RLE currents

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The Research Laboratory of Electronics at the Massachusetts Institute of Technology

MATERIALS RESEARCH: Meeting the Challenge of Microelectronics Technology

Since the discovery of the transistor at Bell Laboratories in 1947, scientists have been challenged by the need to produce materials for highly miniaturized and increasingly fast microelectronic components. Driven by the technology of the information age, scientists have examined the unique properties of semiconductors, fundamentally exploited new combinations of these novel materials, and developed innovative design techniques to miniaturize electronic components. At the heart of this research is the ever-shrinking and exceedingly complex integrated circuit microchip. In addition, the development of microscaled transistors and other electronic components has resulted in systems with larger and faster capabilities, particularly for information processing and high-speed communication.

Every year since 1960, the number of circuit components on the most advanced microchip has nearly doubled. Today, over 4 million transistors can be packed neatly onto one computer memory or DRAM (dynamic random access memory) chip. The dramatic miniaturization of electronic components over the last forty years has raised questions about the physical limits of the materials, devices, and systems involved. Such limitations in materials science are imposed by fundamental

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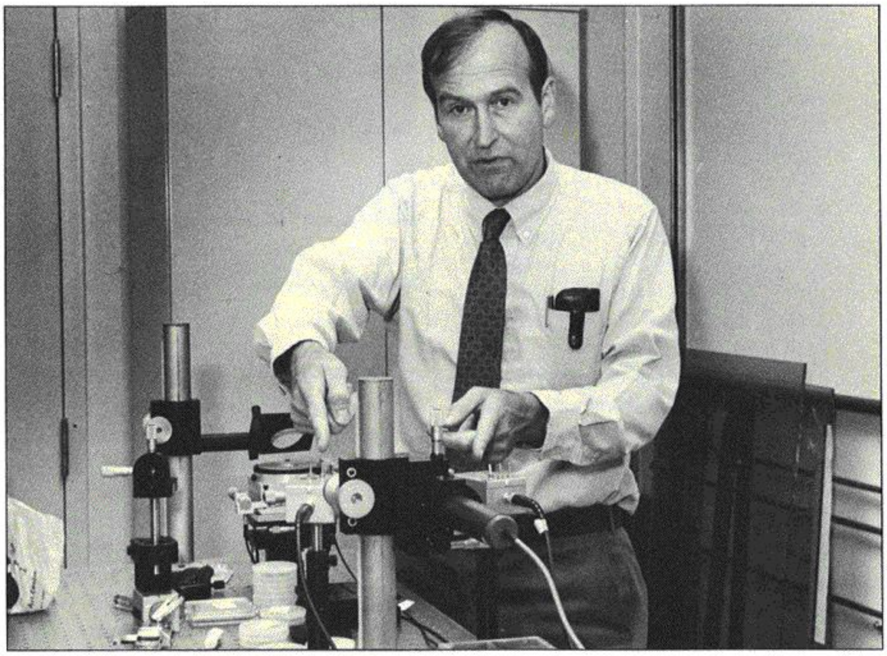


Professor Henry I. Smith explains the development of an alignment system for x-ray nanolithography that should be capable of 100-angstrom precision. Under his direction, RLE's Submicron Structures Laboratory has pioneered new technologies in submicron structures fabrication and explored deep-submicron MOSFETs and the exciting new field of quantum-effect electronics (see related article on page 7). Working with Professor Dimitri Antoniadis and graduate student Ghavam Shahidi, they have discovered that the deleterious hot- electron effects seen in silicon MOSFETs with channel lengths below 0.25 microns actually decrease at linewidths below 0.15 microns. This is apparently because the source-drain transit times are shorter than electron energy-relaxation time. The quantum-effect electronics group (Professors Dimitri Antoniadis, Jesus del Alamo, Clifton Fonstad, Marc Kastner, Leslie Kolodziejski, Patrick Lee, Terry Orlando, and Henry Smith) has demonstrated several novel quantum transport phenomena which can occur in sub-0.1-micrometer structures. It is hoped that their basic research into such quantum phenomena may eventually lead to more advanced computation and electronic systems.

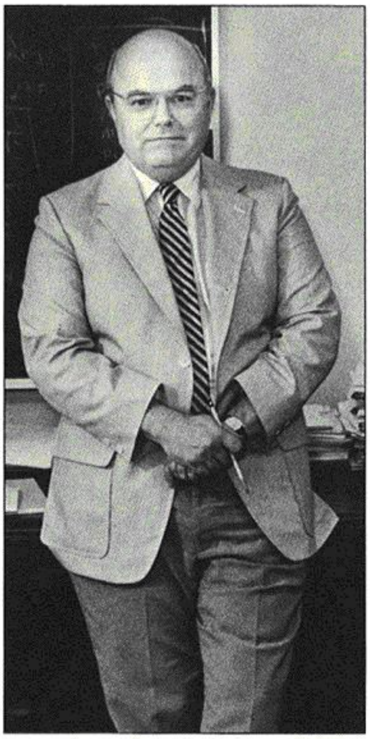
Director's Message

Electronic and optical materials form the basis upon which structures, devices, circuits, and systems are built. They are the starting point for much of RLE's research in electronics and optics, and increasingly they are engineered products that are designed to meet stringent and innovative requirements of the smallest and fastest systems. In earlier days, natural elements like silicon were doped in bulk to form the starting material for electronic integrated circuits. But now, much of RLE research focuses on synthetic materials, using novel techniques of band gap engineering to provide enhanced carrier mobility and desirable optical properties.

The achievement of high-quality, defect-free electronic materials is the focus of several projects aimed at the controlled microstructural evolution of thin films. In this way, device-quality material can be formed on a substrate, and grain boundaries in conducting wires can be oriented to drastically reduce the effects of electromigration. One of RLE's major new emphases is the epitaxial growth of novel materials and devices involving III-V and II-VI heterostructures, using both molecular beam and chemical beam techniques. These expanded experimental programs support the synthesis of materials that involve direct control of single atomic layers as the material is grown, yielding previously unattainable structures and dramatically improved devices.

While epitaxy builds up a material in one dimension, high-resolution lithography permits submicron control of structure and device planar dimensions, providing the world's smallest FET transistor. Focused ion beam techniques also furnish the ability to dope and deposit materials at the submicron scale in the planar dimensions, leading to new device configurations and techniques for surface defect repair. RLE is also heavily involved in the study of superconducting materials, which have recently generated much scientific excitement.

In all of these areas of experimental materials, structures, and devices, RLE leads the development of new fabrication techniques, driven by the needs of electronic and optical systems. Engineered control at atomic dimensions provides the means to synthesize exciting performance that is breathing new life into high-speed miniature systems.



Professor Jonathan Allen, Director, Research Laboratory of Electronics.

MATERIALS RESEARCH
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physical science and the composition, structure, and behavior of the materials used. In the 1960s, the smallest feature size of an electronic circuit was 30 microns. In contrast, today's scientists typically work with electronic structures measuring one micron and below (submicron). By the mid-1990s, scientists anticipate that the smallest features will be approximately 0.1 micron.

Materials research seeks to address these limitations through different fields of investigation: processing and fabrication of silicon and compound semiconductors; fundamental principles underlying materials processing effects; the growth and characterization of crystalline and metallic thin films for microelectronic applications; experiments with novel silicon epitaxy; heterostructure formation in compound semiconductors; and the control of thin-film crystalline structures on amorphous substrates.

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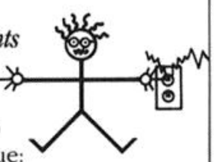
SHORT CIRCUITS



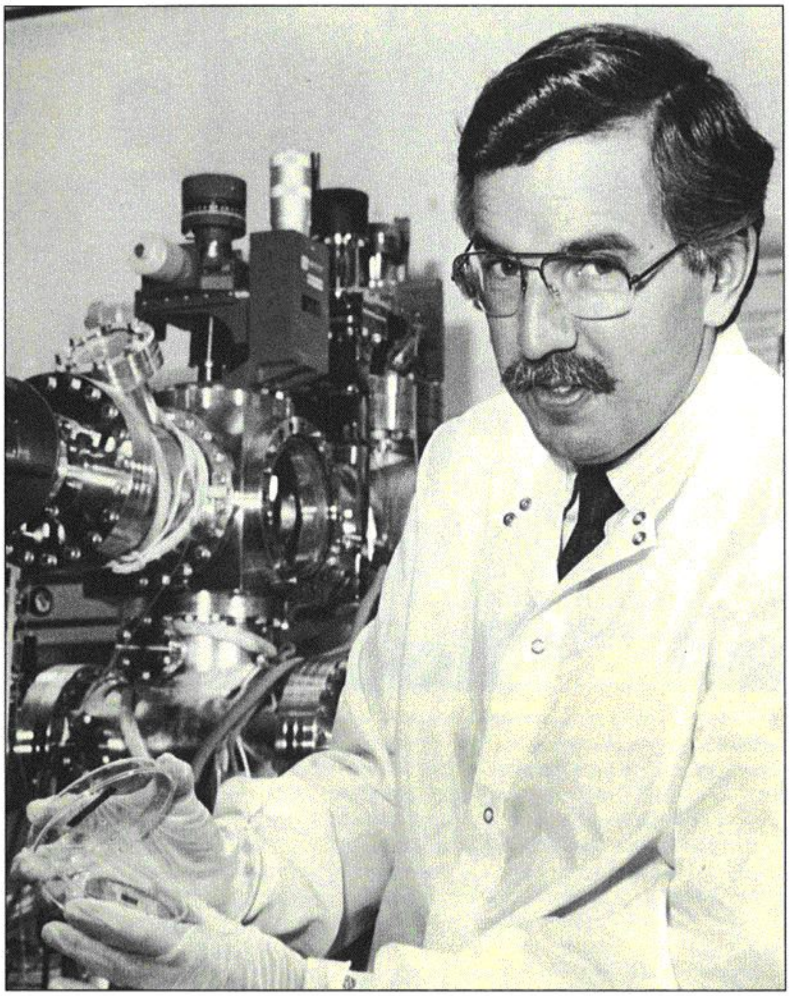
The staff of ***currents*** would like to note the following corrections to the June 1988 issue:

"Faculty Profile," page 11: Dr. Charles V. "Chuck" Shank of AT&T Bell Laboratories in Holmdel, New Jersey, was mistakenly referred to as Chuck Chang.

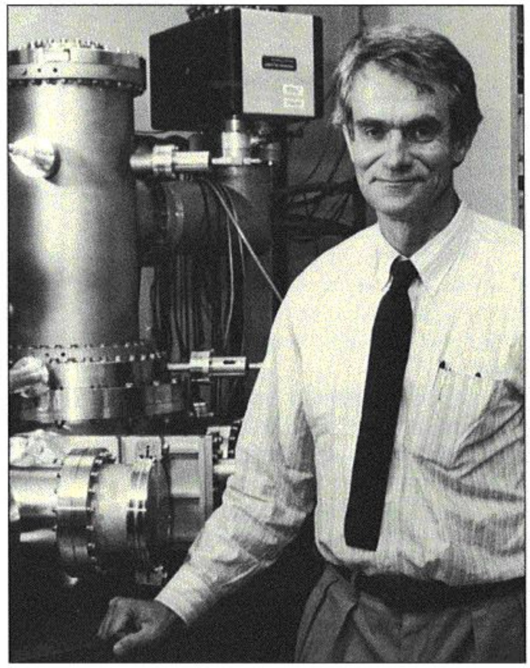
"History of Optics at RLE," page 16: In the 1945 photograph depicting Albert G. Hill and Jerrold R. Zacharias examining a microwave waveguide, Albert McCavour Clogston (left in photograph) was misidentified as George Briggs Collins.

"UPDATE: Communications," page 20: Author Donald George Baltus was misnamed David.

Thanks to our eagle-eyed readers who called our attention to these errors.



Professor Clifton G. Fonstad examines a heterostructure specimen grown by molecular beam epitaxy for use in laser diode fabrication. He has successfully grown state-of-the-art multiple quantum well heterostructures in two materials systems: gallium-aluminum-arsenide/gallium arsenide and indium-gallium-aluminum-arsenide/indium phosphide. In collaboration with Institute Professor Hermann A. Haus, he has incorporated heterostructures in waveguide devices for high-speed, guided wave optical circuits. Professor Fonstad has also demonstrated the growth of strained-layer heterostructures on (111) gallium arsenide, and was the first to observe the internal electric fields in these layers. The growth of strained layers on (111)-oriented substrates will facilitate highly efficient optical modulators for integrated optical circuits, and will enhance laser diode performance.



Principal Research Scientist Dr. John Melngailis uses focused ion beams for patterned deposition from adsorbed gas molecules and for patterned implantation or lithography. The unique capabilities of focused ion beam implantation have been used at MIT to fabricate tunable Gunn diodes and to expose resist features down to 0.05 micron linewidths. With the apparatus shown in the photograph, gold films have been deposited in linewidths down to 0.1 micron. The focused ion beam column is mounted on an ultrahigh vacuum chamber, and will be used for microdeposition of reactive metals such as tungsten or aluminum. It will also be used to develop techniques for x-ray lithography mask repair and for integrated circuit restructuring and repair. In addition to deposition, both of these applications require material removal, or micromilling, with submicrometer resolution. Grooves 0.1 micron wide and 0.2 micron deep have been milled with well-defined, steep sidewalls. The deposition and removal of high atomic number materials, such as gold or tungsten with submicrometer resolution and high aspect ratio, is essential to x-ray lithography mask repair, while good electrical conductivity is required for circuit repair.

An integrated circuit microchip primarily consists of transistors, resistors, capacitors, and various interconnections finely mapped out and fabricated on a single semiconductor crystal. Microchips are made by slicing a cylinder of single-crystal silicon into smooth, ultrathin wafers. The wafers are heated in the presence of oxygen, which results in the growth of a layer of silicon dioxide on the wafers' surface. The surface is then covered with a polymer coating called photoresist, that contains the integrated-circuit pattern exposed by electromagnetic radiation or charged particles. Selected areas on the photoresist are etched away, leaving a circuit pattern on the remaining photoresist.

Next, the silicon is provided with charge carriers by *doping*, a technique used to inject the silicon with impurity elements (charged ions or dopant atoms). Doping transforms specific areas underneath a wafer's surface so that the areas will have different electronic properties than the bulk silicon. Thus, a semiconductor's electrical properties can be changed and closely controlled using doping techniques. Because silicon's few valence electrons are entirely consumed by covalent bonds in the element's lattice, the addition of a dopant with more valence electrons will result in extra valence electrons that are free to conduct electric current. Conversely, when using a

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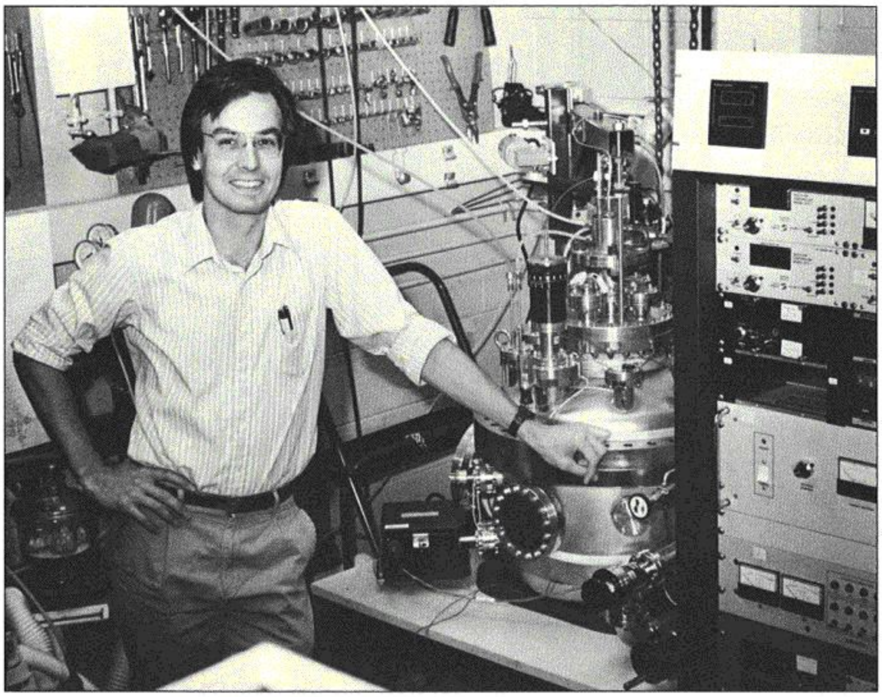
dopant with fewer valence electrons than the semiconductor, positively charged carriers (or "holes") occur, which can move when an electric field is applied to the material. Common dopants are arsenic (with an extra valence electron than silicon) and boron (with one less valence electron than silicon).

Ion bombardment from doping can damage the silicon crystal, so it is slowly annealed, or heated, to remove defects. Simultaneously, another layer of silicon dioxide is deposited to provide an insulating layer and to protect the wafer from high electric fields. The wafers are further processed by depositing metals or alloys by a variety of methods: vacuum evaporation, sputtering, or chemical-vapor deposition. The wafers are sliced into many chips, each containing as many as 4 million transistors per chip, and then mounted in a ceramic or plastic package. (See diagram on page 5, "How a computer chip is made".)

Chips with microscopic bulk and surface defects will not operate properly. The larger the chip, the more likely it will contain defects or deviations from the exact periodicity of the crystal array (dislocations, stacking faults, and grain boundaries). Because good chip yield is inversely related to the chip's size, a chip usually measures less than one square centimeter in size. Scientists are currently exploring new methods to grow larger, defect-free silicon crystals and to enable the creation of increasingly dense integrated circuit elements on a single-crystal chip.

Since external wiring increases the cost of a chip considerably, another challenge is to pack as many interconnects on a single chip as possible. But, problems arise when attempting to microscale electronic devices. For example, the smaller the transistor, the thinner its silicon dioxide insulator becomes. As a result, electrons on a transistor's gate can leak through or "tunnel" into the silicon substrate below, thus affecting the transistor's performance.

In addition, as a result of shrinking the size of interconnections, unwanted motion of component material can occur in the aluminum wires, or interconnects, that join the chip's various electronic elements. This is known as *electromigration*, or current-induced diffusion. The direct cause of electromigration is the increased current density experienced as integrated circuits become smaller. Although the total current in a miniaturized wire might be low, its current density (measured in terms of the amount of current per unit of cross-sectional area) can be large. Once the high current density in the interconnect's depleted region causes movement of aluminum atoms to the low current-density regions, the phenomenon will result in interconnect failure. Connector material actually gets pulled along the wire, and can leave voids in the interconnect. Copper-aluminum alloys have been used in interconnect material to slow the electromigration process. But, with the increasing density of circuit elements, other novel materials and techniques are being investigated to solve electromigration problems.



One area of Professor John M. Graybeal's research is quantum transport in low-dimensional disordered systems. Examples of low-dimensional systems include two-dimensional electron gas trapped on the interface in silicon MOSFETs, and quasi-one-dimensional systems in MOSFETs with narrow gates (a few hundred angstroms wide). Studies of devices in low-dimensional systems have led to the discovery of important fluctuations in resistance in both metallic and insulating regimes. Professor Graybeal continues to explore small device transport phenomena in the quantum regime by observing resonant tunnelling and examining the basic features of edge states in narrow, disordered systems. This will further understanding of the behavior of individual quantum states in microelectronic devices. Here, he is photographed with thin-film sputtering equipment used in his research on the synthesis of high-temperature superconducting films.

The active devices commonly used in today's electronic systems are either bipolar or field-effect transistors (FETs). Although bipolar transistors are fundamental to large computer CPUs (central processing units) and are faster performers than FETs, the FETs form the basis for the computer's memory and are also used in logic operations for small to mid-sized computers.

The most common element in both bipolar transistors and FETs is semiconducting silicon (Si). Semiconductors are solid crystalline materials whose electrical conductivity lies between that of a conductor and an insulator. They are the basis, or substrate, on and within which a microcircuit is fabricated. Silicon possesses many beneficial properties that make it appropriate for use in integrated circuits. As an abundant, naturally occurring element, it can be formed into near-perfect crystals inexpensively. Silicon's band gap (1.12 electron volts), or the energy difference between its valence and conduction electrons, enables it to maintain semiconducting properties over a wide range of temperatures.

When interacting with silicon or other semiconductor materials, electrons exhibit unusual behavior. In semiconductor materials, electrons travel as if their mass was much smaller than electrons travelling in free space. For example, in silicon, an electron travels as if its mass was one-fifth the effective mass of a free electron. Beyond silicon, researchers have already begun to investigate other suitable semiconducting materials. Gallium arsenide (GaAs) is a frequent alternative to silicon, since its carrier mobility enables faster circuit switching times (about two-and-a-half times faster than silicon's). One drawback to gallium arsenide is its lower thermal conductivity. When fabricating smaller devices, the device's switching speed is limited by the substrate's ability to conduct heat away from the device.

Gallium arsenide is a compound semiconductor made up of elements from the periodic table's group III and group V. The periodic table highlights the similar properties of various chemical elements, which are arranged in order of atomic number or weight in horizontal rows (periods) and vertical columns (groups). Circuits based on semiconductor materials from periodic table columns III and V are capable of higher clock rates because electrons move faster in III-V compounds than in silicon, a group IV element. Other high-speed III-V materials include: indium phosphide, gallium-aluminum-arsenide, and indium-gallium-arsenide-phosphide.

Once the beneficial properties of materials and the advantages of microscaling are combined, faster devices can be successfully fabricated. The MESFET (metal-semiconductor FET), created by substituting gallium arsenide for silicon, is faster than a MOSFET. The MODFET (modulation-doped FET) is a quantum-well device that is even faster than a MESFET. A layer of aluminum-gallium-arsenide is deposited on an undoped gallium arsenide

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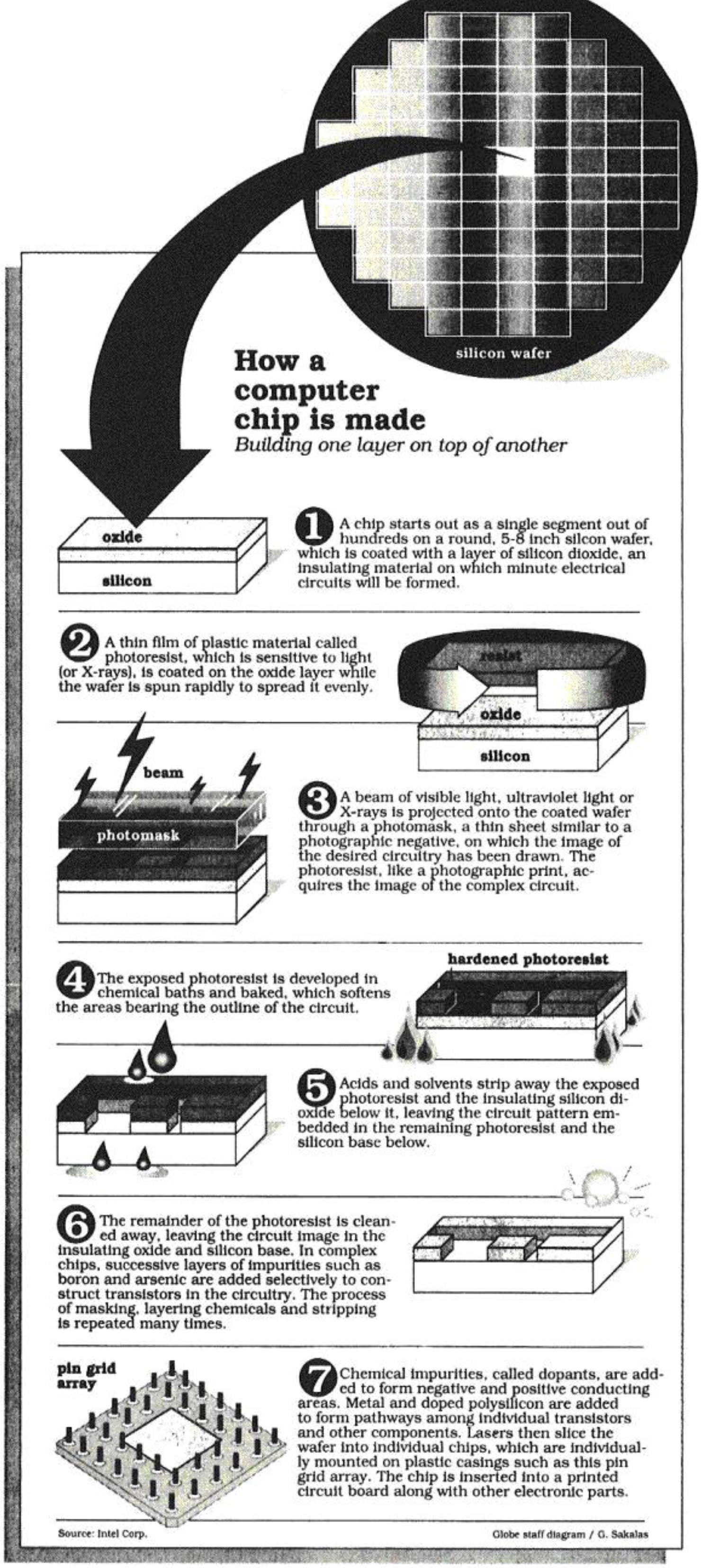
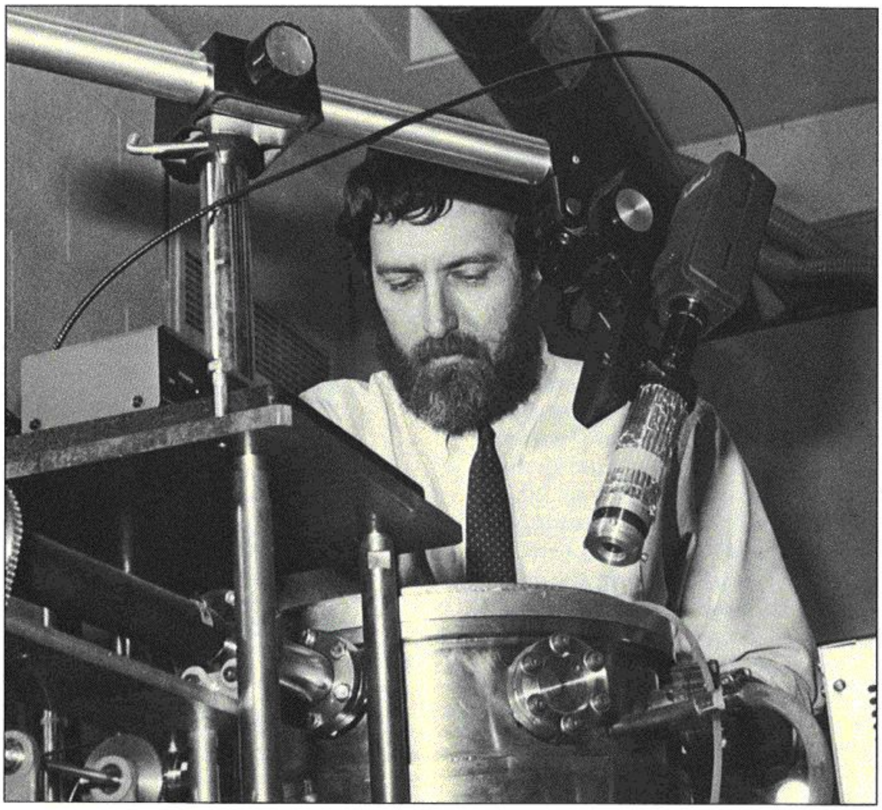


Reprinted courtesy of *The Boston Globe* substrate to form a single-crystal lattice known as a superlattice. The physical properties of these layers provide a "quantum well" to trap electrons from the aluminum-gallium-arsenide. The fast electron conduction in a MODFET is attributed to the absence of dopants in the substrate, which increases its mean free path. Mean free path is the distance an electron or hole can travel before scattering from an atom. The longer the path, the higher the mobility. In future technologies, it may be possible to construct both vertical and horizontal quantum wells so that electrons can travel between cross-sectional "squares" to perform digital operations.

By combining elements from groups III and V, custom-made electronic materials can be produced for various microelectronic devices. One approach to building these devices is *heteroepitaxy*. By layering thin films of different materials on a crystalline substrate, heteroepitaxy can provide a multilayer superlattice, a periodic array of alternate layers made of two semiconductors. The techniques used to grow heteroepitaxial films include: liquid-phase epitaxy, where cooling of a heated solution of desired elements occurs on a substrate; chemical vapor deposition, which exposes the substrate to heated gaseous elements or compounds; and molecular beam epitaxy, which targets heated molecule beams or atoms at a substrate in an ultrahigh vacuum.

Researchers are not restricted to naturally occurring III-V compounds. Although a material's structure and properties determine its performance level and behavior, structural configurations can be changed through closely controlled processing methods. Crystal growing techniques, such as molecular beam epitaxy (MBE), can combine the desired properties of many chosen elements. MBE techniques have been referred to as "spray painting with atoms" by Bell Laboratories, where it was invented. Molecular beam epitaxy can build custom-made semiconductor crystals by depositing different semiconductor compounds in evenly deposited and alternating atomic layers, or films. Beams of a chosen material's atoms or molecules are emitted from heated effusion cells, or crucibles. These beams are aimed at a single-crystal substrate on a temperature-controlled substrate holder in an ultrahigh vacuum chamber. The resulting epitaxy is oriented or controlled growth, with each successive layer resembling the lattice orientation of the layer beneath it. Finished films are uniformly flat to within one atom in depth.



Professor Carl V. Thompson checks a zone melter that was constructed in his laboratory. The apparatus has enabled the correlation of solidification conditions, interface morphologies, and crystalline defect structures at the liquid-solid interface during zone melting recrystallization of thin films for the first time. Professor Thompson's research involves microstructural evolution during polycrystalline and epitaxial thin-film processing, control and modification of structures through post-deposition processing, and the determination of microstructural effects on reliability and other film properties. He has produced a general model that permits quantitative predictions of grain growth rate and final grain sizes in polycrystalline silicon films. Detailed correlations have been made between grain sizes, grain size distributions, and grain orientation distributions with statistics from electromigration-induced failures of aluminum-based interconnects. Currently, he is working on techniques to make very large-grain films that will be resistant to electromigration.

Several analytical techniques are used to characterize microstructures and their properties (such as lattice periodicity and other crystallographic information), and to achieve extremely fine detail that provides a close look at these materials. A high-voltage electron microscope provides sub-100-angstrom resolution, while the scanning electron microscope affords a three-dimensional view at close to 100-angstrom resolution. Materials scientists also use spectroscopy to examine the photon interaction of a specific wavelength (x-ray, ultraviolet, visible, or infrared) with a material's electrons, and the resulting spectrum from that interaction.

Since light's long wavelength is not suitable for etching extremely fine features onto a silicon wafer's photo-

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RLE'S SUBMICRON STRUCTURES LABORATORY: The Size of Things to Come

The Submicron Structures Laboratory (SSL) at RLE was established in 1978 to develop advanced techniques for fabricating submicron structures, and to pursue novel research applications of such structures, ranging from microelectronics to x-ray astronomy. Since its inception, Professor Henry I. Smith has directed SSL's pioneering efforts in micro- and nanofabrication, deep-submicron and quantum-effect devices, crystalline thin films on amorphous substrates, and periodic structures for x-ray optics and spectroscopy.

In its research on x-ray and holographic nanolithography, the SSL has been the leading laboratory in the world, and has exploited its unique technologies to achieve significant firsts in microelectronics and quantum-effect electronics. Silicon MOSFETs with channels shorter than 100 nanometers have been fabricated. The velocity overshoot and reduced hot-electron effects observed in these devices are leading to new concepts for miniaturization of electronics. Studies of quantum mechanical transport in MOSFETs with channels as narrow as 30 nanometers, and in gallium arsenide MODFETs with fine-period grating gates (linewidths smaller than 100 nanometers), are uncovering unanticipated new quantum phenomena which, in the future, may form the basis for advanced electronic and computational systems.

In space provided by the Microsystems Technology Research Laboratory (MIT Building 39), SSL encompasses 1,000 square feet of class 10 clean rooms, and another 1,000 square feet of class 10,000 clean space.

These pictures illustrate the extremely small size of electronic devices and other structures achieved in the Submicron Structures Laboratory at MIT (and elsewhere).

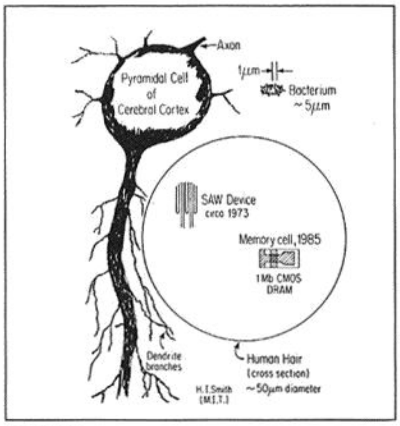


Figure 1

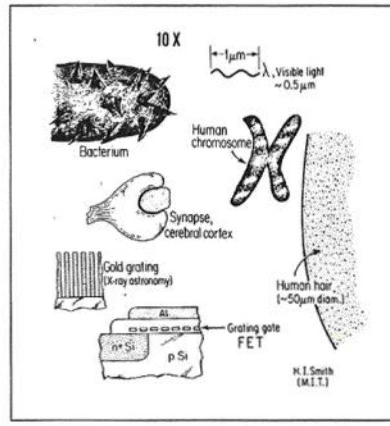


Figure 2

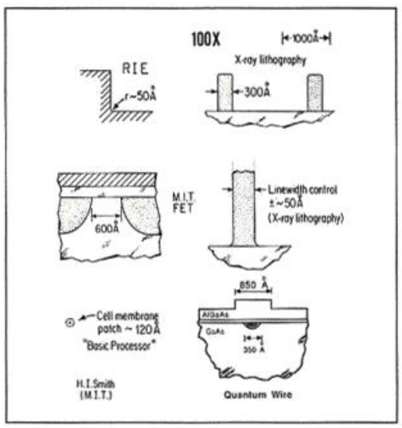


Figure 3

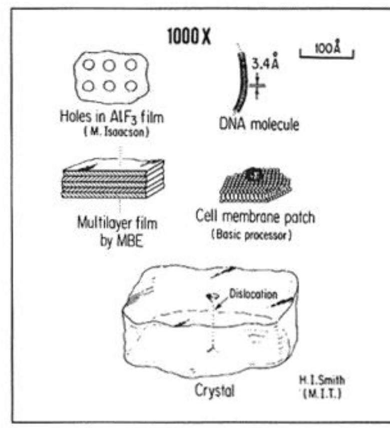


Figure 4

Figure 1 *compares the human hair in cross-section with a surface-acoustic-wave device, a one-megabit memory cell, a one-micron scale marker, a bacterium, and a neuron from the cerebral cortex.*

Figure 2 *is a ten-time magnification of Figure 1, which again shows the human hair in cross-section, a bacterium, and a one-micron scale marker. A human chromosome and a synapse (the interconnection between neurons) are shown next to MIT's work on gold diffraction gratings for x-ray astronomy and a MOSFET device used to study quantum effects in electron transport.*

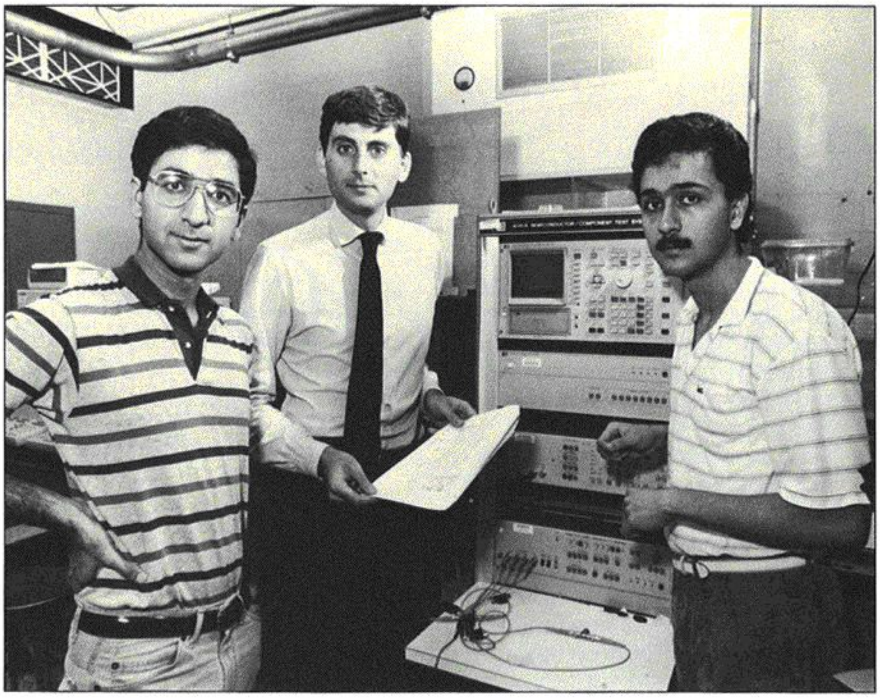
Figure 3 *is a 100 times magnification of Figure 1. The dimensions of a transistor made at MIT (the smallest MOSFET in the world) are shown along with the Submicron Structures Lab's work on reactive ion etching and x-ray nanolithography. The cell membrane patch (the "elemental switch" in biological systems), and the cross-section of a "quantum wire" in GaAlAs/GaAs, only 350 angstroms wide, are shown to scale. The latter is used to study quantum phenomena in a one-dimensional electron conductor.*

Figure 4 *magnifies Figure 1 one thousand times. The holes in* AlF_3 *were made by Mike Isaacson at Cornell using an extremely fine 5-angstrom electron beam. The multilayer film shows the control of layer thickness achievable with molecular beam epitaxy. The cell membrane patch and the DNA molecule are drawn to scale. The dislocation relates to work done at MIT on controlling the location of dislocation in silicon, perhaps leading to some future applications.*

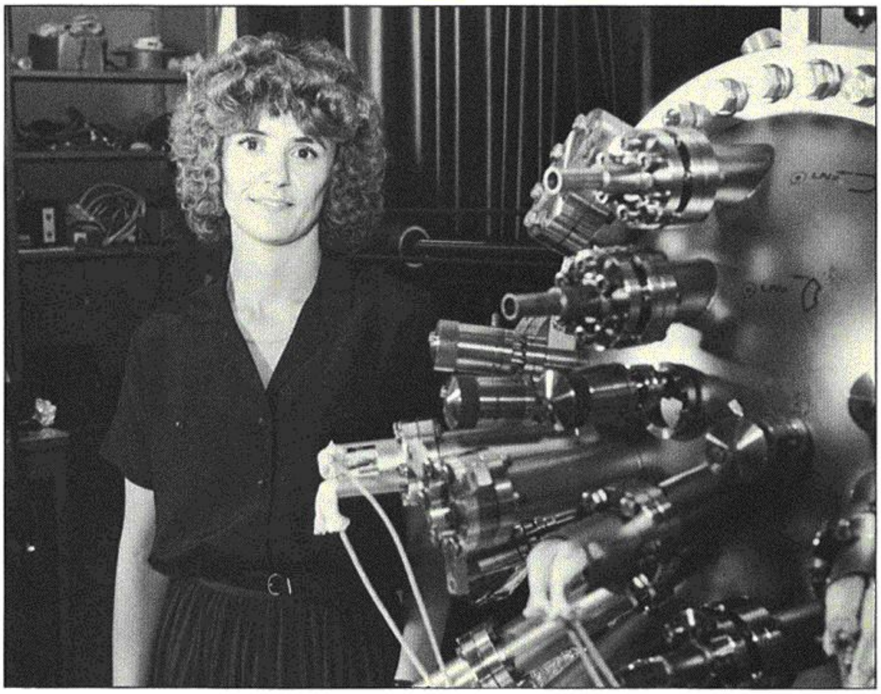
resist, new techniques are being developed. One alternative is high-energy electron beams, because their wavelength is smaller than an atom's diameter. Another technique used to etch extremely small structures on semiconducting chips is x-ray lithography. A number of sources of soft x-rays can be used, including electron bombardment, plasma sources, and synchrotrons. Synchrotrons produce very-short-wavelength x-rays by accelerating charged particles. During acceleration, the particles emit large amounts of electromagnetic radiation, and the resulting radiation can be "tuned" by regulating particle acceleration. High-energy synchrotron x-ray radiation is also an alternative to conventional radiation sources in spectroscopy since its higher radiation intensity is more parallel (or collimated), and extremely precise measurements can be obtained. Synchrotron x-rays can also produce high-resolution x-ray diffraction maps that detail important information on a material's properties and its behavior.

The development of new materials and novel processing technologies rely on a deep theoretical understanding of materials and the development of more powerful analytical tools to study them. Although silicon remains the most industrially important semiconducting material, researchers are considering other options such as cryogenic superconductive integrated circuits, thin films of semiconductors on insulator materials, and substrates created by different materials through molecular-beam epitaxy.

In developing new microelectronic devices, researchers are exploring the benefits of a three-dimensional chip, where the circuit components are stacked in layers instead of solely on the chip's surface. Because most electron transport occurs at the silicon wafer's surface, scientists are attempting to build circuits in layers with conventional deposition techniques, such as vacuum evaporation or chemical-vapor deposition, so that the device will extend above and below the chip's actual surface.



Professor Jesus del Alamo (center) and MIT students Sandeep Bahl (left) and Walid Azzam examine device performance using a semiconductor parameter analyzer. Their experiments measure the characteristics of heterostructure FETs made from indium-gallium-arsenide/indium-aluminum-arsenide semiconductor materials. Professor del Alamo's research involves high-performance semiconductor devices for microwave and optical telecommunications.

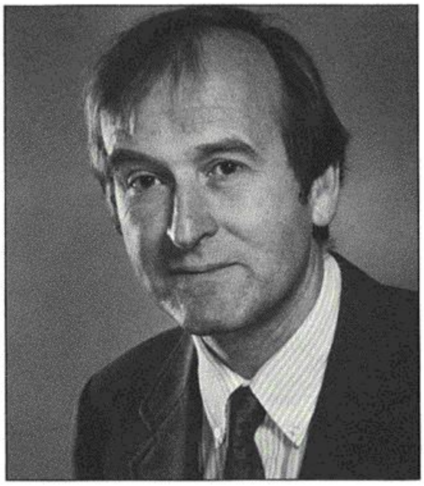


Professor Leslie A. Kolodziejski's research is focused on the fabrication of semiconductor lasers based on II-VI compounds, which contributes to other collaborations in RLE involving quantum-effect devices and special purpose solid-state optical lasers. She uses chemical beam epitaxy to fabricate and characterize II-VI and III-V heterojunctions, the boundaries between two different semiconductor materials. This work furthers understanding of the epitaxial processes involved in using coherent and incoherent light.

FACULTY PROFILE:

Henry I. Smith

From 1968-1980, Henry I. Smith worked on surface-acoustic-wave (SAW) devices and pioneered the development of techniques for fabricating submicron structures at MIT's Lincoln Laboratory. In 1977, he began the process of establishing the Submicron Structures Laboratory at MIT, and joined the faculty full-time in 1980. At present, his research includes nanofabrication, deep-submicron MOSFETs, quantum-effect electronics in sub-100-nanometer structures, crystal films on amorphous and non-lattice-matching substrates, and diffractive elements for x-ray optics and spectroscopy. Professor Smith and his colleagues are responsible for several key innovations and inventions in submicron structure technology and applications: conformable photomask lithography, x-ray lithography, reflective-array SAW devices, interferometric alignment, graphoepitaxy, zone-melting recrystallization, subboundary entrainment, surface-energy-driven grain growth, sub-100-nanometer silicon MOSFETs, and surface superlattice MODFETs in gallium arsenide.



Professor Henry I. Smith

• How did you become interested in surface-acoustic-wave (SAW) devices?

I started working on acoustic-wave devices when I was in the Air Force in the early '60s. These devices used bulk waves, which didn't intersect the surface except when you launched or detected them. During the time I taught at Boston College (1966-68), Dick White at Berkeley invented the surface-wave transducer. That changed the whole field because acoustic devices could then be made in which the wave propagated entirely on the surface. When I came to Lincoln Laboratory in 1968, I was in the microelectronics group, but I interacted with Ernie Stern on SAW devices. Later that year, I joined Stern's group, which was starting a program in surface-wave devices for radar signal processing.

• *Can you describe the transition from your research in SAW devices to developing techniques for submicron structure fabrication?*

In all devices, the pacing element is fabrication. It's easy to go to the blackboard and dream up a new device you'd like to make, or a certain performance level you'd like to achieve. That is *never* the pacing element. What determines whether or not you can do it is if you can fabricate it. I liked to solve problems and get things done, so I gravitated to where the problem was, and that was in microfabrication.

In Ernie Stern's group, I developed fabrication techniques specifically for surface-wave devices. This involved making electrodes with very fine dimensions, and doing it reliably on a variety of substrates. It *had* to be done reliably because, in the early days, we may have had only one piece of some exotic, expensive material that was about ¼-inch wide by ¾-inch long. That was it! We had to do whatever processing was necessary to make a SAW device with the material available. It had to work the first time. In addition, it had to have features beyond state-of-the-art semiconductor device research, and beyond what industrial equipment was able to achieve. So, I developed fabrication techniques specifically suited to high-performance SAW devices. In some cases, they weren't terribly elegant, but they worked.

Later, we got involved in making a type of SAW device called the reflective-array-compressor. This had extremely difficult specifications. It had to work at frequencies above one gigahertz, and that meant electrodes with features below one micron. The electrodes had to be parallel to a very tight tolerance. In addition to I/O electrodes, we had to make a grating in a lithium niobate substrate, where the grating's periodicity varied in a precise way from one end of the device to the other. It was a complicated device, and way beyond what had been done before. So, Dick Williamson and I set out to solve the problems, one at a time. Eventually, we had great success.

In the process of doing those projects, I developed new techniques such as conformable photomask lithography, techniques for ion etching, and some analytical techniques. We also developed an in-house electron-beam lithography capability at Lincoln. This enabled me to do exploratory work in e-beam lithography. Some of this was done with a graduate student, Richard Hawryluk (Ph.D. '74), who investigated electron backscattering effects. During this time, I got the idea for x-ray lithography. It was difficult to juggle all these projects simultaneously, so Dave Spears, who was in another group at Lincoln, came over to help with x-ray lithography development. That came to fruition in 1971. After x-ray lithography and the reflective-array-compressor device became successful, I was able to expand the impact of microfabrication techniques.

In Ernie Stern's group, we didn't have a charter to do research on microfabrication, or SAW propagation for that matter. We were committed to making signal processing devices for radars in the field. So, we didn't have the luxury of time to investigate things thoroughly. You had the feeling that you were hanging on by your fingernails; that tomorrow, things wouldn't work because you didn't understand them thoroughly. I always had an intense desire to investigate questions more deeply. One way to do that was to have graduate students. It was unorthodox at the time, but I always had at least one student working with me. At that time, their salaries were low, so it didn't make much of a dent in the budget, and they didn't detract from the mainline program.

• *How did the Submicron Structures Laboratory get started?*

The major event occurred about 1975. Jay Harris, from the National Science Foundation (NSF), came by to talk about how several areas in engineering and science (electronics, electrooptics, and what was then called integrated optics) were being inhibited because of difficulties in fabricating submicron structures. He talked about establishing a national laboratory dedicated to submicron structures techniques, so that people without facilities could go there to make the devices they wanted. That was the original concept. I was skeptical because it wasn't just a matter of having the right facilities, it was having the know-how. Knowledge is much harder to generate than equipment or central facilities. As a result of Jay's initiative, the NSF held workshops across the country to evaluate the desirability of establishing a national laboratory. Because of those workshops, the lab's proposed theme was shifted to emphasize research on submicron structures as well as the resource concept. In 1976, the NSF circulated a request for proposals to establish a national research and resource facility for submicron structures. I decided to submit a proposal for a center at Lincoln Laboratory. At the time, I didn't have any significant connections with the MIT campus. I received encouragement and help from Al McWhorter, who was head of the Solid-State Division at Lincoln; from people in the director's office at Lincoln; and from Paul Gray who was then MIT's Chancellor.

Proposal writing can be a highly creative activity. That's when I started talking with people on campus. I submitted the proposal, and a site visit followed in April 1977. Later, I found out that our proposal was technically the best. The problem was that we proposed locating the laboratory at Lincoln. Although no one said it in so many words, there was no way that the NSF was going to establish a national laboratory at Lincoln. The NSF urged me to provide an on-campus site for the laboratory, but we couldn't pin down a specific location. Paul Gray assured the NSF that he'd find appropriate space on campus. But, this wasn't enough. Cornell promised to construct a new building for the national lab, and it was awarded to them.

It was probably the best thing that could have happened because it shook up many people at MIT. After the NSF announced the center was going to Cornell, Paul Gray wrote me to say that we should do this anyway. Shortly after that, the director's office at Lincoln asked me to set up a laboratory dedicated to submicron structures there, with money that they'd raise internally. Paul Penfield (then Associate Head of the Electrical Engineering and Computer Science Department) and Peter Wolff (then Director of RLE) asked me if I would consider coming to campus as an adjunct professor and set up a laboratory. Their offer was intriguing. I always enjoyed working with graduate students, and had accomplished a lot through them. I felt that we'd be doing something new by conducting graduate research at the forefront of modern fabrication technology, and that we could pursue novel applications of submicron structures, some of which had come to mind as a result of writing the proposal. The idea of setting up a laboratory not only on campus, but also at Lincoln, specifically devoted to research that we could never do before was attractive. So, I set about to do both.

With help from many people, we established Lincoln's Submicron Technology Program. It was operational by late 1977. And, we did the same thing on campus. John Melngailis, from Lincoln's SAW device group, joined me and came to campus four days a week, while continuing at Lincoln one day a week. During the early days of setting up the laboratory, I was on campus one day a week, and four days a week at Lincoln. That worked well, and we got both laboratories going, and producing exciting results.

In 1980, as both programs were growing quickly, Don Maclellan in the director's office at Lincoln said to me, "You're standing on two chairs, and they're sliding further and further apart. You've got to decide which one you're going to jump onto!" They gave me the option of being full-time either at Lincoln or on campus, but not part-time at both places. I decided to come on campus because that's where my interests really were and because the laboratory at Lincoln was staffed with fully competent people who didn't need me anymore to do their thing. The campus environment gives one much greater freedom. Basically, you can do whatever you can raise the money to do. But, more importantly, it's rewarding to work with graduate students, and the discipline of teaching has an enormous impact on how you approach science and research.

• *Did your submicron structures work stem from previous research at RLE?*

It was new, but there's some interesting history. The very first work in electron beam lithography was done by Dudley Buck at RLE in the late '50s. He died prematurely, and his research also died at MIT. Chuck Crawford, an electrical engineering professor, continued work in charged particle beams and electron optics. But, Chuck didn't do microfabrication, and we never interacted at Lincoln. The submicron work actually started at Lincoln in 1968, and was motivated by the need for SAW devices. Although it was recognized that the technology would someday be important for electronic devices, that was not the driving function.

• *In a recent* Boston Globe *article, you were described as "the father" of x-ray lithography. What has been your role in the technology's development and what suggested the use of x-rays in photolithography?*

I invented a technique called conformable photomask lithography where, using ultraviolet light and evanescent coupling to a photosensitive material, we could get resolution beyond what anybody thought possible. We used that technique to make SAW devices with submicron lines, extreme linewidth control, and what we refer to today as enormous process latitude. I used to brag that we had a 300% exposure latitude at 0.4 micron linewidths,

From left, graduate students William Chu and Anthony Yen, and Professor Smith examine a mask used for x-ray nanolithography. Professor Smith holds a silicon wafer (lower right).

which was an enormous advantage. An individual SAW substrate might cost $1,000, so we couldn't experiment with process parameters; we had to make it work the first time. High yield and process latitude were the driving functions.

One day, I was visited by Iain Mason from University College in London. We discussed conformable photomask lithography, and how far I could push it. After he left, I got the idea to use an x-ray regime phenomenon known as absorption edges. That is, I thought of using a wavelength such that a material whose absorption edge was at a shorter wavelength could be used as a transmitter membrane, and a material whose edge was at a longer wavelength could be used as an absorber. At the time, x-rays were mainly used in medicine and for diffraction analysis of crystal structures. Both use penetrating, short wavelength x-rays. So, I sat down and quickly calculated that the x-ray wavelength one would need for lithography was very different (approximately 10 angstroms). It was a much softer x-ray, because the absorptivity would have to be orders of magnitude higher than in diffraction analysis or medical x-rays.

(There is a semantic problem with x-rays. The same terminology is used for wavelengths ranging from 0.1 to 100 angstroms. But, the absorption of x-rays goes as the third power of the wavelength. So, the behavior between what we call "hard" x-rays and "soft" x-rays can be as different as between microwaves and ultraviolet, for example.)

I calculated the optimal wavelength for x-ray lithography at about 10 angstroms. But, good sources for 10-angstrom x-rays did not exist. In fact, very little work had been done at that wavelength. I figured out what could possibly be used as a mask and what could be used as an absorber. In the first experiment, I used low-energy bremsstrahlung x-rays from a copper target. I experimented with the resist we used for electron-beam lithography and found it was also sensitive to x-rays. I even got a chemist to synthesize a new resist for me that contained mercury, which also worked.

I didn't have much time to devote to the project, but x-ray lithography certainly looked feasible. Dave Spears, who was in a different group at Lincoln, was willing to work on the project. He devoted full-time to the issues involved with the source and the mask. By that time, we knew how to pattern the absorber with an e-beam, but the technology had to be developed to make an x-ray lithography mask. The obvious choices for an absorber were high-density materials with high atomic numbers. Gold seemed like the ideal material, and it still is—gold or tungsten. When Dave came on board, we soon agreed that aluminum was a good source (with an x-ray line at 8.34 angstroms), and we used silicon membranes for the mask material. Although there have been different approaches to x-ray lithography over the years, IBM's multihundred million dollar program at East Fishkill, New York, still uses patterned gold on silicon membranes as masks (which we patented), and wavelengths between 8 and 10 angstroms.

• *Are there advantages in moving from optical to x-ray lithography?*

Yes—process latitude, yield, and linewidth control. In setting up a scanning electron-beam lithography system, I found that we could make whatever patterns we wanted with the electron beam, no matter how fine the linewidth. But, there were disadvantages with the electron beam related to electron scattering and a limited process latitude. Also, the process was extremely slow. I found that it was better to use the electron beam to make a photomask, and then replicate it. If you wanted finer features, it was appropriate to make a mask with the electron beam and then replicate it with x-rays.

One advantage of x-rays is that we can combine many different patterns on one mask, and then expose it all at once. We can make an x-ray mask that combines techniques of electron-beam lithography, photolithography, and holographic lithography. It's similar to combining text from a word processor and photographs from a camera, arranging them on paper, and producing one unified page on a photocopy machine. The electron beam is like a word processor, and the x-ray is like a printing press or photocopy machine.

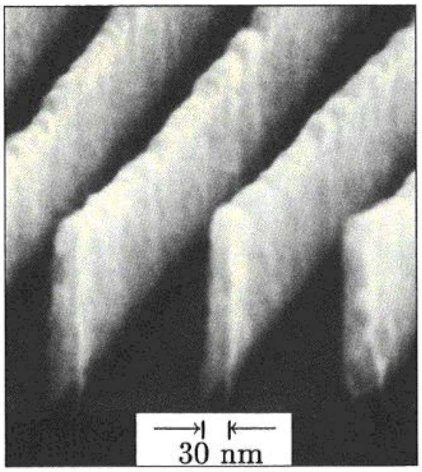
• Is x-ray lithography practical to mass produce memory chips?

We can get fine linewidths with other techniques such as e-beam and even optics. But, x-ray lithography will ultimately be cheaper because one can get fine linewidths together with extremely precise linewidth control and broad process latitude. It also gives a much higher yield because certain defects don't print. For example, in the early days of our research, we observed that dust particles were largely transparent to x-rays, so they didn't print. Our first published paper on x-ray lithography shows a mask with many defects that didn't print.

IBM is pursuing x-ray lithography because it will ultimately be much cheaper. They use a synchrotron, so it tends to be an expensive installation. When completed, the IBM East Fishkill, New York installation will cost several hundred million dollars. IBM and others see x-ray lithography as a way to keep up with foreign competition. In Japan, there are four or five major programs in x-ray lithography, twelve beam lines at Tsukuba, and several companies experimenting internally with synchrotron radiation for x-ray lithography. In this country, there's only one beam line for industrial work—the IBM facility at Brookhaven, New York. Today, in addition to synchrotron-based x-ray lithography, one of the hottest topics is the laser-produced plasma work done at Hampshire Instruments. I consult there, and feel confident that the laser-produced plasmas will enable manufacturers to replace their optical steppers with an x-ray stepper at about the same price, but with much higher yield.

• Can ultraviolet light be used in photolithography?

Most people are betting on ultraviolet light, but, in my opinion, it's wishful thinking. The finest optical projection lithography is being conducted in our laboratory. We have done finer linewidths by optical projection than anyone—1,400-angstrom linewidths. It is certainly possible to produce 1,500- and 2,000-angstrom linewidths by optical projection. But, it's not a *manufacturing* technology. What distinguishes



Scanning electron micrograph of the results of x-ray nanolithography done at MIT. The micrograph shows 300-angstrom (30-nanometer)-wide lines of polymethyl methacrylate (PMMA) exposed and developed on a silicon substrate. Exposure was done by graduate student Anthony Yen, using the carbon K x-ray at 4.5 nanometers.

x-ray from deep-ultraviolet lithography as an approach to commercial integrated circuit production isn't linewidth—it's process latitude.

One thing that makes people shy away from x-ray lithography, particularly managers or planners, is the fact that the mask is a pattern of an absorber on a thin membrane. They're scared that if they poke the membrane, it's going to break. Well, it will break if you poke it! But, for their thickness, membranes *are* extremely strong. If you were to analyze what makes a material strong, and look at the radius of curvature that a material can sustain, you'd find that things get stronger as they get thinner. For example, if you bend glass, it breaks. But, if glass is formed into a very fine fiber, you can wrap it up like fishing line. As a material gets thinner, it can sustain a smaller radius of curvature; it can bend without breaking. The best example is fiberglass, and the same is true for a membrane.

Recently, it occurred to me that nature should have discovered this by evolution. So, I decided to see if this was the case. A dragonfly made the mistake of landing near me, and devoted his wings to science. We looked at the dragonfly's wings in an electron microscope. Their thickness is about the same as that of an x-ray mask (about 2 microns). The wing's membrane must be able to fold when not flying, and go through metamorphosis, rainstorms, and predator pursuit. So it's pretty strong. The intuition that membranes are terrible to work with is understandable, but, there is no problem in developing an engineering technology so we can handle these membranes.

• Are you excited about a current project?

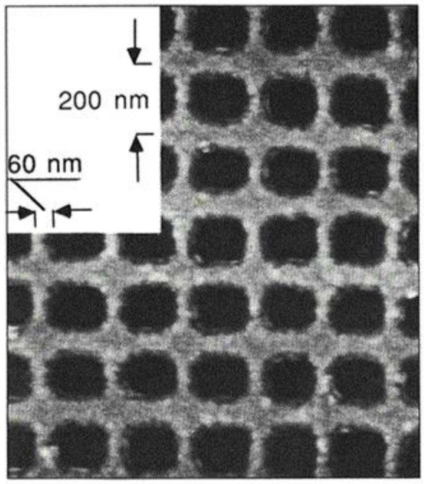
The most exciting things we're doing these days are in the areas of quantum-effect electronics and very-short-channel MOSFET devices. In the latter, we've led the way by showing that ordinary MOS transistors can be made with channel lengths below 1,000 angstroms. We've demonstrated that the effective electron velocity can be much higher than the bulk saturation velocity (we call this velocity overshoot). We also found that short-channel devices have reduced hot-electron effects, which could have an important impact on how small transistors will be scaled. We are interested in making very small devices and studying their *physics*. We aren't simply trying to break a switching speed record. That might be interesting to do, but it's not our focus. (When I say "we," I mean the graduate students who've done the work, Professor Dimitri Antoniadis, and myself.) I see our role as exploring the impact of deep-submicron and nanometer technology on transistor devices. So, we have made devices, demonstrated velocity overshoot in them, determined some of the problems, and confirmed that there is a reduction in hot-electron effects. But, we can't do everything. Now, IBM has picked up this thrust and is making very short-channel devices, confirming our velocity overshoot measurements, and getting a lot of mileage out of making circuits that way.

Another area that we're currently researching will almost certainly have a major impact beyond the transistor age. This is the investigation of quantum-effect electronics as a potential replacement for transistor-based electronics. Even though we can make sub-1,000-angstrom transistors, that approach to electronics is likely to run out of gas in the foreseeable future. The nice aspect about quantum-effect electronics is the highly interdisciplinary work. It involves close interaction with Professors Dimitri Antoniadis, Terry Orlando, Clif Fonstad, and Jesus del Alamo in the Electrical Engineering and Computer Science Department; Professors Marc Kastner and Patrick Lee in the Physics Department; and people at MIT's Francis Bitter National Magnet Laboratory. It also addresses basic issues of condensed-matter physics. Some recent theories developed by Professor Patrick Lee on electron transport are being tested in the devices we make. We don't know how to use quantum-effect electronics in systems yet, but we are scratching the surface by looking at how they behave.

• *What is the progress of your research in quantum-effect electronics?*

We are at a "fun" stage where we are making devices that involve extremely high technology. This is done for, what I call, "academic fun and games." When we make quantum-effect devices, we're usually looking for a particular effect. Then, we make measurements in the devices to see what happens. We always see something unexpected. It's an area of research that couldn't be more exciting. So, we're finding many surprises about quantum effects in condensed-matter structures and devices. We're not alone in doing this. There are many quantum-effect programs around the world because many people see quantum-effect electronics eventually replacing transistor-based electronics. Our unique approaches, especially in x-ray nanolithography, give us some special advantages.

A big question is how are we going to make useful systems. It's exciting to see quantum effects, but what can they do for computation? I think that quantum-effect electronics will play a major role in future computer systems, but these systems will look very different from today's. Beyond that statement, I don't know what I'm talking about. Right now, all we can do is make vague "motherhood" statements and say that a neuron works by communicating between localized patches on a cell membrane surface, and acknowledge that we can do useful computation by



An electron micrograph of a 2,000-angstrom-period (600-angstrom linewidth) metal grid on a AlGaAs/GaAs substrate. The grid modulates the potential seen by a two-dimensional electron gas at the AlGaAs-GaAs interface. As a result, the wave nature of electron transport is manifested in backdiffraction and negative differential transconductance, a quantum-mechanical effect observed for the first time at MIT.

The "Holy Grail," if you will, is to get very strong quantum effects at temperatures such as 77 degrees Kelvin. This means that we need an engineering technology able to fabricate structures reliably and with precise control at dimensions below 500 angstroms. That's the challenge!

means other than those used in conventional computers (which are built as a collection of interconnected switches, where each switch is a transistor). People have proposed doing computation where one cell communicates only with its nearest neighbors. Although I am beyond my field in saying this, we probably will not build a switch-based computer with quantum-effect electronics. There are alternative ways to do it.

• *What are the limits to quantum-effect-electronics technology?*

As in the early days of surface-wave devices, the pacing element is still fabrication. That's the thing that will always slow you down. Today, quantum-effect electronics is complicated by the fact that not only do we need good two-dimensional patterning, etching, and deposition techniques, but the substrate materials are also more challenging. We are generally talking about III-V compound semiconductor materials made in a multilayer configuration. That involves molecular beam epitaxy. Progress in this area requires the high-level expertise of people like Professors Clif Fonstad and Jesus del Alamo, and new faculty member Leslie Kolodziejski. They and their students must be at the forefront of making the high-mobility, low-effective-mass materials which are the building blocks for quantum-effect electronics. Quantum-effect electronics combines the best of molecular beam epitaxy and nanofabrication technologies.

In quantum-effect electronics, we're really talking about *nano*fabrication because we use the fact that when electrons are confined to a small enough space, they behave as waves. There's a trade-off between temperature and dimensions. The finer the dimensions we can make, the higher the temperature at which we can observe quantum effects. The "Holy Grail," if you will, is to get very strong quantum effects at temperatures such as 77 degrees Kelvin. This means that we need an engineering technology able to fabricate structures reliably and with precise control at dimensions below 500 angstroms. That's the challenge!

• *I understand that you have "customers" at RLE for your very fine and precise gratings.*

Peter Wolff's vision and insight as to the importance of bringing submicron structures technology to campus is exemplified perfectly in an interaction that we had recently with Professor David Pritchard and his student David Keith. They were investigating atomic interferometers that utilize atom diffraction off of standing-light waves, and considered doing it with physical gratings. They came to see us about building a reflection grating. Mark Schattenburg of the Center for Space Research, who works in the Submicron Structures Lab on the development of diffraction gratings for x-ray astronomy, suggested that the same gratings used for x-ray astronomy could be used in an atom interferometer. They installed a grating and it worked! This was an amazing experiment because it demonstrated that quantum mechanics really does work for large compound particles like atoms. The things we study in textbooks about quantum mechanics (for example, the particle's wave function goes through all the slits simultaneously) were demonstrated nicely in this experiment. It was fun to become involved in a peripheral way with Dave Pritchard's interferometer. It was a nice application of nanotechnology, and we're excited when this happens.

The Submicron Lab isn't a super machine shop where a user writes up a work order and we try to meet his needs. We see ourselves as collaborators, because the development of a structure needed by a researcher is a highly interactive thing. Dave Pritchard's case is a good example. What he *thought* he wanted for a grating was not what was needed. He had an idea of what he wanted, and asked if we could make it. At first, it sounded like a major project. But, it turned out what we had already developed was more appropriate—a transmission grating rather than a reflection grating. So, you really must interact in order to come up with the best solution.

• *Are you working to build monocrystalline silicon in order to make your own substrates?*

Not exactly. I think you are referring to materials work in collaboration with Professor Carl Thompson. The idea is to explore new ways of producing useful crystalline films. Graphoepitaxy is an example of this. A few years ago, we demonstrated that if we put a very fine grating in a surface, we could influence how crystals grew on that surface. In fact, Dale Flanders, Mike Geis, and I achieved oriented crystal growth on an amorphous substrate, which was unheard of at the time. The graphoepitaxy effect, if viewed more broadly, means that a crystal's external geometry affects its orientation. In other words, the surface energy is affected by the external geometry, and surface energy can make one orientation more favorable than another.

For several years, Carl and I have been looking at surface-energy-driven grain growth. By taking extremely thin films (about 100 angstroms thick, so that a large percentage of the atoms [approximately 2%] is right at the top or bottom surfaces), and manipulating the surface, we can alter surface energy. If we put appropriate indentations in a planar surface, we can modify surface energy. That can influence phenomena like grain growth. Both energetics and kinetics must be taken into account. We are currently working on an extension of the graphoepitaxy effect, which I'm very excited about. It's so far out that I haven't written a proposal yet because no sponsor would touch it until it works.

> If we look at the problems that Michelson had, quite often they were mechanical problems that most people wouldn't have had the patience to solve. Or, they considered the problem to be beneath their dignity. If you take that approach, you miss a lot of opportunities.

Carl and I also worked on zone-melting recrystallization. By taking polycrystalline materials (like silicon) on an amorphous substrate, melting them, and then freezing them in a controlled way, we got the orientations we wanted. This was a collaboration with Mike Geis at Lincoln. It didn't always involve submicron structures, but it frequently involved surface patterning. We found that we could pattern the surface to influence the freezing process.

• *What is needed for further progress in submicron structures and microelectronics?*

What is really needed are young faculty members willing to work in this area. Additional facilities are also needed for molecular beam epitaxy. This is a very crucial need since two new faculty members, del Alamo and Kolodziejski, don't have this equipment. In addition, we don't have an electron-beam lithography system. For now, we've decided not to have one because it's a large capital investment, and we can use other facilities to make x-ray masks. Eventually, we will need our own e-beam capabilities. But, more than anything else, we need young top-quality people working in this area.

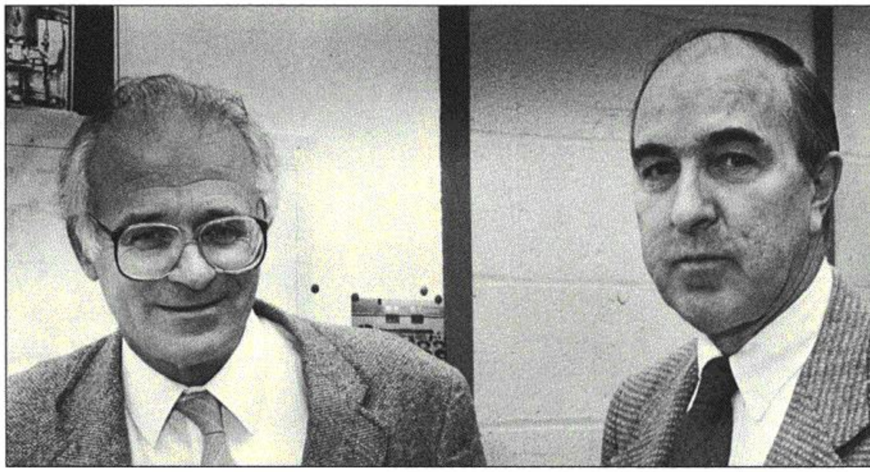
• *Do you have advice for someone contemplating a career in submicron technology?*

Come and do a postdoc here! We will always attract the best students because this is where the action is. Most of our work is done by students working long hours in the lab. It's not done on a blackboard. But, we need to invent new ways to do graduate research. For example, most graduate students are jointly supervised because no single professor has enough expertise to advise on all aspects of the problem. In fact, most students don't have enough time in the normal Ph.D. program to learn everything needed to successfully pursue quantum-effect research. That's why we frequently have two students working together on one project. They tend to develop specialties where one student, for example, might do all the molecular beam epitaxy, and the other student will do other parts of the task. If we take two students and define a project, they tend to quickly settle into what they prefer to do. A great misunderstanding of academic research in the "outside" world is that a professor can tell a student what to do. My experience is that you can't do that. You have to find out what the student likes to do, and go with that. If you tell a student to do something he or she doesn't want to do, it won't get done.

• *One of your colleagues described you as an "unabashed technologist." How would you like to be remembered?*

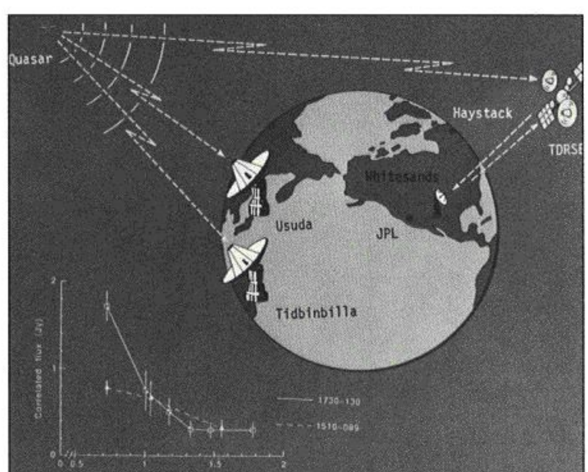
I would say it another way. I'd like to be remembered as someone who respected technology, because technology is the route to success. But, I'd like to think that my interests didn't end with technology *per se*. I think that some people in the history of science were successful because they focused on the pacing element, or the limiting thing. If it happened to be the technology, they went ahead and did it. I could cite Albert Michelson. He attacked the technology of precise measurement and invented the Michelson interferometer. You could call him an unabashed technologist, if you like. But, I see Michelson as someone who vigorously attacked the problem at hand. When he started his work, no one could have predicted that Michelson's instruments would lead to the Michelson-Morley experiment. Although that wasn't what caused Einstein to create the theory of relativity, it was certainly *the* crucial experiment that laid the foundation for relativity. I'm not trying to put submicron structures in the same category, but here is an example of what was being pursued was clearly a technology. The *physics* of interferometers was well understood, but the *technology* was pursued because that was the problem at hand. The impact of developing interferometer technology has been *enormous* in astronomy, optics, and nearly all other areas of science.

I'd like to be remembered as someone who respected technology and solved the problem at hand. When I say respect for technology, I mean that some of the problems we have to solve are very nitty-gritty: how do you make material A stick to surface B? These are nasty little problems. If we look at the problems that Michelson had, quite often they were mechanical problems that most people wouldn't have had the patience to solve. Or, they considered the problem to be beneath their dignity. If you take that approach, you miss a lot of opportunities. Respecting technology involves not taking the attitude that a particular problem is something you can pass on to someone else, or that it's beneath your dignity to solve. If it's a problem, you've got to solve it. Then, it eventually pays dividends.



Dr. Bernard F. Burke, William A. M. Burden Professor of Astrophysics in the Department of Physics (left), and RLE Sponsored Research Staff ***John W. Barrett*** have received the NASA Group Achievement Award for extending very-long-baseline interferometry techniques into space applications. Their work was cited for expert planning and execution of the Tracking and Data Relay Satellite (TDRS) Very Long Baseline Interferometer (VLBI) demonstrations in 1986 and 1987. These demonstrations produced the world's first astronomical space-ground VLBI observations, and proved the technologies for future space-VLBI missions. The VLBI technique, which allows construction of radio antennas as large as earth, involves the use of separate radio telescopes synchronized in phase to record signals on magnetic tape for computer processing.

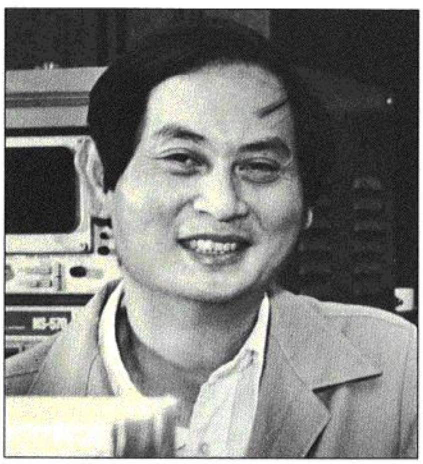
Originally, the TDRS system was not intended for use as an astronomical telescope, since it was built to relay signals from satellites. In the new application, the TDRS is pointed at various quasars, with precise frequency control and recording at White Sands, New Mexico. Other radio telescopes, in Japan and Australia, simultaneously observe the quasars. These Far East stations are necessary because the TDRS station is in geosynchronous orbit over the Atlantic Ocean. In the late 1960s, RLE's Radio Astronomy Group pioneered VLBI developments and demonstrated the existence in space of compact, very intense natural masers less than 0.01 of an arcsecond in angular size. The Rumford Prize recognized this work in 1971. Today, the new VLBI applications permit construction of a radio telescope effectively larger than twice the earth's diameter.



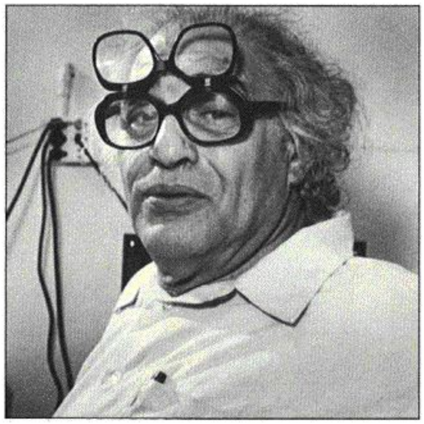
Schematic illustration of the TDRS VLBI experiment.

circuit breakers

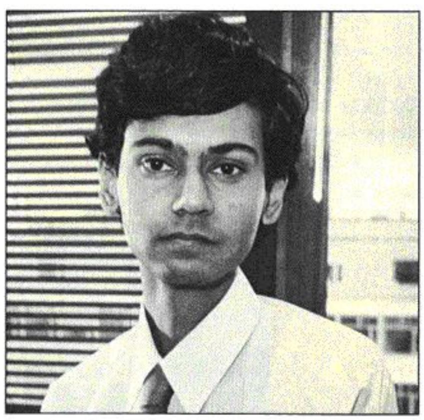
Dr. A. Nihat Berker, Professor of Physics, was named recipient of the highest scientific honor awarded by the Turkish government. The TUBITAK Science Award is given annually by the Turkish Scientific and Technical Research Foundation, and encompasses all fields of science and engineering. Professor Berker's award cited his important scientific contributions, at an international level, in the fields of solid-state and statistical physics.



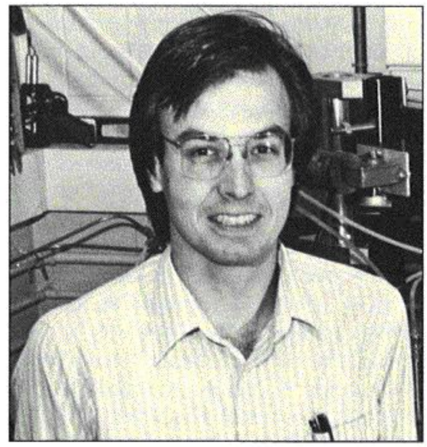
Dr. Sow-Hsin Chen, Professor of Nuclear Engineering, has received the Alexander Von Humboldt U. S. Senior Scientist Award for outstanding contributions in the investigation of interfacial and aggregational phenomena in amphiphile/water/oil systems using small-angle neutron scattering and photon correlation spectroscopy. Professor Chen spent six months visiting physics departments at several West German academic institutions in connection with this award.



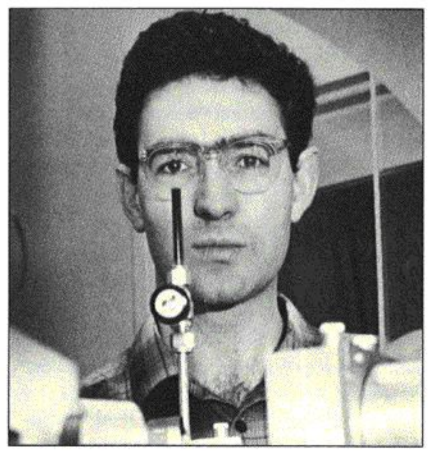
Dr. Jerome Y. Lettvin, Professor of Biology, has retired from the Institute and has assumed a faculty position at Rutgers University. Professor Lettvin has been associated with RLE since 1951. Since that time, he and his colleagues have carried out distinguished research on the bioelectrical processes involved in cognition and sensory perception in living systems. He is widely recognized for his excellent work on vision and pattern recognition published in the 1959 landmark paper, "What the Frog's Eye Tells the Frog's Brain." Professor Lettvin will be maintaining an affiliation with RLE.



Dr. Srinivas Devadas, Assistant Professor of Electrical Engineering and Computer Science, has joined RLE from the University of California at Berkeley, where he recently completed his Ph.D. in high-level CAD synthesis and testing. He has made significant contributions to datapath synthesis and logic synthesis and verification. Currently in RLE's Circuits and Systems Group, he is investigating synthesis from logic to the gate level.

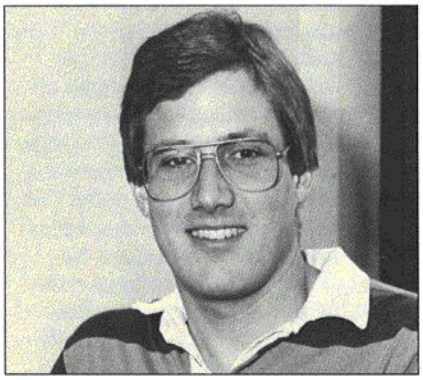


Dr. John M. Graybeal, Assistant Professor in Physics, has joined RLE's Surfaces and Interfaces Group. His research focuses on low-temperature condensed matter physics, and emphasizes superconductivity and novel artificial material structures. His investigations also include the consequences of disorder on superconductivity, the physics of low-dimensional systems, and superconducting vortex motion.



Dr. Simon G. J. Mochrie ('84 Ph.D.), Assistant Professor of Physics, has joined RLE's Surfaces and Interfaces Group. His research involves the stability of both metal and semiconductor surfaces. Before coming to MIT in 1987, he initiated a research program in the structure and stability of clean metal surfaces at AT&T Bell Laboratories. This research has led to a greater understanding of the microscopic structure of Au (100) reconstruction, and the discovery of two new phase transitions (rotational and two-dimensional melting) on that surface.

Dr. Carol Y. Espy-Wilson has been appointed Research Associate in RLE's Speech Communication Group. Working with Professor Kenneth A. Stevens, she was previously a postdoctoral fellow conducting research in feature-based word recognition systems. Dr. Espy-Wilson developed a perceptual experiment using synthetic speech to better understand the primary and secondary features needed to distinguish acoustically similar sounds. She received her B.S.E.E. from Stanford University in 1979, and S.M. ('81) and Ph.D. ('88) from MIT. *(Photo by Mark Wilson)*

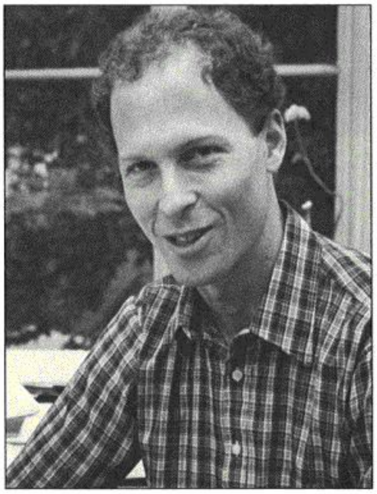


Dr. James R. Glass was appointed Research Scientist in RLE's Speech Communication Group. Since 1985, he has worked with Dr. Victor W. Zue in the area of man-machine communication, and developed the LAMINAR and APACHIE softwares for LISP machine workstations. LAMINAR is an interactive facility used to synthesize speech from different vocal-tract configurations. APACHIE, also an interactive facility, is used to perform acoustic-phonetic analysis of speech. Dr. Glass received his S.B. in 1982 from Carleton University, and S.M. ('85) and Ph.D. ('88) from MIT.

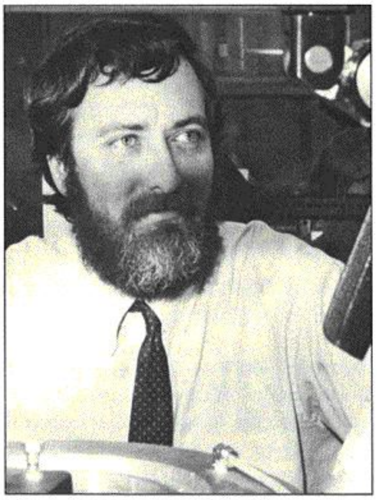
TENURE GRANTED

Congratulations to three faculty members at RLE who were granted tenure, effective July 1988:

Dr. Sylvia T. Ceyer, Class of 1943 Career Development Associate Professor of Chemistry. B.A. ('74) Hope College and Ph.D. ('79) University of California at Berkeley. Before joining the MIT faculty in 1981, Professor Ceyer was a postdoctoral fellow at the National Bureau of Standards. She has received the 1981 Dreyfus Award, the 1987 Harold E. Edgerton Award, the 1988 Baker Award, and the 1988 Young Scholar Award from the AAUW Educational Foundation. She also holds an Arthur P. Sloan Foundation Fellowship and a Camille and Henry Dreyfus Teacher-Scholar grant.

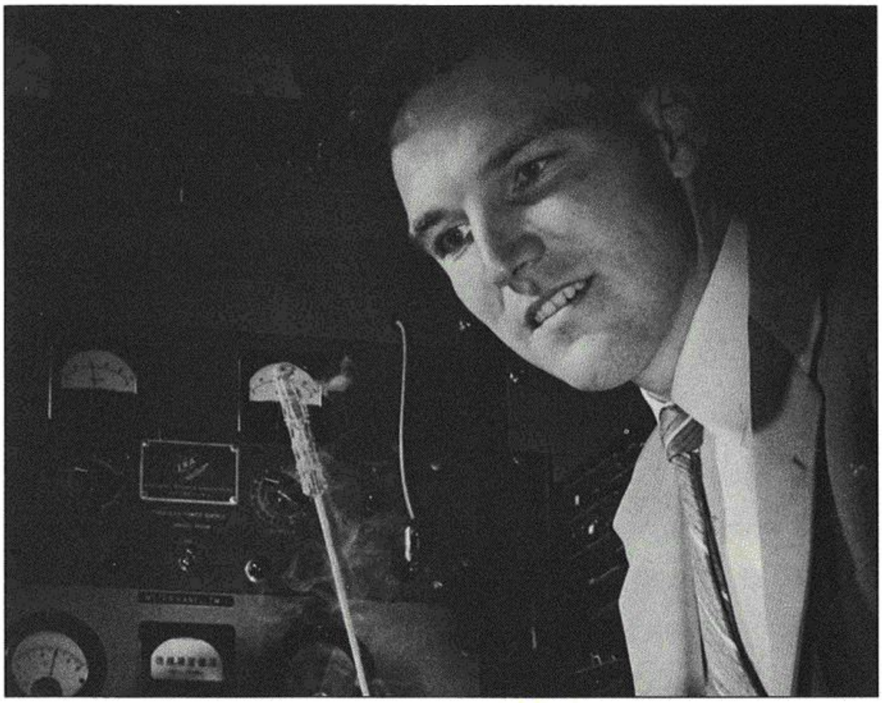


Dr. Keith A. Nelson, Associate Professor of Chemistry. B.S. ('76) and Ph.D. ('81) Stanford University. Professor Nelson came to MIT in 1982 after a postdoctoral fellowship at UCLA. In 1985, he was selected as a National Science Foundation Presidential Young Investigator, and was awarded an Alfred P. Sloan Fellowship in 1987. He recently received the 1988 Coblentz Award for outstanding work in spectroscopy.



Dr. Carl V. Thompson, Associate Professor of Electronic Materials in the Department of Materials Science and Engineering. S.B. ('76) MIT, and S.M. ('77) and Ph.D. ('82) Harvard University. Professor Thompson came to MIT in 1982 as an IBM postdoctoral fellow in RLE. In 1983, he became an Assistant Professor, and was Mitsui Assistant Professor from 1985-87. He is widely known for his fundamental research in thin-film processing and the control of thin-film microstructures for electronic devices.

BACK TO THE FUTURE:
Professor Dudley A. Buck (1927-1959)



"Dudley Buck was one of the most imaginative persons to do research in RLE. His work on computer elements and photolithography was years ahead of the times . . ."

—MIT President Emeritus Jerome B. Wiesner

"The day is rapidly drawing near when digital computers will no longer be made by assembling thousands of individually manufactured parts into plug-in assemblies and then completing their interconnection with back-panel wiring. An alternative to this method is one in which an entire computer or a large part of a computer is made in a single process. Vacuum deposition of electrodes onto blocks of pure silicon or germanium and the subsequent diffusion of the electrode material into the block to form junctions is a most promising method. The successful development of this method would allow large numbers of transistors and all their interconnecting wiring to be made in one operation. Vacuum deposition of magnetic materials and conductors to form coincident-current magnetic-core memory planes is a second promising method that will allow an entire memory to be made in one operation. The vacuum deposition of superconductive switching and memory circuits is a third method that will make possible the printing of an entire computer. The authors feel sure that the most significant milestone in computer component technology will be the announcement by one or more firms, in perhaps 2 years, that all of the technical problems of building a printed system have been solved, and that one of their engineers with his vacuum system can make a digital computer in an hour. . . ."

"An Approach to Microminiature Printed Systems" by Dudley A. Buck and Kenneth R. Shoulders, *Proceedings of the Eastern Joint Computer Conference.*

In December 1958, Dudley Buck presented the above paper outlining a scheme to form a thin film upon which would be placed a resist by electron-beam polymerization of siloxane vapors. Then, a selective removal process would be carried out by means of a gaseous etchant that would leave the desired superconductor as an element in cryotron fabrication. From the time of this paper until his death, Dudley Buck worked on various aspects of vapor deposition of refractory metals as good superconductive films, in the first step of a lithographic technique.

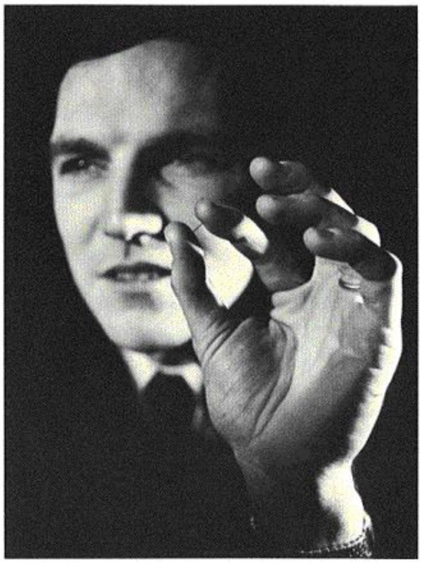
Born in San Francisco in 1927, Dudley A. Buck received his B.S. degree in electrical engineering at the University of Washington in 1948, and spent two years as a communications officer with the U.S. Navy. He entered MIT in 1950, and served as a research assistant on the Servomechanisms Laboratory's Project Whirlwind while working towards his master's degree, which he received in 1952. He served as an Instructor in the Department of Electrical Engineering until 1958, when he received his Sc.D. and was appointed Assistant Professor. He was also associated with both RLE and Lincoln Laboratory.

During his nine years at MIT, Professor Buck made outstanding contributions to the field of low-temperature physics. He was most recognized for the development of the cryotron, a superconductive, magnetically controlled gating device that was hailed as a revolutionary component for miniaturizing the room-sized computers of the '50s. A technical paper, "The Cryotron—A Superconductive Computer Compound," was recognized with the Browder J. Thompson Memorial Prize of the Institute of Radio Engineers in 1957, an award that was made to a scientist under 30 years of age who presented the year's most outstanding paper. Dudley Buck also won an honorable mention in Eta Kappa Nu's selection of the Outstanding Young Electrical Engineer of 1958. During his last two years, he sought to carry miniaturization even further by attempting to make cross-film cryotrons with dimensions only a few millionths of an inch.

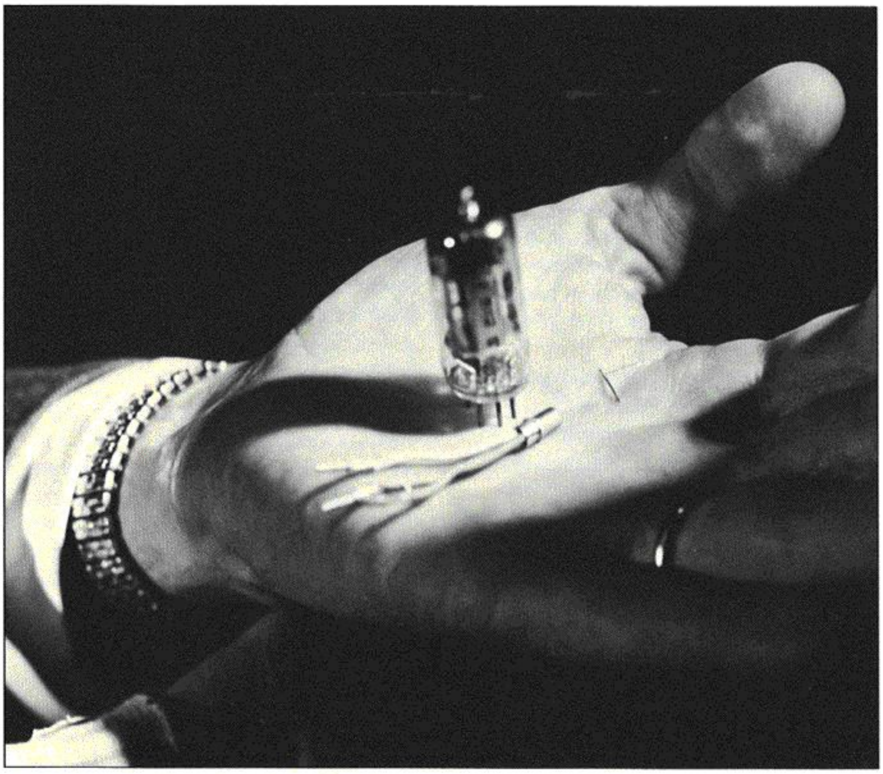
While his professional accomplishments were many and varied, his loyalty to MIT and the thoroughness of his teaching were equally outstanding. In addition to his research, he represented the MIT Admissions Office on high school visits, and exhibited what one colleague called "a contagious quality of optimism, enthusiasm, and just plain joy about each man's work." Because of his strong convictions about the importance of education, and his deep interest in youth, he was elected chairman of the Wilmington School Committee. He was also a former scoutmaster and a lay speaker in the Wilmington Methodist Church.

Dudley Buck's dedication and creativity were sources of admiration to his students and colleagues. Before his untimely death in 1959, he possessed all the attributes of greatness and had already achieved much in a short time.

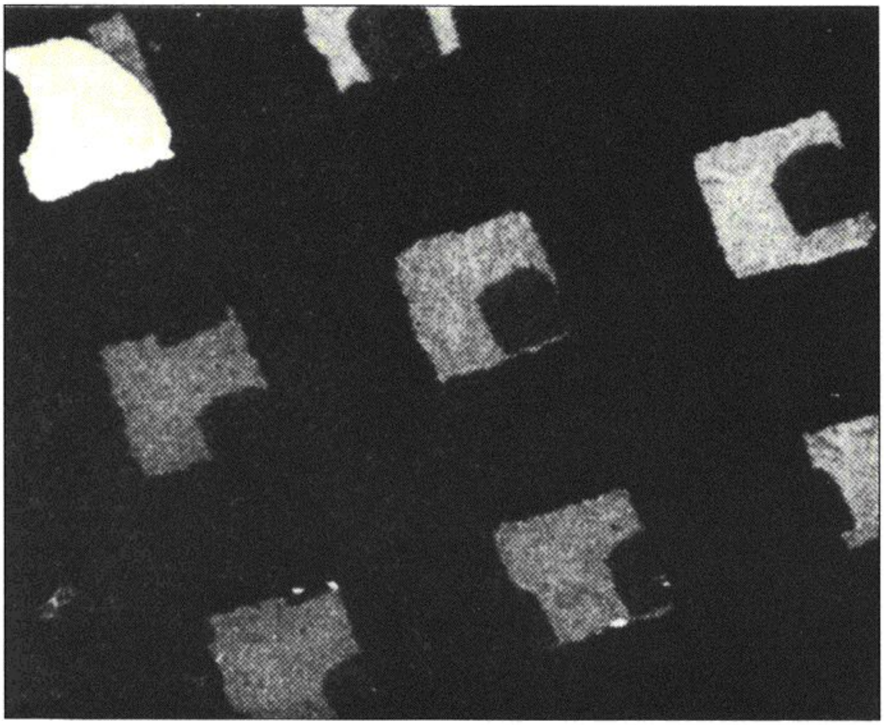
Above the vapors of liquid helium, Dudley Buck compares a fragile, bulky vacuum tube with his cryotron. (Photo Gjon Mili)



The cryotron was man's first practical use of superconductivity—the ability of some metals to conduct current with no resistance at extremely low temperatures (below −420 degrees Fahrenheit). In the hand of its inventor, is the incredibly small cryotron (100 will fit into a thimble). Its operation was based on the effects of magnetic fields on superconductivity at liquid helium temperatures.



First came the vacuum tube, then the transistor. The cryotron was destined to spark another revolution in electronics.



Electron micrograph of a molybdenum film etched into 0.001-inch squares shows Dudley Buck's proposed process to produce etched wiring on a 0.1-micron scale involving the selective removal of a thin film. It differed from conventional systems of the day since the process was carried out in a vacuum system, and electrons or ions replaced light as a means to control the deposition of the resist.

(Photos courtesy of MIT Historical Collections)

UPDATE: RLE Collegium

Collegium Membership

The RLE Collegium was established in 1987 to promote innovative relationships between the Laboratory and business organizations. The goal of RLE's Collegium is to increase communication between RLE researchers and industrial professionals in electronics and related fields.

Collegium members have the opportunity to develop close affiliations with the Laboratory's research staff, and can quickly access emerging results and scientific directions. Collegium benefits include access to a wide range of publications, educational video programs, RLE patent disclosures, seminars, laboratory visits, and an on-line calendar of events.

The RLE Collegium membership fee is $20,000 annually. Members of MIT's Industrial Liaison Program can elect to transfer 25% of their ILP membership fee to the RLE Collegium. After an initial one-year membership, a three-year commitment will be required. Membership benefits are supported by the Collegium fee. In addition, these funds will encourage new research initiatives and build new laboratory facilities within RLE.

For more information on the RLE Collegium, please contact RLE Headquarters or the Industrial Liaison Program at MIT.

UPDATE: Communications

Publications

The following new publications are available:

• The 316-page *Progress Report No. 130* reports research results from all RLE research groups during 1987 and includes an extensive bibliography, index of research project staff, and an RLE personnel roster.

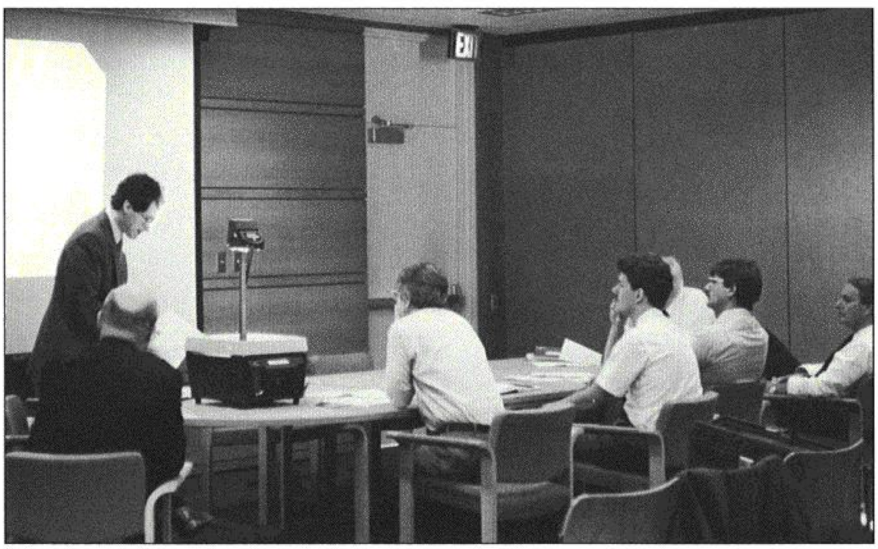
• A companion publication, the *RLE Publications Update*, lists abstracts of reports published by RLE from January 1987 through June 1988. Reports are listed by subject area: general interest, circuits and systems, digital signal processing, image processing, materials and fabrication, optics and devices, physics of thermonuclear plasmas, and speech communication. An author index is also included.

Videotapes

RLE, in cooperation with MIT's Center for Advanced Engineering Study and the Industrial Liaison Program, has videotaped research presentations from two symposia, *Speech Communication and Processing* (December 1987), and *Future Directions in Electronics: 40th Anniversary Symposium of RLE* (October 1986). These color videotapes can be purchased or rented. For further information, please contact Carolyn B. Jones, MIT Center for Advanced Engineering Study, Room 9-234, Cambridge, MA 02139 (617) 253-7444.

The RLE Communications group welcomes inquiries regarding RLE research and publications.

Contact:
Barbara Passero
Communications Officer
Research Laboratory of Electronics
Room 36-412
Massachusetts Institute of Technology
Cambridge, MA 02139
(617) 253-2566



Professor Jacob White (standing) presents his research on custom integrated circuits and computer-aided design to RLE Collegium members from Pitney Bowes during a recent on-campus briefing. (Photo by Dorothy A. Fleischer)

RLE *currents*

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John F. Cook . . . . Photography

Everett Design . . . . Design

Dorothy A. Fleischer . . . . Staff Writer and Editor

Barbara J. Passero . . . . Production and Circulation

Donna Maria Ticchi. . . . . Managing Editor

Henry J. Zimmermann . . . . Advice and Perspective

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