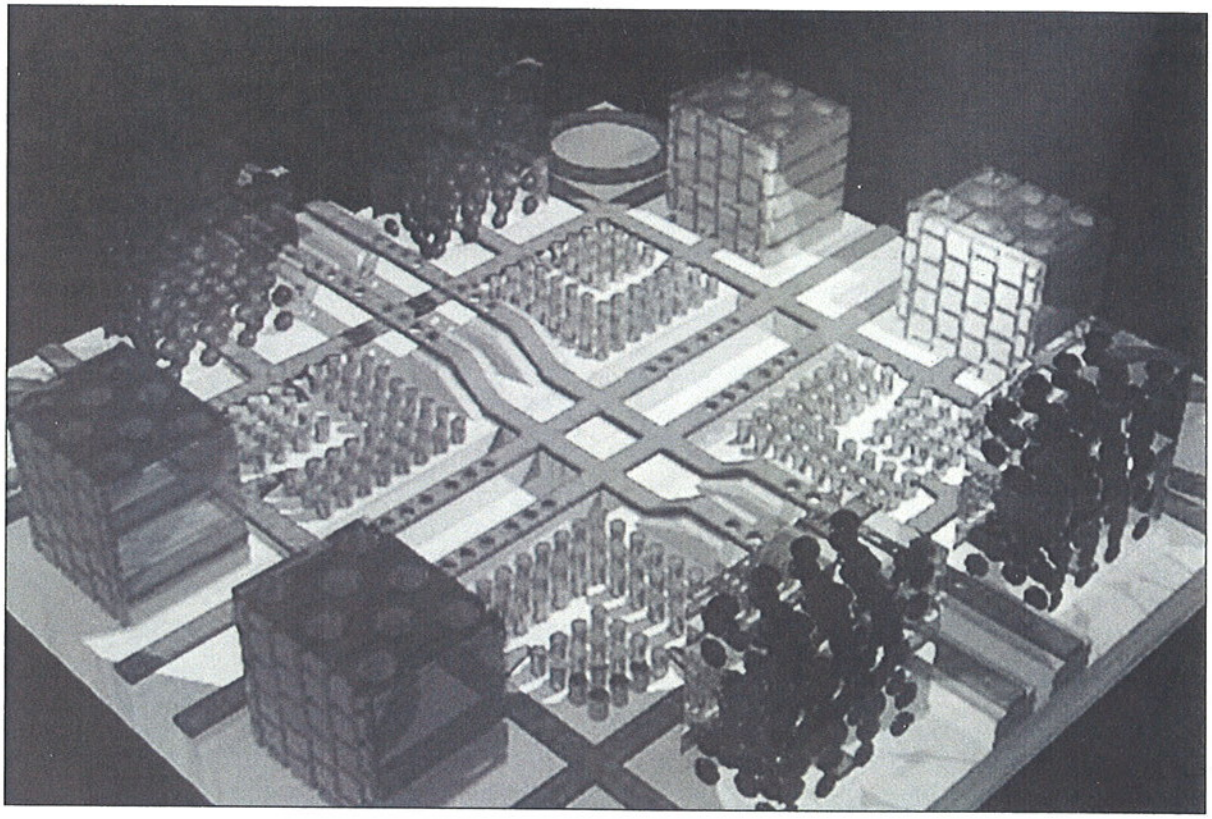


In the 1993 photograph at top, Senior Research Scientist Nathaniel I. Durlach (right) assists Research Assistant Eric M. Foxlin in using a head-mounted display to view a stereo-image virtual environment generated by a computer. Today, Mr. Foxlin is founder and chief technical officer of InterSense, Inc. of Burlington, Massachusetts. (Top photo by John F. Cook; bottom photo by Mark Ostow)

Eric M. Foxlin (SMEE'93) is the founder and chief technical officer of InterSense, Inc. of Burlington, Massachusetts. The company, which develops innovative motion-tracking sensor products and software, was profiled in *The Boston Globe* on April 22, 1998. Mr. Foxlin previously worked in RLE's Sensory Communication group with Senior Research Scientist Nathaniel I. Durlach on head-mounted displays for virtual environments. After completing his degree, Mr. Foxlin founded InterSense in 1996.

When people use conventional inertial tracking systems based on magnetic, acoustic, or optical technologies, they typically experience some degree of interference, jitter, or lag time. InterSense's new inertial and sensor-fusion-based systems have overcome many of these problems by incorporating inherent predictive capability and unlimited scalable tracking range. Product applications include aircraft simulation, driver education, experimental treatments for autism and claustrophobia, architectural planning, combat training, military strategy, and interplanetary space exploration. Mr. Foxlin writes that InterSense is always looking for new engineers to join their staff. The company's Web page is http://www.isense.com/.

The Lighter Side of Photonic Crystals



This photonic micropolis, constructed by Professor John D. Joannopoulos' group, incorporates many elements of their photonic crystal device research. The photonic-crystal buildings house bundles of light while the highways and bridges guide light through narrow channels and around tight corners. The buildings are made of three-dimensional periodic crystals, the roads are one-dimensional periodic crystals, and the forests are two-dimensional periodic crystals. Although they are nonphotonic crystals, conventional ring resonators have been located at the corners because they are well understood and easy to fabricate. A more detailed and full-color view of the micropolis can be seen on the Web at http://jdj.mit.edu/ photons/micropolis.html.

Massachusetts Institute of Technology
RLE currents
Research Laboratory of Electronics
Room 36-412
77 Massachusetts Avenue
Cambridge, Massachusetts 02139-4307

NON PROFIT ORG.
U.S. POSTAGE PAID
BOSTON, MA
PERMIT NO. 54016