ENGINEERING

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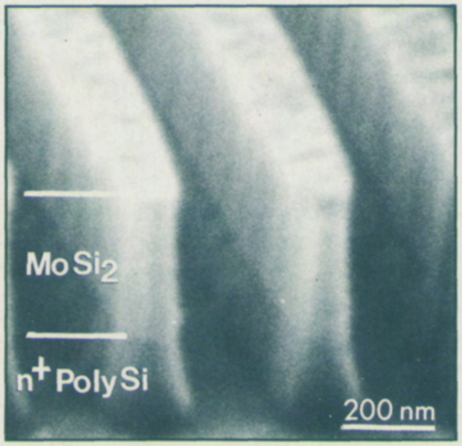
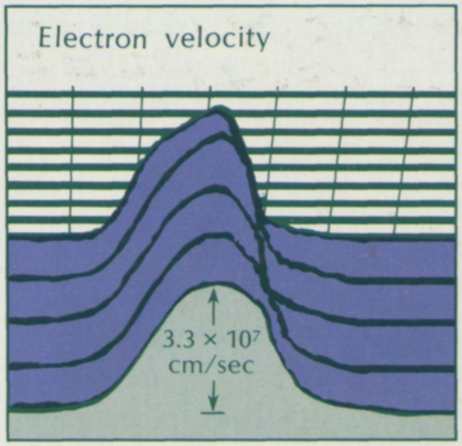
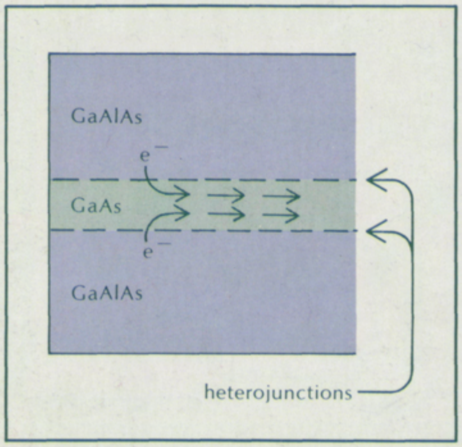
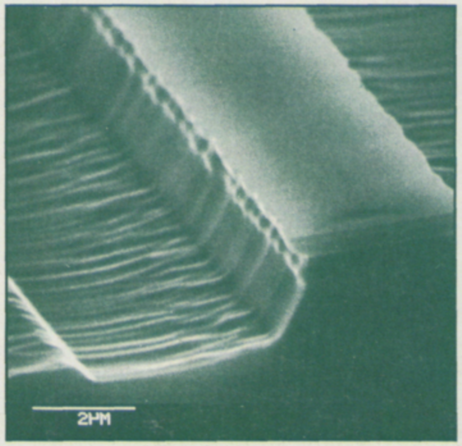


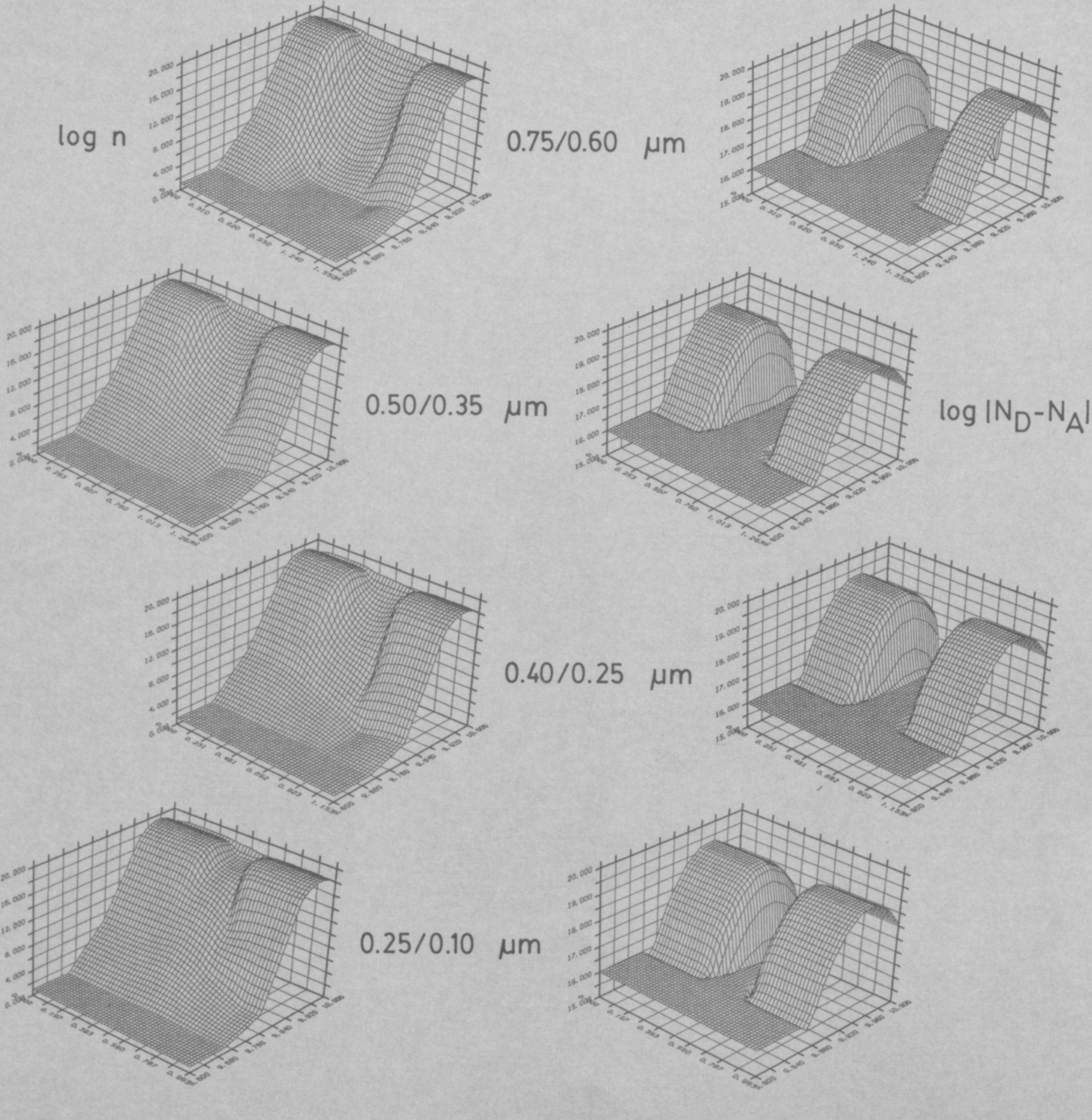






VOLUME 18
NUMBER 3
WINTER 1983-84

$<\mu$: KEY TO IMPORTANT NEW TECHNOLOGIES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IN THIS ISSUE

NOTE ON THIS ISSUE

This is the second part of a two-part series centered on the National Research and Resource Facility for Submicron Structures (NRRFSS) at Cornell University. The Autumn 1983 issue was titled, "Discovery in the Submicron Domain."

Outside cover, clockwise from upper left: Multilayer structure for an MOS device; plot illustrating computer simulation of electron velocity in a fast GaAs device; micrograph of a Josephson edge junction; micrograph of a chemically etched rib waveguide; illustration of electron movement in a quantum well.

Opposite: Scaling study of an n-channel MOS transistor as obtained at Cornell by J. Scarpulla and J. P. Krusius via two-dimensional computer simulation. The series of three-dimensional logarithmic plots represent results for doping density ($N_D - N_A$) on the right-hand side, and for electron density (n) on the left. The dimensions given for each pair are the drawn and the actual metallurgical gate lengths.








Engineering: Cornell Quarterly
(ISSN 0013-7871)
Vol. 18, No. 3, Winter 1983-84
Published four times a year, in summer, autumn, winter, and spring, by the College of Engineering, Cornell University, Campus Road, Ithaca, New York 14853. Second-class postage paid at Ithaca, New York, and additional offices. Subscription rate: $6.00 per year; $9.00 per year outside the United States.

COMMENTARY

Submicron Structures: A Microcosm of Modern Engineering

by Thomas E. Everhart

We live in a rapidly changing world, a world of technology, a world of information. We see dramatic changes in a lifetime. A person eighty years old was born during the infancy of the automobile, around the time of the first flight of a heavier-than-air machine; long-distance communication via telegraph and telephone had been demonstrated, but electronic amplification was still in the future. An eighty-year-old person has lived through the invention of the vacuum triode for signal amplification, the introduction of a host of other vacuum tubes, the invention of the transistor, its evolution into the integrated circuit, and the development of our present very-large-scale integrated (VLSI) circuits. Information modulation has proceeded from audio rates of a few kilohertz to rates of a few gigahertz in operating computers and to much higher frequencies in specialized apparatus.

With such rapid changes, what is constant? What are the fundamentals we should teach engineering students, that will stand them in good stead as they practice their profession? Furthermore, what are research topics that will have impact on the world of the future, that a professor may advise a doctoral student to investigate, reasonably confident that the knowledge learned will be important five to ten years hence, and will form a solid background for future advances?

To answer such questions, it is useful to explore how similar ones were posed and answered ten or twenty years ago. Then the fundamentals of mathematics and science—physics, chemistry, some biology—were the foundations upon which engineering research and design were based. This is no less true today. We use more sophisticated tools to achieve our goals more quickly and more accurately, but the understanding of a problem and its statement, and the judgment as to whether the solution is reasonable, depend on a scientific and engineering knowledge built on the same fundamental foundations. What makes the current scene different is that edifices built on these foundations change more rapidly over an individual's lifetime.

We cannot (and do not want to) prevent this change. As educators, what we hope is that we can provide solid foundations that will serve for any of the new edifices. As engineers, applying science to the needs of society, we also need to understand humans, both collectively and individually—to understand human motivation and economic viability, and to be able to forecast what society will need from us.

THE SIGNIFICANCE OF SUBMICRON TECHNOLOGY

Specialists need to examine their particular areas of learning and research in terms of these long-range objectives. Those of us involved in submicron-structure fabrication, for example, might question how enduring this is likely to be as a field of research, and how likely it is to contribute knowledge with long-lasting applications. The answers involve first, a long-term trend—our movement as a society into the information age—and second, an observation about what sort of scientific knowledge is fundamental.

"There is something very fundamental in extending human knowledge of a dimension . . ."

There is no doubt that we use information more and more in modern society. As information increases, the speed at which it is processed and communicated must increase in order to accommodate the flow of information efficiently and economically. Information cannot be communicated faster than the velocity of light, which is about one foot per nanosecond (one nanosecond is one-billionth of a second), and therefore if any information-processing device (computer) is to operate rapidly, it must be small enough so that the time required for information to travel from one part to another is not a limitation. When we think of the many millions of processing elements in a large computer, we are led inexorably to the conclusion that the entire computer, and hence the elements in it, must be reduced to a very small physical size. A fundamental advantage of integrated circuits is that they can be made with submicron features, and in fact, much of the drive in circuitry and device development has been toward size reduction. When the devices are smaller, more of them can be placed on a given area, and the results are more computing power per manufactured circuit, improved performance, reduced manufacturing cost, and generally improved reliability. These are impelling objectives, and they ensure the preeminence of research and development in submicron structures. Of course, the drive toward smallness pushes against other important considerations, such as signal-to-noise and power-density limits, and to accomplish results that satisfy all the criteria, researchers and developers need a fundamental understanding of materials, electronics, and communications.

The second reason I believe that submicron-structure fabrication will have long usefulness and significant influence on society comes from an observation: There is something very fundamental in extending human knowledge of a dimension, whether it is a spatial dimension or time. When Christopher Columbus sailed to discover the new world, he extended knowledge of the dimensions of our planet (and helped establish in the popular mind that the earth is a sphere, not a flat plate). When the light microscope was discovered, and subsequently improved, new worlds opened as our ability to explore and, more recently, to build at new dimensional scales developed. Similarly, the electron microscope provided much information about the inner structure of materials and biological cells and organisms. The scanning electron microscope has enabled us to see microstructures in their natural three-dimensional perspective, and related instruments have enabled us to analyze the materials in these structures and even to use chemical and physical processes to create artifacts smaller than any ever before made. The cathode-ray oscilloscope has allowed us to "view" time more exactly, and to design faster devices. New fundamental knowledge seems always to be learned as we extend the human province over new dimensional ranges, whether through better telescopes or better microscopes, and hence we are sure that what we learn and subsequently teach about

". . . one of the most important trends of the last several years has been the increasing interaction of industry and academia."

submicron-structure fabrication will contribute to the store of basic knowedge.

INTERACTION BETWEEN EDUCATION AND INDUSTRY

As we study and then make, we also make and then study. In submicron research, the structures we fabricate are themselves so novel that they bear further investigation, and they also provide us with tools to study other naturally occurring or artificially fabricated small structures. Just as the industrial revolution produced machinery, mechanisms, and processes that required further study and more refined tools, so does the information revolution. Cornell, with its national submicron facility, its Semiconductor Research Corporation program, and its Materials Science Center, is in the midst of this action.

Here at Cornell we are also involved with applications of the information revolution. In current research programs, for example, we are studying materials, the earth, and the stars using techniques that depend in part on high-speed computation. We are teaching our students how structures, circuits, and processes can be studied and then designed quickly and effectively using equipment and techniques such as those provided in our Computer-Aided Design Instructional Facility (CADIF).

The contributions of academia have some intrinsic limitations, however. Although university people generate new ideas, propose new devices, and improve old processes or create new ones, they do not manufacture the products that embody these creations. That is why it is important for educational institutions to have alliances with industry. Indeed, one of the most important trends of the last several years has been the increasing interaction of industry and academia.

Our experience at the Cornell College of Engineering is a good example. Representatives of several hundred corporations come to our campus each year. Many firms support us with gifts of equipment, cash, or research grants and contracts. Ideas generated here are developed by industry and made available to society in general, and in turn, we get many new ideas for research and better teaching through these interactions. The partnership benefits all concerned. Industry depends on engineering institutions such as ours for basic research and for personnel capable of developing it, and increasingly, corporations contribute to the quality of education we provide and to our research productivity.

U.S. INDUSTRY AND ITS SOCIETAL BASE

The practical value of a research and development program such as the one in submicron-structure fabrication ultimately depends on its benefits to society, and for the people of the United States, this entails economic success of products. If United States products are to compete successfully in the international arena, they must be not only better in design, but manufactured efficiently and with high standards of quality. In short, they must compare favorably with the best from any nation. If they do not, we lose sales of goods (or services), our tax base goes down, and our people lose jobs at the same time that our government loses the ability to help them in a time of difficulty. Education suffers, too, because a poor society in time will beget poor educational institutions.

As a society, we have to examine our practices, our institutions, and even our underlying sense of values, and determine whether we are agreed on a common set of assumptions on which a stable, viable, and effective society can continue to be built. Such ideas are not the province of engineers, of course. They are the responsibility of every person in society, including the engineers. The problems are too important to be left to politics, although political leadership is needed for their resolution. They are too important to be left to academia, to labor or management, to the legislative or the executive branches of government; and they cannot be solved by popular vote, but rather through a consensus of all parts of society, as groups and as individuals. In terms of a sports analogy, we need to agree that we are involved in a very important game, and if we play by rules that are outdated or incorrect, or if another team uses different rules or has better training practices, we could (and perhaps should) lose.

What comes to mind, of course, is the industrial success of the Japanese nation in recent years. Why has this homogeneous people, living on an island with few natural resources, accomplished such high productivity in electronics and automobiles, as well as in basic industries such as steel? While much has been said about robotics and manufacturing organization, less has been said about the excellent educational system in Japan, and about societal factors such as the national attitudes regarding problem resolution, the loyalty that individuals show to a corporation, and the importance individuals place on meeting their responsibilities.

In the world competition to produce goods and services, the United States has no monopolies. Rapid change of the sort taking place today is an opportunity for us—and for many other nations; whoever seizes the opportunities most quickly and utilizes them best will win in the competition. Technology is essential, but so is organization, cooperation, ingenuity, human understanding, and hard work. For the sake of our competitive stance, and the larger concerns of the health and well-being of our society, the United States and its citizens would do well to consider the value of cooperative effort, the social context of our enterprises, and the integrity of our underlying national purpose.

We believe the national submicron facility, like other facilities at Cornell, supports both our university goals and our national goals. We welcome the cooperation and support of government and industry, as well as individuals, to accomplish these goals. Together, we lay important foundations for the technology needed tomorrow by science and engineering for continuing basic research, as well as for industrial development and production.

Thomas E. Everhart has been dean of the College of Engineering since early 1979, when he came to Cornell from the University of California at Berkeley. An electrical engineer and specialist in electron optics and electron physics with long experience in teaching, research, and consulting, he writes with authority on the broad aspects of submicron-structure fabrication.

Everhart earned the A.B. degree in physics (magna cum laude) at Harvard University, the M.Sc. in applied physics at the University of California at Los Angeles, and the Ph.D. in engineering at Cambridge University, England, where he was a Marshall Scholar and helped develop the scanning electron microscope. He was a member of the Berkeley faculty for twenty years and served as chairman of the Department of Electrical Engineering and Computer Science there. As a National Science Foundation postdoctoral fellow, he conducted research at the Institüt für Angewandte Physik in West Germany, and later as a Guggenheim fellow he spent a year both at Cambridge and at Waseda and Osaka Universities in Japan. He is a member of the National Academy of Engineering, a fellow of the Institute of Electrical and Electronics Engineers, and a past president of the Electron Microscopy Society of America.

A MICROELECTRONICS GLOSSARY*

semiconductor: a solid material such as silicon, germanium, or gallium arsenide, whose electrical conductivity can be modified by many orders of magnitude by introducing suitable impurities into it.

integrated circuit (IC): an electronic circuit containing active electronic components and their interconnects on the same silicon chip.

LSI: large-scale integration of active devices (200 to 20,000) on a single chip.

VLSI: very-large-scale integration of active devices (20,000 or more) on a single chip.

resist: a film of polymer that is spun on a silicon wafer and chemically altered by a process of selective irradiation to define a pattern.

lithography: the definition of a pattern in a layer of solid material by exposure to light, electrons, or ions; the images can have positive or negative tone, as in photography.

etching: removal of parts or entire layers of solid material; based on wet chemistry or dry plasma exposure.

doping: introduction of impurities into semiconductor in order to change the electrical conductivity; both the number of negative charges (electrons) and the number of positive charges (holes) can be changed by many orders of magnitude by doping.

p-n junction: an internal interface in a semiconductor where two oppositely doped areas meet; n denotes the doped area with an enhanced electron concentration and p the area with an enhanced hole concentration.

heterojunction: the interface between two semiconductor layers that have a difference composition (e.g., gallium arsenide and gallium aluminum arsenide).

epitaxy: growth of a crystalline solid film over another piece of solid material.

gate: a metallic or metal-insulator type area that controls the amount of charge flow (electrons or holes) in an active electronic device.

transistor: an active semiconductor device that can either amplify an electronic signal or act as an electronic switch.

bipolar transistor: a transistor made of three semiconducting layers of alternating polarity (n-p-n or p-n-p); the electric charges move from the emitter (n- or p-) to the collector (-n or -p) and are modulated by the base (-p- or -n-); both types of charges (electrons and holes) participate in the transistor action.

field-effect transistor (FET): a transistor in which the charge flow from the source to the drain is controlled by an electric field applied to a gate structure inserted between source and drain; only one type of charge (electrons or holes) makes a transition from source to drain; the charge flow occurs in the channel, a region under the gate.

MESFET: a field-effect transistor with a metal-semiconductor structure serving as the controlling gate for the current.

MOS: metal-oxide-semiconductor assembly that is used both as a control gate for FETs and as a plate capacitor for charge storage.

MOSFET: field-effect transistor with a MOS control gate.

NMOS: MOSFET device or circuit with electrons as the charges moving from the source to the drain.

PMOS: MOSFET device or circuit with holes as the charges moving from the source to the drain.

CMOS: complementary MOS circuit, containing both NMOS and PMOS devices integrated on the same chip.

BC-MOSFET: buried-channel MOSFET, a device with charges flowing from the source to the drain inside the semiconductor at some distance away from the oxide-semiconductor interface.

SC-MOSFET: surface-channel MOSFET, a device in which the moving charges are confined to a thin region immediately adjacent to the oxide-semiconductor interface.

**prepared by G. McConkey and J. P. Krusius*

ULTRASMALL FEATURES

Key to the Future Development of VLSI Technology

by J. Peter Krusius

Understanding and controlling the geometric and electronic characteristics of ultrasmall structures is the basic requirement for developing the electronic hardware of the future. A goal of current research and development is to produce silicon chips with as many as thirty million devices packed onto their half-inch-square surface area. The components will have feature dimensions in the range of 100 nanometers (nm), which is 100 X 10^{-9} meter.

At Cornell, investigators in the VLSI (very-large-scale integration) technology group, which I direct, are exploring the science and technology of semiconductor devices and integrated circuits for future generations of VLSI applications. The approach is both experimental and theoretical, for new physical models, mathematical methods, and tools for computer-aided design (CAD) must be developed for processes, devices, and circuits. Major parts of the work constitute one of the central projects in the interdepartmental Cornell Program on Microscience and Technology, which is supported by the Semiconductor Research Corporation (SRC), a consortium of American semiconductor and systems companies. Additional support comes from the National Science Foundation and industrial sponsors via the National Research and Resource Facility for Submicron Structures (NRRFSS).

Our main focus at the present time is an exploration of new individual processes and full fabrication sequences for metal-oxide-semiconductor (MOS) devices and circuits of both the N-channel (NMOS) and the complementary (CMOS) types (see "A Microelectronics Glossary" opposite). The processes we are developing use such techniques as electron-beam lithography, dry plasma etching (see the article in this series by Edward D. Wolf and Ilesanmi Adesida), ion implantation, and thin-film growth and deposition (see the article by Lester F. Eastman).

We are also concerned with the characterization and analysis of the properties of these ultrasmall structures, and this too requires innovative approaches and new methods because of the small geometrical size and the associated low electronic signal levels in measurements.

A third important aspect of the program is the development of CAD tools, which have become indispensable because the fabrication processes necessary for realizing the specified characteristics are increasingly complex. These processes may have tens of interrelated parameters.

NEW EQUIPMENT FOR A VIGOROUS PROGRAM

Most of the facilities for this research were already available at NRRFSS or in departmental laboratories at the University. Additional equipment is being introduced by the VLSI technology group as part of the facility-development program at NRRFSS.

A major accomplishment this year was the installation of a THERMCO furnace system capable of preparing thin films of materials by any of four basic thermal processes. Process gases of the highest purity, supplied by AIRCO, are used throughout. With this system, a process based on dry

Right: A four-chamber THERMCO furnace is used to prepare materials for processing metal-oxide semiconductor (MOS) structures.

"A goal . . . is to produce silicon chips with as many as 30 million devices packed onto their half-inch-square surface area."

HCl can be used to produce high-quality thermal silicon dioxide films with thicknesses down to 10 nm; these films serve as insulators for MOS control structures and storage elements. Thicker high-quality thermal oxides can also be grown by a process in which the gas source for chlorine is trichloroacetylene; these oxides are used for dielectric isolation structures between individual semiconductor devices that are on the same chip. The THERMCO system is also used for a chemical vapor deposition (CVD) process by which silicon nitride films are deposited under reduced pressure; these films are used in advanced silicon processing for a variety of tasks such as the control of ion diffusion, the fabrication of sidewall spacers for ion implantation, and passivation of silicon chips as protection against environmental effects. In addition, the furnace can be used to anneal substrate materials in an atmosphere that is sealed and inert.

A computer-controlled system for characterizing semiconductor devices is being set up, and software for it developed, in programs supported by the Hewlett Packard Company and carried out jointly with Jeffrey Frey's group (see Frey's article in this series.) The School of Electrical Engineering has been able to greatly enhance its computational resources by the recent addition of two Digital Equipment VAX computers (11/780 and 11/750) and one Data General MV 8000 computer. Simulation and analysis work that was earlier carried out on the Harris S123 minicomputer has been largely transferred to these new, more powerful computers. The addition of a VAX 11/750 computer at NRRFSS has made it possible for researchers in that laboratory to use a new software package, MOS-MANAGER, which we developed for clean-room management and supervision.

Figure 1

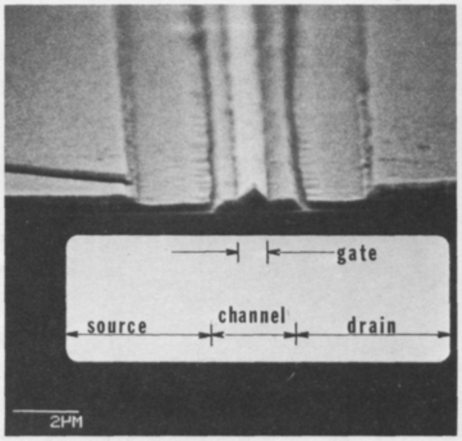


Figure 2

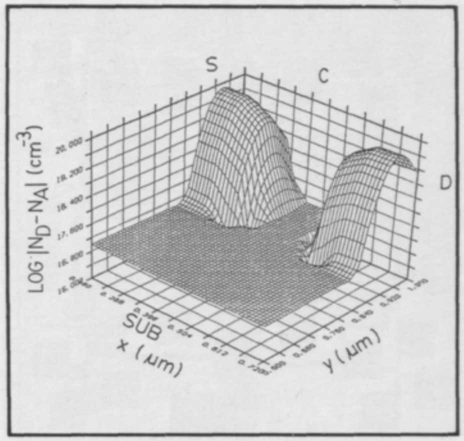


Figure 1. A scanning-electron micrograph of a cross section of a silicon MESFET logic device fabricated at Cornell by Jaime Nulman and J. Peter Krusius. The minimum feature size is the gate length of 500 nm. In order to show the cross section, the chip was cleaved and selectively etched before the micrography was done.

Figure 2. The simulated doping profile of a surface-channel MOSFET device, presented as a three-dimensional plot. The drawn gate length is 300 nm, but because of lateral scattering and diffusion, the final metallurgical gate length is about 200 nm. This profile was obtained with the process simulator CUSTOM developed at Cornell by B. Nassre Esfahani and J. Peter Krusius.

A NEW SWITCHING DEVICE FOR VLSI CIRCUITS

One of the early accomplishments of the VLSI technology group was the development of a full technology for fabricating a silicon metal-semiconductor field-effect transistor (MESFET) for logic devices. This technology is based on electron-beam lithography, ion implantation, dry etching, and techniques for fabricating ohmic contacts and Schottky gates. (These gates, made of refractory metal silicides, control the movement of electrons.)

A cross section of a representative switching device made according to this technology is shown in Figure 1. This device has a gate length of 500 nm and a very short delay time, on the order of 150 picoseconds per gate. It can be fully integrated into a VLSI circuit on a silicon chip. Several small-scale integrated circuits, such as logic gates, ring oscillators, and divide-by-N counters, were implemented with this logic technology.

At the same time the group was working on this fabrication technology, we also developed the first three-dimensional simulator for semiconductor processing. The software program, CUSTOM, is used to describe coupled steps for implanting and diffusing ions with the use of arbitrary mask profiles or—when focused ion beams are employed—under maskless conditions. As an example, the simulated doping profile for a MOSFET device is shown in Figure 2. This device has a metallurgical channel length of 200 nm along the path of the electrons from the source to the drain.

A computer-aided tool for the design and analysis of MESFET devices was also developed. The starting point for this program was the Cornell computer program CUPID (see Frey's article). The upgraded device physics that is incorporated into this new CAD tool allowed the behavior of the MESFET devices in Figure 1 to be simulated with excellent accuracy.

NEW METHODS AND TOOLS FOR DEVICE FABRICATION

The fabrication of the 500-nm MESFET devices and circuits was based on scaled-down but established processing techniques. Our current efforts, aimed at further size reduction, require new processes. We are now working on devices with gate lengths as short as 100 nm: silicon MESFETs, surface-channel MOSFETs (SC-MOSFETs), and buried-channel MOSFETs (BC-MOSFETs). The important difference between these two types of MOSFETs is the speed with which electrons move within them. In the surface-channel devices, the electrons are confined to the interface between the silicon dioxide layer and the silicon substrate. In the buried-channel variety, the electrons travel from the source to the drain, at some distance from the interface. Since the electrons can achieve a greater velocity in devices of this type, BC-MOSFETs have a potential for higher-speed operation than is attained with the more conventional SC-MOSFETs.

Innovative research on processing is

Figure 3

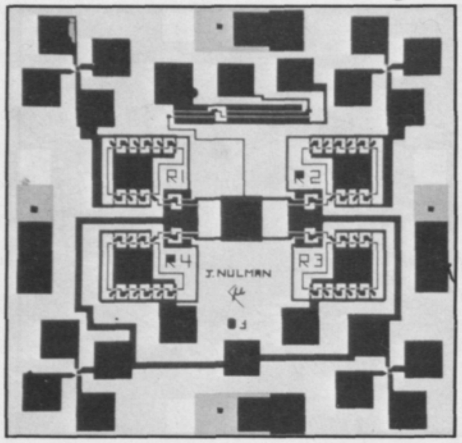


Figure 4

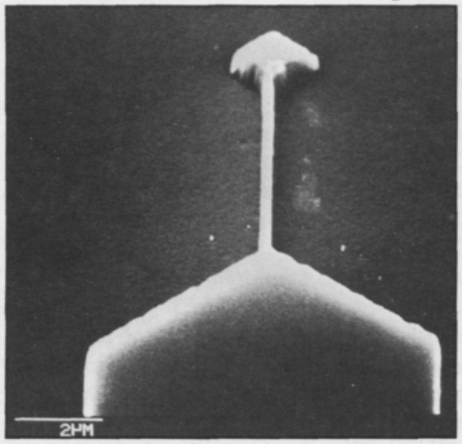
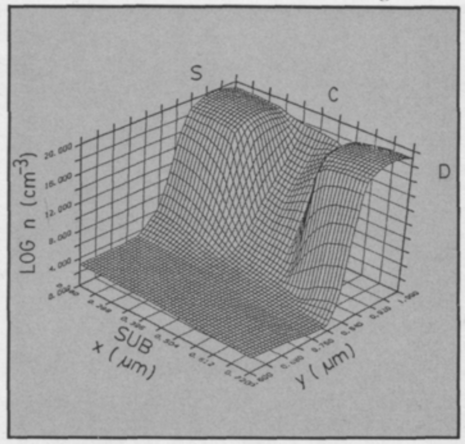


Figure 5a



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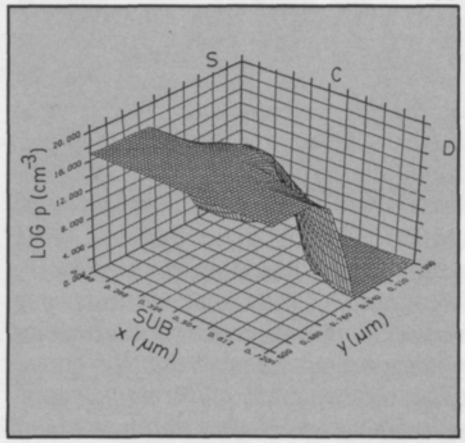

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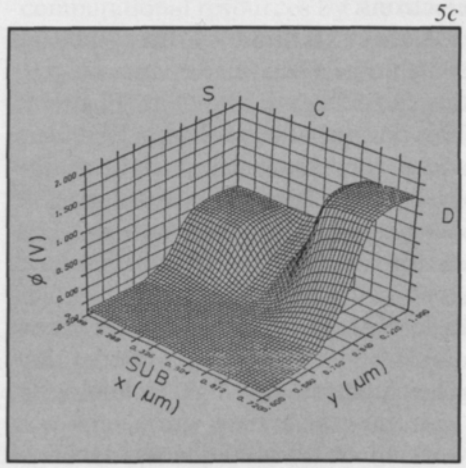


an essential part of the program. An example is the development of a novel patterning technique that is suitable for creating patterns with the ultrasmall dimensions required for future devices. The initial lithography is done with an electron beam, in the usual manner, by drawing a pattern in a positive-tone polymer resist. Removal of the exposed (more soluble) polymer creates a window through which an underlying film of aluminum can be reached. An etch mask is created by exposing the aluminum under the window to the oxidizing action of plasma at low temperature, and this oxide mask is used in subsequent etching of the underlying aluminum and other layers. The oxide pattern is of the original tone, but since the oxide etches very slowly in comparison with the unoxidized aluminum, image reversal occurs during the etching. Features as small as 100 nm have been transferred—examples are shown in Figures 3 and 4. A patent on the invention has been filed.

We are also exploring a way of replacing the currently used techniques

Figure 3. An optical micrograph of a silicon chip with buried-channel MOSFET devices and circuits. The chip area is 1 X 1 mm and the smallest feature size (the gates) is 200 nm. The magnification is only about 100X, and therefore the lines less than 1 micrometer (1,000 nm) wide are not well resolved. This particular chip consists of an insulating sapphire substrate with a thin silicon film that carries the active devices and interconnects. The circuit labeled R1 is a five-stage ring oscillator with two logic inverters loading each gate; it has minimum-gate-length MOSFETs. The other elements shown include test structures, devices, and more circuits. This chip was fabricated at NRRFSS by Jaime Nulman and J. Peter Krusius.

Figure 4. Detail of the gate-level layer for the ring oscillator of Figure 3. This micrograph shows the line of the 200-nm-wide and 1,000-nm-tall gate, which serves as the control structure for one BC-MOSFET device.

Figure 5. Profiles of electron density (a), hole density (b), and electrochemical potential (c) of the SC-MOSFET device of Figure 2. These three-dimensional plots were obtained with the finite-element simulator SEMIFEM by Monte Manning, John Scarpulla, and J. Peter Krusius.

for isolating circuit elements from each other on the silicon chip. These techniques depend on local oxidation of silicon to form a dielectric barrier of silicon dioxide. One alternative is based on an anodic process, carried out in an electrolyte of hydrogen fluoride and water, in which silicon is first converted to a porous form and then oxidized at a low temperature. (Our investigation of this process is supported by IBM.) Another alternative is to form the dielectric structure by suitable backfilling of dry-etched trenches in the silicon.

Of course, characteristics of the MOS structure itself have an important bearing on what can be accomplished. Downscaling requires the formation of insulators that are ultrathin (on the order of 100 Å thick), free of holes, and dielectrically strong, and conductors that have low resistivity and do not introduce diffusing ions into the thin oxide. One of our goals is to achieve the necessary conductivities, which are much larger than those currently obtained with doped polysilicon. We are exploring the use of metal silicides and pure refractory metals as materials suitable for very-small-scale device fabrication.

TOWARD A 200-NM-SCALE NMOS TECHNOLOGY

Our understanding of individual processes and how to control them is now being used in establishing a full fabrication technology for NMOS devices with features on a size scale of 200 nm. Initial design of devices and circuits is in progress.

Device design is based on a simulator called SEMIFEM that originally came from the Swedish Royal University of Technology and was adapted at Cornell. A finite-element simulator, SEMIFEM is capable of handling the nonrectangular geometries of small devices. We are reevaluating and upgrading the underlying device physics and the associated models to make the program suitable use at very small feature sizes. Examples of simulation results—for electron density, hole density, and electrochemical potential of the SC-MOSFET of Figure 2—are given in Figure 5.

We are now fabricating test structures and individual devices in order to refine processes, devices, measurement techniques, and CAD tools. The next step will be to design, fabricate, and evaluate circuits. We will start with elementary circuits, such as logic elements and memory cells, and proceed to complex circuits. The ultimate goal is to serve an ambitious research program that is now being defined in discussions between the Semiconductor Research Corporation and Cornell. Our task will be to develop elements of a 16-megabit dynamic memory that would increase the capacity of a single memory chip by a factor of 250.

Fundamental physical studies, new equipment and software, and the actual fabrication and analysis of devices are all part of the comprehensive program of Cornell's VLSI technology group. The future of VLSI applications, of integrated semiconductor circuits in general, and hence of the electronics industry in this country, depends on the kind of fundamental and innovative research performed here at Cornell in this and related programs.

J. Peter Krusius, associate professor of electrical engineering, is a specialist in the physics and technology of VLSI and submicron structures. He came to Cornell in 1979 to work at the National Research and Resource Facility for Submicron Structures (NRRFSS), first as a Fulbright fellow and then as a research associate and lecturer in electrical engineering; he has been a regular member of the faculty since 1981. He coordinated the Cornell proposal to the Semiconductor Research Corporation that resulted in the initial one-million-dollar funding for the recently established Program on Microscience and Technology.

A native of Finland, Krusius studied at the Helsinki University of Technology for the Diploma Engineer, granted in 1969, the Licentiate of Technology in 1972, and the Doctor of Technology in 1975. He served as a postdoctoral fellow in solid-state physics at Dortmund University in West Germany, and then returned to the university in Helsinki as a lecturer and engineer in the Electron Physics Laboratory. Concurrently, he was a senior research associate at the Semiconductor Laboratory of the Technical Research Center of Finland in Otaniemi.

SMALL-SCALE PHYSICS FOR LARGE-SCALE ELECTRONIC CIRCUITS

by Jeffrey Frey

Because future generations of VLSI (very-large-scale integrated) circuits will have to provide faster operation and more functions at a given cost, the physical size of their components must be smaller. Size reduction of electronic devices is therefore a major concern of designers and researchers.

As these devices shrink in size, new problems arise. When critical dimensions are well below a micrometer (a millionth of a meter, often called a micron), unexpected circuit elements, known as *parasitics,* become troublesome. Further, many approximations used to solve problems in classical solid-state physics—approximations that have facilitated the design of current devices—become too divorced from reality in this size range, and must be abandoned.

To tackle these problems, researchers need to acquire a basic understanding of the physics lying behind the operation of very small devices; to be effective, experimental studies must be illuminated by the simulation of physical processes with the use of computers.

BEHAVIOR OF ELECTRONS IN VLSI DEVICES

For some years, our research group at Cornell has been using both computer-aided simulation and experimental test structures to study the physics of submicron devices. Early work in two-dimensional device simulation included the development of the Cornell University Program for Integrated Devices (CUPID), which is suitable for describing the physics of the small silicon and gallium arsenide (GaAs) transistors now being designed into VLSI circuits. CUPID is not, however, adequate when the dimensions of devices are less than a micron because it does not incorporate device physics completely enough.

To meet this need, we have developed a more complex program, COOPID, which properly describes phenomena that occur in materials such as GaAs when device dimensions are very small. For example, the energy exchange between electrons and the electric fields in devices may take a time on the order of several picoseconds; and although such a time is negligible in terms of today's devices, it becomes a significant fraction of the device switching speed as the physical size decreases to the submicron level. In materials like GaAs electrons can travel much faster than they can in larger devices, and our work is intended to show how to utilize that speed in the design of fast devices.

The ability of COOPID to describe phenomena that occur in extremely short times in GaAs is demonstrated in Figure 1, which compares COOPID results with those of the simpler program CUPID. The figure shows that COOPID is able to reveal the performance-enhancing effects of electron transport in very small devices. Measurements with experimental devices bear out the validity of the COOPID simulation.

COMPUTER SIMULATION FOR TWO KINDS OF DEVICES

Although somewhat different short-time-scale effects occur in bipolar and metal-oxide-semiconductor (MOS) devices based on silicon—those most commonly used for VLSI circuits—we

Figure 1. Describing the physics of devices with submicron dimensions.

a. *Plots comparing two Cornell-developed programs for simulating physical processes in very fast gallium arsenide devices. The parameter that is illustrated is the electron velocity, which is more accurately represented by COOPID than by CUPID. The "gate" is the electrode that controls the electron flow in the device. The very large electron velocity predicted by COOPID implies that devices of this type should operate at very high speeds.*

b. *A three-dimensional plot similar to those generated by computer in the Cornell research project. The parameter illustrated is electron velocity, as in Figure 1a, and the program used is COOPID. The view is down into the inside of a "box" representing the inside of a transistor. The data show the electron velocity at five different depths within the device.*

Figure 1a

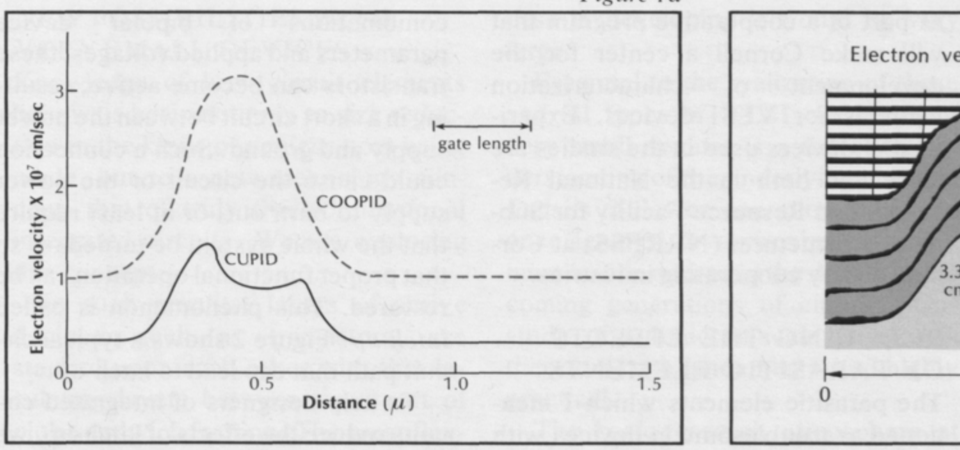
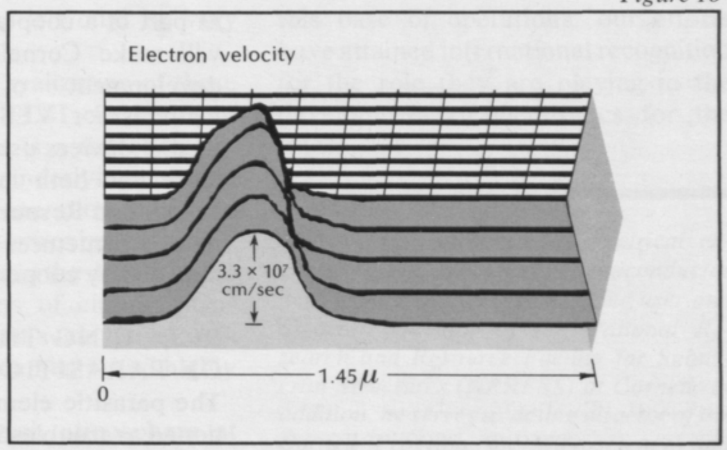


Figure 1b



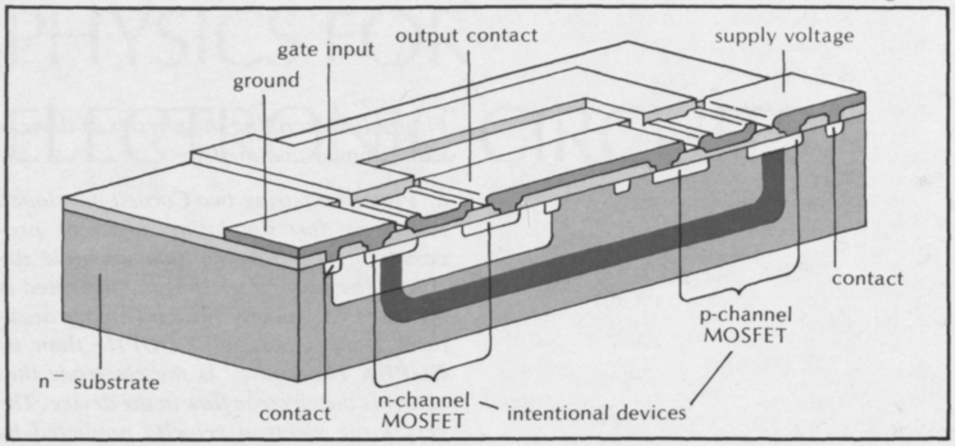
are bringing the techniques developed for the design and analysis of GaAs devices to the silicon world.

Bipolar devices are created in silicon by introducing impurities into certain regions. One result of the very high concentrations of impurities that must be used in many parts of the device is a modification of the energy band structure, called *band-gap narrowing*. Also, the time it takes electrons to cross the active regions of these devices becomes comparable to the picosecond time scale of basic physical processes. Because of effects like these, we are developing simulation techniques that incorporate the appropriate physical effects.

The modeling of submicron-scale MOS devices is being studied in two ways. First, we are assessing currently available two-dimensional modeling programs in order to establish what types of devices and what types of analyses each of these programs is best suited for. In addition, we are examining the physics of electron transport in the very thin layers—just beneath the device surface—into which the "important" electrons are compressed. Eventually, we hope to be able to enhance the simulation programs now available for MOS devices, since these are generally semi-empirical and do not properly incorporate the physics of electron transport.

Our work with both MOS and bipolar devices is facilitated by automated test equipment that enables us to compare experimental and theoretical results. This equipment was provided by Hewlett-Packard at no cost to Cornell,

Figure 2



". . . the payoff for success in developing (a three-dimensional circuit) would be very large."

as part of a cooperative program that will make Cornell a center for the development of characterization methods for VLSI devices. Experimental devices used in the studies are fabricated both in the National Research and Resource Facility for Submicron Structures (NRRFSS) at Cornell, and by cooperating industries.

REDUCING THE EFFECTS OF PARASITIC ELEMENTS

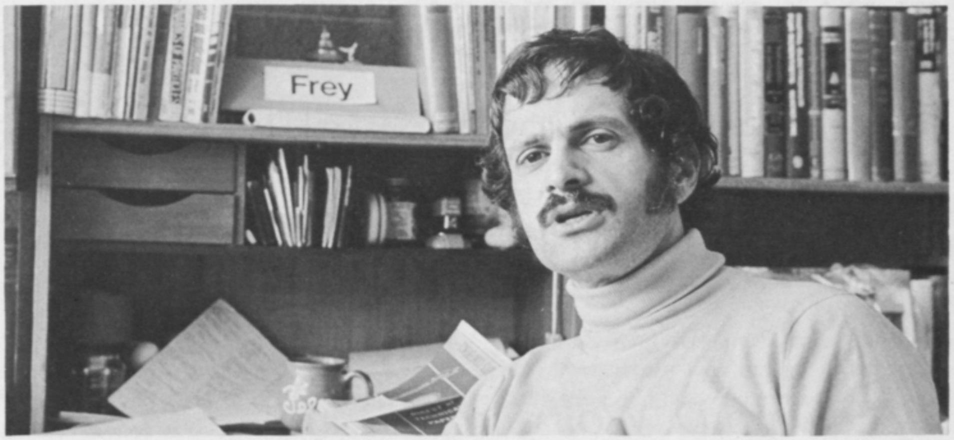
The parasitic elements which I mentioned as troublesome in devices with submicron dimensions are a problem particularly in the circuit family known as Complementary MOS, or CMOS. In these circuits, both p-channel and n-channel (positive-conductor and negative-conductor) devices are used in a way that reduces power consumption to very low levels. In fact, truly portable computers will be possible only with CMOS VLSI.

Unfortunately, the use of both p-type and n-type silicon regions makes it very easy for unwanted bipolar transistor elements to be formed accidentally in the circuit. With certain combinations of bipolar device parameters and applied voltages, these transistors can become active, resulting in a short circuit between the power supply and ground. Such a connection could cause the circuit or the power supply to burn out, or at least require that the whole system be turned off so that proper functional operation can be restored. This phenomenon is called *latch-up*. Figure 2 shows a typical circuit path that can lead to latch-up.

To help designers of integrated circuits reduce the effects of latch-up, we are developing a program called PATHFINDER (for PATHological element FINDER), a computer-aided design (CAD) tool that identifies parasitic elements on the basis of both horizontal geometry (that is, circuit layout) and vertical geometry (process variables). PATHFINDER locates not only the active parasitic elements in CMOS circuits, but also the passive ones, including resistances and capacitances, and it can analyze ordinary MOS and bipolar circuits as well as CMOS circuits. The output of PATHFINDER is a circuit diagram

Figure 2. A diagram of a circuit path that includes unwanted parasitic elements. The path in color indicates where unintentional bipolar transistors will exist. The Cornell program PATHFINDER helps designers reduce the effects of this phenomenon, called latch-up.

showing the integrated circuit as it was designed, plus all the important parasitic elements. This equivalent circuit can then be analyzed using standard circuit-simulation programs.



NEW POSSIBILITIES WITH VERY SMALL DEVICES

Knowledge of how circuit elements behave is basic not only to size reduction in the kinds of devices now being made, but to a new technology concept, that of truly three-dimensional integrated circuits. We are exploring this concept.

In such circuits, layers of active devices, such as transistors, are stacked upon each other with thin insulating layers between, in a sort of club-sandwich fashion. The great flexibility of both vertical and horizontal connections that this kind of structure makes possible could lead to tremendous advances in the ways computers are designed. Applications would be wide-ranging, for such components as systolic processors, interleaved memory and logic circuits, and integrated sensors and data processors. Superfast computers and pattern recognition may be made possible. Although such a three-dimensional circuit is still a concept—only limited experimental results on two-level circuits have been achieved so far—the payoff for success in developing it would be very large.

Essential to the realization of these and all types of VLSI circuits with very small devices is a thorough understanding of the underlying physics. Details of device operation that were once ignored or approximated away must be considered in the design of the coming generations of circuits. Our study of submicron-scale physics is therefore both fundamental and highly practical.

The basic-research atmosphere at Cornell, and the access to our excellent facilities, makes this an ideal place for such studies. We have the capacity to actually fabricate experimental submicron-scale structures in the NRRFSS laboratory, to simulate them on DEC, DG, Harris, HP, and IBM computers in the School of Electrical Engineering, and to test them in our new Hewlett-Packard measurements center. In addition, we have support from the Semiconductor Research Corporation for the Program on Microscience and Technology that was recently established at Cornell. With this base of operations, our efforts have attained international recognition for the role they are playing in the development of electronics for the future.

Jeffrey Frey, professor of electrical engineering and specialist in semiconductor devices and circuits, is an active user and associate director of the National Research and Resource Facility for Submicron Structures (NRRFSS) at Cornell. In addition, he serves as acting director of the Cornell Program on Microscience and Technology sponsored by the Semiconductor Research Corporation.

After receiving the B.E.E. degree at Cornell in 1960, Frey did graduate work at the University of California at Berkeley, earning the Ph.D. in 1965. As a graduate student, he held a Howard Hughes fellowship and worked at the Hughes Research Laboratories. Before joining the Cornell faculty in 1970, he was employed by the Watkins-Johnson Company, served as a NATO postdoctoral fellow at the Rutherford High Energy Laboratory in England, and was a research associate at the United Kingdom Atomic Energy Research Establishment at Harwell.

DRY PROCESSING

New Techniques for Etching Submicrometer Structures

by Edward D. Wolf and Ilesanmi Adesida

A crucial step in the fabrication of electronic devices is the etching of desired patterns into a wafer. Currently this is accomplished with chemical baths, but for the very small devices needed for future very-large-scale integrated (VLSI) circuits, these "wet" methods do not transfer the pattern adequately because of lateral etching, and "dry" etching with gaseous ions is needed.

The National Research and Resource Facility for Submicron Structures (NRRFSS) at Cornell is one of the laboratories in which research in dry etching is yielding an assortment of improved processing techniques. These include plasma etching (PE), reactive-ion etching (RIE), and reactive-ion-beam etching (RIBE). In discussing our work at NRRFSS in these areas, we hope to show why dry processing has become the main technique for pattern transfer in VLSI etching technology, and what progress is being made in developing it.

ETCHING AS A STEP IN DEVICE FABRICATION

The significance of etching techniques can be explained in terms of the overall process of fabricating an electronic chip, a process that encompasses a wide range of techniques developed in intensive research over the past twenty years.

Figure 1

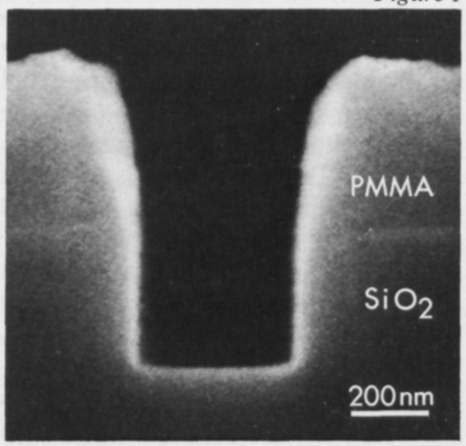


Figure 1. Reactive-ion etching. The "high and narrow" profile was obtained with CHF_3 gas, which acts on SiO_2 more strongly than it does on the polymeric "resist" material.

In a typical process, a wafer—now usually silicon—is coated with a *resist,* a film of polymeric material—such as a photo-polymer or poly(methyl methacrylate) (PMMA)—that is sensitive to radiation and also resistant to chemical treatment. Next a pattern is created by exposing the surface, or a selected area of it, to light (in photolithography) or, for finer patterning, to radiation of shorter wavelength (as in electronbeam, ion-beam, or x-ray lithography). After exposure, the more soluble resist material is washed away in a developer, and then the pattern in the resist is transferred to the wafer by an etching process.

As the dimensions of electronic devices have become smaller, allowing more functions to be performed by the same size chips, the processing requirements have become more stringent. Conventional photolithography, for example, does not produce fine enough patterns because the wavelength of light is too large. Similarly, wet etching has serious limitations as the submicrometer regime is approached: specifically, low resolution

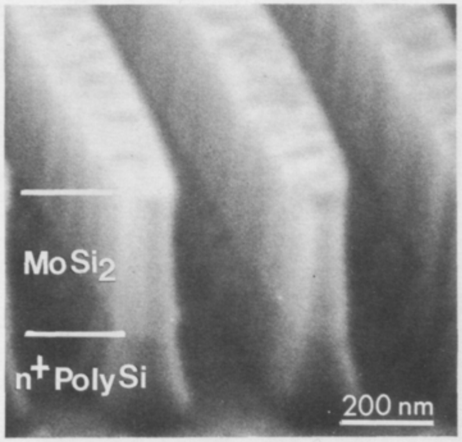


Figure 2. Reactive-ion etching. This multilayer structure was etched in a plasma consisting of a gaseous mixture of SF_6 and O_2.

and very limited control of the etching profile. Dry methods have the advantage of providing anisotropic profiles, in which the etching progresses selectively in only one direction rather than evenly in all directions, as is the case with conventional wet processes. This characteristic allows much improved transfer of the high-resolution patterns created with electron, x-ray, or ion-beam lithography. Larger height-to-width ratios can be achieved in the etched impression, for example. With dry etching, structures never before possible can be fabricated.

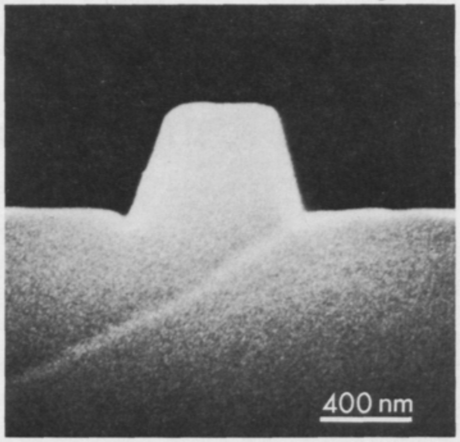
NRRFSS PROGRAMS IN DRY ETCHING

One of the aims of our Cornell programs in dry etching is to contribute to an understanding of these novel methods and how they can be applied to pattern transfer at submicrometer dimensions. For example, we have studied the resistance of PMMA to etching by reactive ions; in particular, we were interested in the use of this high-resolution resist as a mask in the etching of various dielectrics. It was found that by using a fluorine-deficient fluorocarbon gas such as CHF_3, a high selectivity could be obtained between PMMA and silicon dioxide. This means that the CHF_3 gas, which is in a plasma state, etches silicon dioxide faster than it attacks the PMMA. The result is a highly anisotropic, "high and narrow" profile, such as the one shown in Figure 1. Much of this work was done by Jeffrey Chinn for his Master of Science thesis. The equipment he used is a parallel-plate RIE system, which was partially a gift to NRRFSS from the Applied Materials Corporation.

In studies with two visiting scholars from China, Zhang Min and Li Jian-Zhong, the RIE technique is currently being used to study the etching properties of polysilicon and refractory metal silicides in various gas mixtures of SF_6 plus oxygen, and SiF_4 plus chlorine. The refractory metal silicides such as molybdenum silicide and tantalum silicide are important because they have smaller contact resistance than aluminum—the standard contact material for silicon devices—and therefore are increasingly being used for contacts and interconnections in VLSI silicon devices. A typical structure that needs to be etched in silicon metal-oxide-semiconductor (MOS) devices, for example, is the silicide/polysilicon/silicon dioxide stack. The etching of this multilayer structure, which has high-resolution features and anisotropic profiles, has been done using an SF_6 and O_2 gas mixture, with results as shown in Figure 2.

RIBE, in which the etching is accomplished with a *beam* of reactive ions, offers some advantages over RIE: several parameters such as ion energy, ion current density, and the composition of background gas, can be varied independently. In studies with Jeffrey Chinn, we recently used a RIBE system (donated to NRRFSS by Varian-Extrion) to investigate the etching of gallium arsenide (GaAs) with an inert and a reactive-ion beam in the presence of background molecular chlorine. The chlorine, coming from either the ion beam or the background gas, was found to impinge on the specimen with significant effect. It was

Figure 3a



3b

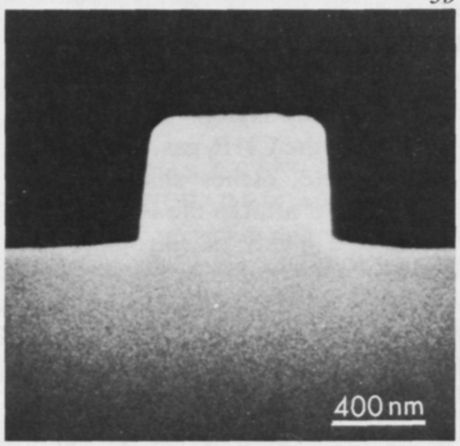
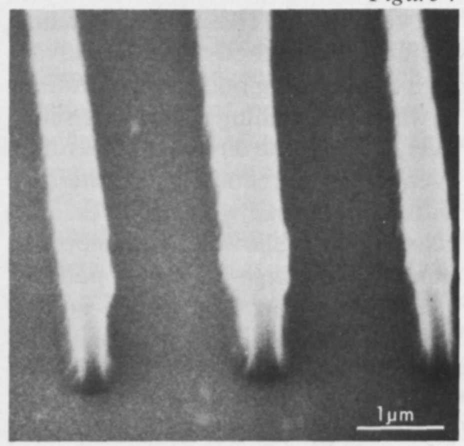


Figure 3. Reactive-ion-beam etching. These samples of GaAs were etched by a beam of ionic chlorine in the presence of molecular chlorine. The profile was found to be influenced by both sources of chlorine; for example, the profile in 3a is less vertical than the one in 3b, which was obtained in the presence of a higher concentration of molecular chlorine.

Figure 4. Dry development in ion-beam lithography. These resist features, about 0.3 micrometer wide, were obtained in a process in which a pattern is created by implanting silicon ions in a thin-film resist and then exposing it to O_2 plasma.

Figure 4

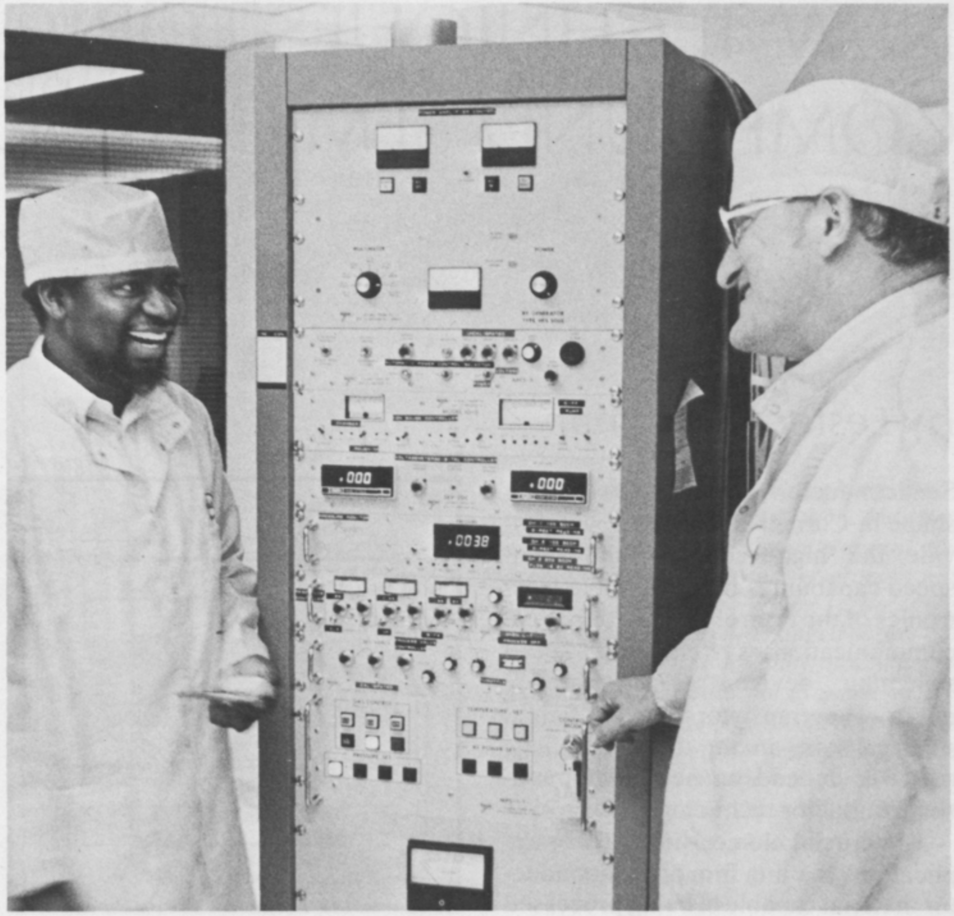


"With dry etching, structures never before possible can be fabricated."

found, for instance, that an increase in the amount of chlorine present in the background altered the wall profile from an overcut slope to a nearly vertical one (see Figure 3). Overcut profiles are usually found where the etching mechanism is mainly physical, caused by energetic ions, while the vertical wall resulted from both physical and chemical etching mechanisms. Such profile control would be impossible with the use of wet processing, in which etching proceeds equally in all directions.

In work related to that of Benjamin M. Siegel of Cornell's School of Applied and Engineering Physics, we have also been investigating other forms of ion-beam lithography in which resist development can be performed using dry etching. Our approach to the fabrication of a structure has been to implant low-energy (40 keV), high-dose (1 X 10^{15}/cm^2) silicon ions into resists, and to follow this with reactive-ion etching in an oxygen plasma. During the RIE process, the thin layer of implanted silicon reacts with the ambient oxygen to form SiO_2, which then inhibits further etching. Using this method, we have obtained etch ratios greater than 11 between unexposed and exposed areas. Features as small as 0.3 micrometer in linewidth have been fabricated in a PMMA film one micrometer thick, as shown in Figure 4.

Although dry processing techniques can produce spectacular results, as we have demonstrated, much of the development has been by trial and error, on the basis of empirical derivations. To fully realize the potential of these methods, further studies of the physical and chemical events occurring on a wafer surface in a plasma or ion-beam environment are needed. In our work at NRRFSS, therefore, we are incorporating analytical instruments such as electrostatic-energy analyzers, mass analyzers, and optical spectroscopes into our etching system in order to study fundamental etching processes. The results of these studies should help in identifying parameters that are needed to optimize dry-etching methods for device fabrication.



Edward D. Wolf, director of the National Research and Resource Facility for Submicron Structures (NRRFSS) and professor of electrical engineering at Cornell, conducts research at the facility in the science and technology of microfabrication. Ilesanmi Adesida, a visiting assistant professor of electrical engineering and a research associate at NRRFSS, is a co-principal investigator in some of these studies.

Wolf is prominent nationally and internationally in the areas of submicrometer lithography and pattern transfer. He came to Cornell in 1978 from Hughes Research Laboratories, where he was a senior scientist and section head in the Electron Device Physics Department. He has also carried out research at the Rockwell International Science Center and at the University of California at Berkeley. He received his undergraduate education at McPherson College, earned the doctorate in physical chemistry at Iowa State University, and was a research associate at Princeton University.

Adesida joined the NRRFSS staff as an IBM postdoctoral fellow in 1979, became a research associate in 1981, and this year was appointed as a visiting assistant professor. A citizen of Nigeria, Adesida came to the Lawrence Berkeley Laboratory in 1971 as an International Atomic Energy Agency trainee in nuclear counting techniques, and later, before completing graduate study, he returned to the same laboratory for a year's work as an electronic engineer. He received the B.S., M.S., and Ph.D. degrees from the University of California at Berkeley in 1974, 1975, and 1979.

NEW TECHNIQUES FOR GROWING COMPOUND SEMICONDUCTORS

by Lester F. Eastman

Semiconductor devices now taking shape in Cornell laboratories will provide the high-frequency and high-speed capabilities needed for the electronics of the future. Lasers for optical communications systems, high-speed switching devices, high-frequency microwave transistors, and efficient solar cells are among the applications that will depend on new compound-semiconductor technology.

The crucial element in all these applications is a thin film of semiconductor material capable of being processed to yield high-performance devices. Particularly useful are compound semiconductors, such as gallium arsenide (GaAs), whose crystal structure forms alternating layers of different atomic constituents (see Figure 1). These layers are a basis for the creation of very small electronic devices through a variety of processing procedures such as photolithography and ion implantation. When layers of different composition are juxtaposed, or when desirable constituents are introduced in a controlled manner, the possibilities multiply.

Figure 1a *1b*

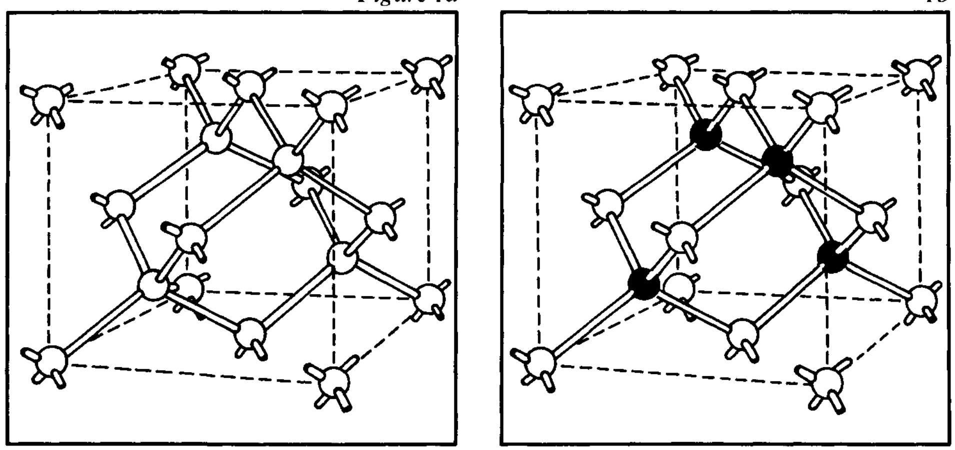


Figure 1. The similar crystal structure of silicon and gallium arsenide, two basic semiconductor materials used for VLSI fabrication.

a. *The "diamond" lattice structure is seen in the single-element semiconductors silicon and germanium.*

b. *The "zincblende" lattice structure is seen in such compound semiconductors as gallium arsenide (GaAs), gallium phosphide (GaP), and indium antimony (InSb). For GaAs, for example, the Ga atoms are generally represented by the solid circles, and As atoms by the open ones.*

In the work in my laboratory at Cornell we rely particularly on two techniques for growing "tailor-made" compound semiconductor materials: *molecular-beam epitaxy* (MBE) and *organometallic vapor-phase epitaxy* (OMVPE). The outstanding advantage of MBE and OMVPE is that they make it possible to grow layers of single-crystal films with certain desired characteristics. For example, a layer of one compound semiconductor can be grown on top of a layer with a different composition; the interface

". . . specimens as thin as one atomic layer . . . can be constructed."

between the layers is called a *heterojunction* (see Figure 2). Abrupt interfaces at heterojunctions are wanted because they are capable of defining features on a size scale of a few atomic layers. Likewise, it is desirable to have abrupt changes in the *doping profile*—the distribution of ions that are incorporated into the host semiconductor material to form particular structures (see Figure 3). Features such as these, grown with MBE or OMVPE, yield structures with submicron dimensions in the growth direction. Lithography can then be used on top of the grown layer to yield structures with submicron dimensions in the two other directions, parallel to the surface.

SOPHISTICATED EQUIPMENT AND A VIGOROUS PROGRAM

Two MBE machines and one OMVPE machine are available at Cornell. The first MBE system, a Varian 360, was funded by the National Science Foundation (NSF) under the original contract for NRRFSS. Later a larger MBE machine, the Varian Generation

Figure 2

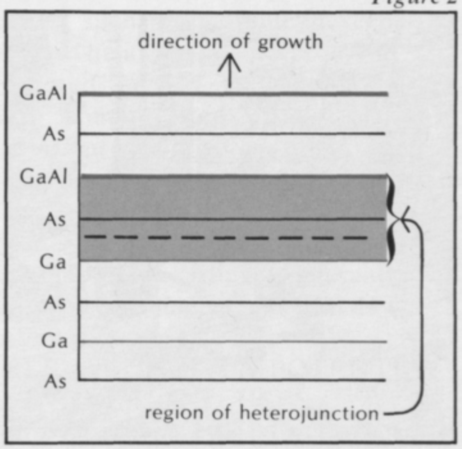


Figure 2. A representation of a heterojunction in an epitaxially grown semiconductor material. In a gallium arsenide crystal, for example, the Ga and the As atoms form alternating layers (see Figure 1). But if the composition were to be changed during the growth process—to an alloy of aluminum and gallium arsenides, for example—there would be an interface, called a heterojunction, between the two crystalline forms. Such an alloy might contain, for example, 40 percent AlAs and 60 percent GaAs, and be denoted as $Al_{.4}Ga_{.6}As$.

Figure 3

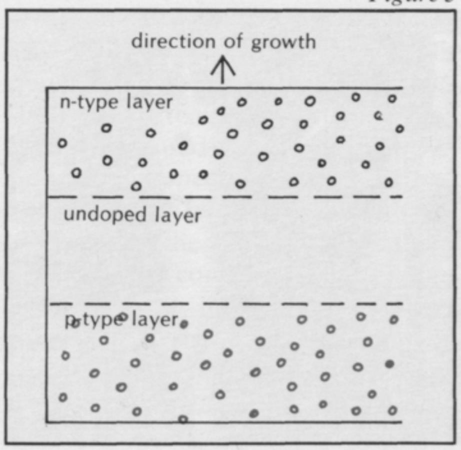
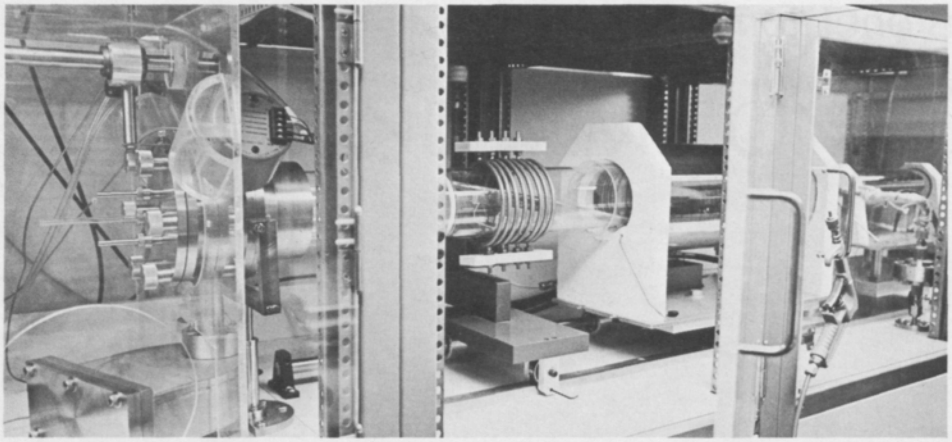
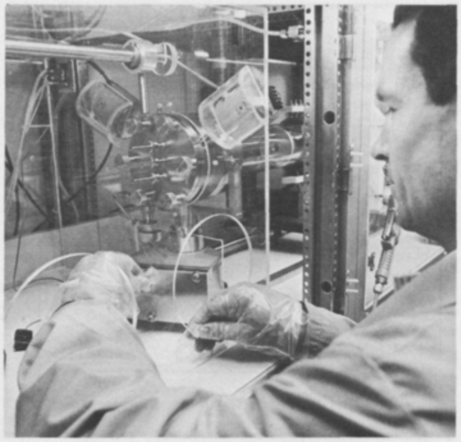


Figure 3. A representation of doping profiles. The dopants, which are ions, are incorporated in a controlled manner into the host semiconductor material (such as silicon or gallium arsenide) so as to form desired electronic structures (such as transistors). Abruptness in the ion-density changes makes it possible to reduce the physical size of electronic devices. In the diagram, black dots represent donor ions, which create an n-type layer, and red dots represent acceptor ions, which create a p-type layer.





Equipment important to the research on compound semiconductor materials is available at Cornell.

Above: This organometallic vapor-phase (OMVPE) machine is used for growing thin semiconductor layers with the desired characteristics.

Right: Using the OMVPE is D. Ken Wagner, one of the Cornell developers of the machine.

Below: A postdoctoral researcher operates the Varian 360 molecular-beam epitaxy (MBE) machine, one of two such systems in laboratories at Cornell.

II, was purchased with Department of Defense (DOD) funds provided through Cornell's Joint Services Electronics Program (JSEP) and some affiliated programs. The OMVPE machine was also funded mainly by JSEP and affiliated programs.

The MBE systems are essentially turn-key instruments, ready to operate. The OMVPE machine, not available in that form, was completely developed and constructed at Cornell in a cooperative effort by faculty and senior staff members and Richard J. M. Griffiths of England's Royal Signals and Radar Establishment, who spent nine months at Cornell as an expert consultant on the project.

In both the MBE and OMVPE areas, senior staff members on long-term appointments are responsible for training graduate students in the use of the systems, as well as for safety provisions and equipment maintenance. Colin E. C. Wood, the first of these staff members, worked in MBE for about five years; now in charge is Gary Wicks, with the temporary part-time assistance of A. Robert Calawa of Lincoln Laboratory. D. Ken Wagner, working with Professor Joseph M. Ballantyne, assumed responsibility for the cooperative research on the OMVPE system after Dr. Griffiths had left, and recently he was joined by J. Richard Shealy, one of our doctoral graduates.

Compound semiconductor materials, devices, and their circuits and applications constitute a large area of research at Cornell. Nearly half the graduate theses in electrical engineering, plus a number in applied physics and a few in materials science and engineering, are on this topic. Six faculty members and six senior staff members are heavily involved in JSEP projects, which account for one-fifth of the total funding in this technical area. The rest of the costs are covered by other DOD contracts, by substantial industrial contracts and fellowships, and by a limited amount of NSF funding. The following brief descriptions provide examples of what is being accomplished in the area of compound semiconductors and related devices grown by MBE and OMVPE.

BASIC STUDIES OF SEMICONDUCTORS

Fundamental research on the growth and properties of thin layers of crystalline semiconductors is the basis of technological development of microwave devices. Semiconductor compounds like GaAs, alloys like aluminum gallium arsenide (AlGaAs), single-crystal semiconductors like germanium, and single-crystal metals like aluminum are studied, along with their associated heterojunctions. Properties that are desired in semiconductor layers for electron devices are high purity and freedom from unwanted defects that trap electrons or holes, as well as abrupt or controlled composition and doping profiles.

With the MBE, crystals are grown at a rate of one atomic layer per second; specimens as thin as one atomic layer and materials with special periodic layers only a few tens of angstroms thick can be constructed. The materials studied include not only GaAs and AlGaAs, but semiconductor compounds and alloys containing other Group III and Group V elements such as indium and antimony: GaSb, InAs, GaInAs, AlInAs, and AlGaInAs, for example. The growth of AlInAs on GaInAs, forming a heterojunction important for optical-fiber communication systems, was pioneered in our laboratory. GaAs and AlGaAs have been studied also by OMVPE, and that system will be used for work with compounds and alloys containing indium and phosphorus.

This fundamental research entails characterization of the materials, which is carried out with equipment funded by JSEP and other DOD contracts. We measure pertinent properties such as photoluminescence at liquid helium temperature, and far-infrared internal photo emission; we use computerized deep-level (trap) transient spectroscopy; and we examine doping profiles by various methods including capacitance-voltage measurements. All these measurements are critical to guarantee the high performance of electron devices.

RESEARCH WITH POTENTIAL ENGINEERING USES

Among the specific structures being studied are *modulation-doped heterostructures,* which are promising for field-effect transistors (FETs). In modulation doping, ions are incorporated intermittently to form structures with the desired doping profiles. In modulation-doped heterostructures, ions have been left out of a channel on one side of the heterojunction, and electrons are contributed to this undoped region by the doping ions on the other side of the heterojunction (see Figure 4*a*). These electrons move along the channel parallel to the heterojunction, and because it is an

". . . we have achieved a switching time of 15 picoseconds, a record for this structure."

Figure 4a

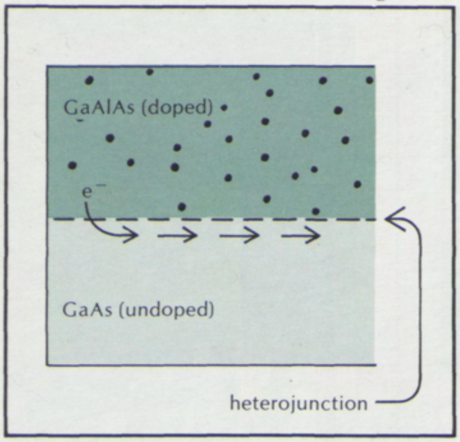


Figure 4b

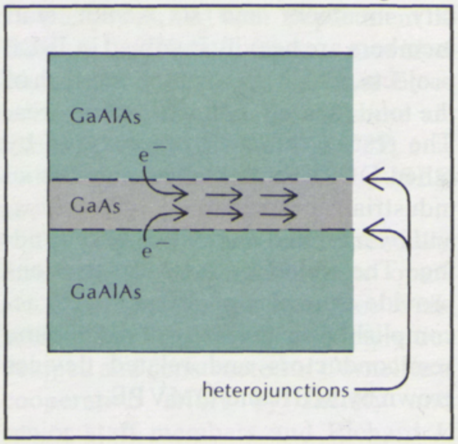


Figure 4. Heterostructures with engineering applications.

a. *In a modulation-doped heterostructure, electrons move out of a doped layer (AlGaAs in this example) into an undoped layer (GaAs), which has a lower potential energy. These electrons go into transverse resonant motion, but also can be made to move rapidly along a channel parallel to the heterojunction. (They remain in the channel because of the attraction of the ions on the opposite side of the potential barrier.)*

b. *In a quantum well, electrons are trapped between two heterojunctions; they go into resonant motion, but can also be made to move rapidly along the channel. The quantum well, 15 to 500 Å wide (equivalent to 12 to 400 atom layers), is one of the smallest thicknesses that can be made reproducibly.*

open path, they have high mobility and saturation velocity. The modulation-doped structures that have been studied so far are AlGaAs/GaAs and AlInAs/GaInAs.

Heterojunction bipolar transistors with the high-frequency and high-gain performance needed for satellite communications are another kind of device being grown by MBE. Such devices are also being tested for high-speed phototransistors used in communication systems based on fiber optics. In devices of this kind, the electrons pass over the heterojunction potential step, acquiring kinetic energy to send them quickly through the transistor. In our laboratory these devices have been grown using AlGaAs/GaAs and AlInAs/GaInAs.

Structures that have been grown and studied for use in various microwave and optical devices include not only single heterojunctions, but also *quantum wells* (see Figure 4*b*), which are very narrow channels formed between two heterojunction potential barriers. Here at Cornell quantum wells as thin as 15 Å—among the smallest useful man-made structures ever produced—have been successfully grown, and tested for photoemission. An aspect of the Cornell research in this area is the development of lasers based on various quantum-well structures; such lasers have potential use for modulating light emission in very high-speed optical-fiber communication systems.

BALLISTIC ELECTRON MOTION: AN ORIGINAL IDEA

An important concept based on the Cornell research on compound semiconductors is that these materials allow electrons to move at very high ballistic velocities. In fact, electrons can travel at speeds about six times their normal velocity, a capacity of very great importance for the fabrication of high-speed electronic devices.

This concept of ballistic electron motion developed out of studies, made five years ago, of electron dynamics across short GaAs structures. These studies indicated that electrons accelerated in semiconductor materials can preserve a kinetic energy nearly equal to their potential drop, and that the electron momentum remains nearly in the desired direction. It was shown that in lightly doped GaAs, electrons accelerated by limited voltages applied across a distance of 0.4 micrometer or less achieved an average velocity of at least 4 X 10^7 centimeters per second. This compares with an average velocity of about 1.2 X 10^7 cm/sec for long devices in which electron transport is collision-dominated. An even greater velocity—an average of more than 7 X 10^7 cm/sec over distances less than 0.6 micrometer—can be reached when electrons in lightly doped GaAs are quickly accelerated across a potential step and allowed to drift rapidly in a weak electric field. Detailed modeling of devices with ballistic electrons has been completed recently in Japan, verifying the Cornell concept.

The idea of utilizing fast ballistic injection of electrons has led to the

Figure 5

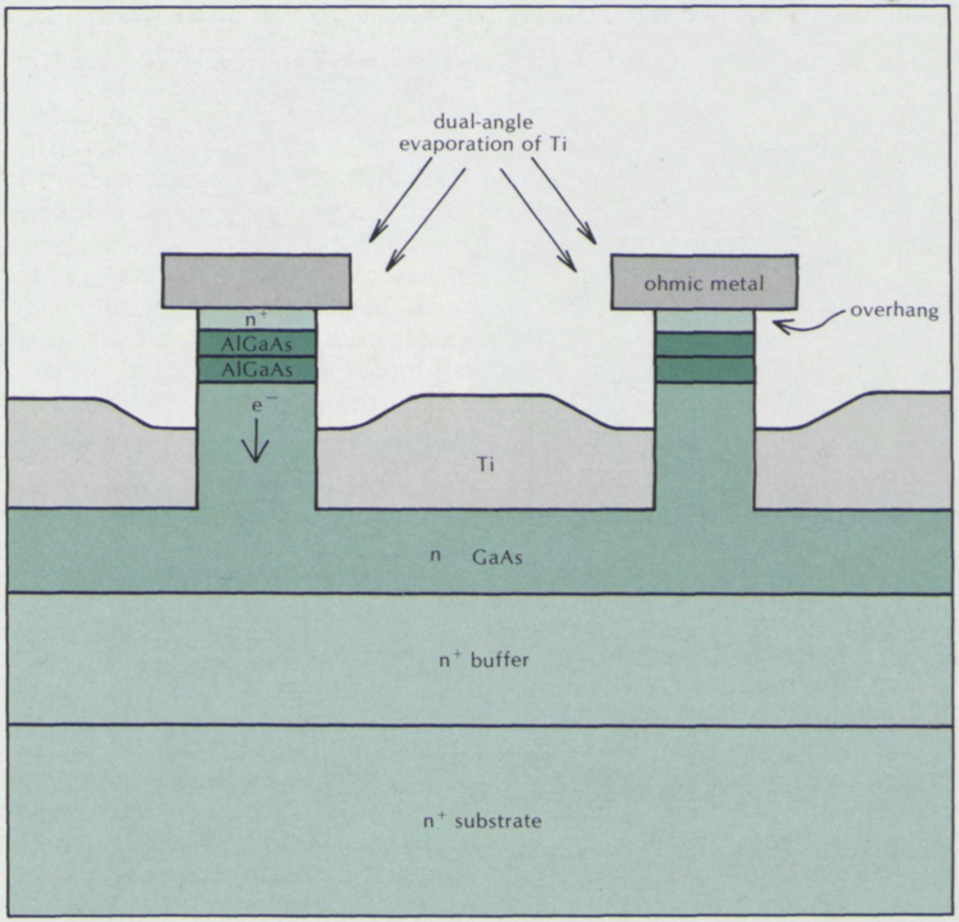


Figure 5. A vertical field-effect transistor (FET), in which electrons travel at ballistic speed. First an ohmic metal (such as germanium plus gold) has been deposited in strips on top of the structure. Then vertical channels have been etched in eptiaxially grown layers of semiconductor material (such as aluminum gallium arsenide). Finally, a metal like titanium has been deposited by angle evaporation along the sides, forming a potential barrier called a gate. An overhang created by the etching process in turn causes an uneven buildup of titanium.

Electrons, whose source is the ohmic metal, travel down through the vertical channels at ballistic velocity. The drain is the heavily conducting n^+ buffer and substrate. (The n^+ buffer protects the semiconductor layers from unwanted impurities in the substrate.) Of the two grown AlGaAs layers indicated in the diagram, the upper one has an aluminum content that rises slowly from top to bottom; this makes it easy to raise the energy of the electrons. At the bottom of the lower AlGaAs layer, the abrupt reduction of aluminum content to zero abruptly reduces the energy, "shooting" the electrons ballistically downward into the GaAs.

A micrograph of such a device is shown in Figure 6.

invention in our laboratory of several devices, including heterojunction bipolar transistors with fast transits of electrons. Now the concept is being applied to *vertical FET transistors*, in which electrons travel at ballistic velocity through vertical channels in the semiconductor (see Figures 5 and 6). Future transistors of this kind are expected to operate at the high frequencies, near 100 GHz, that are needed for satellite communication systems.

Logic devices that run on very low power and are capable of switching in

Figure 6

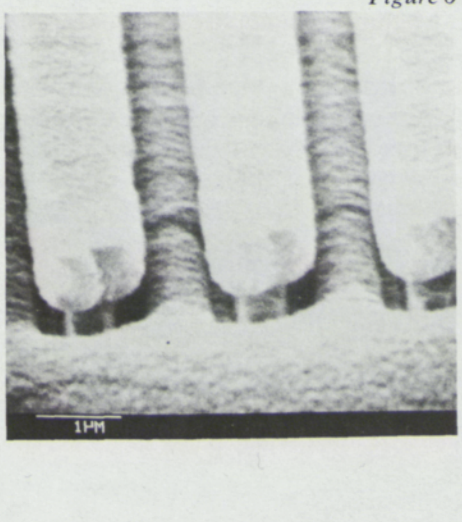


Figure 6. A field-effect transistor (FET) with a vertical channel structure. This experimental transistor is called BEST (for Ballistic Electron Schottky-gate Transistor)—an appropriate acronym, since it is considered the best for high-current-density, high-frequency operation. Features diagrammed in Figure 5—the channels, the ohmic metal layer, the overhang, and the evaporated-metal gate—are seen here. The gate length is 0.15 micrometer, the periodicity is 2 micrometers, and the channel width is 0.5 micrometer.

Ph.D. Research Yields World Record for Low Switching Time

Sadler

A Cornell student working on his doctoral research has achieved a result that advances state-of-the-art electronics. A submicron structure he has devised provides the fastest switching time ever recorded for an important type of semiconductor device.

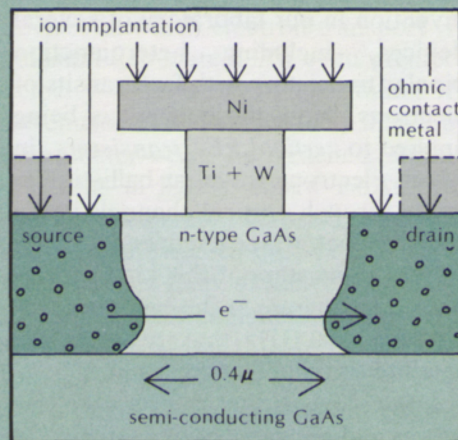
The graduate student, Robert Sadler, worked with Professor Lester F. Eastman on his thesis research. He completed his degree requirements in December and has begun work at the ITT laboratories in Roanoke, Virginia, where he will help develop a new division emphasizing high-frequency, high-speed electronic devices. At Cornell Sadler was a Hughes fellow and the research was a cooperative project with the Hughes Aircraft Company; Sadler worked during the summers at the Hughes research laboratory in Malibu, California.

According to Eastman, Sadler's work provides "what everybody in the industry is after—all the speed that is possible to get in a device that operates at room temperature." The device is a gallium arsenide doped channel field-effect transistor, and its special feature is what Sadler describes as a "T-gate ion-implanted self-aligned structure." It has a switching time of only 15 picoseconds (a picosecond is 10^{-12} or one trillionth of a second) at 300° K. The only device with a shorter switching time is the experimental modulation-doped heterostructure described in these pages by Eastman. With modulation doping, a T-gate structure such as the one Sadler worked on should produce devices with switching times of less than 5 picoseconds.

Sadler's work has also set a new world record for the lowest switching energy, which equals power dissipated multiplied by switching time. For one of Sadler's devices, this "power delay product," as it is commonly called, is 2.4 femtojoules (2.4×10^{-15} joule), the lowest value yet reported for any device operating at room temperature.

Eastman commented that the thesis is "one of the strongest I have ever seen," and that the research results are "among the most outstanding that have been achieved so far at the national submicron facility at Cornell."

Below: A schematic, not drawn to scale, showing the T-gate structure. Fine-line electron-beam lithography is used in the fabrication of a metallic structure with two layers—nickel and a titanium-tungsten alloy. The alloy is etched away a precise distance to form the T-shaped overhang, which acts as a mask during subsequent implantation of ions into the semiconductor (GaAs) material beneath it. Source and drain contacts are formed by placing ohmic contact metal over the GaAs. Electrons move under the influence of an applied voltage and accelerate to very high velocities in the unobstructed GaAs.

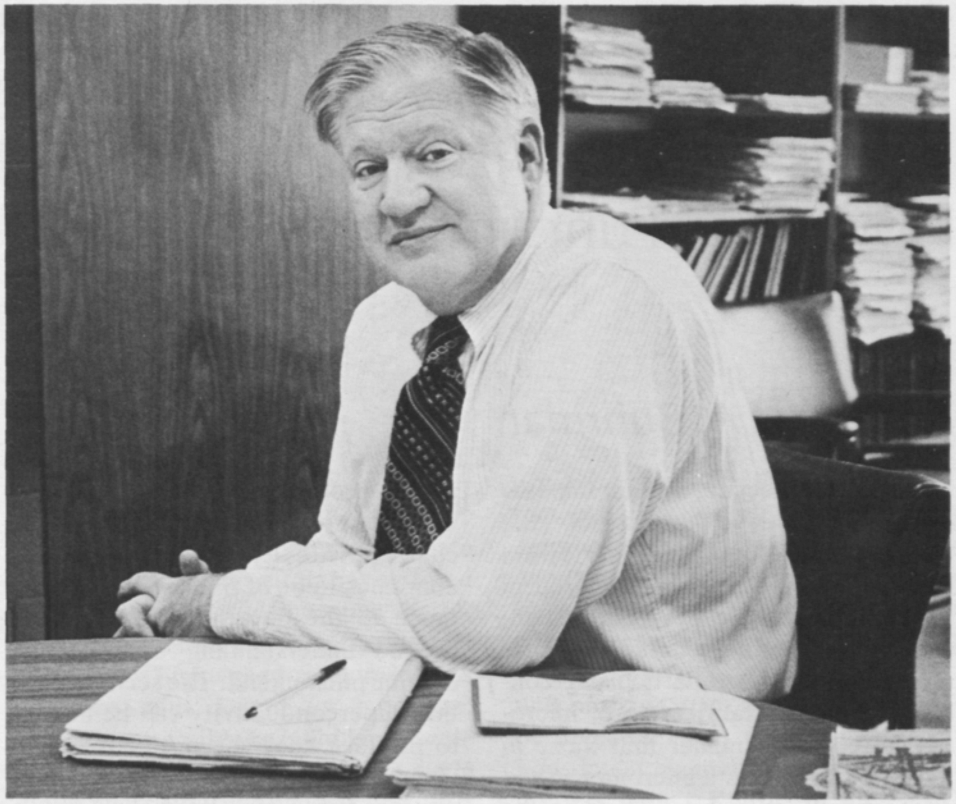


less than 5 picoseconds should also be possible with various configurations of this FET. This speed is anticipated with use of the modulation-doped AlGaAs/GaAs structure and closely spaced ion-implanted source and drain contacts. We have made significant progress in this direction. Using short (0.75-micrometer) doped channels rather than modulation-doped channels, we have achieved a switching time of 15 picoseconds, a record for this structure. (See the insert on the facing page.)

A MAJOR CORNELL EFFORT AND ITS RESULTS

The high technology of MBE, and to a less extent OMVPE, that has been developed at Cornell opens the way to important new electron devices based on compound semiconductors with submicron features. As I have briefly discussed, devices now being developed here include various transistors for applications at high frequency or high speed: improved conventional FETs, modulation-doped FETs, vertical FETs with ballistic electron injection, and heterojunction bipolar transistors. Also under study are high-speed optical devices, such as detectors and quantum-well lasers.

In addition to advancing the technology itself, this program has another important function, which is to provide a focus for graduate research and education. Cornell graduates who participate in the fruitful project work will be leaders in the development of submicron electronics. Directly and indirectly, the Cornell program in semiconductor materials and devices looks to the future.



Lester F. Eastman, professor of electrical engineering, received three degrees from Cornell and has been a member of the faculty since he completed the doctorate in 1957.

His work has included an active program of research in microwave solid-state electronics since its beginnings. At the present time he directs one of the largest research programs in the College of Engineering. Included is an investigation in compound semiconductor materials and electronic devices that is funded by more than $2 million a year from the Joint Services Electronics Program; other affiliated programs; and projects supported by several industries. Eastman's research is carried out partly in conjunction with the National Research and Resource Facility for Submicron Structures (NRRFSS) at Cornell.

Eastman has had experience in industrial research and development as well. He was a founder of Cayuga Associates, developers of prototype microwave semiconductor devices; he has been a consultant to other electronics manufacturers; and he has spent leaves at the RCA Laboratory and at Lincoln Laboratory of the Massachusetts Institute of Technology.

He is a fellow of the Institute of Electrical and Electronics Engineers and was that society's national lecturer on electron devices during 1983. He serves on several national and international conference committees and is a member of the U.S. Government Advisory Group on Electron Devices.

SUPERCONDUCTORS IN MICROSTRUCTURES

How They Function and What They Can Do

by Robert A. Buhrman

Over the past decade, a major impetus driving the development of the technology of submicron fabrication has come from scientists involved in the study and application of superconducting electronic phenomena. These scientists have been particularly concerned with the fabrication of microstructures even smaller that those in the range just below a micrometer, and consequently they have been at the forefront in developing new fabrication technologies and in pushing those technologies to smaller and smaller dimensions. Along the way, they have established numerous "firsts," such as the production of the smallest working electronic device, the smallest wire, the smallest electrical contact.

This concern with the infinitesimal has been motivated by two related facts. One is that superconductivity is characterized by length scales that typically range from less than 0.1 micrometer (μm) to somewhat greater than one μm. These lengths are the distances over which parameters (such as magnetic fields or current density) can vary in a superconductor. Being able to probe the response of a superconductor on a scale smaller than these characteristic lengths has been and continues to be of fundamental importance to the development of an improved understanding of superconducting phenomena. The second fact is that superconductivity can be utilized to produce specialized electronic devices of unparalleled speed and sensitivity. It has long been known that, up to a point which we are now only just approaching, this speed and sensitivity is inversely proportional to the size of the device structure. Thus we have both a scientific and a technological imperative to continually seek to shrink the size of the superconducting microstructures.

SUPERCONDUCTORS AND THE JOSEPHSON EFFECT

The superconducting state is exhibited by many metals when they are cooled to temperatures within five or ten degrees of absolute zero. Perhaps the most striking characteristic of this state is that there is no resistance to the flow of electricity up to some maximum current, called the critical current.

In 1962 Brian Josephson made two rather startling predictions about what would happen when two superconductors were weakly connected together. In essence, the first prediction was that when the connection, or *Josephson junction* was made, a small dc electrical current could flow between the superconductors with no resistance. Unlike a current in a single. superconductor, the maximum possible amplitude of this supercurrent could be modulated *periodically* by very small applied magnetic fields. This has become known as the *dc Josephson effect*.

If a current greater than the maximum possible supercurrent is caused to flow, the connection begins to act much like a normal resistor: the dc supercurrent disappears and an electrical voltage appears across the connection. Josephson's second prediction applied to this situation. The prediction was that while the dc supercurrent would now be zero, there would be an ac supercurrent oscillating

". . . a unique combination of unparalleled switching speed and very low power dissipation."

back and forth between the two superconductors. The frequency of this oscillating supercurrent would depend directly on the electrical voltage across the connection and on some fundamental constants of nature. The relation is that for every additional microvolt (10^{-6} volt) that appears across the connection, the frequency of oscillation increases by 485 megahertz (10^6 hertz). This oscillation, which can continue to frequencies greater than 10^{13} hertz, is known as the *ac Josephson effect*.

THE USEFULNESS OF JOSEPHSON EFFECTS

A wide range of electronic devices that utilize the dc and ac Josephson effects can be produced. These include magnetometers, voltmeters, voltage-tuned microwave oscillators, microwave and millimeter wave mixers, and infrared detectors, as well as digital electronic circuits.

Josephson junctions offer a unique combination of unparalleled switching speed and very low power dissipation that has for some time made them the object of a major research and development effort directed toward the mainframe supercomputer of the late 1980s. Recently this effort has suffered a significant setback because of difficulties encountered in designing and fabricating high-speed random-access memory with Josephson junctions. While it is possible to build large-scale logic circuits that offer machine cycle times well below one nanosecond (10^{-9} second), solving the memory problem will require new memory circuit designs or new knowledge and application of device physics. This difficulty has pushed the eventual construction of a superconducting supercomputer further into the future; but it also presents new research opportunities.

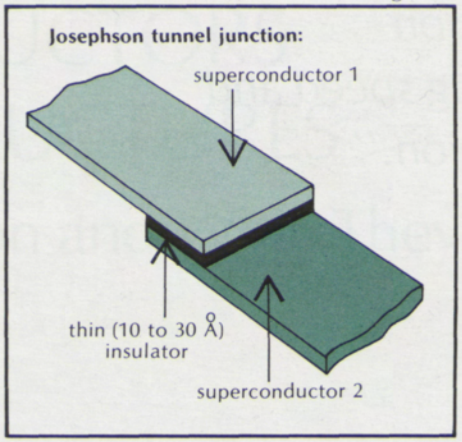
Actually, the development of circuits and sensors based on the Josephson effects has proceeded rapidly in recent years. These devices include small-scale, very-high-performance digital circuits such as analog-to-digital converters; very-high-speed analog circuits; and very-high-sensitivity electromagnetic sensors. As an example of what can be achieved now with the Josephson effect, we can consider the superconducting magnetometer. The sensitivity of this instrument was recently brought close to the absolute limit set by the uncertainty principle—to within a factor of three or four of the smallest unit of magnetism that could possibly be detected. This magnetometer can now detect magnetic field charges that are less than 1×10^{-13} of the earth's magnetic field. The quantum-mechanical limit in high-frequency millimeter-wave detectors has also been achieved recently. And since the ultimate switching speed of a Josephson junction can be approximately 0.1 picosecond (10^{-13} second), further advances in very-high-speed digital electronics are also probable.

The object of all research on Josephson devices is to produce reliable, high-quality Josephson junctions with very small dimensions. The key to successful basic research into superconducting electronic phenomena is to attach very small electrical probes to superconducting structures. These tasks have been a major focus of

Figure 1. A schematic representation of a Josephson tunnel junction. The junction is at the area of overlap between two films of superconducting metal which are separated by a very thin layer of insulating material. A weak electrical connection is made by electrons tunneling through the insulator.

Figure 2. Edge junction fabrication. Steps in the process are illustrated (not to exact scale). (a). An Al_2O_3 layer is deposited to act as a mask during etching of a niobium (Nb) film. (b). A faceted edge is left after the exposed Nb has been etched away. (c). Using a stencil fabricated by electron-beam lithography, a very thin oxide layer is formed on a small section of the Nb edge by exposure to a beam of ionized molecular oxygen. Then a second metal film (lead plus bismuth) is deposited through the stencil. The Pb-Bi is the counterelectrode; the layering of Nb, Nb_2O_5, and Pb-Bi constitutes the second Josephson junction, with dimensions that are determined by the thickness of the Nb layer and by the width of the fabricated stencil.

Figure 1



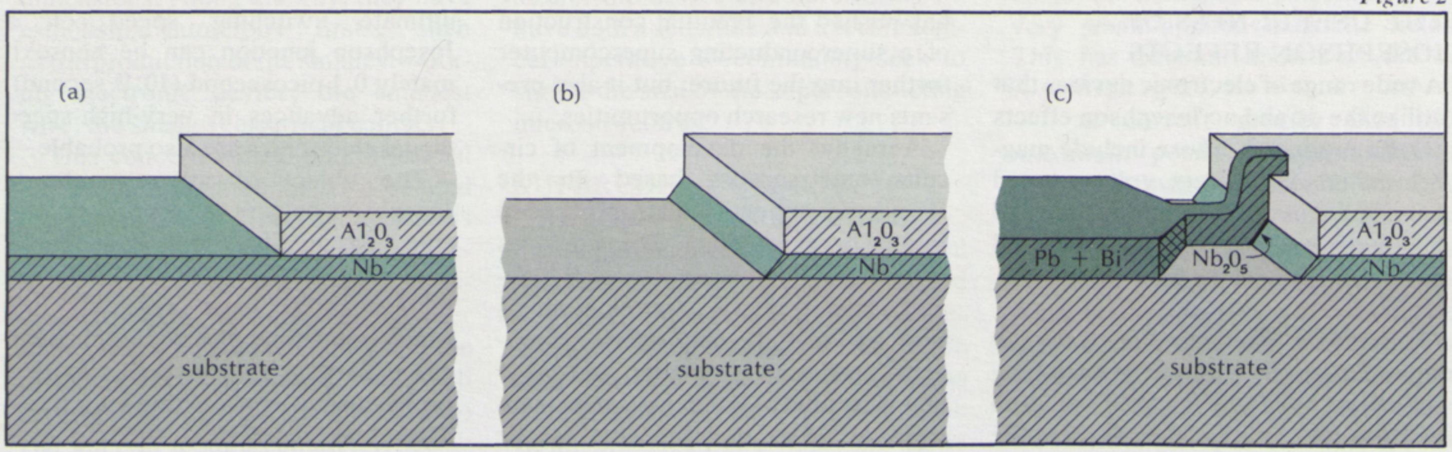
our research at the National Research and Resource Facility for Submicron Structures (NRRFSS) here at Cornell.

A CORNELL RECORD FOR FAST SWITCHING TIME

The most successful form of a Josephson junction consists of two superconducting metal films separated by a very thin insulator. In building the structure, one metal film is coated with the insulating material, which is usually an oxide of the metal. This material is typically five to ten atomic layers thick, and its average thickness often must be controlled to better than 0.5 angstrom (one Å is 10^{-8} centimeter). The insulated metal is then covered by another superconducting metal film. The Josephson junction is in the area of overlap between the two metal films (see Figure 1). Since electrons can tunnel through the very thin insulating material from one layer of metal to the other, this structure provides the means of attaining the required weak connection between the two superconductors.

The speed of a Josephson junction is a very strong function of how thin the insulating tunnel barrier can be made while still retaining the Josephson effects. Recently we developed a new process for growing very thin oxide layers that yields junctions with very short switching times. The process consists of directing a precisely controlled beam of ionized oxygen molecules onto a clean surface of a metal film in a high-vacuum environment; properly done, it yields very good oxide layers that are only a few atoms thick and have an average

Figure 2



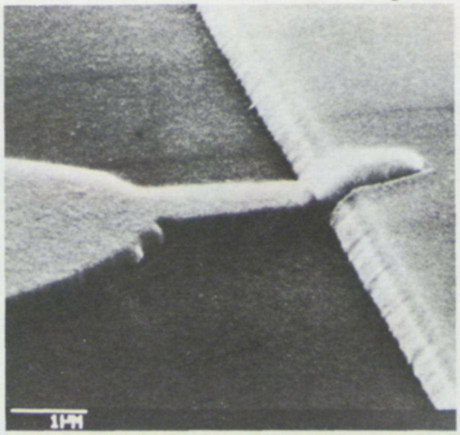
thickness controlled to within 0.5 Å. With this process we have produced junctions with switching times (indirectly measured) less than 0.1 picosecond. This apparently sets a world record.

AN EDGE JUNCTION FOR BETTER PERFORMANCE

The performance of Josephson junctions in device applications is also very strongly a function of how small the cross-sectional area of the junction is. If everything else is held constant, the smaller the junction the better—at least until the junction area is less than about 10^{-10} square centimeter. A graduate student, Alan Kleinsasser, recently developed a technique for successfully producing such small junctions; the fabrication steps are illustrated in Figure 2.

The procedure is as follows. First, a thin (about 0.1 μm) film of a superconductor metal, usually niobium (Nb), is partially covered by a relatively thick (about 0.2 μm) film of insulating material, such as aluminum oxide. The exposed portion of the Nb film is then etched away, leaving only the edge of the covered Nb film exposed. Next, microlithography techniques are used to define a stencil that has a very small gap crossing the exposed edge; the oxygen-ion-beam process is used to produce a very thin oxide layer through this stencil, and then a second metal—such as lead plus bismuth—is deposited through the stencil. When the stencil is removed, the result is a Josephson "edge" junction, in which one dimension of contact is defined by the thickness of the original Nb film, and the other by the microlithography process. A micrograph of such a junction is shown in Figure 3.

Figure 3



This edge-junction technique originally utilized photolithography to produce junctions with an area of about 10^{-9} square centimeter. Subsequently, another graduate student, Brian Hunt, improved the process by substituting electron-beam lithography, and was able to produce junctions 10^{-10} square centimeter in area. Such junctions are currently being used in our laboratory in a variety of electromagnetic-sensor experiments.

TOWARD A NEW TYPE OF TRANSISTOR

A basic question regarding Josephson junctions that is currently of considerable interest concerns the manner in which the electrons that have tunneled through the barrier come into equilibrium with the environment of the second metal film. A better understanding of this equilibration process could possibly lead to the development of a new type of superconducting transistor. Study of this process requires that a second junction, to serve as a probe,

Figure 3. A micrograph of a Josephson edge junction. This was made with a scanning electron microscope (SEM).

Figure 4. A schematic representation of a double edge junction. The heavy arrows indicate the conduction path of injected electrons.

Figure 5. A SEM micrograph showing the structure of a double edge junction.

Figure 4

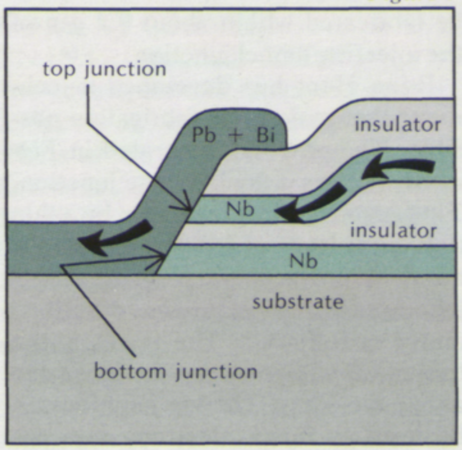
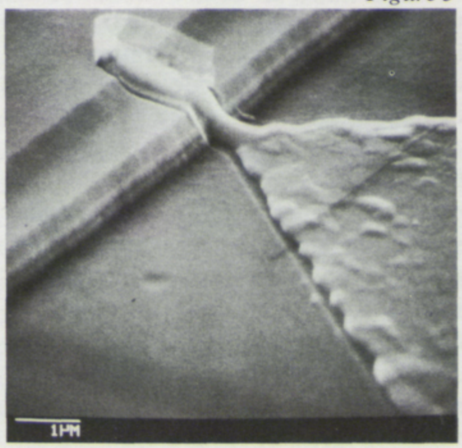


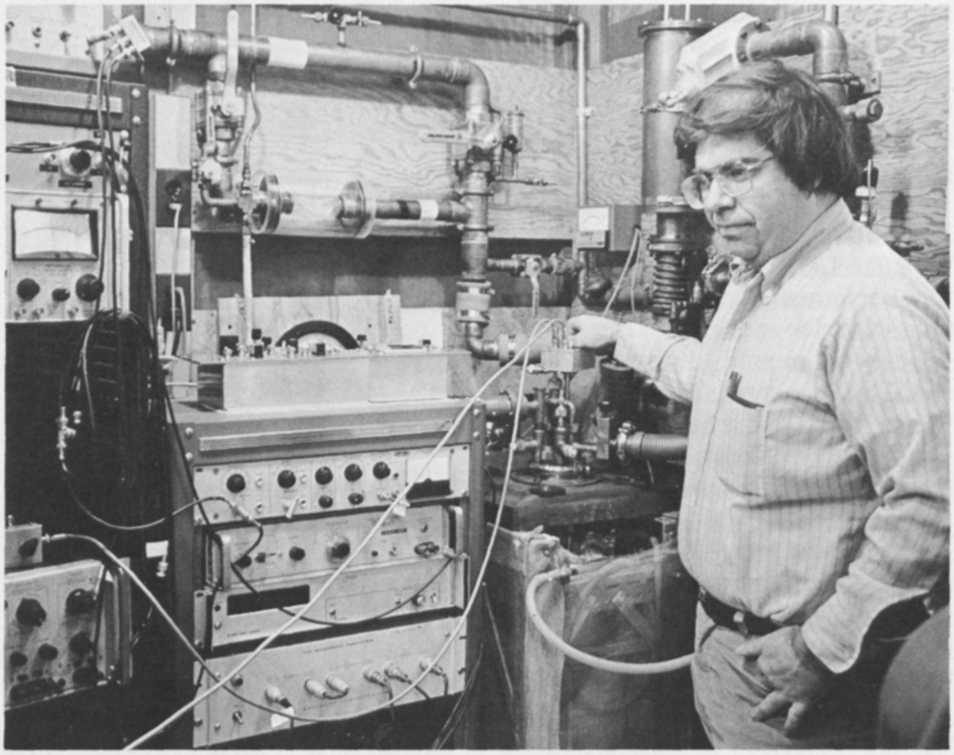
Figure 5



be fabricated within about 0.2 μm of the injecting tunnel junction.

Brian Hunt has developed a technique that makes this fabrication possible. The process, illustrated in Figure 4, creates a double edge junction. First, two Nb films separated by a thin (0.05 μm) layer of insulating material are laid down, and then the edge-junction fabrication process described above is followed. The result is the formation of two edge junctions, one above the other. The top junction can be used to inject electrons into the shared top electrode. The bottom junction can be used for probing: by examining the current-voltage characteristic of the bottom electrode, information can be obtained regarding how far the equilibration process has proceeded 0.05 μm downstream from the injection site. A micrograph of one of these structures is shown in Figure 5. With these double edge-junction structures, we have been able to examine nonequilibrium processes in superconductors on a length scale that has never before been reached.

I have given two examples of the kind of research in superconductivity that can be accomplished with the use of equipment available at NRRFSS. By investing in the development of microfabrication technology, we at Cornell have been able to realize rich scientific and technological dividends in the field of what we sometimes call micro-superconductivity research. Currently, smaller and more complicated microstructures than those described here are being designed. Our expectation is that by continually pushing the state-of-the-art of microfabrication technology, we will continue to make rapid progress in understanding superconductivity and in developing new or better applications of superconductivity phenomena.



Robert A. Buhrman, a specialist in solid-state and low-temperature physics, is a professor of applied and engineering physics at Cornell. He has been closely associated with the National Research and Resource Facility for Submicron Structures (NRRFSS) since its beginnings; he has served as associate director of the laboratory and supervised the User Research Program, in addition to conducting a research program. This year he is continuing his research at NRRFSS while on sabbatical leave.

Buhrman holds the B.E.S. degree in engineering physics from The Johns Hopkins University and the M.S. and Ph.D. degrees in applied physics from Cornell. He has been a member of the faculty here since he received the doctorate in 1973.

MICROFABRICATION FOR GUIDED WAVE OPTICS

by Gregory J. Sonek and Joseph M. Ballantyne

Communication by light waves is an idea that has been with us since the time of the ancient Greeks, who observed that a glass rod is capable of guiding light. In the nineteenth century, English scientists discerned that a narrow jet of water could be a medium for light transmission. And nearly three decades ago, the prototype of the present-day optical fiber came into being.

Why communicate optically? Since the information-carrying capacity of electromagnetic waves increases with frequency, the transmission and processing of signals at optical frequencies can be performed over a very large bandwidth, with low transmission losses and immunity from electromagnetic interference.

Advances in several important areas have made optical communications a reality in recent years. There is the *low-loss optical fiber,* a guiding medium that is capable of providing long-range signal transmission with minimal attenuation at the operating wavelengths of the diode laser. There is the *semiconductor diode laser,* a source of coherent light waves, which has proved to be an extremely reliable, highly efficient, and long-lived generator of light. And there is an entire family of miniaturized optical components that are being developed for future applications in high-performance optical communication systems.

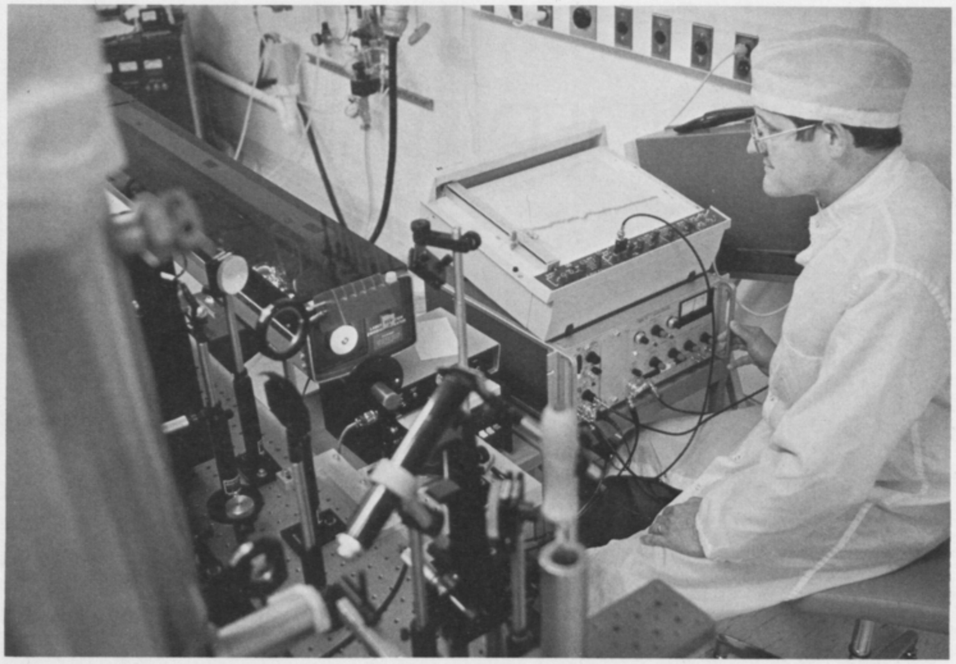
Such optical communication devices, required for processing and manipulating the light signals, are made possible by the fusion of two separate technologies—microwave engineering and thin-film optics. Concepts from both of these areas have been applied to the development of thin-film waveguides and other passive optical structures. The integration of many different components on a common substrate results, ultimately, in an *integrated optical circuit,* in which planar thin-film optical structures have replaced the bulkier components commonly found on an optical bench. The term *integrated optics* is used to describe the studies of thin-film phenomena and the optical devices based on that research.

WORK AT CORNELL ON INTEGRATED OPTICS

The development of integrated optical devices is one of the ongoing research efforts at the National Research and Resource Facility for Submicron Structures (NRRFSS) at Cornell. Here optical sources such as diode lasers, and light-guiding elements such as thin-film waveguides, are developed and tested.

Although many different materials can be used for fabricating optical components, crystalline layers of semiconductors such as gallium arsenide (GaAs) and aluminum gallium arsenide (AlGaAs) have the advantage of allowing the integration, on the same substrate, of both a laser and a waveguide or another component. This is possible because both devices can be made using the same materials. One merely has to change some parameter, such as impurity-atom concentration or the fraction of aluminum in a given layer, to produce layers capable of guiding light, or even generating it.

In attempting to apply highly sophis-



In the NRRFSS laboratory, Professor Ballantyne demonstrates an optical technique based on photoluminescence. The technique is used to characterize materials for the production of semiconductor lasers and optical waveguides.

"We have been able to fabricate periodic structures . . . with periods as small as 230 nanometers."

ticated microfabrication tools such as electron-beam lithography, holographic interferometry, or reactive-ion etching to the production of guided-wave optical devices, one is confronted with problems that are significantly different from those encountered in the production of integrated electronic circuits. The most serious difficulty in the patterning of optical structures is in obtaining good edge definition. It is estimated that edge variations of 50 nanometers (50×10^{-9} meter) would lead to losses of 10 percent per centimeter. Therefore, edges that are smooth to 10 or 20 nanometers are required if light-scattering from waveguides is to be minimized and low-loss transmission achieved. Among other requirements is a large aspect ratio (the ratio of length to width) for waveguides, and high absolute accuracy in the period and groove spacing of periodic structures.

LITHOGRAPHIC TECHNIQUES FOR OPTICAL DEVICES

A lithographic process capable of meeting all the requirements for optical device patterning does not yet exist, but several different lithographic techniques have produced excellent results for specific applications.

Electron-beam lithography is one of the promising patterning techniques, though it is not without drawbacks. For example, it is desirable for some applications to have highly curved waveguides with smooth sidewalls, but the standard electron-beam pattern generator is not capable of producing smooth continuous curves. Bends and curves must be approximated as "primitive" shapes such as rectangles and trapezoids, which the pattern generator is capable of producing, and the resulting waveguide has significant edge roughness and shows substantial scattering losses. Examples of several waveguides patterned with electron beams are shown in Figure 1. In these so-called *rib waveguides* the light-guiding layer, GaAs, is sandwiched between two layers of AlGaAs. This geometry, known as a *double heterostructure,* confines the light and is capable of guiding it across an entire optical chip.

A study of how various processing techniques affect losses on electron-beam-patterned waveguides is presently underway. Low-loss guides will eventually be used as tuning elements for semiconductor lasers or as modulators in integrated optical circuits.

Laser holography, an optical interference exposure process, is another lithographic technique that is used extensively in our laboratory. We have been able to fabricate periodic structures—an important element in guided-wave optics—with periods as small as 230 nanometers. Even finer periods have been achieved by using a novel period-division scheme that allows one to effectively halve the period of the grating.

One use for a periodic grating is as a coupler for diffracting light into a thin-film waveguide. This process is depicted schematically in Figure 2. Such

Figure 1a 1b

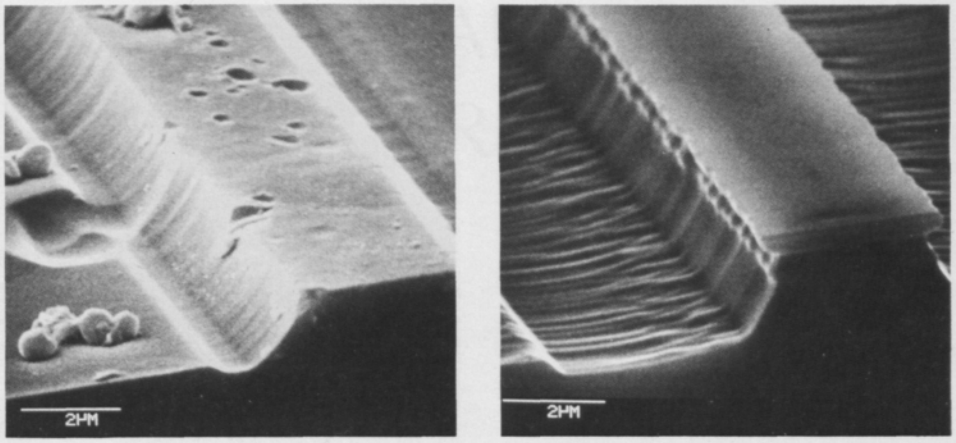


Figure 1. A micrograph of two rib waveguides—structures that provide confinement of light in two dimensions. The waveguide in a *was formed by ion milling, and the one is* b *was chemically etched.*

Figure 2

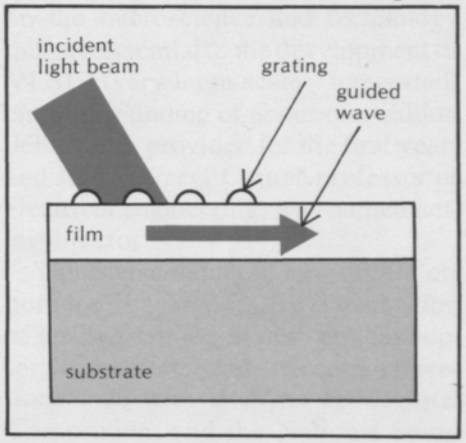
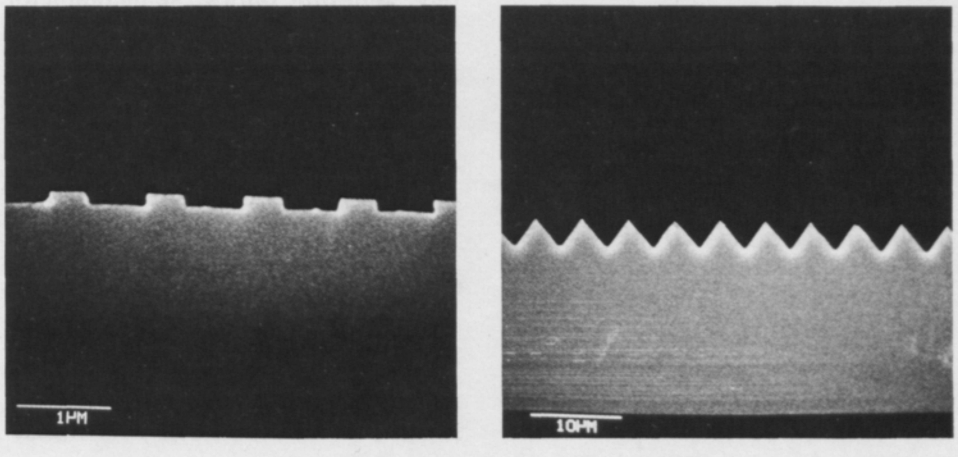


Figure 2. Schematic showing how a periodic grating can be used to couple light into a thin-film waveguide.

Figure 3. Profiles of gratings fabricated at Cornell by means of laser holography. Such profiles can be modified by various etching techniques.

Figure 3a 3b



gratings can also be used as end-reflecting mirrors in so-called "distributed Bragg reflector" semiconductor lasers, or as frequency-selective filters for multiplexing and demultiplexing (scrambling and unscrambling) light of many different frequencies. Examples of grating profiles that can be obtained with the laser holographic technique and additional processing steps are shown in Figure 3.

Integrated optics provides a good illustration of interdisciplinary research, for it draws on work from such diverse areas as optical fiber technology, thin-film optics, semiconductor physics, and advanced lithographic techniques. Integrated optics, with its great technological potential, also demonstrates the wide applicability of submicron techniques. Electronics is not the only technology to benefit from the resources of NRRFSS.

"... the fusion of two separate technologies—microwave engineering and thin-film optics."

Joseph M. Ballantyne is director of Cornell's School of Electrical Engineering and an active member of the National Research and Resource Facility for Submicron Structures (NRRFSS), which he helped organize. Gregory J. Sonek is a graduate student who is working with Ballantyne on the research described in their article.

Ballantyne received bachelor's degrees in both mathematics and electrical engineering from the University of Utah, and he earned the Ph.D. in electrical engineering at the Massachusetts Institute of Technology in 1964. He joined the Cornell faculty that year. His experience includes consulting and summer work with a dozen industrial firms and government laboratories in the areas of semiconductor, ferro-electrical, magnetic, and optical materials and devices. He has been a National Science Foundation senior fellow at Stanford University and was elected a senior member of the Institute of Electrical and Electronics Engineers.

Sonek studied at the Polytechnic Institute of New York for the B.S. degree in physics, granted in 1979. He received the M.S. in applied physics from Cornell in 1982. He has worked summers at the Naval Weapons Center in China Lake, California, and at the Harry Diamond Laboratories in Adelphi, Maryland. He is a member of the American Physical Society and the honorary societies Sigma Pi Sigma and Sigma Xi.

MULTIDISCIPLINARY RESEARCH: KEY TO PROGRESS AT NRRFSS

The national submicron facility, centered in Knight Laboratory, is a highly visible physical manifestation of Cornell's research and development in microstructures fabrication, but in reality it is only a part of a large multidisciplinary research effort in microelectronics and semiconductor materials, devices, and circuits at the University. In fact, it was the existing research base that in 1977 won for Cornell the competition for the National Research and Resource Facility for Submicron Structures (NRRFSS).

The current effort comprises over $8 million in research each year, and draws faculty, students, and staff from at least ten academic departments at Cornell. Research is sponsored in both individual faculty projects and "umbrella" programs under which an agency or industrial source provides a single, large grant to the University for work directed along certain lines. Such a target area often cuts across the traditional disciplinary boundaries, and in these cases the result is a unique and fruitful multidisciplinary collaboration. In the area of microelectronics, these special programs at Cornell include the Semiconductor Research Corporation (SRC) Program on Microscience and Technology, the Joint Services Electronics Program (JSEP), and the Program on Submicrometer Structures (PROSUS).

Another essential component is the graduate-studies program in microelectronics and related fields, which prepares students for research and teaching leadership in industry and academia. The graduate program draws on many resources besides the state-of-the-art NRRFSS facilities: on the extensive course offerings of a number of academic departments, the supervision by faculty members who are leaders in their fields, and direct or indirect support from industry and government.

Various parts of the overall program are discussed in the following sections.

THE CORNELL-SRC CENTER OF EXCELLENCE

In the fall of 1982, Cornell was selected by SRC as the site of one of its first "centers of excellence" for research on the microscience and technology that are essential to the development of VLSI (very-large-scale integrated) circuits. Funding of about one million dollars was provided for the first year, and Jeffrey Frey, Cornell professor of electrical engineering, was named acting director.

The Semiconductor Research Corporation is a cooperative organization of leading United States semiconductor, computer, and telecommunications industries such as IBM, Intel Corporation, and the National Semiconductor Corporation. SRC was organized with the intention of supporting research that both increases the knowledge base and provides for the training of new researchers in fields of engineering and physical sciences that are related to semiconductors and computers. An additional benefit was considered to be better interaction among industrial and academic researchers in a field that is now central to modern electrical engineering.

Now in its initial phase, the new center at Cornell encompasses work of nineteen faculty members in four

CURRENT RESEARCH AT THE CORNELL-SRC CENTER

Principal Investigators	Projects
Applied and Engineering Physics:	
Robert A. Buhrman	Thin Oxide Layers
Electrical Engineering:	
Joseph M. Ballantyne	Monolithic Optoelectronics for Interchip Communications
G. Conrad Dalman	Experimental Studies of Transmission Lines for Monolithic High-Speed Circuits
Jeffrey Frey	Multi-Level Integrated Circuits
Peter Krusius	Technology and Physics of MOS Devices; Molecular-Beam Epitaxy for Multi-Layer Device Structures Involving Silicon and Silicides
Charles A. Lee	Dual-Surface Thin Silicon Devices of 0.05 to 1.0 Micrometer Thicknesses
Edward D. Wolf	Reactive Ion-Beam Etching and Electromigration of Submicrometer Refractive Metal Silicide Structures
George J. Wolga	Semiconductor Materials Deposition and Processing Using Laser Photochemistry and Structure Modification
Materials Science and Engineering:	
Dieter G. Ast	Microdefects in CZ and FZ Silicon
John M. Blakely	Defects and Morphology at Interfaces
David T. Grubb	Multi-Level Interconnect Systems
James W. Mayer	Metallization, Interconnects, and Bonding
Arthur L. Ruoff	High Selectivity RIE and RIBE Based on Near-Surface Modification
David N. Seidman	Mechanisms for the Nucleation and Growth of Metal Silicides Produced by Thermal Treatments and/or Ion Irradiations
Physics:	
Neil W. Ashcroft	Theory of Periodic Submicron Structures
James A. Krumhansl, John W. Wilkins	Noise Mechanisms in Small Devices
Robert C. Richardson	Conduction Noise in Microstructures
Robert H. Silsbee	Physics of Metal-Array-Gate FET Structures

schools or departments (see the table listing faculty members and project topics). The center operates within the College of Engineering, and much of the experimental work takes place at NRRFSS.

It is anticipated that in future years funding will increase somewhat as SRC's specific goals and unified program are established. For example, the Cornell participants are formulating a study of the problems that will be encountered in production of a 16-megabit memory chip, which would be sixty-four times as dense as chips that are only now emerging from laboratories. According to Frey, an examination of the anticipated design and production problems "could utilize very well the basic research skills of the diverse corps of researchers that Cornell can bring together."

PROSUS: A MEDIUM FOR TECHNOLOGY TRANSFER

The industrial-affiliates program, PROSUS, was founded by the University in 1978 to provide United States industries with a "window" onto Cornell research in the fields of submicrometer and semiconductor science and technology. The aims included information exchange and a strengthening of interaction between industries and the University. The program would also provide some funding in support of the Cornell research and academic program in these areas, major capital and other support for NRRFSS (most of the research of interest would be carried out there), and seed money and equipment support for certain specific projects.

The program was organized by Cornell Professor Joseph M. Ballantyne (now the director of the School of Electrical Engineering). During its first year, there were twelve industrial members; now there are about thirty, representing nearly all the major companies in the semiconductor industry. More than forty Cornell faculty members are also associated with the program; their research comprises a wide diversity of projects, most of which are conducted at the submicron facility. The program, which is coordinated through NRRFSS, is now headed by Professor Jeffrey Frey, the associate director of NRRFSS for PROSUS and industrial relations. Senior Research Associate D. Ken Wagner serves as assistant director.

PROSUS industrial members have made generous donations of major equipment and have provided seed funding and equipment support for a number of projects. In 1982-83 there were five such projects: Metallization of Silicon (with Thor N. Rhodin of Applied and Engineering Physics as principal investigator); Thin Fluoride Films (Michael S. Isaacson, A&EP); Multimicroprocessor Computer System (Anthony P. Reeves, Computer Science); Laser Photochemical Materials Growth (George J. Wolga, Electrical Engineering); and Miniature Tunable Infrared Laser (Clifford R. Pollack, Electrical Engineering).

In return for their $15,000-a-year membership fee or equivalent gifts in kind, PROSUS members receive increased access to Cornell research results through a variety of mechanisms. Review meetings are held on campus every year, visits between Cornell and company researchers are arranged on request, and newsletters and research reports are mailed periodically. Contacts between industries and Cornell professors and graduate students are facilitated, with benefits such as the identification of subjects for possible research collaboration, and help in arranging for faculty members to serve as industrial consultants. The past year has seen a great increase in interest in PROSUS: attendance at the 1983 meeting (on the theme of "Lithography for VLSI") was nearly double that of the preceding year.

Left: Administrators of the Cornell industrial-affiliates program PROSUS are Jeffrey Frey (at right), director, and D. Ken Wagner, assistant director. Frey is also acting director of the SRC Program on Microscience and Technology.

THE JOINT SERVICES ELECTRONICS PROGRAM

As the name suggests, JSEP is jointly supported by the United States army, navy, and air force; the program at Cornell is monitored by the latter. The work of more than sixty researchers in the area of compound semiconductor materials, devices, and circuits is partially supported by JSEP, at a level of nearly one million dollars a year.

Lester F. Eastman, professor of electrical engineering, is director of the Cornell JSEP program. He has described it in some detail elsewhere in this *Quarterly* series.

RELEVANT ACADEMIC OFFERINGS AT CORNELL

Cornell course work at both undergraduate and advanced levels encompasses nearly every aspect of the design and fabrication of microstructures and devices. The emphasis is on "hands-on" laboratory experience, an opportunity that is made possible by the extensive facilities of NRRFSS and other University laboratories.

Most of the courses are offered by

the School of Electrical Engineering, the School of Applied and Engineering Physics, and the Department of Materials Science and Engineering, although courses in many other areas—such as computer science—are also valuable for students who wish to specialize in submicrometer and semiconductor science and technology. A partial listing is given in the table.

The building of a respected and effective center in any area of research takes time, money, people, programs, and facilities, a generalization that is especially true of a highly technical, specialized, and competitive field such as submicrometer semiconductor microscience and technology. The Cornell research record is evidence of the innovative ways that can be found to meet the challenge of multidisciplinary research programs and to garner their rewards. It is anticipated that in the years ahead NRRFSS will also become an effective "bridge" between the biological microsciences and submicrometer physical electronics.

EXAMPLES OF COURSE OFFERINGS

Electrical Engineering:

Introduction to Lasers and Optical Electronics
Microwave Theory
Electronic Circuit Design
Semiconductor Electronics I and II
Microprocessor Systems
Quantum Electronics I and II
Solid State Microwave Devices and Circuits I and II
Opto-Electronic Devices
Solid State Devices I and II
Materials and Device Physics for VLSI
VLSI Digital System Design
VLSI Technology
Computer Processor Organization and Memory Hierarchy
Computer Networks and Distributed Architecture
Parallel Processing
Image Processing

Applied and Engineering Physics:

Electronic Circuits
Electron Optics
Microcharacterization
Intense Pulsed Electron and Ion Beams
Microprocessing of Materials
Physics of Solid Surfaces and Interfaces

Materials Science and Engineering:

Electrical and Magnetic Properties of Materials
Microprocessing of Materials
Senior Materials Laboratory
Physics of Modern Materials Analysis
Electron Microscopy
Electrical and Magnetic Properties of Materials (advanced)
The Effects of Radiation on Materials
Amorphous Semiconductors

"The Cornell research record is evidence of the innovative ways that can be found."

REGISTER

New Faces, New Assignments

■ Of the thirteen professors who joined the College faculty this past year, five are in computer science and four in electrical engineering. Three women are among the new faculty members.

New assistant professors in the Department of Computer Science are *Joseph L. Bates, Dina Bitton, Peter A. Fejer, Gregory F. Johnson,* and *Abha Moitra.*

Bates, who is a specialist in programming logic, received the doctoral degree from Cornell in 1979. Since that time, he has remained in the department as a research associate, working on a project based on his thesis research. A native of Baltimore, he received both the B.A. and M.S.E. degrees from The Johns Hopkins University in 1973, at the age of eighteen.

Bitton is an Israeli citizen who earned her B.Sc. and M.Sc. degrees in mathematics at the Technion. Her doctorate, in computer science, was awarded by the University of Wisconsin in 1981. A specialist in database systems and parallel algorithms, she was a research fellow at the Weizmann Institute (in Israel) for one year, and an assistant professor at the University of Wisconsin until her appointment at Cornell.

Fejer attended Reed College as an undergraduate, and received the Ph.D. in mathematics from the University of Chicago in 1980. He has been at Cornell since that time, serving as H. C. Wang Assistant Professor in the Department of Mathematics. A specialist in logic, he has now been given a joint appointment in the Department of Computer Science.

Johnson, whose specialty is programming languages, majored in mathematics at Pomona College and worked as a systems programmer at IBM's Research and Development Laboratory before beginning graduate study. In 1983 he received the doctorate from the University of Wisconsin with a concentration in computer science.

Moitra was born in Jodhpur, India. In 1972, she ranked twenty-seventh in a field of sixty thousand applicants for the Indian National Science Talent Scholarship. She received an M.Sc. in physics from the Birla Institute of Technology and Science, and a Ph.D. in computer science from the Tata Institute of Fundamental Research in 1981. A specialist in distributed programming, she worked at the National Centre for Software Development and Computer Techniques before coming to Cornell.

The four new faculty members in the School of Electrical Engineering are *Ilesanmi Adesida, Clifford R. Pollock, John Treichler,* and *Sally L. Wood.*

Adesida is a specialist in microfabrication who has been working as a research associate at the National Research and Resource Facility for Submicron Structures (NRRFSS) at Cornell. He will now be an assistant professor, affiliated with both electrical engineering and NRRFSS. A Nigerian citizen, Adesida received the Ph.D. in 1979 from the University of California at Berkeley.

Pollock, a specialist in quantum electronics, joined the faculty last spring as an assistant professor. He studied electrical engineering as both an undergraduate and a graduate student at Rice University. After receiving the Ph. D. in 1981, he worked at the National Bureau of Standards before coming to Cornell.

Treichler's appointment is as an associate professor. After majoring in electrical engineering as an undergraduate at Rice University, he spent four years in the Navy, where he rose to the rank of lieutenant. He received the Ph. D. from Stanford University in 1977, with a specialty in digital signal processing. Before coming to Cornell, he worked as a senior research scientist at ARGOSystems, of Sunnyvale, California, and as a lecturer at Stanford.

Wood is also from Stanford, where she was awarded the Ph. D. in 1978. A specialist in digital signal processing, image processing, and bioengineering, she was employed by Telesensory Systems, of Palo Alto, California, where she helped develop optical character recognition for use in machines that read for the blind. She continued this research for the Veterans Administration. Subsequently, she worked for Contour Medical Systems, where she developed three-dimensional models and displays from two-dimensional CT images for surgical planning. She has been appointed as an assistant professor.

The School of Chemical Engineering appointed *Douglas Clark* to its faculty beginning in the 1984 spring term. He received his undergraduate education at the University of Vermont, and earned the Ph. D. from the California Institute of Technology in 1983. A specialist in biochemical engineering, he will continue his research on the transport of macromolecules through porous media as an assistant professor at Cornell.

In the Department of Geological Sciences *Teresa E. Jordan* was named acting assistant professor. A specialist in sedimentary geology who received the Ph. D. from Stanford University in 1979, Jordan has been working as a research associate in the department.

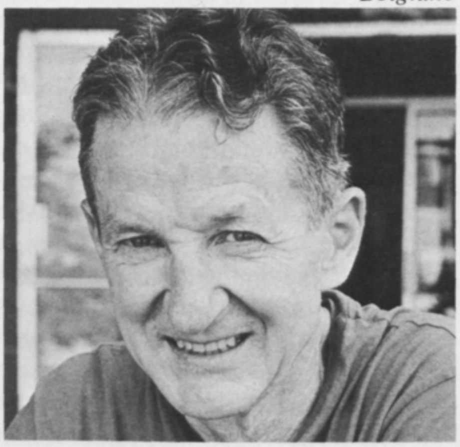
Michael O. Thompson was appointed assistant professor in the Department of Materials Science and Engineering, beginning in the 1984 spring term. He received his undergraduate training at the California Institute of Technology. His doctoral work, in the area of rapid energy deposition phenomena, was conducted at Cornell with Professor James W. Mayer.

The School of Operations Research and Industrial Engineering has appointed *Robin Roundy* as an acting assistant professor. He expects to finish his dissertation (at Stanford University) this year. A specialist in production scheduling, he has worked as a consultant on stock market analysis for the Allstate Research and Planning Division.

Streett

Torrance

Bolgiano



■ Administrative changes include several in the Office of Dean Thomas E. Everhart.

William B. Streett has assumed a broader role in his position as associate dean; his responsibilities now include all areas of the dean's activities. A professor of chemical engineering, Streett spends half his time in the dean's office. He came to Cornell in 1978 from the U.S. Military Academy at West Point, where he was a faculty member and director of the Science Research Laboratory, which he founded. His current research includes study of thermodynamic properties of fluids at high pressures, and computer simulation of molecular liquids. He is a West Point graduate and holds M.S. and Ph.D. degrees from the University of Michigan.

Kenneth E. Torrance, professor of mechanical and aerospace engineering, replaced Streett as half-time associate dean for graduate study and research. Torrance, a specialist in heat transfer and computational fluid dynamics, joined the Cornell faculty in 1968 as an assistant professor of thermal engineering. He holds the B.S., M.S., and Ph.D. degrees in mechanical engineering from the University of Minnesota, and had early experience conducting research at the National Bureau of Standards.

Also a half-time associate dean is *Ralph Bolgiano,* professor of electrical engineering, who is in charge of professional programs. His responsibilities include supervision of placement activities, direction of the Engineering Cooperative Program, and coordination of the Master of Engineering program. Bolgiano holds the B.S., B.E.E., M.E.E., and Ph.D. degrees from Cornell, and his experience includes a five-year period, before he began doctoral studies, as a development engineer with the General Electric Company. A specialist in tropospheric radiophysics and atmospheric turbulence, he has been a member of the electrical engineering faculty since 1958.

■ Other administrative changes include several in the leadership of schools and departments.

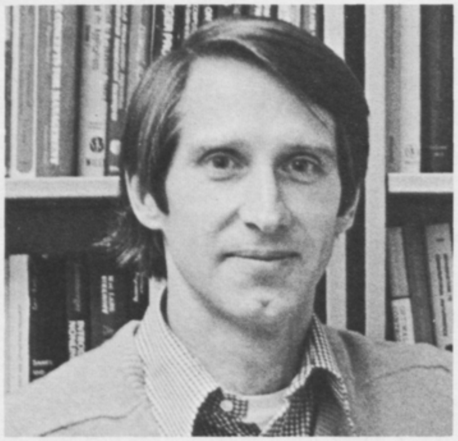
Watt W. Webb has been serving as director of the School of Applied and Engineering Physics since January, 1983. A specialist in biophysics and chemical physics, he has been a member of the Cornell faculty since 1961. Webb was educated at the Massachusetts Institute of Technology, earning the B.S. degree in 1947 and the Sc.D. in metallurgy in 1955. After completing his undergraduate program, he worked for the Union Carbide Metals Company, and after completing his doctorate, he returned there and became coordinator of fundamental research and assistant director of research. Webb has been honored as a Guggenheim fellow and is a fellow of the American Physical Society. His current professional activities include serving as an editor for *Physical Review Letters*.

Keith Gubbins has become director of the School of Chemical Engineering, replacing *Julian C. Smith,* who stepped down after serving as director for eight years. Gubbins joined the faculty as the Thomas R. Briggs Professor of Engineering in 1976. He was educated at the University of London,

Webb

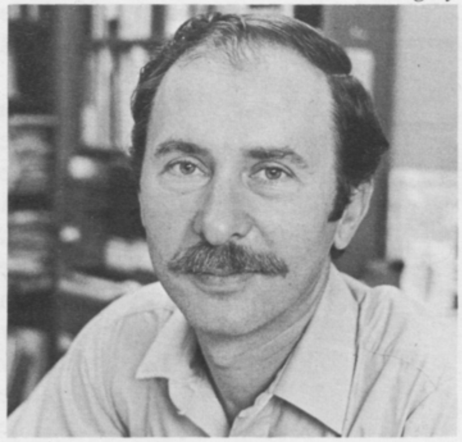
Gubbins

Trotter



Shoemaker

Gergely



earning the B.Sc. degree in chemistry, and the postgraduate diploma and the Ph.D. in chemical engineering. He previously taught at Imperial College, London; the University of Guelph, Ontario, Canada; the University of Kent, England; and the University of Florida. He conducts an active research program in the thermodynamic properties of liquids and liquid mixtures, and has published several books, as well as numerous professional papers.

In the School of Operations Research and Industrial Engineering, the new director is *Leslie E. Trotter, Jr.*, who has been serving as associate director. Trotter is a Cornell Ph.D.; he received the degree in 1973 after earning the A.B. at Princeton and the M.S. at the Georgia Institute of Technology. He joined the Cornell faculty in 1975 after several years as a research associate at the University of Wisconsin and a faculty member at Yale University. Beginning in 1977, he spent two years on leave at the Institute for Econometrics and Operations Research at the University of Bonn, West Germany, doing research on discrete optimization.

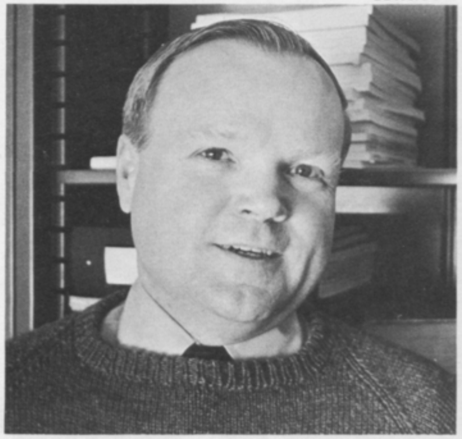
In the School of Civil and Environmental Engineering, *Christine Shoemaker* has been appointed associate director, and *Peter Gergely* has been named chairman of the Department of Structural Engineering.

Shoemaker, an associate professor in environmental engineering, is a specialist in pest management, water resource systems, and mathematical ecology. She was graduated from the University of California at Davis and earned the Ph.D. in mathematics at the University of Southern California. In 1971 she came to Cornell as a research associate in entomology, and the following year joined the engineering faculty. She has served on panels on pest management for the National Academy of Sciences and, currently, for the Food and Agriculture Organization of the United Nations. At Cornell she is a member of five graduate fields: civil and environmental engineering, applied mathematics, ecology and systematics, agricultural engineering, and entomology.

Gergely, a professor, joined the structural engineering department in 1963 after receiving his Ph.D. from the University of Illinois. His undergraduate education was at the Technical University of Budapest in Hungary, and at McGill University in Canada. His research specialties include structural mechanics, shells, earthquake engineering, and reinforced and prestressed concrete. He is registered as a professional engineer in New York State, has been employed as a structural engineer, and has spent sabbatical leaves with the Pittsburgh-Des Moines Steel Company, the Hungarian Academy of Sciences, the University of Toronto, the Lawrence Livermore National Laboratory, and the University of California at Berkeley. He is a fellow of the American Society of Civil Engineers and the American Concrete Institute, and has received four national awards from these societies.

Richard W. Conway is acting chairman of the Department of Computer Science while *David Gries* is on sabbatical leave.

Hudson



■ Appointments in industry-affiliated capacities include that of *Jeffrey Frey,* professor of electrical engineering, as acting director of the new Cornell Program on Microscience and Technology. This program operates in connection with the "center of excellence" in microscience and technology that was recently established here by the Semiconductor Research Corporation.

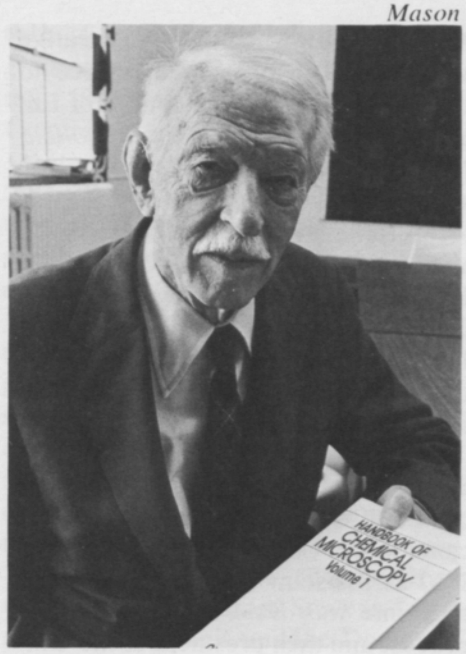
Ronald Hudson was named associate director of the Cornell Manufacturing Engineering and Productivity Program; *John A. Muckstadt,* professor of operations research and industrial engineering, continues to serve as program director. Hudson has a Cornell undergraduate degree in mechanical engineering and the M.S. in industrial engineering and operations research from Stanford University. From 1969, when he completed his study at Stanford, until he came to Cornell in 1983, he was a manager in planning and consulting for the Xerox Corporation. Earlier he worked at the Lockheed Missiles and Space Company as a systems analyst and at the General Dynamics Corporation as an engineer.

Clyde Mason Dies at 85

■ Six months after the publication of the fourth edition of his textbook on chemical microscopy, *Clyde W. Mason,* professor emeritus of chemical engineering, died on December 8 at the age of eighty-five. Mason, who held the Emile M. Chamot Professorship of Chemical Microscopy, retired in 1966 after thirty-three years of teaching.

Mason was an internationally recognized authority in his field. His specialty areas were the microscopical properties and behavior of chemicals, construction materials, and manufactured products. He was the founder and first chairman of the Division of Analytical and Micro Chemistry of the American Chemical Society, and served as chairman of the Education Committee of the American Society for Metals. His publications include a textbook, *Introduction to Physical Metallurgy,* and the *Handbook of Chemical Microscopy,* which he originally wrote with Chamot in two volumes. Volume I of the handbook was the publication that appeared last June in a fourth edition, with Mason as the sole author.

Mason



Mason was born in 1898 in Watertown, South Dakota. He earned an undergraduate degree at the University of Oregon and a Ph. D. in chemistry from Cornell.

He is survived by his wife, Elizabeth, of Ithaca; a daughter, and a son.

Berth

Berth Becomes WPI Vice President

■ The plaque read, "for creative thought and distinguished service to the Cornell University College of Engineering." The recipient was *Donald F. Berth,* who was leaving Cornell after twenty years to become vice president for university relations at his alma mater, Worcester Polytechnic Institute (WPI). The occasion was a farewell dinner, on his last night in Ithaca, attended by a large contingent of the professors, deans, and support staff with whom he had worked.

The inscription fairly summarized the character of Berth's Cornell career, if not the substance. He first came to the College of Engineering in 1962 as assistant to the dean, who at that time was Dale R. Corson, later provost and then president of the University. Berth's activities rapidly expanded to cover not only administrative tasks, but the development of instructional programs, the establishment of an advising and counseling system for undergraduates, the founding of *Engineering: Cornell Quarterly,* which he served as editor for seven years, and the development of a promotional publications program. He found time to handle public relations and publicity, to help with the College admission program, and to teach an occasional short course in entrepreneurial engineering. His wish to keep in close touch with students led to his direction (with Richard H. Lance) of the Engineering Cooperative Program a few years ago.

As an assistant and then associate dean, his work spanned the administrations of four deans of the College: Corson, Andrew Schultz, Jr., Edmund T. Cranch (now president of WPI), and Thomas E. Everhart.

Most recently his major responsibilities were in the area of corporate relations and development. Fundraising for the College was unusually effective during his years as development officer. He gained a reputation for understanding the various needs of the institution, and the ability to match those needs with the interests of sponsors and donors. He was effective also in helping to organize and promote special laboratories and consortia with industry. Significantly, the funding Berth helped implement supported students, faculty positions, and educational programs, as well as buildings, equipment, and renovation.

Berth's academic background is in chemical engineering; he holds bachelor's and master's degrees in that speciality from WPI. His first job was at Corning Community College in upstate New York, where he was the assistant to the president and director of admissions, and taught chemistry and physics. He also served for a time as an administrator at Hampshire College, and he has been a consultant to several other educational institutions.

Berth's new position returns him to his native state and to an institution with which he has maintained close ties. His Cornell experience will contribute to his work at WPI, for his responsibilities there encompass many of the areas in which he worked here. "Don has had a long and distinguished association with the College," Dean Everhart commented. "We shall miss him greatly, and wish him well as he undertakes this important position for his alma mater." —GMcC

Honors for Alumni, Professors, and Students

■ A new engineering professorship in honor of a prominent alumnus was established last fall. The *Charles W. Lake, Jr.* Professorship in Productivity was announced at a special ceremony on campus on September 23.

Lake, a 1941 Cornell graduate in administrative engineering, recently retired as chairman and chief executive officer of R. R. Donnelley & Sons, the world's largest commercial printing firm. He served Cornell for many years as a member of the Engineering College Council, and he was chairman of that advisory group for seven years. Also, he was a Cornell trustee from 1973 through 1978, and has been named a Presidential Councillor.

The endowed professorship was funded at $1.4 million with gifts from Lake and the R. R. Donnelley firm. In his remarks at the ceremony, Cornell President Frank H. T. Rhodes pointed out the appropriateness of a chair in productivity, an area in which Lake has been a leader and in which the College of Engineering is developing an active program. Rhodes remarked on Lake's outstanding contributions to the nation, the community, and the University, as well as in his professional career.

Above: Charles W. Lake, Jr. (at left) participated in a ceremony to announce the new Lake professorship. With him is Cornell President Frank H. T. Rhodes.

Other participants in the ceremony included Thomas E. Everhart, dean of the College of Engineering, and Gaylord Donnelley, honorary chairman of the firm's board of directors.

■ A Cornell electrical engineering graduate, *Lynn W. Ellis,* has received the 1983 Award in International Communication from the Institute of Electrical and Electronics Engineers (IEEE). Now an independent consultant on international business, Ellis spent most of his career with the International Telephone and Telegraph Corporation (ITT), and has served at the national level on various advisory groups on telecommunications and space communications. He is a fellow of the IEEE and of the American Association for the Advancement of Science, and has a Letter of Commendation from the Secretary of Commerce. He holds the B.S.E.E. degree from Cornell, the M.S. from Stevens Institute of Technology, and the Doctor of Professional Studies in Management from Pace University.

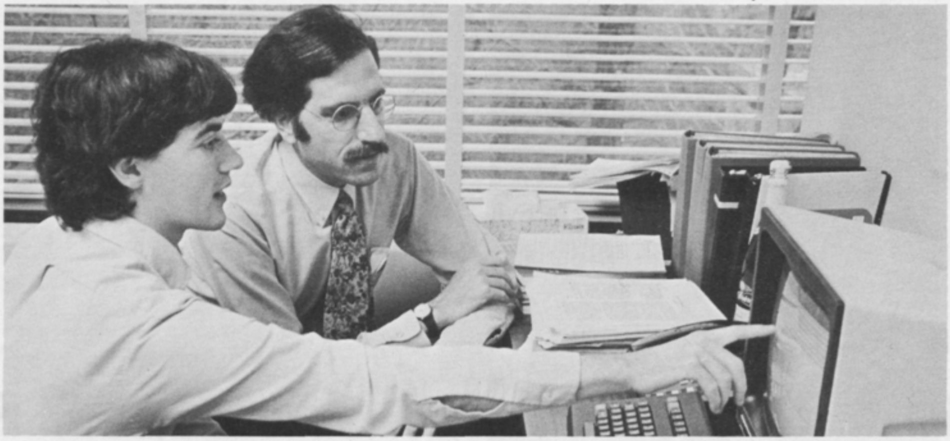
■ Two Cornell researchers received the Paul Rappaport Award of the Institute of Electrical and Electronics Engineers for the year's best paper on electron devices. They are *Jeffrey Frey,* professor of electrical engineering, and *Robert Cook,* his former Ph. D. student who is now employed at the IBM General Technology Division in Fishkill, New York. The winning paper concerns research discussed by Frey in this issue of the *Quarterly* (see page 12).

■ *Thomas J. Santner* was selected by student vote last spring as the year's outstanding professor in operations research and industrial engineering. (Lionel I. Weiss, earlier reported here as the recipient, actually was chosen for the preceding year.)

■ A Cornell Ph. D. thesis in computer science won the 1983 Doctoral Dissertation Award of the Association for Computing Machinery (ACM). The recipient was *Thomas Reps,* who earned his Ph. D. in 1982 under Associate Professor *Ray T. Teitelbaum,* and since then has been a postdoctoral associate in the Department of Computer Science.

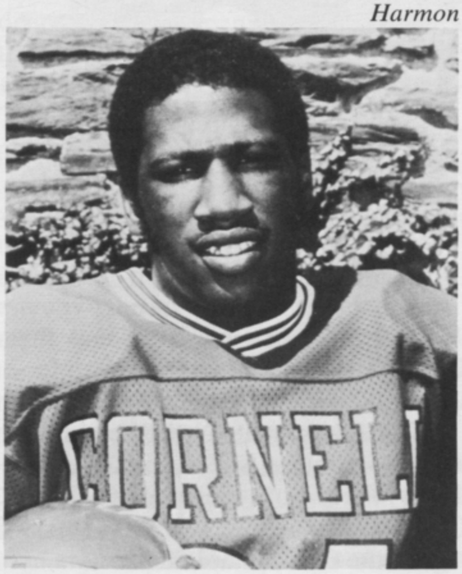
The award provides a $1,000 prize and publication of the work by the M.I.T. Press. Publication was set for mid-February, 1984, to coincide with the announcement of the award at the ACM national conference. This is the second time the annual award has been made.

■ *Thomas D. O'Rourke,* associate professor of civil and environmental engineering and specialist in soil-structure interaction, was awarded the Collingwood Prize of the American Society of Civil Engineers at its annual convention this fall. He was cited for a paper on ground movements caused by braced excavations; it appeared in the society's journal in 1981.



Reps and Teitelbaum

■ Cornell football star *Derrick Harmon*, a senior in engineering physics, was named Ivy League Player of the Year this fall. Later he was drafted by the Oklahoma Outlaws in the seventeenth round of the U.S. Football League. Other football honors he has received this year include selection by the *Ithaca Journal* as athlete of the year.



Harmon

The Outlaws are one of the six U.S. Football League expansion teams. Although he expressed interest in the Oklahoma team, Harmon may have other professional opportunities: the National Football League draft will be in April.

In 1982 Harmon was named to the All-Ivy First Team and the Academic All-American First Team, and won an AP All-America honorable mention. Also that year he received Cornell's Charles Colucci Award for the non-senior who makes the greatest contribution to the team.

Harmon, a 5-10, 196-pound tailback from Queens, New York, led the Big Red in rushing. During his Cornell career, he carried the ball 546 times for a total of 3,074 yards, an average of 5.6 yards per carry. (At Cornell this is second only to the rushing record of Ed Marinaro, who ran for 4,715 yards.) Harmon was only the fourth rusher in the Ivy League to exceed 1,000 yards in a season.

Equally impressive is Harmon's scholastic record. He has frequently made the dean's list.

FACULTY PUBLICATIONS

Current research activities at the Cornell University College of Engineering are represented by the following publications and conference papers that appeared or were presented during the four-month period March through June, 1983. (Earlier entries omitted from previous Quarterly listings are included here with the year of publication in parentheses.) The names of Cornell personnel are in italics.

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ENGINEERING
Cornell Quarterly

Published by the College of Engineering, Cornell University

Editor: Gladys McConkey

Associate Editor: David Price

Circulation Manager: Linda Van Ness

Graphic Art Work: Francis Russell

Composition and Printing: Davis Press, Inc. Worcester, Massachusetts

Photography credits:
Russ Hamilton: 5
Charles J. Harrington: inside back cover
Jon Reis: 1 (top left, second row left), 39, 42 (top), 43, 44 (center, right), 45 (right), 46, 47
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Cornell Quarterly
(ISSN 0013-7871)
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