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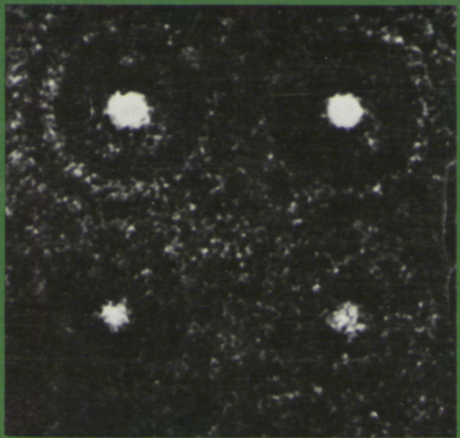
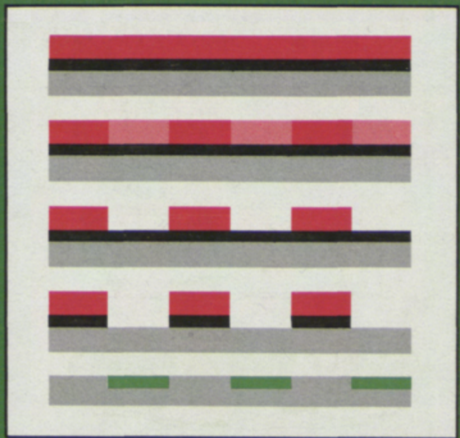

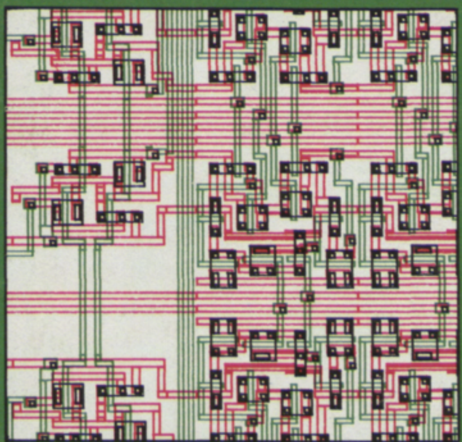


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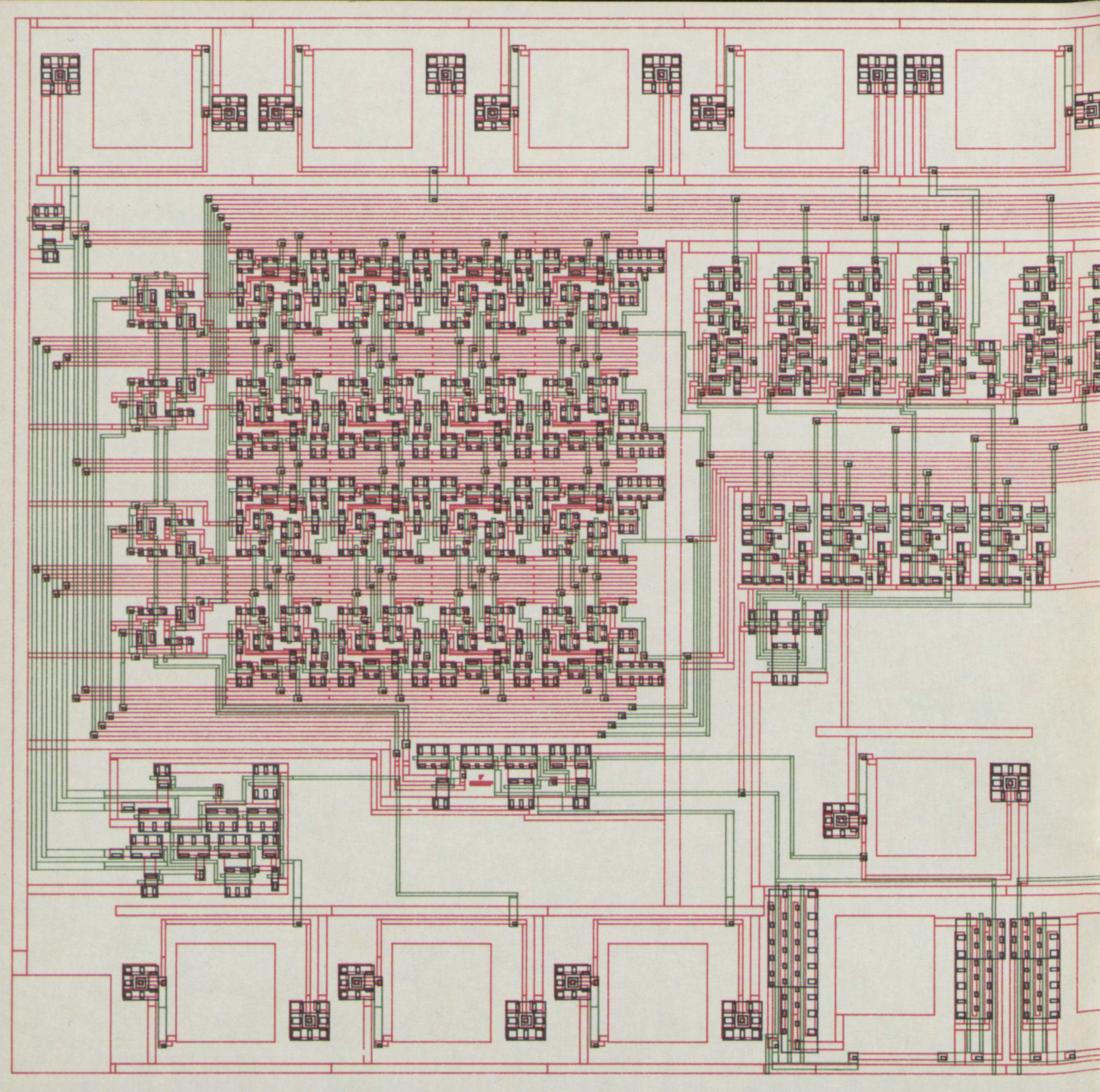
DISCOVERY
IN THE SUBMICRON
DOMAIN



IN THIS ISSUE

IN THE NEXT ISSUE

A companion issue this winter will feature technological accomplishments at the National Research and Resource Facility for Submicron Structures (NRRFSS).

Opposite: Part of a 4-micrometer field-effect transistor designed on NRRFSS graphics equipment by Cornell graduate students. Outside cover, clockwise from upper left: An optical micrograph of apertures smaller than the wavelength of light; steps in electron-beam lithography; outside Knight Laboratory; inside the laboratory; part of a chip design.





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DISCOVERY IN A NEW DOMAIN

Research at the National Submicron Facility

by Edward D. Wolf

At the national submicron facility at Cornell, we are helping to open up a rich and previously inaccessible domain. Its borders are defined by size, with a range extending from the vicinity of a micrometer down to the diameter of atoms. New approaches are needed to reach this domain, and new ways must be found to understand it and operate within it. But it offers exciting possibilities for discovery and development.

The challenge of our mission is not only intriguing, but important, for our work at the National Research and Resource Facility for Submicron Structures (NRRFSS) is centered on microelectronic structures and materials, a crucial area in our high-technology world. The drive is toward smaller and smaller features because most microelectronic devices and circuits operate faster, consume less power, execute more functions, and cost less per circuit function when the size of their features is reduced. New fabrication technologies are bringing the dimensions (as measured in line width) of device and circuit features down to the micrometer (10^{-6} meter) and even nanometer (10^{-9} meter) level, and it is in this range of size that conventional microelectronic devices will find their limits and new devices will be developed.

SUMMARY OF UNITS

Several units of length are currently used in connection with research at NRRFSS. This table summarizes their relationships.

Meters (m)	Micrometers (μm)	Nanometers (nm)	Angstroms (Å)
1	10^6	10^9	10^{10}
10^{-6}	1	10^3	10^4
10^{-9}	10^{-3}	1	10
10^{-10}	10^{-4}	10^{-1}	1

NRRFSS: A NATIONAL CENTER AT CORNELL

Cornell became a national center for activity on this new frontier with the establishment of NRRFSS in 1977. On the basis of the University's existing and proposed programs in microelectronic devices and materials and related research, the National Science Foundation (NSF) selected Cornell to receive a five-year, $5-million grant to initiate the program, and a five-year renewal grant was awarded in 1982. The facility was organized by Joseph M. Ballantyne of Cornell's School of Electrical Engineering (he is now the School director), with the cooperation of other faculty members from several departments and schools. The University provided a new building especially designed for the NRRFSS activities: the Knight Laboratory (named for Cornell alumnus and Presidential Councilor Lester B. Knight).

Now, in our sixth year, it is time to take stock of where we have been and where we are headed: not an easy task, since the facility and its program have grown so rapidly and developed in such depth and complexity that even those of us most closely associated with it have been surprised.

The overall purpose as mandated by NSF was to help catalyze the exploration of submicrometer science and technology and provide a focus and a

". . . it is in this range of size that conventional microelectronic devices will find their limits and new ones will be developed."

resource for our national research efforts in this direction. The idea was original; and from its inception, NRRFSS has embodied a growing cooperative spirit among government, academic, and industrial sponsors—a spirit that can only benefit all these constituents.

The objectives of Cornell and NSF in establishing the facility were:

- to promote and carry out research to advance the art of submicrometer fabrication technology and to train scientists and engineers in this field;
- to provide a resource, primarily for use by the university community, to fabricate advanced devices or research structures which require submicrometer dimensions;
- to stimulate innovative research, in a variety of fields, that will shed light on fundamental physics or materials problems which affect or limit applications of submicrometer technology;
- to keep the technical community informed of progress at the facility.

These far-reaching goals remain as important today as when they were formulated, and the facility continues to strengthen its research and resources. Dedicated to discovering the concepts, techniques, and thin-film materials for the next generation of electronic devices, NRRFSS is the only national laboratory located at a university that has the required capability, in equipment and expertise, for multilevel processing at dimensions of 0.25 micrometer and below. Furthermore, it is unique in that it is open to visiting researchers from other universities, from government, and from industry.

The program now involves some two hundred researchers. They include about thirty-seven Cornell faculty members from ten departments, sixteen faculty members from other universities, twelve scientists from industrial and government laboratories, twenty-five research associates, and more than one hundred graduate students from across the nation. The group of research associates provides the equivalent of nine full-time technical staff members to operate, maintain, and develop highly specialized equipment and processes, and to assist visiting and resident users. The annual budget, initially $750,000, now totals about $2.2 million.

THE DUAL APPROACH: USE AND DEVELOPMENT

Project work at NRRFSS is coordinated in two programs: *User Research,* in which the facility functions as a resource for investigators from laboratories throughout the nation; and *Facility Development Research,* in which the aim is to provide NRRFSS with state-of-the-art resources for microfabrication and microanalytical technologies, and to advance microstructures engineering and science for the benefit of researchers everywhere. Both programs help provide a pool of trained personnel familiar with the exotic and often very expensive instrumentation of these technologies—a pool of experts that is vital to the United States' effort to compete successfully with foreign microelectronics industries.

Robert A. Buhrman, Cornell professor of applied and engineering physics, was appointed associate di-

FACILITY-DEVELOPMENT RESEARCH, 1982-83

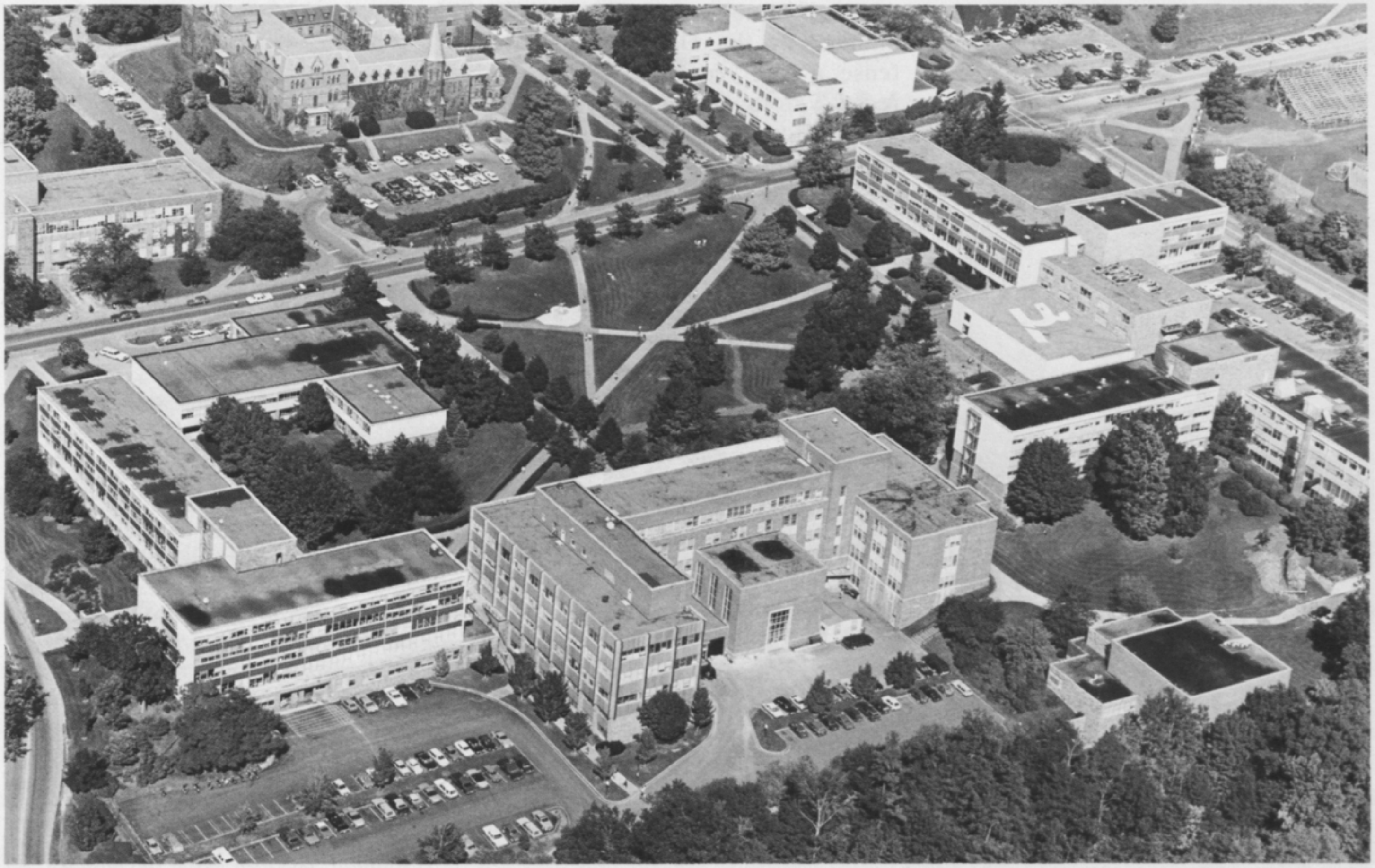
Principal Investigators	Areas
Applied and Engineering Physics:	
R. Buhrman	Submicron lithography and ion processing
M. Isaacson	Production and characterization of nanostructures; Resources for computer-aided design of charged-particle optics
T. Rhodin	Ultra-high-vacuum microfabrication processes
B. Siegel	Development of a field-ion source for submicron fabrication
J. Silcox	Exploratory STEM studies
Electrical Engineering:	
J. Ballantyne	Technology for guided wave optics
P. Krusius	Intrinsic electronic defects in laterally confined MOS/VLSI-like Si/SiO_2/polysilicon/silicide thin-film systems
C. Lee	Lateral resolution limits of activated ion-implanted species in semiconductor substrates using advanced ion and electron lithographies
E. Wolf	Reactive-ion and ion- and electron-scattering effects in submicron fabrication
G. Wolga	Laser use in the photochemical processing of materials
Materials Science and Engineering:	
J. Mayer	Backscattering facility and silicide formation for submicron structures
A. Ruoff	Inorganic resists and reactive-ion-beam etching

rector of NRRFSS in 1980, and he has been largely responsible for the coordination and success of the User Research Program, which is expected to continue to grow over the next few years. In one aspect of the program, researchers from laboratories as near as Syracuse and as far away as San Diego visit the facility to conduct experimental work for relatively short periods of time, typically for three to five days. Long-term visitors are also welcome at the facility for periods of up to two years. Both types of users return to their home laboratories with valuable experience in instrumentation and processes that they would not have been able to get otherwise.

A number of significant technical accomplishments have been made as a result of the user program. These include the use of molecular-beam epitaxy in the synthesis of GaAs and related compound semiconductors for high-speed devices and circuits; the development of SOS MESFET logic; the production of superconducting devices; the fabrication of bubble-memory devices; the development of high-speed photoconductive detectors; the fabrication of deep-ultraviolet wire polarizers; and the fabrication of microelectrode neural-recording arrays, microthermisters, electrodes of submicrometer diameter for electrochemistry experiments, and infrared notch filters. (Descriptions of some of the user activities are given in the article beginning on page 15.)

In the Facility Development Research Program, a variety of microfabrication capabilities have been developed and made available to the users of NRRFSS. At the same time, NRRFSS scientists have undertaken microstructure-engineering research programs that promise to have a major impact on the rapidly expanding field. The emphasis is on features with dimensions of 0.1 micrometer or less. For example, NRRFSS researchers, using an electron beam with a diameter of 0.5 nanometer (0.0005 micrometer!) have produced the smallest artifacts ever reported.

The capabilities of NRRFSS include very-high-resolution electron-beam lithography and pattern generation, x-ray lithography, and ion-beam lithography; thin-film growth and processing; and Auger microanalysis. Improvements are continually developed and introduced; in ion-beam lithography, for example, the ion implanter now used will be augmented by a new high-brightness gaseous field-ion source. Several types of dry etching have been studied and optimized in order to improve ultrahigh-resolution lithography; these include ion milling, reactive-ion etching, reactive-ion-beam etching, chemically assisted



The logo for the submicron facility (<μ) is visible from above on the roof of Knight Laboratory on the engineering quadrangle. (Construction is now in progress in the area shown in the foreground at left— see page 54.)

ion-beam etching, and conformal vapor etching. In all the experimental work carried out so far, it has been found that pattern-transfer processes in which these dry-etching techniques are used are limited only by the resolution of the preceding exposure process and not by any inherent fundamental limit due to the etching itself. Many of these technologies are described in this issue of the *Quarterly* and in the one that follows.

The activities of NRRFSS are centered primarily in Knight Laboratory, a $3.8-million specially-constructed building conveniently connected to Phillips Hall, home of the School of Electrical Engineering. The 20,000-square-foot building provides 7,500 square feet of class 1000 clean laboratory space with twenty-four laminar-flow clean benches for class 10 or better processing. There are also thick concrete slabs, mechanically isolated from the building, to support vibration-sensitive instruments. In addition, the instruments are positioned to minimize electromagnetic interference and are supplied with voltage regulators and isolation transformers with individual electrolytic grounding systems. The laboratory contains twenty-one major equipment sites (see "A Walking Tour of the Knight Laboratory" in this issue).

THE GROWING FIELD OF SHRINKING STRUCTURES

NRRFSS is continually seeking ways to expand and strengthen its function as a national resource. A major effort is to make the facility more accessible through its outreach program, which includes an organization for industrial affiliates, summer research programs for visiting scientists, and short courses to familiarize engineers and scientists with the potentials of the technology. The facility appears to have captured the interest of the public, as well as of the scientific, technical, and industrial communities; the print and television media have given extensive coverage to NRRFSS.

The significance of work in the submicron domain cannot be overemphasized. Microelectronics already affects the daily lives of everyone—even schoolchildren are becoming familiar with microprocessors—and the prospects for new and expanded applications are excellent. The promise of smaller, higher-speed devices with better performance is part of the stimulus for the Very-High-Speed Integrated Circuits (VHSIC) program initiated by the Department of Defense a few years ago and for the recently formed Semiconductor Research Corporation (SRC). There is also a need for smaller, more sensitive sensors in a wide range of disciplines such as electrochemistry, neurophysiology, and ultrahigh-pressure solid-state research.

When a basic parameter such as size is extended to new dimensions, there is often fundamental new science to be revealed, and sometimes new technology to be developed. We have seen this happen at the two extremes of smallness and largeness, in high-energy particle physics and cosmology. But there is also a very important intermediate domain of size, spanning the three orders of magnitude from one micrometer down to one nanometer, in which development may have effects on society that are just as profound. This region is now becoming accessible for further study and control by means of nano- and microfabrication techniques. Exploration here will lead to the optimal development of conventional microelectronic devices, and quite probably to the emergence of new physical and biological constructs of devices, circuits, and systems.

At NRRFSS, we know from experience that submicron research is an exciting field—one in which technological developments and fundamental scientific research go hand-in-hand and advances often lead to important new territory. The national submicron facility is our gateway to this fascinating new domain.

Edward D. Wolf, a specialist in scanning-electron-beam microfabrication and surface chemical physics, came to Cornell in 1978 as professor of electrical engineering and director of the newly established national submicron facility.

After receiving the Ph.D. degree in physical chemistry from Iowa State University in 1961, he was a postdoctoral research associate at Princeton University. Subsequently he worked at Rockwell International Science Center, and in 1965 joined Hughes Research Laboratories, where he led the research and development of high-resolution electron-beam techniques for diagnostics and computer-controlled microfabrication of devices and circuits. He also did research in scanning electron microscopy at the University of California, Berkeley in 1968.

Wolf has served with the Department of Defense Science Board Task Force on the VHSIC Program, and the University Advisory Committee of the Semiconductor Research Corporation. He is on the editorial board of IEEE Spectrum, *and is the U.S. member of the European Microcircuits Engineering Conference Steering Committee. He is also an adviser to the Center for Submicron Technology at Delft University, in the Netherlands.*

A WALKING TOUR OF KNIGHT LABORATORY

by Hillary Rettig

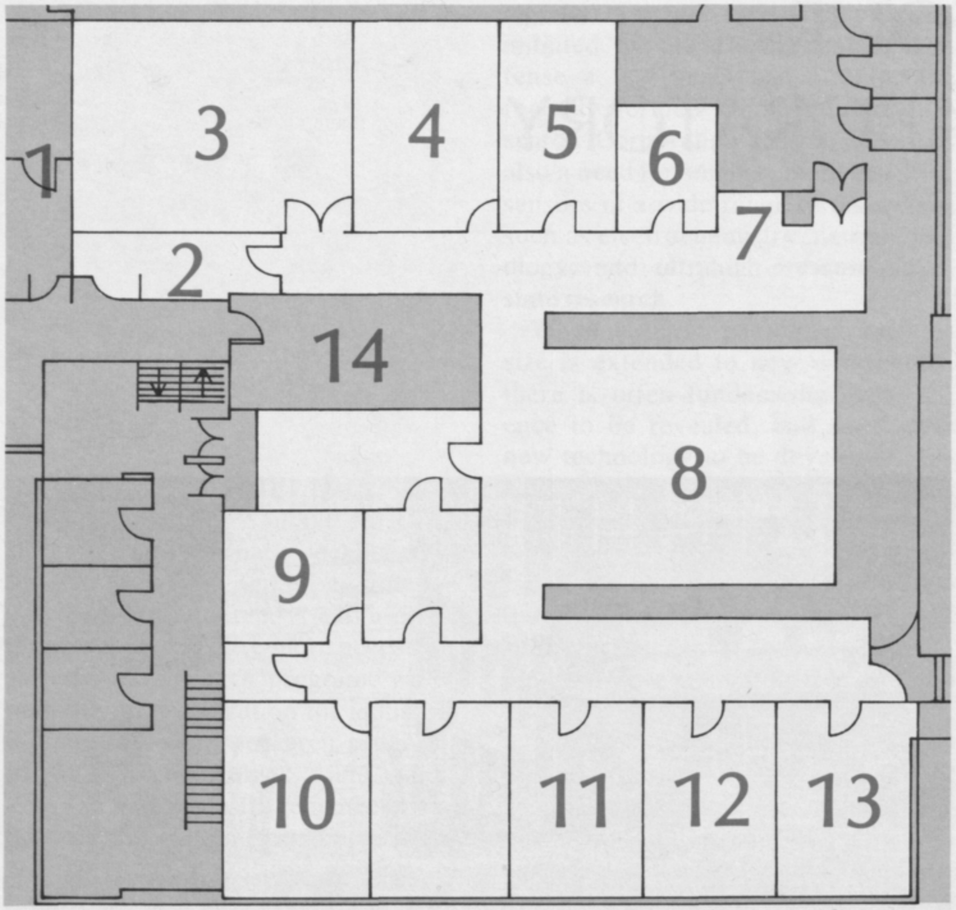
The moment you enter Knight Laboratory, home of the National Research and Resource Facility for Submicron Structures (NRRFSS), you are aware of being in a place that is very different from your average research laboratory. From the basement, which houses the extensive support systems, to the roof, which sports the facility's $<\mu$ logo, the laboratory provides a unique and fascinating glimpse into a research environment that is, quite literally and by necessity, another world.

Why another world? As the name indicates, the research here focusses on matter smaller than one millionth of a meter (or 1/25,000 of an inch)—about 1/100 the diameter of a human hair. This dimension defines the two major requirements considered in the design, construction, and operation of Knight Laboratory: the need for cleanliness (since even a minute particle of dust would have a catastrophic effect on a submicron experiment) and the need for a stable environment for the complex and extremely sensitive equipment.

Knight Laboratory cost $3.8 million to build and an additional $5 million to equip. An unusual—and costly—structural feature is the provision of separate foundations for instrument rooms; concrete slabs nearly a meter thick and resting on compacted earth isolate the sensitive equipment from external vibrations. Intrinsic to the structure are facilities such as special high-purity air conditioning and special electrical supply lines.

These aspects of the laboratory are not apparent to visitors, however. They are more apt to wonder why there are no external windows in the laboratory portion of the building (the purpose in eliminating windows is to reduce thermal imbalances caused by seasonal variations in the weather). And they frequently comment on the logo painted on the roof (it was put there just for fun—at no extra cost). In the following pages, we take an informal "walking tour" through Knight Laboratory to learn a little more about the equipment and how it is used.

Figure 1



Above: Rooms on the Knight Laboratory tour are used for (1) computing; (2) donning clean-room garments; (3) ion implantation; (4) holographic lithography; (5) photolithography; (6) photomask preparation; (7) MOS processing; (8) processing; (9) SEM research; (10) STEM research; (11) E-beam microfabrication; (12) ion-beam lithography; (13) SAM research; (14) conferences. Unnumbered rooms are general laboratory areas and (at extreme left) offices. The clean room, 7,500 square feet in area, is unshaded.

Right: 1. Computers are seen through a window in the computing room.

1 Our first stop is the *computing and computer-aided design (CAD) facility,* the only section of the technical laboratory not kept stringently clean. There are two rooms here: the outer one, containing terminals, and the inner one, which houses the facility's two computer systems. The Applicon AGS/860 VLSI Design computing system is a sophisticated graphics computer used by students and other personnel to design, sketch out, and edit complex, multi-level patterns for integrated circuitry. The Digital Equipment Corporation PDP 11/60 provides computational backup for many equipment systems within the laboratory, and also supports a Grinnell image-display system and other graphics devices.

Nearly all other laboratory work is done in the "clean room," a special area isolated from the dust, temperature fluctuations, and other hazards of our everyday environment. The clean room at NRRFSS is Class 1000, which means that it contains fewer than one thousand "large" (bigger than one-half micrometer) particles in

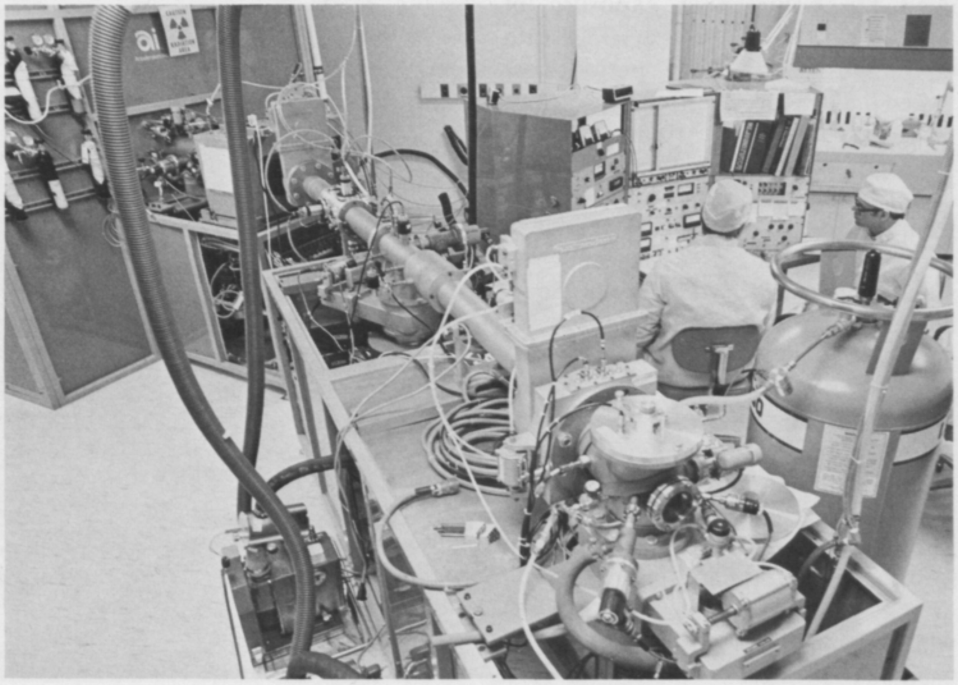
1

2. The "togging room" also serves as an airlock between the outer areas and the "clean room."

3. The ion-implantation system includes cylinders of gas (upper left) and the accelerator.

2

3



each cubic foot of air (there are 300,000 particles per cubic foot in a normal office environment). After a brief stop at what for some people is the most intimidating piece of equipment in the laboratory—the shoe-cleaning machine—we are prepared to enter the clean area.

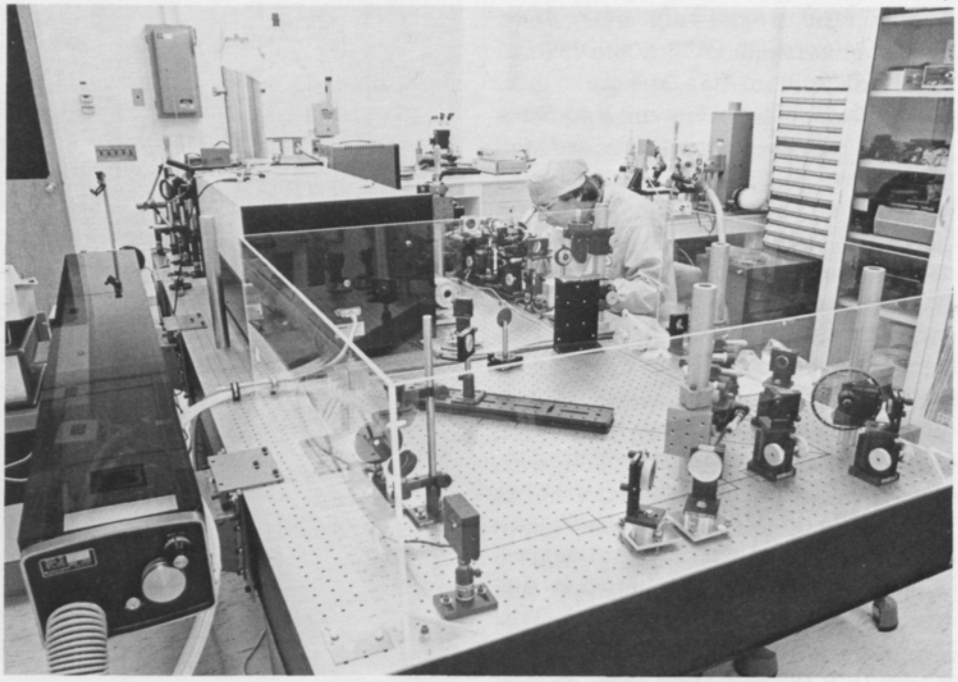
2 We do this through an *airlock*, a special passage that serves as a connector between the world within and the one without. The air pressure is higher in the airlock than it is in the reception area, so that dust is blown outward when the door is opened. A large sign warns: "No Smoking! No Eating! No Drinking!" Another forbids the wearing of cleated-sole hiking boots, which can track in mud and salt—a particular problem during Ithaca winters. We don special clothing to guard against laboratory contamination by lint: plastic booties, a plastic bonnet, and a lab coat. We pass through another door (more air blows outward) and enter the laboratory proper.

3 The first room we come to within the clean area houses the Accelerators, Inc. *ion implanter,* a small accelerator that can dope (implant) very minute, very specific quantities of an impurity in precise concentrations and at precise locations within a crystal, changing its characteristics dramatically.

4. A krypton laser system and associated optical parts are provided in the holographic lithography laboratory.

5. Photolithography equipment includes an optical projection mask aligner (foreground) and a contact mask aligner (in back).

4



4 Making sure that the red "warning" light outside the next door is off, we proceed to our next stop, the *holographic lithography* room, which houses a krypton ion laser and associated optical components for generating fine gratings. The laser, which rests on a special shock-absorbing air table, is used for holographic exposure of large-area (2 cm X 2 cm) gratings with continuously adjustable periods between 0.22 and about 1 micrometer.

5

5 In the next room we find the *photolithography systems,* which are used when extremely fine resolution is not necessary. These systems comprise a 4:1 Canon Optical Projection Mask Aligner (which provides minimum feature size of 0.8 micrometer with distortion less than ±0.1 percent over a field size of 1 square centimeter) and a Cobilt 400A Contact Mask Aligner (which provides lithographic capability down to 5 micrometers on wafers of various sizes up to 3 inches). In this room, and in the next, overhead lighting is kept in the yellow-red range, as normal white light exposes the photoresist used on the wafers.

6 The next room houses the *photomask systems,* which are used to produce photomask plates for the Canon and Cobilt mask aligners. The equipment includes a first-reduction camera, a David W. Mann optical pattern generator, and a David W. Mann photorepeater.

7 Outside, a sign indicates that we have arrived at a special part of the laboratory, the *metal-oxide semiconductor (MOS) processing area.* Because it must be kept especially clean, this area is restricted to access by staff and faculty members who are directly involved in its use. The equipment here is used to explore the limits of short-channel MOS integrated circuits, and acts as a springboard to the fabrication of very-high-resolution devices on thinned substrates. A Thermco Brute American four-chamber diffusion system allows the preparation of ultra-high-purity materials: high-quality silicon dioxide based on TCA or dry HCl; silicon nitride formed by low-pressure chemical vapor deposition (LPCVD); and substrate materials thermally annealed in a sealed and inert-atmosphere system. Four of the facility's twenty-four laminar-flow hoods are dedicated to this activity. These hoods provide a steady stream of filtered, clean air for delicate processing; they maintain the cleanest environment—close to class 10—within the laboratory.

6

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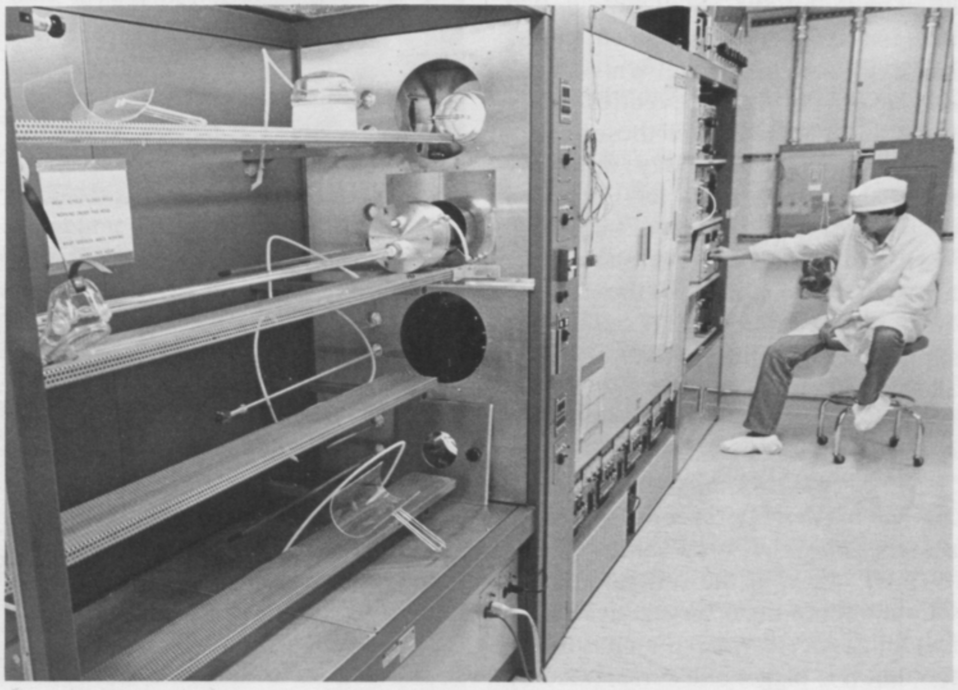

6. Photomask plates are prepared in a special laboratory.

7. MOS processing equipment includes four furnaces.

8 We come next to the *central processing area* of the facility, a large room containing *reactive-ion etching systems* by Applied Materials and by Plasmatherm, a Varian *reactive-ion-beam etching system,* a Commonwealth Scientific *ion mill,* two *evaporators,* and other instrumentation used for dry-process etching and anisotropic chemical treatment of samples. These machines are less sensitive to the vibrations that can ruin "direct-write" lithographic processing and can be housed in a less isolated environment.

9 The next major instrumentation site is for the Cambridge Instruments stereoscan *scanning electron microscope (SEM),* used for sample analysis. The technology behind this instrument dates only to 1958 or so (Thomas E. Everhart, dean of engineering at Cornell, was one of the pioneers in its development during his days at Cambridge University), and up to the early seventies, there were fewer than five of these instruments at Cornell. Today there are more than ten, used as important diagnostic tools in the physical, chemical, and biological sciences. Our tourguide asks us to fix the components of the system in our minds: the sophisticated control/monitor panel and the electron column. We will be seeing them again in just a moment.

10 And sure enough, in the next room, which houses a VG Microscopes *scanning transmission electron microscope (STEM),* we spot the control panel—only it's three times larger, nearly ten feet long. An electron column is there, too, but it is bigger and surrounded by

8

9

Tour stops include (8) the central processing area, used for dry-process etching and chemical treatment of samples; (9) the SEM laboratory (where Dean Everhart is shown demonstrating the scanning electron microscope); (10) the STEM (scanning transmission electron microscope) laboratory, which houses a large electron column as well as the control panel pictured; (11) the room for electron-beam microlithography; (12) the laboratory in which a high-brightness field-ion source is being developed; and (13) the SAM (scanning Auger microprobe) facility for surface elemental analysis.

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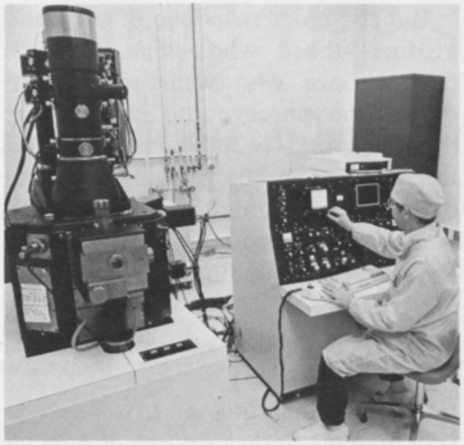

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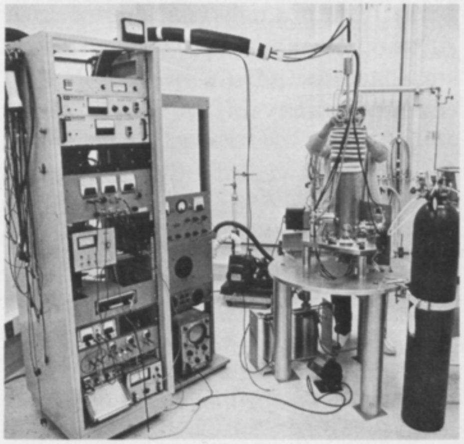

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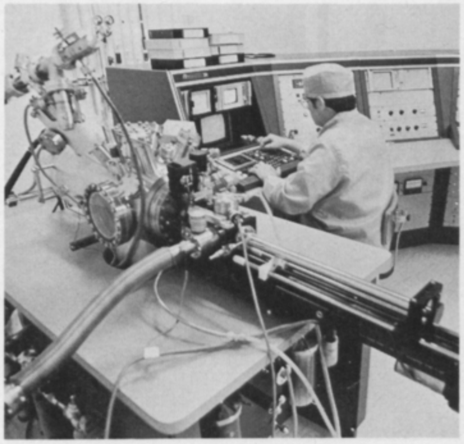


rings of magnets. The purpose of the magnets, we learn, is to allow the beam to be focused much more finely than is possible in a standard SEM. The electrons in the STEM are of higher energy, and instead of simply creating a latent exposure pattern, they can actually etch the sample. There are fewer than ten of these instruments in the United States. Researchers at NRRFSS have used this one to create the smallest artifacts ever recorded—letters so tiny that the *Encyclopaedia Brittanica,* all thirty volumes of it, could, in principle, be reproduced on a postage stamp.

11 Down the corridor a bit we come to the room housing the Cambridge Instruments *electron beam (E-beam) microfabricator*. Again we recognize a control panel and electron column with origins in the SEM. In this case, however, the instrument provides a *directed* beam of electrons, which can be used to write patterns with line widths as small as 0.15 micrometer. It is controlled by a 13-bit pattern generator directed by a PDP 11/34 minicomputer that can accept preprocessed digital input from the computer-aided design system. The stage of the E-beam microfabricator, which can accept substrates as large as four inches square, is controlled by a laser interferometer; its measured position is accurate to 600 Å.

12 The next room houses Cornell's unique *high-brightness field-ion source,* a system that provides a very bright source of H_2^+ for ion-beam lithography and other beam processing in the submicrometer region.

13 The final laboratory room on our tour houses a Physical Electronics *scanning Auger microprobe (SAM),* which allows surface elemental analysis in ultrahigh vacuum with a best spatial resolution of about 2,000 Å. This elegant analytical tool is routinely used for semiquantitative analysis of metal and semiconductor structures; it can detect all elements except hydrogen and helium.

We look around, preparing to reenter the less protected realm outside the clean room. People pass by, shuffling in their booties; at any given time, there may be up to twenty staff members, professors, and graduate students in the clean room. Regular staff members and students wear blue lab coats and visitors wear white. If there's a problem, you look for someone in blue. We note that general equipment such as microscopes and chemical hoods is located throughout the laboratory so that the movement of workers is reduced, and therefore also the risk of contamination.

We retrace our steps back through the airlock and take off our "clean gear." A quick tour of the basement reveals a jungle of machinery (reminding some visitors of the engine room of a large ocean liner) that provides support for all the equipment we have just seen. Here are the sources of the very purest water and air systems, of vacuum systems for cleaning and laboratory operations, of separate isolated electrical feeds for each room. The air conditioner is huge—the main handler alone, with its multiple banks of rows upon rows of filters, is the size of a Pullman railroad car.

14 The final stop on our tour is the *conference room*. This is where most visitors to the laboratory are escorted; displays illustrate the techniques and instrumentation used at the facility, and highlight some of the notable research accomplishments. An interior wall is glass, providing a wide window through which visitors can observe clean-room activity without having to get suited up. Staff members occasionally feel as though they were on display as they pass by a glass wall with people peering through it at them, and visitors, captivated by the idea of objects with submicron dimensions, are apt to have the sensation of looking into a different world. A favorite story, part of the growing lore of the submicron facility, is about the reporter who, upon meeting Ed Wolf, the director of NRRFSS, exclaimed, "But you're such a big guy!" Wolf, who once played basketball for Kansas State, grins when he tells that one. "That reporter," he says, "must have thought this was a lab for small scientists instead of small science."

Stop 14 on the tour is the conference room, shown (below) from the inside and (above) from the clean laboratory. The glass window between the two areas separates the two worlds of the submicron facility.

14

But the chief response of staff and visitors—those who wear blue lab coats, those who wear white, and those who observe the proceedings through glass—is to be impressed by the facilities and by the achievements they make possible. You don't need an electron microscope to appreciate the marvels of submicron research.

Hillary Rettig received the B.S. degree in 1979 from the Cornell College of Agriculture and Life Sciences, where she concentrated in microbiology and general studies.

She has worked as a secretary in Cornell's Laboratory of Atomic and Solid State Physics, and is currently administrative supervisor of the National Research and Resource Facility for Submicron Structures. She is also a freelance writer who contributes articles on scientific topics—as well as on cinema, history, and feminism—to regional and national publications. She not only contributed the article printed here, but was largely responsible for assembling the material in this issue.

USING THE SUBMICRON FACILITY

A Unique Opportunity for Researchers Throughout the United States

A researcher anywhere in the United States has the opportunity to come to Cornell to work at the national submicron facility. This feature distinguishes the Cornell facility from any other microstructures science and technology laboratory in the nation, and is one of the most exciting and challenging aspects of its operation.

The User Research Program was one of the primary goals of the National Science Foundation when it announced, in 1977, the $5-million grant that established the National Research and Resource Facility for Submicron Structures (NRRFSS); and from the beginning, it has been an intrinsic part of the facility's activities. Each user project draws on the talent and resources of NRRFSS, of Cornell scientists in various fields, and of visiting researchers, and the result is a unique and fruitful synergy that cuts across institutional and disciplinary lines. User projects at NRRFSS have embraced not only electrical engineering, physics, and materials science, but also biology, medicine, and agriculture.

Most user projects involve a series of short visits to the facility. A typical visit lasts from several days to two weeks and includes not only use of the instruments (often with instruction), but consultation with resident scientists and participation in seminars and other interactions with faculty, staff members, and students. There is currently no user fee (except for occasional expendable items) for investigators from academic institutions, but there is a user fee for those from industrial or government laboratories.

More than sixty user projects involving about 170 non-Cornell and Cornell investigators—students, faculty members, research associates, and industrial and government scientists—are currently underway. A partial list of these projects (Tables 1 and 2) gives an idea of the variety of research that is fostered by the NRRFSS resources. Some of the work by Cornell people is described in other articles in this *Quarterly* series.

The application procedure is simple. Generally, researchers begin by

Table 1. CURRENT NON-CORNELL USER PROJECTS
(Partial Listing)

Home Laboratory	Projects
Bell Laboratories	A systematic study of ring-oscillator delay as a function of gate length in GaAs FETs and selectively-doped heterojunction FETs
University of California at San Diego	Diffraction lenses in planar dielectric waveguides; Silicide formation for contacts to shallow junctions and fine-line interconnects
Carnegie-Mellon University	Interfacial processes at Au/GaAs and Pd/GaAs; Submicron structures in magnetic devices
Drexel University	Metal-insulator-semiconductor pinhole photodetectors and solar cells
Eastman Kodak Company	E-beam exposure of micropositive and negative resists
University of Florida	Noise in submicron structures
GTE Laboratories	Gratings for surface-electromagnetic-wave spectroscopy in semiconductors
Howard University	Development of short-gate FET devices
Lawrence Livermore National Laboratory	Condenser lenses for x-ray microscopy and microprobe analysis
Los Alamos National Laboratory	Electron-phonon coupling in semiconductors in the picosecond laser-melt regime
McDonnell Douglas Corporation	Molecular-beam epitaxy for modulation-doped field-effect transistors
M.I.T.	Bipolar heterojunction transistor MBE layers
Naval Ocean Systems Center	Fabrication of submicron silicon MOSFETs
Naval Research Laboratory/ SUNY-Buffalo	Spectroscopy of impurities and defects in quantum-well structures
Ohio State University	Optical filter array
Pennsylvania State University	Oxidation and silicide formation study on low-energy ion-beam-processed Si
University of Pennsylvania	Formation of planar protein crystals by epitaxial growth on etched-line patterns
Rensselaer Polytechnic Inst.	Development of microscopic thermister network
Sandia National Laboratories	Electromigration in submicron-linewidth films
SUNY-Buffalo	Electrochemistry at very small electrodes
University of Virginia	Low-noise, high-cutoff-frequency GaAs Schottky-barrier mixer diodes
Vought Corporation	Infrared switch using a metal-grid filter on a phase-transition film
Woods Hole Oceanographic Institution	Fabrication of standard test images for high-resolution video microscopy

writing or calling the facility for information on resources and capabilities. After studying the *NRRFSS User's Manual* and other publications, and after preliminary discussions with Edward D. Wolf, the director of the facility, the researchers submit a short proposal for outside review by selected persons in the NRRFSS referee pool.

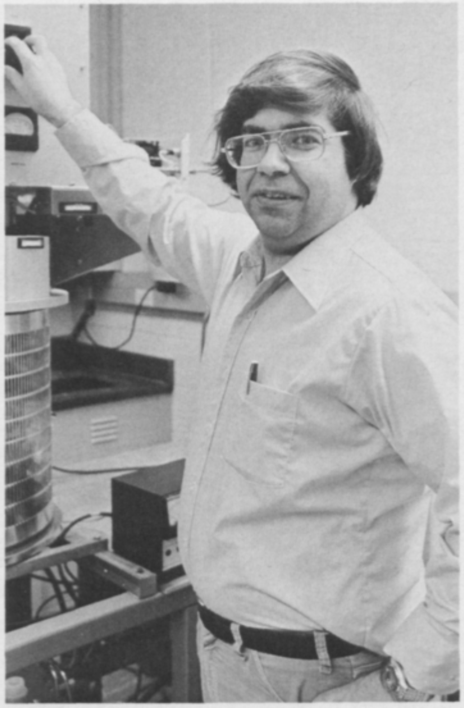
In most cases, user projects are funded by other agencies and therefore have been previously reviewed, but NRRFSS nevertheless conducts its own reviews, based on specific technical and nontechnical criteria, to ensure that each project has scientific merit and is in keeping with the mission and charter of NRRFSS. The pool of technical referees includes users, members of the facility's governance bodies (the Program Committee and the Policy Board), and other leaders in microstructures science and technology throughout the United States. Each non-Cornell proposal is reviewed by two non-Cornell reviewers; proposals from Cornell are reviewed by one non-Cornell and one Cornell referee.

The final decision is made by the Program Committee, composed of thirteen experts in the fields of microstructures science and technology; ten of these—four from Cornell and six from outside the University—are voting members. Projects approved by this committee are scheduled for equipment usage and personnel assistance at the laboratory. At this point the associate director of the facility and various members of the staff take over.

In accordance with the guidelines

Table 2. CURRENT CORNELL USER PROJECTS
(Partial Listing)

Principal Investigators	Projects
Applied and Engineering Physics:	
R. Buhrman	Superconducting devices
A. Lewis, M. Isaacson	Angstrom-resolution light microscopy with submicron apertures
W. Webb	1/f noise in submicron structures
Astronomy:	
J. Houck	Metal-mesh filter for infrared Fabrey-Perot interferometer
Electrical Engineering:	
J. Ballantyne	Compound semiconductor materials and integrated optoelectronic systems
L. Eastman; with S. Mukherjee, G. Wicks, and D. Woodard	Compound semiconductor materials, devices, and circuits; Self-aligned ion-implanted GaAs ballistic MESFET super-high-speed integrated circuits; Ballistic GaAs heterojunction bipolar transistor for EHF; Study of GaAs short FET for microwave high performance; Ultra-high-speed GaAs devices; Structures for high-frequency transistors; GaInAs double heterostructure laser-grown by MBE; A comparison of ion-implanted and epitaxial GaAs for high-performance power FETs
J. P. Krusius	Submicron silicon devices and circuits: MESFETs; Dielectric isolation for submicron VLSI; Fundamental study of the technology and physics of MOS devices with ultra-short physical gate lengths
W. Ku	Low-noise submicron MESFETs and monolithic microwave integrated circuits
D. K. Wagner	Design and development of a high-efficiency AlGaAs concentrator solar cell
G. J. Wolga	Picosecond optoelectronic measurement and materials; Electroluminescent materials preparation and structure
Electrical Engineering/Materials Science and Engineering:	
C. Lee, J. Mayer, G. Eckhardt	Fundamental phenomena of metal/compound interfaces
Materials Science and Engineering:	
J. Mayer	Ion-beam mixing of thin films; Metal silicides: ion-beam mixing
R. Raj	Submicron grids for strain-field measurements
A. Ruoff	Electrode structures for ultra-high-pressure materials-science research
Physics:	
J. Reppy	Josephson structures for superfluid helium: experimental
R. Richardson	Submicron structures at very low temperatures
R. Silsbee	Interfacial spin transport; Physics of two-dimensionally modulated FET structures



Robert A. Buhrman, an associate professor of applied and engineering physics at Cornell, supervised the User Research Program as associate director of NRRFSS from 1980 to 1983. He is on sabbatical leave this year. A user himself, Buhrman conducts research on superconductivity devices and thin-film conduction.

"... a unique and fruitful synergy that cuts across institutional and disciplinary lines."

established for the facility, the criteria for approval of user projects are:

- A project should involve microminiaturization, especially in the submicrometer range, in a substantial and innovative way.
- A goal of the project should be to significantly advance the art of submicrometer technology or its applications to engineering or to scientific research.
- The chief purpose should not be to make use of services that are commercially available.
- The nature of the project should be such that the specialized equipment or expertise available at the facility will make an essential and important contribution to the outcome of the work.
- The project should provide educational opportunities for personnel associated with the work.

About eighty projects from Cornell and laboratories across the country have benefitted from the work at NRRFSS since its beginnings six years ago. The User Research Program, in turn, has contributed to the vitality and value of the laboratory, and its success may have significant implications for high-technology research in general: The NRRFSS experiment has demonstrated the viability of programs cooperatively supported by government, universities, and industry.

Researchers who would like to receive more information on the User Program or discuss possibilities for such a collaboration are invited to write or telephone Professor Edward D. Wolf, director of the National Research and Resource Facility for Submicron Structures. The address is: NRRFSS, Cornell University, Knight Laboratory, Ithaca, New York 14853. The telephone number is 607/256-2329.

IMPROVED POLYMERS FOR ADVANCED LITHOGRAPHY

by Ferdinand Rodriguez

In some of the earliest recorded experiments in *photolithography*, conducted in 1822, J. N. Niepce was able to produce a pattern (*graphos*) on a stone (*lithos*) surface by the interaction of light (*photos*) with a polymer.

Niepce began by spreading a thin film of a natural resin, bitumen of Judea, on a smooth stone surface. After the film had dried, it was exposed to sunlight through a partial mask. Where struck by sunlight, the resin became crosslinked and insoluble; where protected by the mask, it remained soluble. When the soluble film was washed away, there remained a pattern of insoluble resin that could be used for printing, since, unlike the bare stone, it could be wetted by ink. Prints were produced when paper was pressed against the ink-wetted pattern.

Producers of computer chips use basically the same process of photolithography, although the materials have changed. The silicaceous stone has been replaced by a silicon wafer and the bitumen of Judea by special synthetic polymers. And while the major active component of sunlight, ultraviolet radiation, is still used to produce most chips, a beam of electrons has been found to be superior. This is because ultraviolet light has a basic limit of resolution of about one micrometer, and if as many as a million circuit elements are to be packed on a tiny silicon chip, some features have to be smaller than that. A beam of electrons can be used to draw a line as narrow as 0.1 micrometer or less.

THE TECHNIQUE OF E-BEAM LITHOGRAPHY

In electron-beam lithography, the general procedure (see Figure 1) consists of five steps:

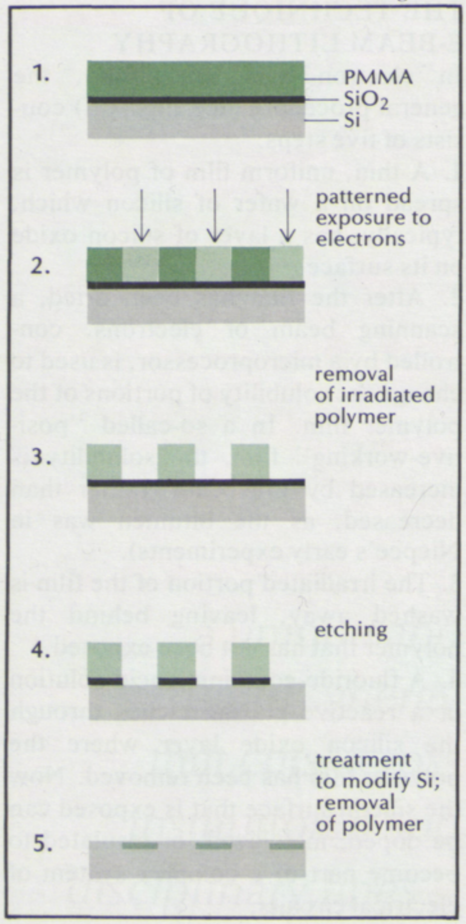
1. A thin, uniform film of polymer is spread on a wafer of silicon which, typically, has a layer of silicon oxide on its surface.
2. After the film has been dried, a scanning beam of electrons, controlled by a microprocessor, is used to change the solubility of portions of the polymer film. In a so-called "positive-working" film, the solubility is increased by the beam (rather than decreased, as the bitumen was in Niepce's early experiments).
3. The irradiated portion of the film is washed away, leaving behind the polymer that has not been exposed.
4. A fluoride-containing acid solution or a reactive plasma etches through the silicon oxide layer where the polymer film has been removed. Now the silicon surface that is exposed can be doped, metallized, or insulated to become part of a complex system of electrical circuits.

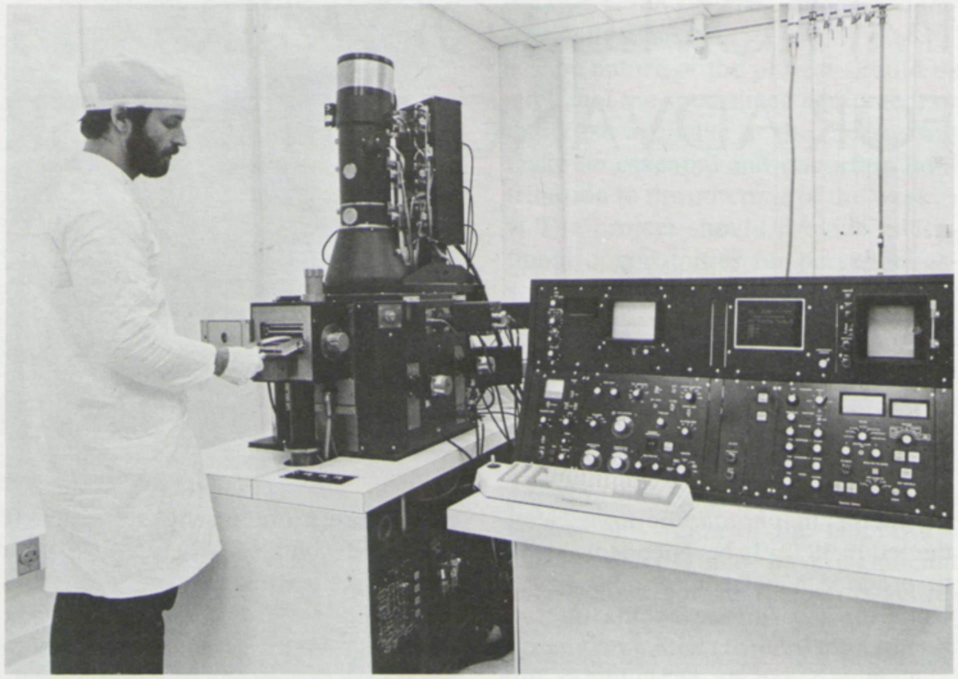
The Cornell project on polymers for advanced lithography is directed by Professor Rodriguez, a member of the School of Chemical Engineering, and Professor S. Kay Obendorf of the Department of Design and Environmental Analysis. The experimental work is being conducted by Charles C. Anderson, Wendy J. Cooper, Philip D. Krasicky, Yarrow Namaste, and Karin U. Pohl. The high-resolution line exposure and SEM work is carried out with Richard Tiberio and Edward D. Wolf in the Knight Laboratory. The International Business Machines Corporation provides financial support.

Right: NRRFSS provides equipment for electron-beam lithography.

Figure 1. The five basic steps in electron-beam lithography used to produce an electronic chip. Variations of the cycle are repeated until all the needed components have been formed.

Figure 1





5. The original polymer film is removed, leaving the whole wafer ready for another cycle of lithography, doping, etc. Half a dozen or more cycles may be required to produce even a simple calculator chip.

DEVELOPING POLYMERS OF HIGH SENSITIVITY

The polymer used in processing the chip is called a *resist* because it resists the etching process. By acting as a temporary mask, it protects the silicon oxide layer. A good electron-beam resist should adhere well to the substrate and be sensitive to the radiation; the response of the polymer to the electron beam is, obviously, a characteristic that controls the speed of production. A polymer that has a highly desirable combination of properties as an electron-beam resist is PMMA, poly(methyl methacrylate), more commonly known as the plastic Lucite or Plexiglas. It is the same polymer that is used to make stiff contact lenses and the housings for automobile taillights.

One measure of resist sensitivity is the minimum dose of electron radiation needed to obtain a useful pattern. In the case of PMMA, about 50 microcoulombs per square centimeter ($\mu C/cm^2$) will decrease the molecular weight of polymer enough to permit a pattern to be made cleanly in a film about one micrometer thick. Another, less direct, technique for determining sensitivity is to measure the change in molecular weight that occurs on irradiation. The number of times a polymer chain is "snipped" into

Figure 2a

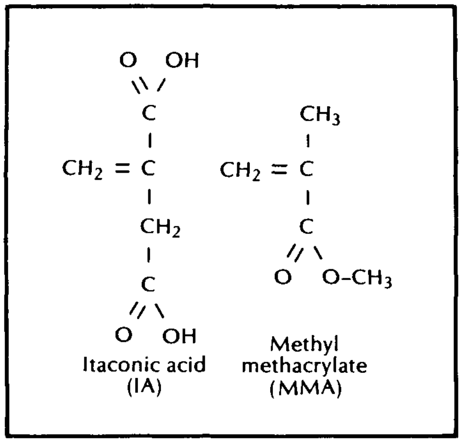


Figure 2b

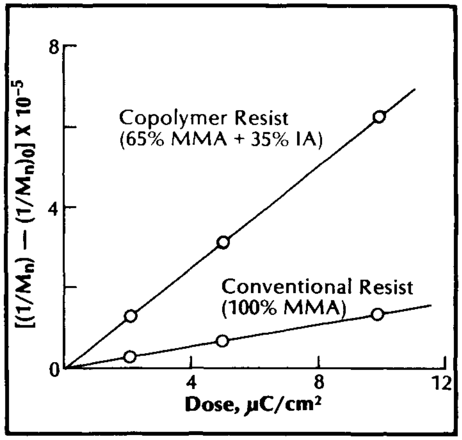


Figure 2. Copolymerization as a means of increasing the sensitivity of a resist.

a. *Cornell researchers have experimented with copolymers of itaconic acid (IA) and methyl methacrylate (MMA).*

b. *Tests show that such a copolymer exhibits greater sensitivity to electron irradiation than does PMMA, the polymer formed from MMA alone. Here sensitivity is measured in terms of the decrease in number-average molecular weight, M_n, upon exposure to 40-kV electrons in doses ranging from 2 to 10 μC/cm². The molecular-weight decrease reflects the extent to which polymer chains are broken as a result of the radiation; in this example, the number of chain scissions for a given dose is more than five times as great for the copolymer as for the polymer of MMA alone.*

smaller pieces as a result of exposure to a given dose of electrons can be calculated from molecular-weight change.

An increase in the sensitivity of PMMA without a loss of desirable properties can be achieved by adding a second ingredient as the polymer is being formed. At Cornell, we have found that itaconic acid copolymerized with methyl methacrylate makes a very sensitive material: the same dose of electrons causes a much greater change in molecular weight than occurs in PMMA (Figure 2). Modern chromatographic methods of analysis permit the entire molecular-weight distribution to be determined with a very small sample; many analyses could be made with the few milligrams of polymer that make up the film on an ordinary wafer.

TESTING THE PERFORMANCE OF POLYMER RESISTS

An even more demanding test is to make an actual pattern using the polymer and to develop features of one micrometer or less. Each processing step has to be investigated when a new material is being evaluated. With our itaconic acid copolymer, for example, high temperatures must be avoided during drying because of anhydride formation.

". . . production engineers will be able to select polymers with the particular properties required."

Figure 3

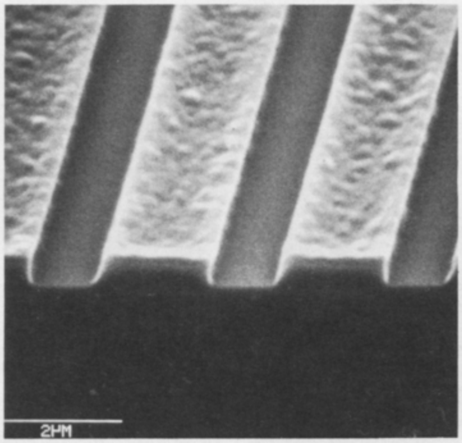


Figure 3. A greatly enlarged photograph of vertical-line profiles obtained with the copolymer illustrated in Figure 2. Exposure dose was 10 μC/cm² at 20 kV. The lines, only one micrometer wide, were made using the Cambridge E-beam lithography machine for exposure and 2-methoxyethyl acetate for development.

It has been necessary also to devise a rational system for selecting solvents. We have established that the thermodynamic criteria for solvent selection can be defined in terms of the solubility parameter which describes the energy holding materials together. The polar, nonpolar, and hydrogen-bonding propensities of each solvent must be dealt with separately. But thermodynamics is not the whole story; the kinetic parameters of diffusivity and viscosity enter into the dissolution process. We have had to develop a method of measuring the rate at which a polymer dissolves—a method based on the observation that the intensity of a laser beam reflected from the thin polymer film describes a sinusoidal curve because of interference as the polymer dissolves. An important part of our ongoing work is to describe the dissolution process in terms of the simplest number of thermodynamic and kinetic parameters.

Pattern evaluation is the ultimate test of the resist. The itaconic acid copolymer would be expected to perform well, since it decreases in molecular weight rapidly upon exposure to electrons; and our experiments have shown that this is, indeed, the case. Figure 3 shows a pattern which required a dose of only 10 μC/cm² to create features with vertical walls. In order to produce this pattern, much effort was made to optimize the solvent composition and the film-preparation conditions.

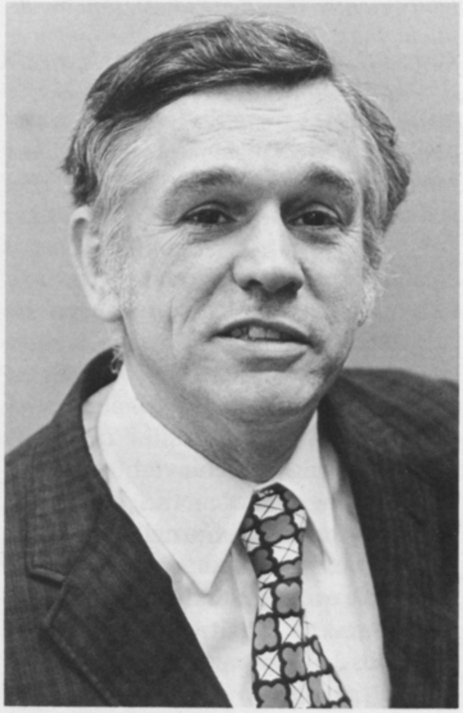
Other polymer structures are under investigation as resist candidates; after all, it may be that no one polymer is optimal for all chip production. In our laboratory we have used free-radical, anionic, and cationic polymerization techniques to prepare a variety of polymers, and are testing their performance. Studies such as ours are making available an array of resists with correlated properties, so that in the future production engineers will be able to select polymers with the particular properties required for particular applications.

As chip features become smaller, the properties of resists become more crucial, and so does the availability of a range of resist materials with predictable properties. Polymer research based on sound principles of science and engineering is providing the necessary resources and will meet the demands imposed by advanced lithography techniques.

Ferdinand Rodriguez, a specialist in polymer systems, is a professor of chemical engineering at Cornell.

After receiving the B.S. and M.S. degrees from Case Institute of Technology, he served as a safety engineer at the U.S. Army Biological Warfare Center. Following his discharge, he studied for his doctorate in chemical engineering at Cornell, and was appointed to the faculty immediately after receiving the degree in 1958.

Rodriguez is author of the textbook Principles of Polymer Systems, *published by McGraw-Hill. He has been a consultant to the Union Carbide Company, Rome Cable Corporation, and Imperial Chemical Industries, in England. At Cornell he received the Excellence in Engineering Teaching Award in 1966.*



MICROSTRUCTURES AND MATERIALS SCIENCE

at the National Submicron Facility

The most exciting engineering and science often come from places where two or more fields converge: the combination of techniques and expertise results in novel approaches to problems, and sometimes to unforeseen and fruitful solutions. An excellent example is the interrelation between the science and technology of microstructures and the science of materials. As demonstrated in work at the National Research and Resource Facility for Submicron Structures (NRRFSS) at Cornell, microfabrication techniques open the possibility of structuring new materials on a near-molecular scale, and new materials may make possible new microdevices by providing previously unavailable properties.

At NRRFSS a variety of techniques and equipment for the growth and analysis of semiconductor materials is available to Cornell and non-Cornell scientists and engineers, and many of the researchers are concerned with materials development, either directly or in terms of device fabrication. A brief survey of the areas of NRRFSS activity from the viewpoint of materials demonstrates how the distinction between fields of research diminishes along with size in the submicron regime.

BEHAVIOR MODIFICATION IN THE SUBMICRON WORLD

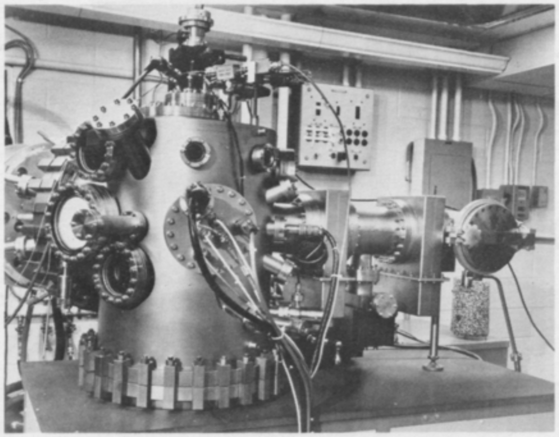
As the dimensions of semiconductor devices are made smaller and smaller, the materials from which they are constructed begin to behave differently. When the dimensions approach characteristic scattering lengths, it is necessary to consider material structure in radically different ways.

New materials are grown either by combining existing materials in novel arrangements, or by doping materials with impurities. In both cases, even minute changes in character and composition can result in materials with completely new properties, of enormous potential applicability and value.

One of the most important ways of growing submicron materials is by *epitaxy,* the technique of arranging atoms in single-crystal layers upon a crystalline substrate so that the crystal lattice structure of the new thin film exactly duplicates that of the substrate. An extremely uniform film is produced, and the dopant level can be controlled precisely. Two techniques available at Cornell are *molecular-beam epitaxy (MBE)* and *organometallic vapor-phase epitaxy (OMPVE).*

MBE achieves crystal growth through the reaction of multiple molecular beams with a heated single-crystal substrate in an ultrahigh-vacuum environment. Each molecular beam issues from a separate furnace containing the element—tin (Sn), aluminum (Al), gallium (Ga), arsenic (As), or manganese (Mn). Shutters direct the gas onto the substrate crystal, where it is deposited as a very homogeneous layer. Opening and closing the control shutters and manipulation of the furnace and substrate temperatures allows precise control over the composition of the layers.

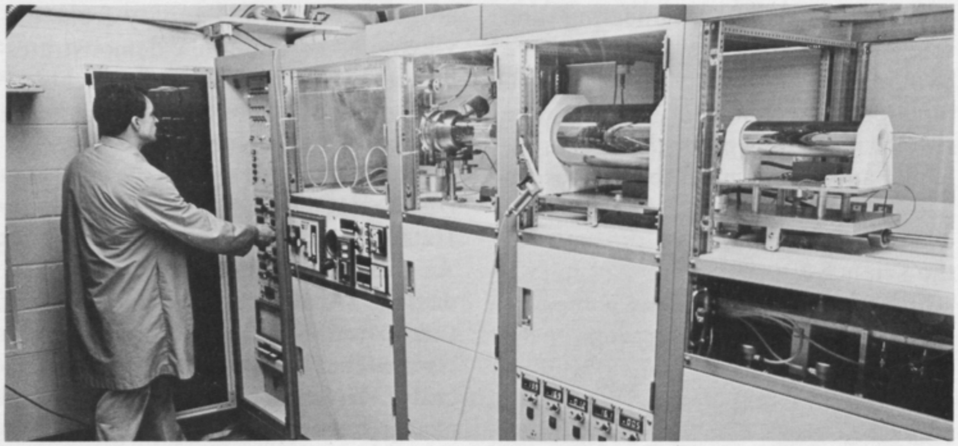
Cornell engineering professor Lester Eastman, working in collaboration with numerous Cornell and non-Cornell researchers, uses MBE for



Left: The molecular-beam epitaxy (MBE) system available at NRRFSS is used for crystal growth. GaAs and related semiconductors are being developed for microwave devices.

Below: The organometallic vapor-phase epitaxy (OMVPE) system was constructed at Cornell. Shown with the instrument is one of the developers, D. Ken Wagner.

Facing page: Professor Charles Lee works with the ion-implantation system to study and develop techniques for device fabrication.



the synthesis of gallium arsenide (GaAs) and related compound semiconductors for high-frequency and high-speed microwave and optical devices. By precise manipulation of epitaxial layers, these researchers have fabricated many new materials and structures, including a transistor with nearly ten times the electron velocity characteristic of most semiconductor materials. Other types of transistors, in which electrons travel a short, vertical distance through an epitaxially grown layer instead of along a longer horizontal "channel," may also, one day, result in faster and smaller microdevices. MBE is also an important and versatile technique in combination with other technologies, including electron-beam lithography and ion implantation.

An organometallic vapor-phase epitaxy (OMVPE) system has been constructed by Richard Shealy and D. Ken Wagner under the supervision of electrical engineering professors Joseph Ballantyne, Lester F. Eastman, and Chung L. Tang. Wagner, senior research associate and assistant director of NRRFSS, currently supervises its operation.

The system consists of a cold-wall reactor tube through which reactant gases pass over the substrate supported on a heated graphite susceptor. The reactants, in a gas stream of purified hydrogen, consist of organometallic compounds of gallium, aluminum, and arsine (AsH_3). Under proper conditions (susceptor temperatures of 600 to 800°C), the organometallic compounds react with the arsine at the hot substrate to produce a single-crystal film which grows at a rate of about one nanometer per second. Doped films are produced by introducing small quantities of dopants, such as selenium and zinc, into the reactor. The thickness and composition of the films can be controlled through reactant flow rates, and operation at reduced pressures can produce more abrupt interfaces between layers—an important feature for certain devices such as quantum well lasers and modulation-doped transistors.

Ion implantation, or the doping of

substrates with minute, carefully controlled amounts of impurities, is another technique used to create novel materials. It is a common industrial technique, and its use has dramatically increased the yield in integrated circuits with thousands of transistors and diodes, but it is also a valuable research tool.

An ion-implantation system consists of an ion source, an accelerator, and a magnetic field to separate or select the ions of interest. Ions such as As^+ and B^+ are produced by the source and accelerated through a potential in the range of a few tens of kilovolts to about 300 kV, reaching velocities of the order of 10^8 centimeters per second. They are then sent through a magnetic separator and scanned in x-y manner to uniformly cover the sample being implanted. Finally, they strike a target (the semiconductor substrate) and embed themselves in the first few thousand angstroms of the surface layers. Implantation allows precisely controlled, very uniform doping across a relatively large area. Purity of the dopant is ensured by mass analysis of the ion beam, and since there is very little lateral spread of the beam, very small devices can be fabricated.

Electrical engineering professor Charles Lee and others are studying the ion-implantation techniques in the hope of extending its limits even farther. They have used the NRRFSS ion-implantation system to study lattice location of implanted impurities, their annealing activity, and the annealing of the inevitable damage to crystalline structure that occurs when highly energized ions strike the target surface.

FINDING OUT WHY PROPERTIES CHANGE

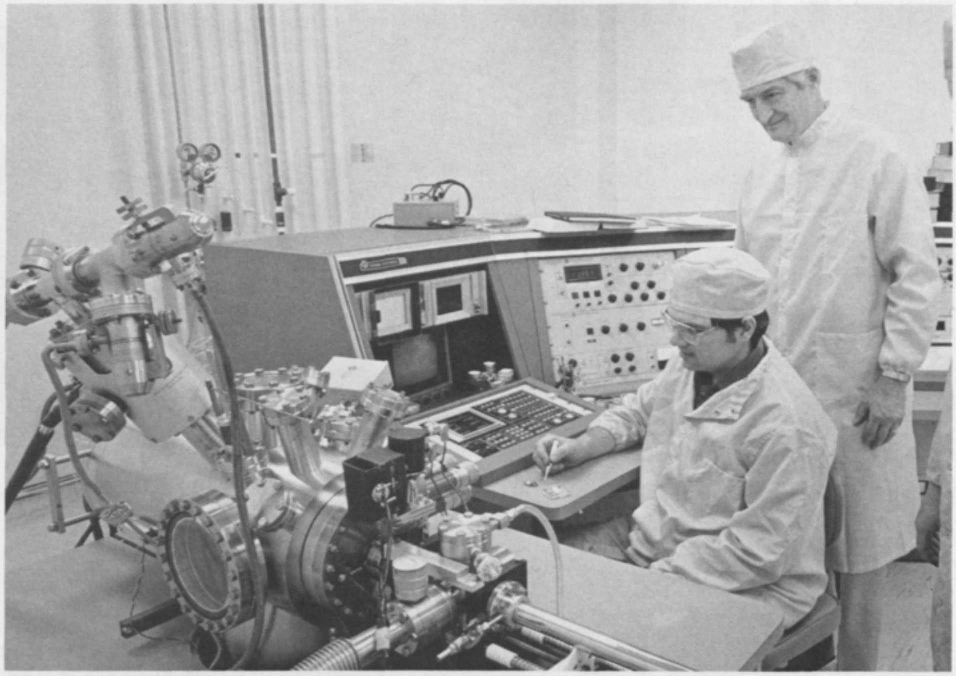
Just as important as the growth and fabrication of materials and devices is their analysis. NRRFSS researchers are determining the impurity levels and concentrations in the grown layers using an array of analytical tools. Three of the major systems available at NRRFSS—for Auger electron spectroscopy, Rutherford backscattering, and electron-energy-loss spectroscopy—are discussed below. In addition, the laboratory offers instrumentation for photoluminescence, deep-level transient spectroscopy (DLTS), secondary-ion mass spectroscopy (SIMS), and convergent-beam electron diffraction.

One of the most widely used techniques for the analysis of materials and microdevices is *Auger electron spectroscopy*. It is used both in industry and in research. By measuring the number and energy of electrons emitted from a sample during bombardment by electrons in high vacuum, the Auger can give very precise information on electron properties and chemical bonding of layers and on film composition. Depth resolution in the Å range, close to atomic distances, can be attained. Thor Rhodin of Cornell's applied and engineering physics faculty, and Lynn Rathbun, a NRRFSS research associate, are studying the limits of this technology and its applications to the microanalysis of layered structures.

Another system that analyzes microstructures through their composition is the *Rutherford backscattering facility,* located in Bard Hall and operated under the supervision of materials science and engineering professor James Mayer. Essentially a tool for near-surface analysis, its basic component is a million-volt Tandetron accelerator that produces a 2- to 3-MeV beam of helium ions. These energetic ions are used to provide submicron depth microscopy—profiles of concentration, interface composition, and film thickness—in the near-surface regions of solids. Concentration depth profiles with a

Right: Auger electron spectroscopy is used for analysis of surfaces and near-surface layers. Researchers at Cornell include Research Associate Lynn Rathbun (seated) and Professor Thor Rhodin.

Below: Professor John Silcox (left) and colleagues inspect the STEM system used for research involving electron-energy-loss spectroscopy. (The equipment is now installed in the clean room of Knight Laboratory)



resolution of 100 Å can be obtained, and data acquisition is fast, requiring about 15 minutes per sample. Another advantage is that the structural properties of the samples are not degraded by the exposure to MeV helium ions. With single-crystal substrates of semiconductors such as silicon (Si) or GaAs, or metals such as beryllium or nickel, the ion beam can be channeled along axial and planar directions and hence be used to probe for the locations of impurities, interface disorders, or lattice defects.

As a facility associated with NRRFSS, the MeV accelerator has been used to investigate ion implantation in Si, the composition and thickness of III-V semiconductor layers grown by molecular-beam epitaxy, and reactions between deposited metal films and semiconductor substrates. Other applications include studies of composition and structural changes in ion-beam modification of materials, growth kinetics in solid-phase epitaxy, silicide formation with near-noble and refractory metals, diffusion barriers in aluminum- and gold-based metallization layers on semiconductors, and interdiffusion in thin-film polymers. The facility has been used for several user projects.

Electron-energy-loss spectroscopy is another very promising technique for chemical analysis of extremely small volumes—on the order of nanometers. When high-energy electrons such as those in the probe of a scanning transmission electron microscope (STEM) pass through a solid sample, they are scattered and lose energy. Some energy is lost to the atoms that compose the solid, in amounts characteristic of the scattering atom; these energy losses can be measured and used to deduce the concentrations of different kinds of atoms. The electrons also lose energy because of electronic excitations characteristic of the solid, and energy-loss spectroscopy in an instrument such as the STEM can provide not only chemical, but electronic characterization. Since silicon is a prime material for device manufacture, quantitative, thin-film studies with high spatial resolution are important, and the STEM provides this capability. John Silcox, professor of applied and engineering physics, and Kevin Lee, his student, are conducting research in this area, and have initiated work on the preparation and characterization of silicon films 200 to 600 Å thick. Professor Michael S. Isaacson is also active in this field.

SUBMICRON TECHNIQUES IN MATERIALS RESEARCH

In several user projects, submicron technology is used in the construction of micro-electrode arrays for making measurements on various physical systems. An example is a project of Janet Osteryoung, a professor at the State University of New York at Buffalo, that involves large-scale-integration (LSI) electrode arrays for studying size effects in electrochemical reactions.

Left: Professor Myunghwan Kim uses LSI electrode arrays for studies of neuron behavior. The specimen in the dish is the North American crayfish Procambarus clarkii.

Certain biological studies are also made possible by LSI electrode arrays. Cornell electrical engineering professors Myunghwan Kim and William Heetderks (who is now entering private medical practice) use LSI arrays constructed at the submicron facility in their research on neuron behavior. Arrays of this kind are necessary for the study because of the small physical scale of neurological action and the complexity of nervous systems, even in simple invertebrates. Also, sensors able to detect minute fluctuations of action potentials across cell membranes could prove vital in the effort to understand cellular phenomena, including cancer.

A third program for fabricating small electrodes is directed by Arthur Ruoff, professor of materials science and engineering at Cornell. These are interdigitated electrodes, used for experiments at ultrahigh pressures, of the order of one megabar or greater. Because pressures this high can now be attained only in very small volumes, there is a need for measuring instruments that will fit within them; for pressures of one megabar, interdigitated electrodes with a period of less than one micrometer are required. The approach of Ruoff's research group is to create high pressure within an assembly, containing the electrode "fingers", that is positioned between a flat diamond anvil and a spherical diamond indentor with very small tip radius. Using this technique, the researchers have been able to produce an insulator-to-metal transition in a thin film of solid xenon. They are looking ahead to the production of "metallic" noble-gas solids, which would have important ramifications, both for solid-state theory and for energy technologies. And some day metallic hydrogen may serve as a fuel for a fusion reactor or as an inexpensive lightweight rocket fuel.

Ruoff's work is typical of the materials research at NRRFSS in its originality, scientific nature, ultimate applicability, and, of course, its attention to the fascinating unexplored areas of the micrometer and nanometer region.

ELECTRONS, IONS, AND PHOTONS IN SUBMICRON RESEARCH

1. Nanolithography with Electron Beams

by Michael S. Isaacson

In the rapid and spectacular development of microelectronics, the diminution of circuit features has been the chief impetus in the technology. As more and more elements have been packed on silicon chips, efficiency has gone up and cost has come down. There is an intrinsic limitation, however, in the reduction that can be achieved with photolithography, the chief patterning method used in the industry today: the limitation set by the wavelength of light. If structural features are to be shrunk even further, the technology must rely on ionizing radiation of shorter wavelength, such as electrons, ions, and x rays.

The smallest artificial patterns ever reported were created by electron-beam lithography in the national submicron facility here at Cornell (see the etchings reproduced on page 30). At the present time I am working with graduate student Andrew Muray in an NSF-sponsored research program aimed at investigating the ultimate size limits of this technique. The dimensions we are concerned with are in the range of nanometers (nm); elements of this size may have features more than two orders of magnitude smaller than those in most of the electronic devices that are now being fabricated. We call patterning on this scale *nanolithography*.

Why are we interested in creating features this small? Apart from the general trend toward miniaturization in electronics is the fact that structures in the size range below 100 nanometers (0.1 micrometer) are potentially useful in a wide array of technologies that are not oriented toward electronics. Also, a large number of scientific problems involve the behavior of matter at these scales.

The possibilities are intriguing. For example, the fabrication of metal or metallized wafers with arrays of apertures 50 nm or less in width makes possible the construction of a light microscope with spatial resolution one-tenth the wavelength of visible light (this is discussed in part 3 of this article). Quasi-two-dimensional crystals might be produced by creating regular patterns on substrates on a scale of 10 nm or less. Fine metal wires about 10 nm in diameter could be fabricated—an ability that is of interest in the study of electron-localization phenomena in metals. Strips such as this could also be used to fabricate simple "rulers" for metrology at that size scale.

LITHOGRAPHIC PROCESSING WITH ELECTRON BEAMS

Electron-beam lithography is similar to photolithography, which was practiced long before anyone thought of an electronic chip, but which became the basis for the modern industry. Essentially, photolithography is a process in which light illuminates a polymer-coated substrate through a mask or stencil and the exposed areas are developed (much as with a photographic film), leaving the pattern imprinted in the polymer. After removal of the more soluble exposed material, the unexposed polymer acts as a "resist", protecting the substrate against subsequent etching, and the patterned silicon is then treated to form microscopic elements such as metal wires, resistors, capacitors, and transistors.

Figure 1

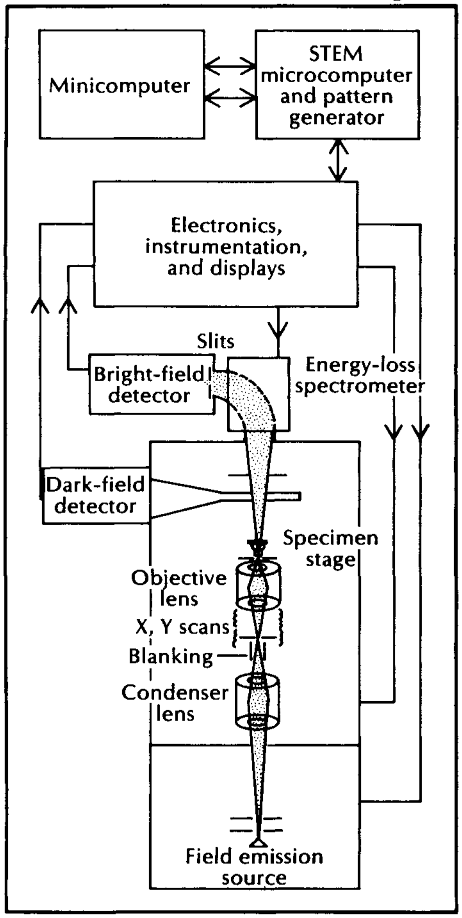


Figure 1. A schematic of the modified scanning transmission electron microscope (STEM) with a field-emission source at room temperature.

The smallness of these structures is limited by the wavelength of the light (about 400 nm for ultraviolet, which is usually used).

The size limitation can be thought of as a function of the fineness of the patterning tool. If one wants to create a fine line in a lithograph for printing, one uses a scribe with as small a point as possible. (In fact, lithographs made during the eighteenth and nineteenth centuries have line detail approaching the sizes available in many commercial integrated circuits!) When using radiation other than visible light, one would also like the "scribe", or probe, to have as small a diameter as possible. In our research carried out at the national submicron facility, we use a modified scanning transmission electron microscope (STEM) with a field-emission source (Figure 1). This instrument can produce one nanoampere of 100-keV electrons in a beam 0.5 nm in diameter. In other words, the "scribe" is small but very powerful: it can impart a half million amperes (or 40 gigawatts) per square centimeter into the structure to be patterned.

Our program follows two lines of research: the investigation of new materials that may be useful as patterning resists at the nm size scale, and the extension of existing technology that relies heavily on polymer resists of high molecular weight.

NEW MATERIALS FOR USE AS RESISTS

Techniques already available have been able to produce structures with features only 10 to 20 nm in size. The resists used in work reported in the literature have been conventional polymers or polymeric material made by the so-called Langmuir-Blodgett trough method, and the size limits have been thought to be due to secondary electrons which would have a range sufficient to expose the polymer at some distance from the incident beam. In other studies, ***in situ*** polymerization of surface-borne organic molecules by electron radiation has resulted in isolated lines that are slightly smaller—8 to 12 nm in width. In this case, the limits are thought to be due to the diffusion length of the molecules on the surface, and to the thickness of polymer needed as a resist against the ion etching that is used later in the process of forming the circuit elements.

One might imagine that, independent of other constraints, the ultimate pattern size would be limited by the polymer's "grain size," which is probably of the order of 5 nm (estimated on the basis of the molecular weight, in the range of 10^4 to 10^6 daltons for conventional resists). With this in mind, we have investigated var-

Figure 2. Bright-field micrographs showing patterns with features 2 nm in diameter etched into metal halide films by electron beams. These structures are the smallest artifacts ever reported.

a. *A pattern etched into a NaCl crystalline film supported on a thin carbon substrate. The upper portion of the figure shows a micrograph of an intact TMV virus (negatively stained) on the same sample taken under the same electron optical conditions. The incident beam energy was 100 keV. The image as represented here is magnified about a half-million times.*

b. *Lines 2 nm in width etched into a 30-nm-thick LiF film supported on a thin carbon substrate.*

c. *A larger field of lines etched in LiF. This micrograph shows the effect of the polycrystalline grains on the pattern. The bar corresponds to 100 nm.*

Figure 2a

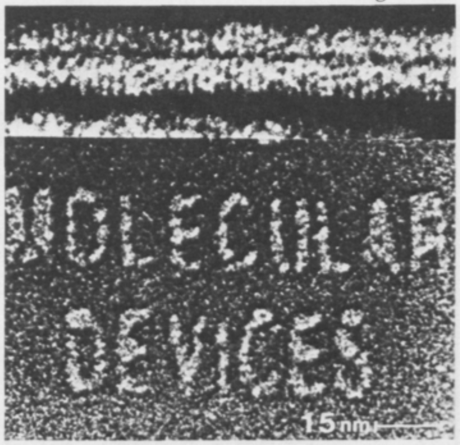


Figure 2b

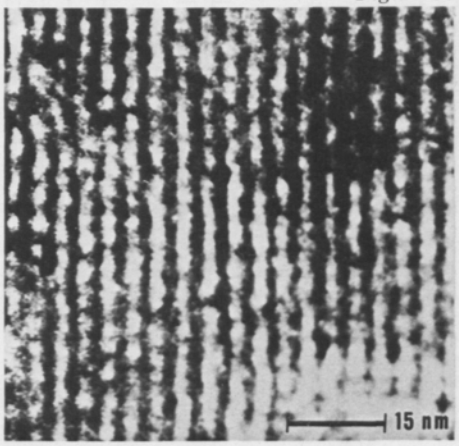
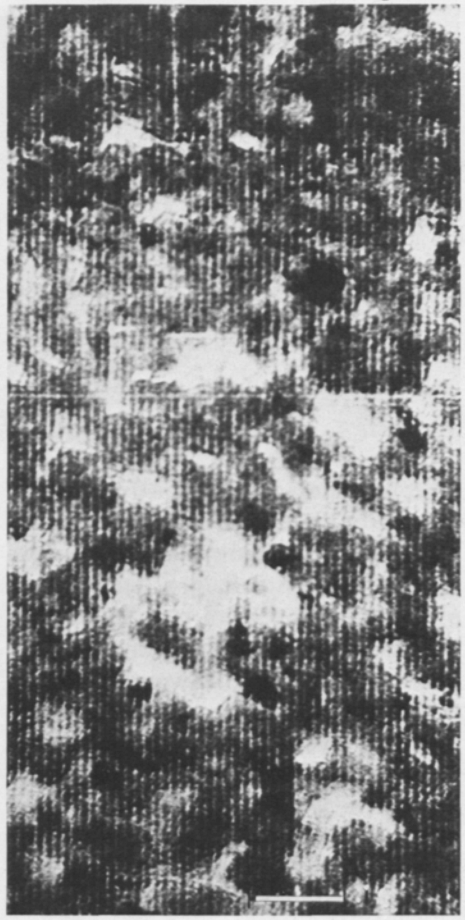


Figure 2c



ious small molecules—in the molecular-weight range of 10^2 daltons—that might keep the pattern-size limits down to the level imposed by the polymer grain size. An attractive possibility is that such molecules could be directly vaporized by the electron beam, simplifying the lithography process by eliminating the need for chemical removal of exposed resist material.

Figure 2 shows some examples of troughs about 2 nm wide etched in crystalline sodium chloride (NaCl) and lithium fluoride (LiF) films. Most of the alkali halides can be vaporized by an electron beam; the doses required for vaporization of films 30 nm thick (ours were 30–50 nm thick) range from 10^2 coulombs per square centimeter for NaCl to 10^{-2} coulombs per square centimeter for LiF. NaCl, although it may have limited applications for practical material patterning because of its slow deterioration in a normal atmosphere, has a property that makes it useful for studying size limitations that are due solely to the properties of the alkali halides: micrographs can be made of directly etched NaCl structures with doses much lower than the vaporization dose.

Using LiF, we have been able to etch 2-nm holes clear through self-supporting crystals 0.5 micrometer thick. This aperture size may be less than the range of secondary electrons in the material, and the limitation may be due to inelastic scattering, which is nonlocal in nature. We are now conducting experiments to directly measure the range of inelastic scattering.

A demonstration of how a nanometer "ruler" can be fabricated is given in Figure 3. This structure, with marked spacings of 10 nm, was

Figure 3

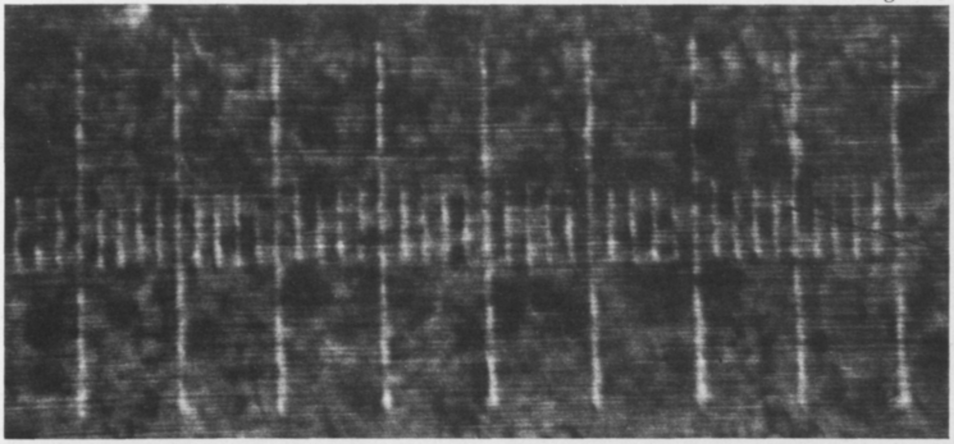


Figure 4

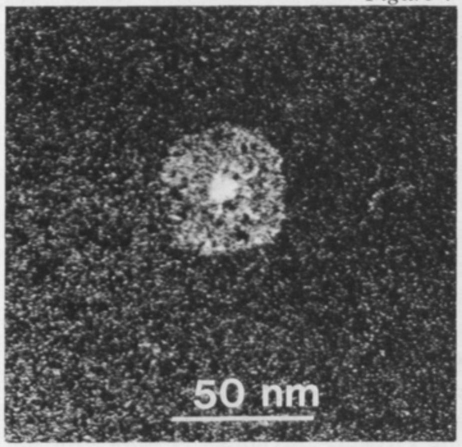


Figure 5

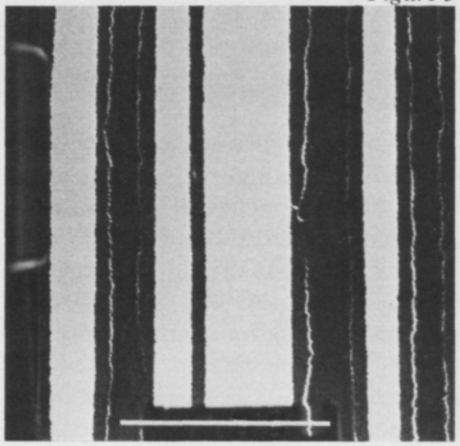


Figure 3. A nanometer rule made by etching LiF on silicon with an electron beam.

Figure 4. Metal apertures produced by an electron beam in a AuPd film supported on a single-crystal silicon window. The central hole goes through the metal and the silicon.

Figure 5. Self-supporting wires of metal on silicon, created by electron-beam lithography. The bar at the bottom corresponds to 150 nm.

created by direct electron-beam etching of LiF on silicon.

EXTENDING THE USE OF POLYMER RESISTS

To explore the fabrication limits of conventional polymer resist technology, high-resolution apertures were fabricated with poly (methyl methacrylate) (PMMA) as the resist material. Illesanmi Adesida, a research associate, collaborated in this work.

We used single-layer films of PMMA about 60 nm thick, deposited on uniform pinhole-free single-crystal silicon windows 80 μm square and 50 nm thick. Electron beams about 0.5 nm in diameter were used in all the experiments. The procedure was to expose the films to the electron beam, which creates a pattern by breaking down the polymer to more soluble molecules. After development of the PMMA, the resist pattern is transferred into the silicon window by a reactive-ion etching process. Either a groove or a clear-through slot or hole can be etched.

Figure 4 shows the backside of a resist that has been etched in this way and then metallized by evaporating onto it a 30-nm-thick film of gold-palladium (AuPd). The etchant has produced an undercut in the silicon; the central hole (8 nm in diameter) goes clear through the metal and silicon. Metals containing arrays of apertures 10 to 50 nm in diameter have been fabricated using this method. (The immediate purpose was to provide a structure that could be used to build the light microscope discussed in part 3).

Slots etched completely through a 50-nm-thick silicon window can be seen in Figure 5. The bright-field micrograph shows AuPd deposited on the remaining silicon; the dark regions are the metal and the light regions are clear-through holes.

THE LARGE POTENTIAL OF SMALL SIZE

Our work is still at an early stage. We have only begun to explore the many potential materials that may be useful for pattern transfer at the nanometer

"The Cornell research in electron-beam nanolithography is being conducted at or near the ultimate limit of miniaturization."

scale. And although we have encountered what appear to be practical problems associated with delineating structures below the 2-nm scale, we still do not know the ultimate size limit of fabrication using finely focused electron beams. These two aspects of nanolithography are interconnected, and their simultaneous investigation should lead to new knowledge in a synergistic manner. The study of materials will help elucidate the mechanisms of electron lithography, and research on the physical limits of patterning with electron beams may give rise to new materials and insight into material properties.

The Cornell research in electron-beam nanolithography is being conducted at or near the ultimate limit of miniaturization. Its relevance to the electronics industry, and to other technologies that require small structures, is apparent, and equally important is the fundamental scientific information the research will reveal. In the modern world, large images can be cast by the smallest of patterns.

Michael S. Isaacson, an associate professor in the School of Applied and Engineering Physics, specializes in work with the scanning transmission electron microscope. He came to Cornell in 1979 after teaching at the University of Chicago and working at the Enrico Fermi Institute there. Earlier he served as a staff scientist at Brookhaven National Laboratory.

Isaacson received the B.S. degree in engineering physics from the University of Illinois at Urbana and the S.M. and Ph.D. in physics from the University of Chicago. He held an Alfred P. Sloan Foundation fellowship in 1975–77 and received the 1976 Burton Award from the Electron Microscopy Society of America for outstanding contributions by a scientist under the age of thirty-five.

2. Ion Beams for Very-High-Resolution Lithography

by Benjamin M. Siegel

A focused beam of ions provides a promising pathway to a new class of ultrasmall devices. It is the path being followed by our research group at Cornell, one of only a few in the United States that are now working on ion-beam systems for fabricating structures with dimensions on the scale of nanometers.

The leading approach to the fabrication of structures this small is currently electron-beam lithography. As Part 1 of this article indicates, electron beams can create the smallest features yet produced. Still, electrons create certain limitations not imposed by ions, and it may be that ion-beam technology will have a significant place in future technology.

Our approach is based on the breakthrough development in our laboratory of a high-brightness source of charged hydrogen molecules (H_2^+). This gaseous field-ion source provides a very bright beam of low-mass ions suitable for work at the nanometer level. Gary Hanson, senior research associate, had primary responsibility for carrying out this project.

Now we are getting underway with the conversion of a prototype high-speed electron-beam lithography system, given by the Hewlett-Packard Company, to a machine that will use our H_2^+ source. The people at Hewlett-Packard called their instrument ''Hermes'' after the winged messenger of the Greek gods who was also the god of science and commerce. We call ours HERMES II.

Figure 1

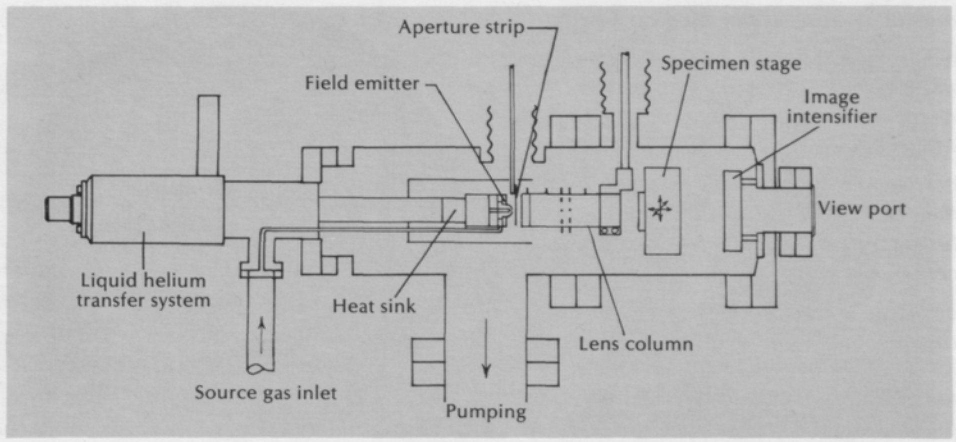


Figure 1. The field-ion probe system developed at Cornell for study of direct ion-beam writing. It produces a very bright beam of charged hydrogen molecules.

ION BEAMS AT THREE SUBMICRON LEVELS

Our high-intensity H_2^+ source (Figure 1) has possible applications in three ranges of submicron size: (1) 0.1 to 0.5 micrometer (μm), the range in which

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The work described here is being conducted as a NRRFSS facility-development project with support from the Advanced Research Projects Agency.

Figure 2. Images demonstrating the high-brightness ion beams obtained with the gaseous (H_2^+) field-ion source. High angular currents are obtained by operating a processed tungsten tip at liquid helium temperatures under carefully controlled conditions of the gas supply. The images that are obtained depend on conditions such as the applied voltage and the method used for processing the tip.

a. A conventional field-ion micrograph imaged with hydrogen. The pattern, from a field-desorbed tungsten tip, shows atomic sites.

b. A ring of bright field-ion sites showing the emission of H_2^+ ions from an annealed tungsten tip. The flat tip face forms the center of the ring.

c. A field-ion site of very high brightness: the angular current density was measured as 60 microamperes per steradian. This ion beam is from a defect structure in an annealed tungsten tip.

Figure 2a

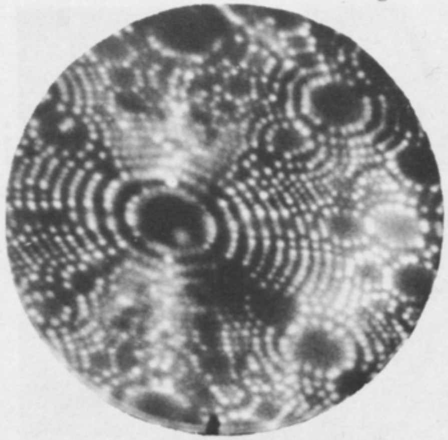


Figure 2b

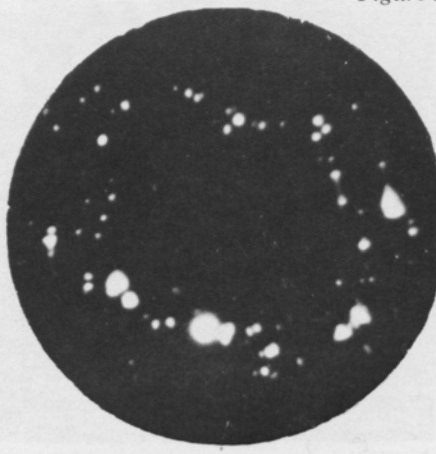
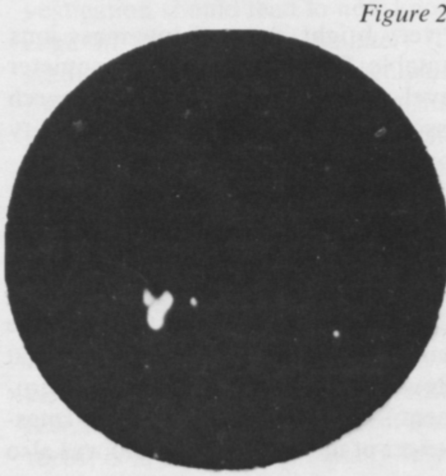


Figure 2c



electron-beam technology is primarily developing at the present time; (2) 10 to 100 nanometers (nm), a range in which electron beams can produce lines only on very thin substrates or at high accelerating voltages (50–100 kV); and (3) 10 to 100 angstroms (Å). In each of these areas, ion-beam technology has the potential of making significant and unique contributions.

In the *0.1 to 0.5 μm range,* electron-beam lithography is limited by backscattering of electrons, especially when the substrate is relatively thick, and by the rather low sensitivity of the resist materials. To get around the proximity effect, electron-beam lithographers must introduce complex computer control of exposure, or use special multilayer resists. With ion beams, the backscattering problem does not occur and thick substrates can be used with a single resist layer or even no resist at all. Also, resists such as poly(methyl methacrylate) (PMMA) are fifty to one hundred times more sensitive to ions than to electrons. Another advantage is that the depth of penetration of ions into the resist can be controlled by varying the energy of the incident beam.

In the *10 to 100 nm range,* ion probes provide a means of directly producing, on thick substrates, lines that are separated by spaces equal to the line width. Electron beams can fabricate thin lines, but cannot space them close together; and x-ray lithography requires masks. Patterns with features this small are of very great interest because devices could be made with very compact architecture, capable of complex operations. Of course, many basic questions about the physics and properties of very small objects and about the interaction of ion beams and materials must be answered before devices of this size can actually be fabricated.

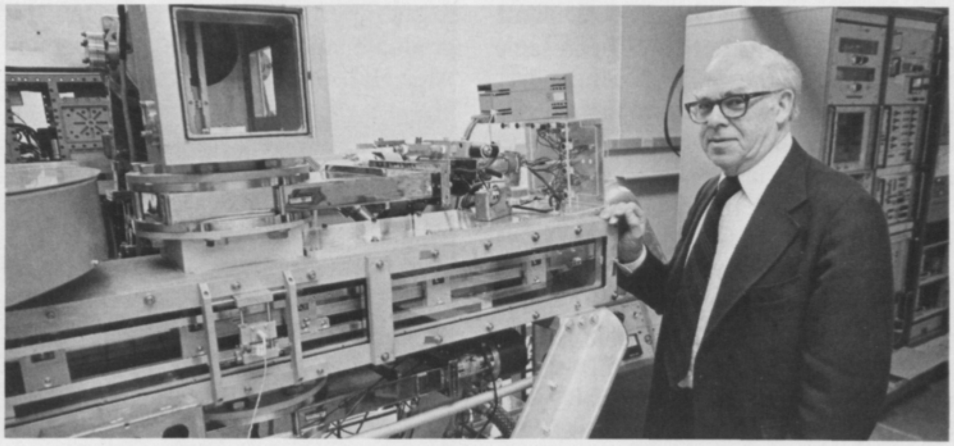
In the *10 to 100 Å range,* high-intensity ion probes could be important for elemental analysis. The concentrations of atomic species near or at the surface of solids or thin films could be determined by mass analysis of atoms sputtered by the ion probe. This would be useful in a variety of studies, including many at NRRFSS.

"... ion-beam lithography will have at least three major advantages over electron-beam lithography."

ADVANTAGES OF ION BEAMS FOR NANOLITHOGRAPHY

In general, we expect that ion-beam lithography will have at least three major advantages over electron-beam lithography: much greater sensitivity, no proximity effects caused by the generation of secondary electrons, and controlled depth of penetration. The highly developed instrumentation of electron-beam lithography could be applied directly to ion-beam systems, essentially by simply replacing the particle source and the column optics. The result could be a high-speed system capable of precision fabrication of densely patterned structures with very small dimensions.

Much remains to be done before ion-beam lithography achieves its potential. For example, at the extremes of miniaturization we are considering, we do not know how the properties of materials scale with linear dimensions, volume, or surface-to-volume ratio. The scaling of structures and processes will require investigation of phenomena such as electromigration, current-density effects, tunnelling, fluctuations and ion implantation.



Our work is cut out for us. But we have HERMES II to help us.

Benjamin Siegel has been a member of the Cornell faculty since 1949 and a full professor since 1959. An electron microscopist, he is at the School of Applied and Engineering Physics.

After earning the B.S. and Ph.D. degrees at the Massachusetts Institute of Technology, he served as a research associate there and at the California Institute of Technology, Harvard University, and the Weizmann Institute of Science.

He has spent sabbatical leaves at the Hebrew University in Jerusalem, Israel; the MRC Laboratory of Molecular Biology in Cambridge, England; and the Salk Institute in LaJolla, California. In 1973–74 he served as president of the Electron Microscopy Society of America. In 1982 he received a Presidential Award from that society for "outstanding contributions to the field of electron microscopy."

3. Light Transmission Through Submicron Apertures

by Aaron Lewis and Michael S. Isaacson

For the first time, structures as small as a polymer molecule have been seen with visible light. This seemingly impossible result was accomplished recently in collaborative research we are conducting at Cornell.

The reason that features this small—in the range of 300 to 500 angstroms (Å)—cannot ordinarily be resolved in a light microscope is that the wavelength of visible radiation is larger than 300 Å; even ultraviolet light, at the short end of the scale, is in the range of 4000 Å. Because of this intrinsic limitation, the fabrication of patterns with submicrometer dimensions (1 micrometer = 10,000 Å) has come to depend on a beam of electrons instead of a beam of light for the lithographic process.

Our research has shown that there is, nevertheless, a way to adapt light for applications in this dimensional range. The method is to pass the beam through very small apertures that have been created by means of electron-beam lithography. To avoid dispersion of the transmitted beam, the light is used at a surface very close to the apertures. So far, we and our graduate students Andrew Muray and Alec Harootunian have focused on the physics of visible radiation that has passed through apertures 0.05 to 0.025 micrometer in diameter—one-tenth to one-twentieth the wavelength of the incident light. We have demonstrated that the necessary apertures can be constructed in a controlled fashion and that visible radiation can, indeed, be transmitted through them with high efficiency.

Our research now is proceeding in

Figure 1

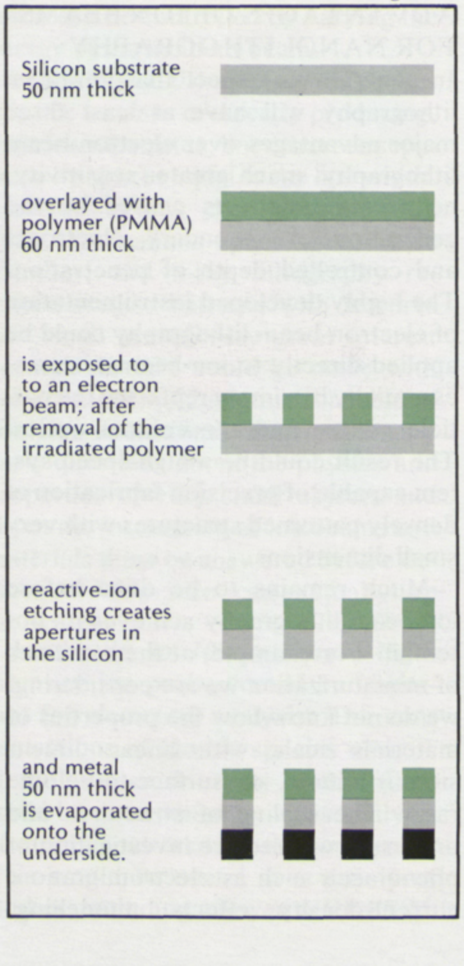


Figure 1. The procedure for constructing regular arrays of apertures narrower than 0.05 micrometer. The technique makes use of the microprocessor-controlled scanning transmission electron microscope (STEM) at NRRFSS.

The steps illustrated in this cross-sectional schematic produce a metallized surface on the silicon side of a wafer coated with PMMA. This was the method used in the Cornell experiments. Alternately, the metal can be evaporated onto the PMMA side. It is also possible to remove the silicon and the PMMA, leaving a free-standing metal film.

Figure 2a

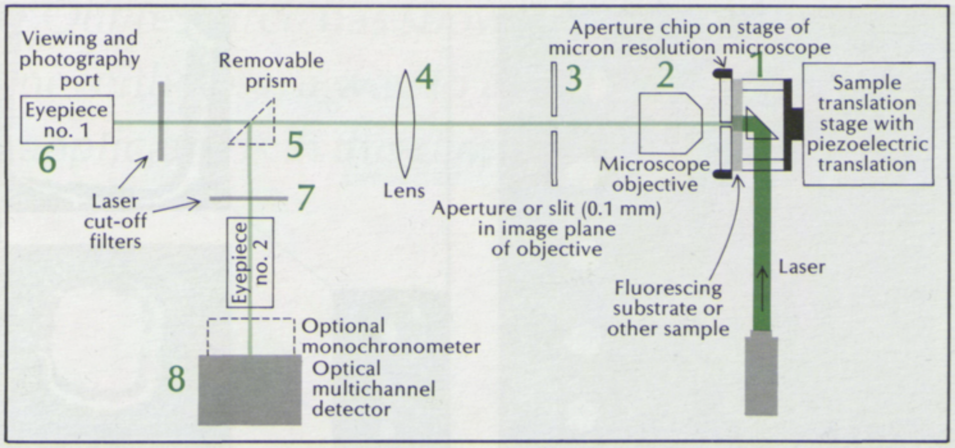


Figure 2b

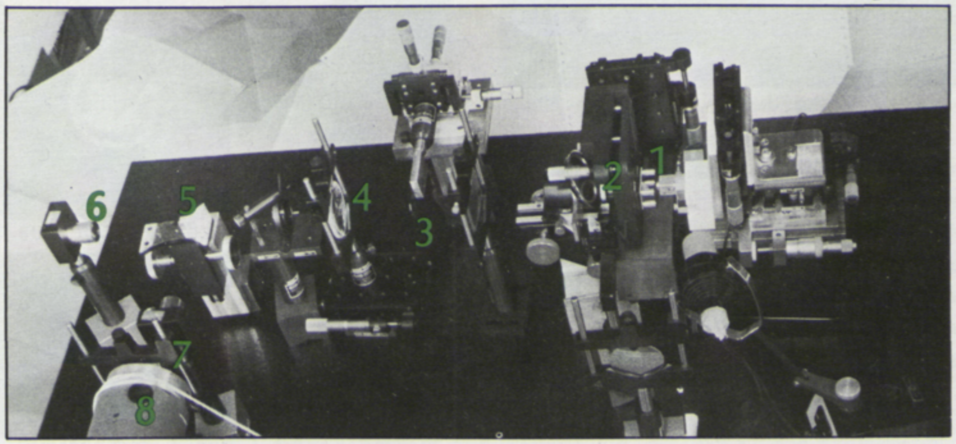


Figure 2. The scanning optical microscope under development at Cornell.

a. *A schematic with various parts numbered. Not shown is a device that allows the laser beam to be propagated with total internal reflectance, a capability that permits illumination of only an 800-Å surface layer of the sample. This device can be substituted for the prism in the piezoelectric translation stage.*

b. *A photograph showing a recent configuration of the flexible system. The numbered parts correspond to those in* a.

several directions. Through experimental and theoretical investigation, we are seeking to understand the fundamental physical factors that permit or constrain the transmission of visible radiation through these very small apertures. Also, we are exploring the nature of the transmitted light at several ranges of distance from the apertures: the near field, the Fresnel, and the Fraunhofer regions. As this fundamental knowledge accumulates, we are using it in the development of a light microscope that can image features in the range of 500 Å, and we are "reversing" the microscope technology to generate lithographic patterns with feature sizes less than one-tenth the wavelength of the illuminating light source.

CREATING AND VIEWING SUBMICRON HOLES

A well-defined array of apertures as small as 0.008 micrometer in width can be made in silicon wafers by means of the microprocessor-controlled electron beam of the scanning transmission electron microscope (STEM). The process is outlined in Figure 1. The final step indicated in the figure produces a specimen with apertures extending through three layers—the silicon substrate, the polymer, and metal—that have a total thickness of about 0.16 micrometer.

The apertures can be viewed in the optical microscope being developed in our laboratory. The photograph and the schematic in Figure 2 show the present state of the instrument. The arrangement is flexible so that new design ideas can be incorporated as they evolve. This prototype device differs from conventional light microscopes in having a piezoelectrically-driven stage with nanometer resolution for mounting the sample, and a micro-resolution stage for the aperture array. Also, the design makes it easy to bring a laser beam at grazing incidence between the sample and the aperture array.

A light micrograph of one of the early aperture arrays is shown in Figure 3. This array consists of rows of apertures ranging in size from 0.24 to

Figure 3

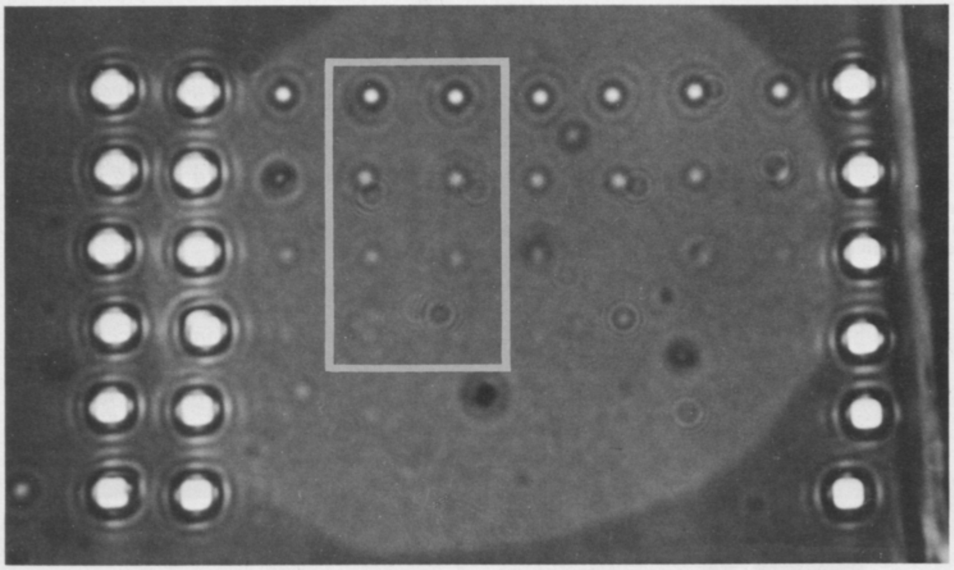


Figure 4

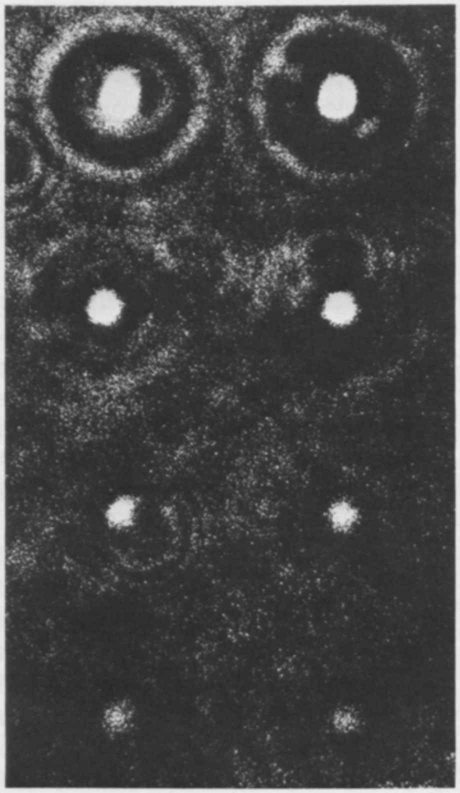


Figure 5

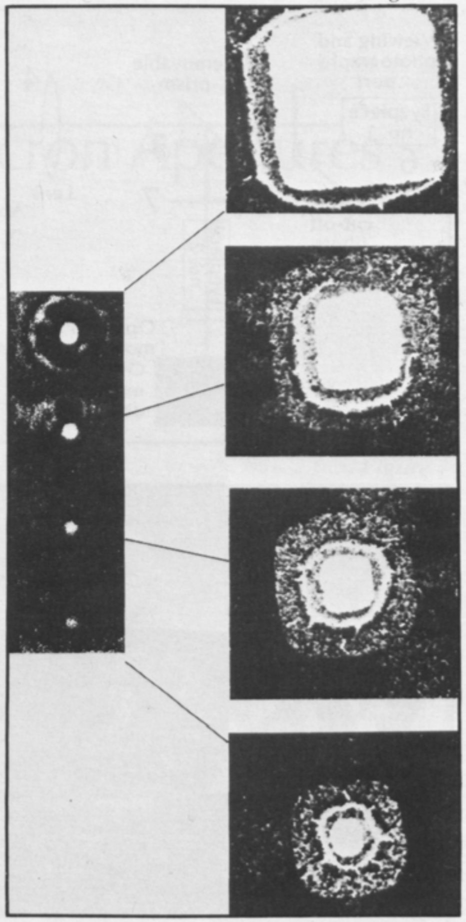


Figure 3. A light micrograph of an aperture array fabricated with the STEM. The large (2-micrometer) squares are there to help in locating the submicrometer apertures, which range in size from 0.24 micrometer (2400 Å) at the top to 0.008 micrometer (80 Å) at the bottom. The smallest do not show up in this reproduction because the camera adjusts the lens aperture to the brightest elements. This aperture array was fabricated at NRRFSS with the collaboration of Research Associate Illesanmi Adesida.

Figure 4. The area bounded by the green rectangle in Figure 3. The smallest aperture is 0.03 micrometer or 300 Å—the size of a large polymer molecule. This image, obtained in far field, clearly shows Fresnel fringes.

Figure 5. A comparison of light (at left) and electron (at right) micrographs of a column of apertures. From top to bottom, the aperture sizes are 0.24, 0.12, 0.05, and 0.03 micrometer. This column of apertures is the same as the column on the right in Figure 4.

0.008 micrometer, bracketed by 2-micrometer squares which aid in locating the holes. This image was obtained using a simple microscope illuminator that has a spectral output maximizing at 0.5 micrometer (5000 Å). With such an experimental arrangement, we have been able to see clearly the holes 0.015 micrometer in size, and we are optimistic that with laser illumination and a new electronic feature—a cooled optical multichannel analyzer that provides spatial resolution and temporal integration—we

"Our research has shown that there is, nevertheless, a way to adapt light for applications in this dimensional range."

will be able to detect light that has been transmitted through the 0.008-micrometer apertures.

The aperture sizes were established by directly comparing our light micrographs with electron-microscopic images that provided accurate measurements of the aperture dimensions. A comparison is shown in Figure 5. The four apertures, ranging in size from 0.24 to 0.03 micrometer, are the same as those in the right-hand column of Figure 4.

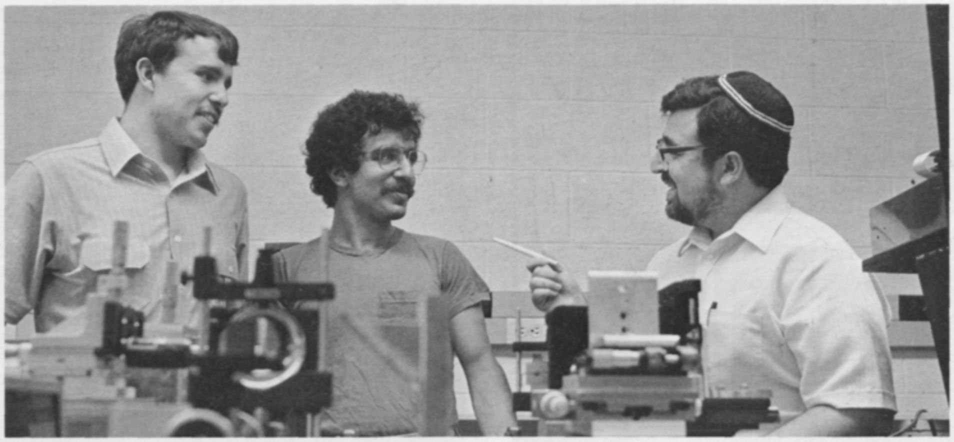
TOWARD A 500-Å SCANNING OPTICAL MICROSCOPE

With the aperture array in place in our microscope, we have been able to detect laser-excited 6000-Å fluorescence from a perylene sample placed in near field to the aperture. These experiments are now being extended to test the resolution of a scanning optical microscope that would use nanometer apertures and a pattern with comparable dimensions to probe a sample.

The test pattern, constructed by means of electron-beam nanolithography, is a perylene grating with lines 500 Å or less in width separated by varying distances. This test pattern will be mounted on the piezoelectrically-driven stage and scanned across the microscope aperture in near field. A laser positioned at grazing incidence will illuminate an 800-Å layer of surface molecules. The optical multichannel detector should record fluorescence intensity that alternates as a function of the position of the grating (the intensity will be a convolution of the grating structure and the near-field radiation pattern).

Several pieces of experimental evidence have made us optimistic about the ultimate success of such a high-resolution scanning optical microscope. A decade ago research with microwaves of 3-mm wavelength essentially demonstrated a microwave microscope with a resolution one-fifteenth the wavelength of the incident radiation. In our own laboratory we have observed an expected sharp decrease in the intensity of fluorescence transmitted through the apertures as the distance between aperture and fluorescing sample is increased. Also, we have been satisfied with the structural rigidity of the apertures and the ease with which we have been able to mechanically scan samples in 100-Å steps.

What is the rationale for building a light microscope with a resolution of only 500 Å when resolution two orders of magnitude better is easily achieved with an electron microscope? The chief reason is that no available microscope in the 500-Å range can image objects in air without the destructive effects of ionizing radiation. A high-resolution microscope using visible radiation would allow a variety of objects, from living cells to integrated circuits, to be viewed nondestructively in their native environments. Furthermore, since such a microscope could be used to image spectral phenomena such as fluorescence and enhanced resonance Raman scattering from surfaces, it would be possible to make chemical maps of dynamically changing systems. The fine time resolution of laser beams would be especially valuable in such applications.



Professor Lewis (at right) confers with his graduate students Robert Eric Betzig (at left) and Eric Harootunian. Betzig, who joined the group very recently, is beginning research on the lithography aspects of the project. Hartootunian is working on the submicrometer light microscope.

FUNDAMENTAL PHYSICS AND OTHER APPLICATIONS

The methods used to construct such a nanometer-resolution light microscope can be reversed to generate features with dimensions less than the wavelength of light. Our technique is to expose a thin (500 Å) polymer resist through an aperture array positioned close to the polymer surface. After the resist is developed, it is coated with gold so that it can be viewed with a scanning electron microscope.

We have two objectives in carrying out these experiments. First, we want to investigate how the interaction of the light with the resist varies according to the distance between the aperture array and the polymer surface. Such measurements will accurately determine the extent to which the radiation "spreads out" after it passes through the apertures. The sharpness and the configuration of the patterns will give us critical information about the ultimate resolution that can be achieved through this approach.

Our second aim is to explore the technological implications of these fundamental studies. The promise is that it will be possible to generate photolithographic patterns unconstrained by the wavelength of the light source.

In addition, we are continuing our research into the mechanisms that constrain the transmission of light through nanometer apertures. For example, we have observed an apparent discontinuity in the radiation transmitted through the aperture as a function of incident intensity. We are investigating such effects and the physical phenomena they may be signalling. This work includes experiments with apertures of different geometries, study of the temperature and polarization dependence of the light transmission, and measurement by means of electron-energy-loss spectroscopy of the plasmon frequencies in and around the aperture.

In all its aspects, our project makes use of a great many recent technological developments—in nanolithography, piezoelectric nanometer translation, tunable laser techniques, and low-light-level optical detection—and it promises to yield new tools as well as new knowledge of physical phenomena. The work has turned out to be an exciting blend of basic and applied research with significant implications for technology and medicine.

Aaron Lewis and Michael S. Isaacson are faculty members of the School of Applied and Engineering Physics.

Isaacson also contributed the first article in this group of three (see the biographical sketch on page 32).

Since coming to Cornell in 1971, Lewis has directed an active research program involving laser spectroscopy. His work involves both biological and physical systems (he recently wrote for the Quarterly *about research on a solar cell based on a bacterial pigment).*

Lewis, who was promoted to the rank of full professor this summer, studied at the University of Missouri and at Case Western Reserve University, which awarded him the Ph.D. in chemical physics. As a postdoctoral researcher, he worked at Case Western Reserve on physical studies of the visual process and at Cornell on protein chemistry.

He has held Guggenheim and Alfred P. Sloan Foundation fellowships, and this spring he was awarded a U.S. army fellowship for work at the Letterman Army Institute of Research in San Francisco, and a Fulbright fellowship for research in Israel.

MICROPHYSICS FOR THE FUTURE

1. Periodic Submicron Structures

by Neil W. Ashcroft

Little by little the allure of small things is beginning to take hold in the community of condensed-matter physicists. It is not simply because small structures have been unavailable until now. As we know from the venerable science of colloids, this is not the case: by chemical and evaporative techniques, it has been possible to fabricate aggregates of particles whose characteristic sizes have been as small as 20 Å (or 0.002 micrometer). But these particles are usually not uniform in size or shape, and there is generally no regularity in the way they are arranged in space.

This is now changing, and changing quickly. Small structures can be made with prescribed dimensions smaller than 1,000 Å, and in principle they can be connected with wires whose thickness is about 300 Å. There is nothing in the laws of physics that prevents the contemplated construction of structures as small as 100 Å. And most interesting of all, there is the possibility of producing *regular arrays* of nearly identical particles, arrays that will make possible a whole new assortment of ultrasmall structures. This possibility is one that is being investigated theoretically by my research group.

The research described here is supported by the Semiconductor Research Corporation.

GEOMETRIC ARRAYS ON A SMALL SCALE

Imagine regularly spaced arrays of submicron particles produced in both two and three dimensions. The former are planar arrays; the latter can be regarded as "crystal structures" with cubic or more complex order. Actually, these might be better called "super-crystals", since each little particle probably has its own local crystalline order (though at present we can't guarantee an orientational perfection or coherence from one particle to another). Possible uses of such arrays include the construction of devices that are sensitive to the presence of radiation whose frequency is in a particular range, as determined by the geometry and scale of the array.

Geometrically uniform arrays of submicron features such as apertures can also, in principle, be fabricated. The development of the technology and examples of its possible applications are discussed by Michael Isaacson and Aaron Lewis in other articles in this issue. For instance, they describe a light microscope that can resolve features one-tenth or less the size of those at the current limits of magnification by visible-radiation microscopy.

CHANGE IN PROPERTIES WITH DECREASING SIZE

What is fascinating about the prospect of producing periodic submicron structures is the fact—well known in physics—that many phenomena do not scale with size in a simple way. In the following article, Bob Richardson discusses some examples drawn from the worlds of low-temperature physics, phonon physics, and resonance physics. In these the manifestation of "smallness" is predicted to be quite dramatic. Perhaps a more unusual example is the notion that sim-

". . . many of the concepts traditionally accepted in solid-state physics are simply no longer valid on these new length scales."

ply by making a normal metal wire smaller and smaller in thickness, we can actually induce the most fundamental of all phase changes—that is, the change from a metal to an insulator. This is the so-called *localization phenomenon*, a quintessentially quantum-mechanical effect that says that the resistance of an ultrathin wire can grow exponentially with its length.

This is surprising behavior for a material we normally think of as a metal, and perhaps it may even be the first cautionary flag in the drive to ultimate smallness.

Another warning flag is the unintentional but nevertheless inevitable disorder that is present in even the most meticulously prepared submicron arrays. This can be seen in our study of super-crystals of GaAlAs spheres embedded "periodically" in GaAs host material. The word "periodically" is used advisedly, because in real systems we cannot match the theoretician's pristine order. The spheres vary slightly in size and from time to time they are displaced from perfect repetition. This disorder, unwanted though it may be, must be included in a realistic description of the system. It is the same kind of problem that must be faced in the theory of random electron systems: too much disorder can "localize" electrons that would otherwise be free to move across such systems.

These are two examples of the basic issues under study in the burgeoning field of microscience, which provides the underpinnings of microelectronics and microfabrication. For condensed-matter physicists, microscience means the physics of small structures, both isolated objects and aggregates of them. It also embraces the physics of their surfaces, and their junctions and interfaces with other objects, both large and small.

Particularly intriguing is the discovery that many of the concepts traditionally accepted in solid-state physics are simply no longer valid on these new length scales. For instance, how should we view the transport of charge in our super-crystal of closely spaced small structures—a model, perhaps, of tight arrays? Obviously, we have two areas of concern: intraparticle transport and interparticle transport. In the former, the particles are small enough that we can no longer rely on our familiar "free electron" pictures. And in the latter, we have to consider the fact that when an electron hops onto a small submicron structure, it can actually change the potential of that structure locally. This is certainly not our normal view of transport in simple solids.

LIMITS TO SMALLNESS IN MICROSTRUCTURES

How do we tackle these problems in which one small structure begins to interact with some of the surrounding structures; how do we describe an active device that is no longer isolated from the processes of its neighbors? It is not possible to go into details here, but one way of approaching such systems in general terms is to expand the notion of energy bands in a way that parallels the expansion of our concept of a crystal into that of a super-crystal. Transport—for example, the

flow of charge through the system—is then treated by the standard methods of solid-state and semiconductor physics, but with the new interactions characteristic of the super-lattice included. One objective is to examine the motion of carriers in a given small structure in terms of the dynamics and local fields produced by surrounding structures. To do this, we have to depart somewhat from the idea of truly independent charge carriers, a difficulty that makes this problem quite challenging.

The significant implication, of course, is that there is surely a limit to smallness in the construction of devices and memories, in the sense that the basic elements of these tiny tributes to our technology can be said to act independently. Though we may be some distance from this point, the potential for "cross-talk" between cells—an interaction associated with their own fluctuations in charge and current—is indeed a problem in achieving the limit of smallness. Happily, some of these questions border on some quite fundamental issues of solid-state physics, and for this reason collaboration between the physicists and the microfabrication community is developing rapidly.

"He that contemneth small things shall fail by little and little." The judgment in the Apocrypha is probably correct.

Neil W. Ashcroft is professor of physics and director of the Laboratory of Atomic and Solid State Physics at Cornell.

After receiving the B.S. and M.S. degrees from the University of New Zealand, he went on to earn the doctorate at Cambridge University, in 1964. He came to Cornell as a research associate in 1965 and was appointed to the faculty the following year.

Ashcroft is co-author of Solid State Physics, *published by Holt, Rinehart and Winston. He is a scientific consultant to Los Alamos National Laboratory, and a member of the National Academy of Sciences Panel on Condensed Matter Physics.*

". . . there is surely a limit to smallness in the construction of devices and memories . . ."

2. Submicron Structures at Very Low Temperatures

by Robert C. Richardson

Tiny uniform cylinders only a fifth of a micrometer in diameter and a fifth of a micrometer high are helping our research group at Cornell answer some basic questions about solids at temperatures close to absolute zero.

The small particles are produced by electron-beam lithography in the laboratories of NRRFSS, the submicron facility at Cornell. Their usefulness is that they are suitable as specimens for probes of thermal activity over very small distances at very low temperatures. The great scientific interest of the research lies in the fact that in this thermal region near absolute zero the usual ideas about transport processes in solids are not valid, and our measurements should lead to revisions of fundamental theory.

Equilibrium temperatures well below 1 mK (0.001 degree Kelvin) can be obtained with current techniques, but there are some important unanswered questions about what is meant when we say a body is in equilibrium at such temperatures. Our aim is to investigate the thermal excitations in metals and insulators under these minimum working temperatures, using physical probes that are small enough to be applicable.

The research discussed in this article is conducted under a contract with the Office of Naval Research.

AT THE LOWER LIMITS OF SIZE AND TEMPERATURE

To illustrate the fundamental nature of the problems faced, I have constructed a table that lists some characteristic dimensions related to (1) *thermal effects* at the minimum working temperature of modern low-temperature physics (taken as 1 mK), and (2) *size effects* at the minimum practical dimension of present-day microstructures technology (taken as 0.1 micrometer or 10^{-7} meter). Some of the contrasts apparent in the table are quite remarkable.

Consider first some characteristic frequencies. At 1 mK the "noise frequency" is 20 megahertz (MHz); above this cut-off level, there should be no random thermal excitation. This

CONTRASTING THERMAL AND SIZE EFFECTS

	1. Thermal Effects T = 1 mK	**2. Size Effects** x = 0.1 micrometer
Frequency	$kT/h = 2 \times 10^7$ *(noise cut-off)*	$E_0 = h/(8mx^2) = 9 \times 10^9$ *(single electron in box)* $\Delta E = E_0 N^{-1/3} = 2 \times 10^7$ *(state spacing in a metal)*
Length	$hv_{sound}/kT = 200\ \mu m$	$hv_F/E_F = 175\ \mu m$
Electric Field	$kT/e = 86$ nV	$\Delta E/e = 86$ nV
Magnetic Field	$kT/\mu_B = 15$ G *(electronic spin polarization)* $kT/\mu_N = 27$ KG *(nuclear spin polarization)*	$\Delta E/\mu_B = 15$ G

noise "cut-off" is expressed in column 1 of the table as $kT/h = 2 \times 10^7$. Column 2 gives corresponding information about the characteristic spacing of energy states in a hypothetical 0.1-micrometer cube. The energy states of a single electron in this cube would be separated by a frequency of about 10^{10} Hz. What is "noise" in such circumstances? If we use a Fermi gas model for a metal such as copper with N electrons in the same "isolated" box, the separation between states is reduced by the factor $N^{1/3}$, but we still have a frequency spacing of about 10^7 Hz between the allowed states of the system. Our metal has become a rather peculiar quantum gas. The continuum picture of the energy states is no longer valid, and our thermal energy is comparable to the electron-energy-level spacing. In this regime, our usual ideas about the transport processes must undergo rather severe changes.

Another interesting question arises when we think about small-scale insulators at these low temperatures. If we characterize the thermal vibration of a "typical" insulator as having a sound velocity of 4×10^3 meters per second, we calculate that the wavelength of a thermal phonon at 1 mK (column 1 in the row labeled "length") is 200 micrometers. In column 2, a calculation in terms of the Fermi velocity, v_F, and Fermi energy, E_F, comes out to 175 micrometers. How will such a length ever fit into our 0.1-micrometer box? Obviously, it does not; and so again we find that under these circumstances our picture of heat transport in a lattice must be drastically revised.

Figure 1

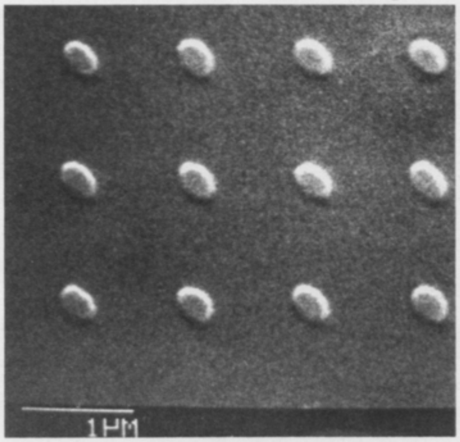


Figure 1. Part of an array of small metal "boxes" to be used in low-temperature studies of size effects in metals.

The array was fabricated in the NRRSFF laboratory by electron-beam lithography. A film of the photo-resist material (PMMA) was exposed to a rapidly hopping electron beam. After exposure, a solvent was used to remove the resist material from the portion of the film struck by the electron beam. The holes were then filled with aluminum (in this case, the metal was deposited by evaporation). Finally, the remaining resist material was dissolved, leaving the "pancakes" of aluminum on a silicon substrate. The same method can be used for producing arrays of a variety of metals.

The shape of each of the "boxes" is nearly the same, although it might not be exactly circular. Here the dots are elliptical because of small aberrations in the electron-beam optics.

The other quantities in the table are listed as suggestions for possible probes of the system. The characteristic electric potentials are of the order of tens of nanovolts, and the characteristic magnetic fields required for large polarization of electronic moments or nuclear magnetic moments are of the order of tens of gauss and tens of kilogauss, respectively. We conclude that our 0.1-micrometer metal box contains a quantum gas that is "invisible" to the 1-mK sound radiation, but can be studied by a number of practical probes. The required electric fields are not too small and the useful magnetic fields are not too large.

E-BEAM LITHOGRAPHY FOR NMR EXPERIMENTS

In pursuing this line of research, we have been using nuclear magnetic resonance (NMR) as a tool for probing the temperature and the excitations in small particles. The magnetic susceptibility of the nuclei in the crystals gives a measure of the temperature, and the thermal time constant pertaining to the time required for the nuclear magnetism to come to equilibrium gives a method for monitoring the number of thermal excitations remaining in the particles. The rationale for the equilibrium measurements can be explained qualitatively: In metals, for instance, the nuclear magnetic moments are relaxed through interaction with the conduction electrons, but at temperatures so low that the thermal energy is less than the spacing between the energy states of the electrons in a box of finite size, it should become much more difficult for the nuclear magnetic moments to come to equilibrium. In fact, it is not clear what process will produce spin relaxation in this peculiar limit.

Our initial experiments have been done on powder samples of metals and insulators. A problem is that in

"... our measurements should lead to revisions of fundamental theory."

Above: Professor Richardson (at left) was assisted in the research discussed here by graduate student Chris Hammel, who performed the lithography experiments at NRRFSS.

powders there is a wide distribution of specimen size, so that even though we observe phenomena which are quite different from those exhibited by large (or bulk) solids, the specific effects related to the particle dimensions have not been quantitatively measured. For this reason, we will use electron-beam lithography to prepare a large quantity of nearly identical small particles for the low-temperature NMR experiments.

An additional problem might be that the total specimen size required for reasonable NMR sensitivity is about 10^{17} nuclei, which means that for a typical material we need roughly 10^9 "boxes" of the size we can produce by electron-beam lithography. (This amount is called a *gigadot* by the graduate students working on the project.) But preliminary studies make the approach look quite feasible. Of course, the particles are not actually box-shaped; they are small cylinders 0.2 micrometer in diameter and 0.2 micrometer high.

Our research provides an example of the fundamental problems that can be addressed in modern microphysics. The extremes of low temperature and small size that are now attainable open up important new areas of investigation and new methods to accomplish the work.

Robert C. Richardson, a professor of physics at Cornell, is associated with the Laboratory of Atomic and Solid State Physics, as well as NRRFSS.

After receiving the B.S. and M.S. degrees from Virginia Polytechnic Institute, he earned the Ph.D. degree from Duke University in 1966 and came to Cornell as a research associate in the Department of Physics. He was appointed to the faculty the following year.

A specialist in nuclear and solid-state physics, Richardson was a co-discoverer of the superfluid phases of ^3He. He has twice been a Guggenheim Fellow.

REGISTER

Burton, Hartman, McGaughan: Emeritus Professors Looking Ahead

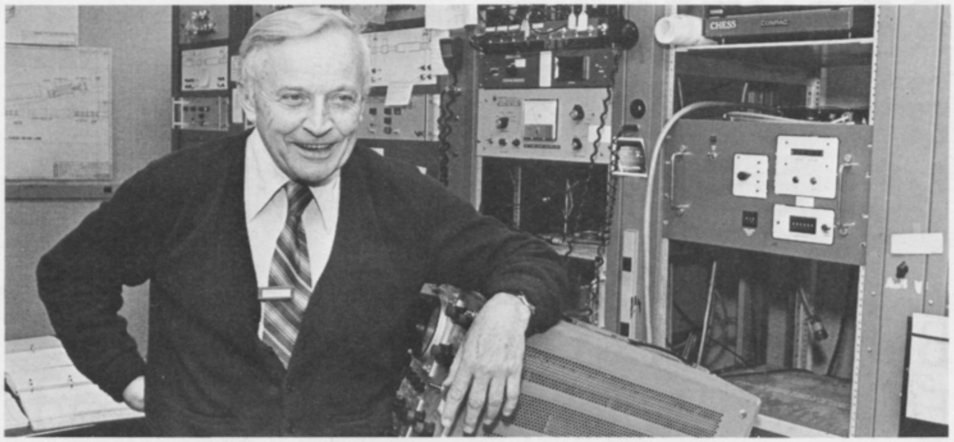
When Malcolm S. Burton, Paul L. Hartman, and Henry McGaughan first came to Cornell, a row of faculty houses stood where Phillips Hall is now, beginning salaries were around $4,000 a year, assistant professors taught as many as five classes a term, and there were few graduate students and federal research dollars. That was in the 1940s, soon after World War II. Over the years these men, from three different departments, contributed to the remarkable development of Cornell engineering. This summer they became professors, emeritus.

■ Mal Burton and his wife, Hazel, have headed for northern California, where they will set up a new home. "I want to continue to do new things," he said in a conversation this spring, "and look forward rather than back." He may build a house himself, extending skills he has practiced for almost forty years. Still, the culmination of a long university career triggers recollections of its beginnings. This summer, between curriculum planning for the coming year's students and packing up

Burton

thirty-seven years' worth of belongings for the trip west, Burton was apt to reflect on how different the campus looked when the Engineering Quad was the site of temporary barracks, with woods along the side of the gorge. Olin Hall, where he first taught as a member of the chemical and metallurgical faculty in the era of the "Dusty" Rhodes directorship, was the only building of the projected modern engineering campus.

Burton did a lot of planning for Bard Hall, built in 1963 to house a newly formed department, now Materials Science and Engineering. He was named assistant director of the department and later served as acting director. His professional activities have included industrial consulting, and his publications include a textbook, *Applied Metallurgy for Engineers*. Later he moved into administration, serving as head of the Division of Basic Studies and, in recent years, as associate dean of the College with special responsibility for academic affairs and as director of the Engineering Cooperative Program.



He has shepherded the College and its students through successive changes in programs, adapting curricula to emerging needs. He has served on innumerable University, College, and departmental committees, mostly concerned with educational policy.

Burton was educated in Massachusetts, earning the B.S. degree in mechanical engineering at Worcester Polytechnic Institute in 1940, and the M.S. in metallurgy at the Massachusetts Institute of Technology. He taught at M.I.T. for several years during the war before coming to Cornell in 1946. The Burtons' children grew up in Ithaca and have all located in California, anticipating their parents' move across the country.

■ Paul Hartman's reflections have taken the form of an anecdotal account of physics at Cornell, a history he has helped shape for thirty-seven years. The manuscript, now being passed around in Carpenter Hall, is written with the thoroughness of a veteran scientist and teacher, and with a characteristic spark and humor. He is not really retiring, however, since he plans to continue to be active in developing both undergraduate teaching programs and the experimental facilities at CHESS, the Cornell high-energy synchrotron source.

Actually, Hartman has been associated with Cornell for almost half a century, for after graduating from the University of Nevada in 1934 with a degree in electrical engineering, he came here for graduate study in physics. After receiving the Ph. D. in 1938, he was an instructor for a year before working for seven years at the Bell Telephone Laboratories, and then he returned to Cornell as a member of the physics faculty in 1946. He and his wife, Peggy, have made their home in Ithaca ever since; their three daughters were reared here.

One of Hartman's first activities at the University was to help establish the engineering physics program, and he has continued on the faculties of both the Department of Physics and the engineering unit which is now the School of Applied and Engineering Physics.

His professional activities have included sabbatic, summer, and consulting work with the Hughes Aircraft Company and the Los Alamos Scientific Laboratory. He has served as an editor of the *Review of Scientific Instruments* and has published extensively in this field of physics. An important paper concerned an early investigation, with D. Tomboulian, on sychrotron radiation; another significant publication is a collaborative paper, written during his years at Bell Laboratories, that became a standard reference on the use of the magnetron as a generator of centimeter waves.

At Cornell Hartman has been a member of numerous committees, including the Materials Science Center executive committee, and he has served as secretary of the University faculty, and as a member of both the University Senate and the Faculty Council of Representatives.

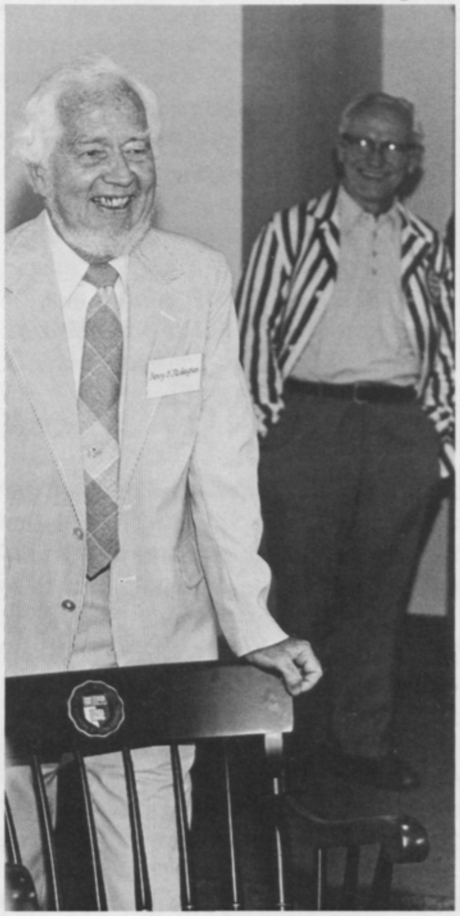
■ Henry McGaughan's field is electrical engineering; over the years he has taught the fundamentals of the discipline—electronics, electrical systems, network analysis and synthesis, and statistical communication theory —to thousands of Cornell engineers. He is in a good position to assess changes in the electrical engineering program, which he said has increasingly emphasized theory and also the technique of mathematical modeling of systems that is so essential for practitioners today.

McGaughan received the B.S.E. degree in physics from the University of Michigan in 1941. Until 1946 he was employed by the U.S. Naval Ordnance Laboratory as an electronics engineer, working principally in underwater sound measurement and analysis and in the design and testing of acoustic homing devices; he received the Navy's Meritorious Civilian Service Award for this work. He came to Cornell as an instructor and part-time graduate student in 1947, and two years later completed work for a master's degree. He has been a full professor in the School of Electrical Engineering since 1960.

McGaughan has been active in educational affairs at the University, College, and School levels. He has twice served as graduate faculty representative in electrical engineering, and has been a member of numerous committees, including the President's Committee for Special Educational Programs and College faculty groups on educational policy and curricula. His consulting work has been primarily in systems and communication theory, particularly with reference to anti-aircraft defense systems and radar jamming and anti-jamming. During the 1950s he spent a leave as a visiting professor at the former Cornell Aeronautical Laboratory, and in the 1960s he spent a sabbatical leave as a visiting professor and technical assistance expert at Chiao-Tung University in Hsinchu, Taiwan.

One of his particular pleasures has been the opportunity his career has given him to travel, and he and his wife, Ruth, are planning more trips, to visit grown children and see new parts of the world. One of McGaughan's hobbies is photography, and he will add to his extensive collection of pictures from around the world.

McGaughan



Professor McGaughan was guest of honor at the Electrical Engineering alumni breakfast in June. As an alumnus smiles in the background, McGaughan accepts the gift of a Cornell chair.

These three professors were feted at a variety of special occasions this spring. A dinner for Burton, for example, brought together colleagues from throughout the College, reflecting his wide-ranging activities and influence. Paul Hartman Day was celebrated under the auspices of his two departments; the events included a colloquium at which the featured speaker was Dale Corson, president emeritus of the University, former Dean of Engineering, and colleague of Hartman on the physics faculty (they once shared an office). McGaughan was the guest of honor at the Electrical Engineering alumni breakfast during spring reunion, an occasion that appropriately brought together current colleagues and associates and generations of alumni who studied under him.

Working in different fields and in different ways, all three of these professors have made lasting contributions to engineering at Cornell. —G.McC.

A Seasonal Harvest of Awards

A Guggenheim fellowship, election to the National Academy of Engineers, and prizes from professional societies were among numerous honors garnered by College personnel this spring. A few of the awards are noted here.

■ *David Gries,* professor and chairman of the Department of Computer Science, was named a Guggenheim Fellow and will spend the 1983-84 academic year at Oxford University investigating sequential and concurrent programming methodology. A textbook by Gries, *The Science of Programming,* was recently published by Springer-Verlag.

■ *Raymond C. Loehr,* the Liberty Hyde Bailey Professor of Agricultural Engineering, was among forty-nine engineers in the United States elected to the National Academy of Engineers this year. Loehr was cited for his "international leadership in research, engineering analysis, education, and management practices for solution of waste disposal problems." Selection for membership in the academy is generally considered the highest professional distinction that can be conferred on engineers.

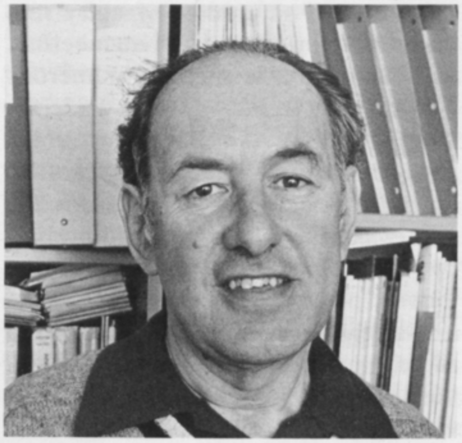
Others now at Cornell who were previously elected are *Thomas E. Everhart,* professor of electrical engineering and dean of the College of Engineering, and *Dale R. Corson,* emeritus president of the University and professor of physics, who also served as engineering dean.

■ *Gerald Salton,* professor of computer science, was honored as the first recipient of the SIGIR Award from the Special Interest Group on Information Retrieval of the Association for Computing Machinery. The award, for "outstanding and continued achievements" in research, was accompanied by a $500 prize. Salton's achievements cited in the presentation include work on the SMART system for information organization and retrieval, and subsequent experimentation that has resulted in "significant developments in theories of indexing, clustering, and feedback."

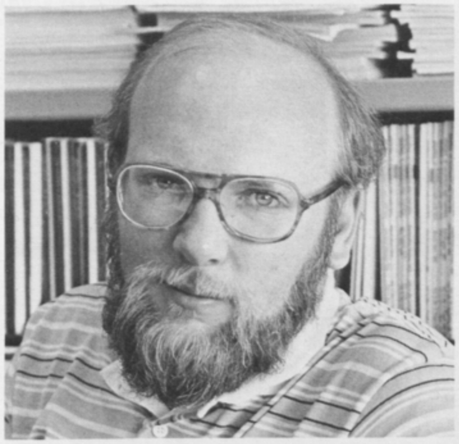
Gries

Loehr

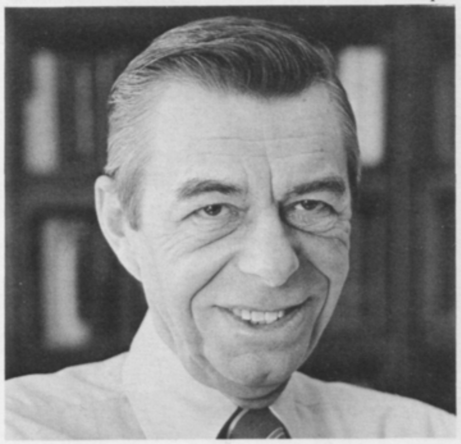
Salton



Johnson



Thorpe



■ *Özalp Babaoğlu,* assistant professor of computer science, shared the 1983 D. J. Sakrison Memorial Prize from the Department of Electrical Engineering and Computer Science at the University of California, Berkeley, where he completed his doctoral work in 1981. The $2,000 prize was awarded jointly to Babaoğlu and an associate who worked together on the development of the Berkeley-UNIX computer operating system, which is now used in computer science departments throughout the country.

■ *C. Richard Johnson, Jr.,* associate professor of electrical engineering, received two awards from the national honorary society Eta Kappa Nu. This spring he was honored at the organization's annual banquet as the 1982 winner of the Recognition of Outstanding Young Electrical Engineers. A few weeks later, at Cornell's annual student-faculty EE banquet, he was awarded the 1983 C. Holmes MacDonald Outstanding Teaching Award for Young Electrical Engineering Professors.

■ *Raymond G. Thorpe,* associate professor of chemical engineering, received the annual $1,500 Excellence in Engineering Teaching Award at the College this spring. He was previously selected in 1974. The award is sponsored by the Cornell Society of Engineers and Tau Beta Pi, national honorary society in engineering, and is based on nominations by students in the College. Thorpe is a specialist in phase equilibria and fluid flow.

■ *Gerhard Jirka* is a recipient of the 1983 Walter L. Huber Civil Engineering Research Prize of the American Society of Civil Engineers. An associate professor, he is currently on sabbatical leave at the Institute for Hydromechanics of the Federal Institute of Technology in Zürich.

■ Outstanding instructors named by student groups this spring included *Lionel Weiss,* who was elected for the fourth year by the student chapter of the Institute of Industrial Engineers. In Civil and Environmental Engineering, Chi Epsilon members elected *Thomas D. O'Rourke* as Professor of the Year and teaching assistant *Kenneth Hofer* as Teacher of the Year.

■ *Jery R. Stedinger,* assistant professor of civil and environmental engineering, was cited for excellence in refereeing from the editors of *Water Resources Research,* published by the American Geophysical Union.

■ *Engineering: Cornell Quarterly* received an Exceptional Achievement Award in the 1983 competition of the Council for Advancement and Support of Education (CASE), the national organization of university professionals in public affairs and publications. In recent years the *Quarterly* has consistently received this rating, the highest in the annual judging.

■ *Simpson Linke,* professor of electrical engineering, also won an award in the CASE competition. His article, "Global Hydroelectric Power via Reflector Satellites," in the Spring, 1982 issue of *Engineering,* was cited in the Best Articles of the Year category.

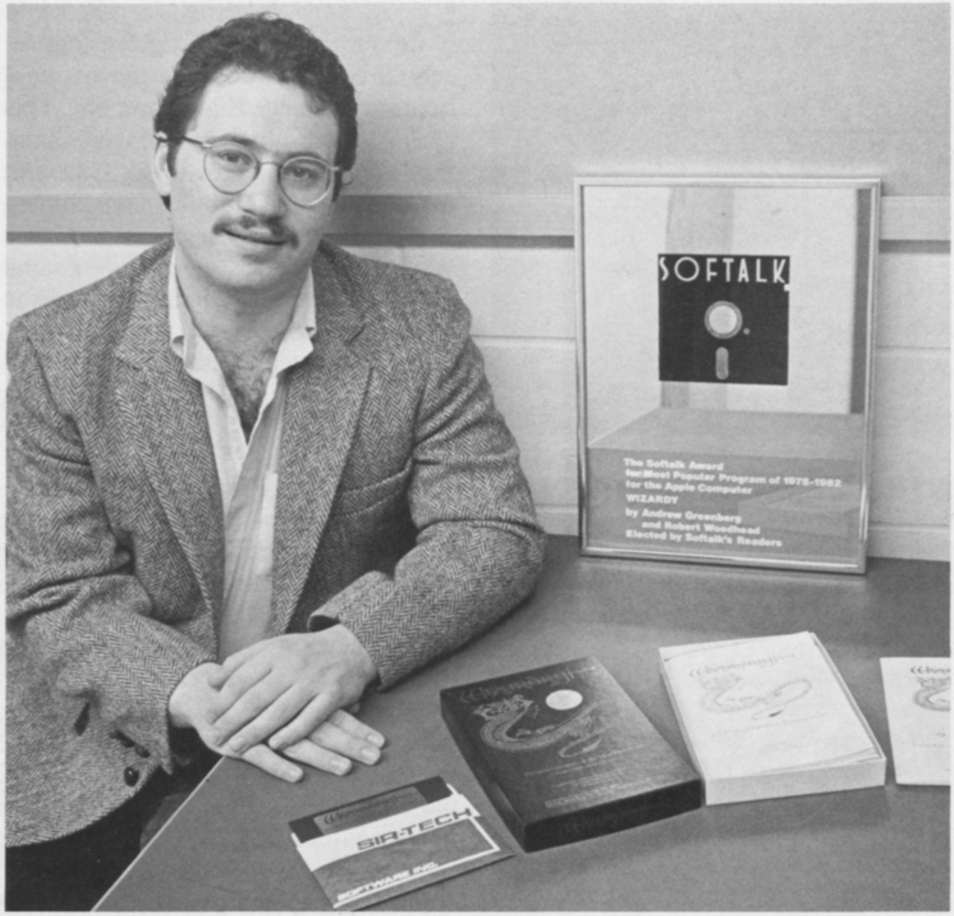
■ *Andrew C. Greenberg,* a graduate student in computer science, was one of the developers of a computer game that won a prize this spring. The fantasy game, *Wizardry,* sold over 100,000 copies, making it the winner of the Softalk Award for the Most Popular Program of 1978-82 for the Apple Computer. Greenberg and his collaborator, *Robert Woodhead* (who was an undergraduate at Cornell) have found computer games a lucrative sideline to more serious professional work. Three other games will be on the market this summer.

■ *James Maroney,* a graduate student in the School of Electrical Engineering, won a new award for teaching assistants sponsored by the Cornell Society of Engineers and Tau Beta Pi. A baccalaureate graduate of The Cooper Union, Maroney was in his third year of graduate study, specializing in microwave theory.

■ Many graduating seniors were awarded prizes for academic excellence at the end of the spring term. The following four are among those reported to the *Quarterly*.

John Hiele won the Pertsch Prize, which is given for outstanding performance during the first six terms in electrical engineering. He earned the $1,000 award with a grade-point average of 4.1 (better than an A). During his senior year he was president of Eta Kappa Nu and was instrumental in setting up the Summers Tutoring Program, which provides help to students in seven basic electrical engineering courses. In September he will enter Harvard Medical School.

Greenberg



Anita U. Huedepohl received the Chester Buchanan Memorial Scholarship, an award that is given annually to a geology major who has been recommended by the department faculty. Currently valued at $1,000, the scholarship was established in 1936 by Mrs. Claire F. Buchanan in memory of her son, a Cornell alumnus killed in a plane crash. Anita Huedepohl will begin graduate work at Stanford University in the fall.

Gregg O. Wellenkamp and *William R. Boorujy* won the Sibley Prize, which is given to the two seniors having the highest grade-point average in the Sibley School of Mechanical and Aerospace Engineering. Both winners received additional prizes—Wellenkamp the McManus Design Award and Boorujy the Frank O. Ellenwood Prize, which is awarded to the student who earns the highest grades in the required sequence of courses on power production. Boorujy was also named the outstanding senior by the student branch of the American Society of Mechanical Engineers.

VANTAGE

New Fellowship Honors High School Teacher

A ninety-four-year-old high school mathematics teacher was recognized this spring when an alumni couple established a Cornell engineering fellowship in her honor.

The Harriet Davis Fellowship in Applied Mathematics was endowed by Donald P. Berens and Margaret Schiavone Berens, both Class of '47. It will be awarded annually to a student in a graduate field of engineering in which mathematics is applied to important technological problems.

Donald Berens studied under Miss Davis at Washington High School, in Massillon, Ohio, where she taught from 1914 to 1957. Three more of her former students have become professors at Cornell: Jack E. Oliver, geological sciences; John F. Burton, industrial and labor relations; and R. Kenneth Horst, plant pathology. They were all present at an inaugural ceremony held on campus May 12.

Right: Former students Oliver, Burton, and Horst stand behind Miss Davis and Berens at the gathering in celebration of the Harriet Davis Fellowship.

Groundbreaking Ceremonies

Two new structures are now being built at the west end of the engineering quadrangle. Ground was broken last fall for Snee Hall, future home of the Department of Geological Sciences, and this spring for a new wing of Hollister Hall that will house the DeFrees Hydraulics Laboratory. The new space will provide the geology department with its own specially equipped building, and the School of Civil and Environmental Engineering with improved experimental facilities for studying the motion of water.

Left: Among the speakers at the groundbreaking for Snee Hall was Thomas E. Everhart, dean of the College of Engineering. Above: Mrs. Snee received some help with the gold-painted spade from President Frank H. T. Rhodes.

Snee '25

DeFrees '29

Above: Gerhard H. Jirka, a professor of fluid mechanics, spoke at the groundbreaking for the new laboratory. Right: Mrs. DeFrees with Richard N. White, director of the School of Civil and Environmental Engineering, and Dean Everhart.

Pew '08

Snee Hall, built around an atrium extending through its four stories, will include laboratories, offices, and seminar rooms. It is to be ready in late 1984. Major facilities in the DeFrees laboratory are a 105-foot wave flume, an 80-foot tilting flume, and a large wind/water tunnel.

The buildings were made possible by three prominent alumni. The estate of William E. Snee provided $6 million toward the $11.2 million projected cost of the geology building; the Joseph N. Pew, Jr. Trust has awarded $1 million outright, and made a challenge grant of another $1 million, contingent on the raising of $2 million from other sources by November 15, 1983. The late Joseph H. DeFrees and his wife, Barbara, provided funds for the hydraulics laboratory.

Cornell's Answer to the Brooklyn Bridge

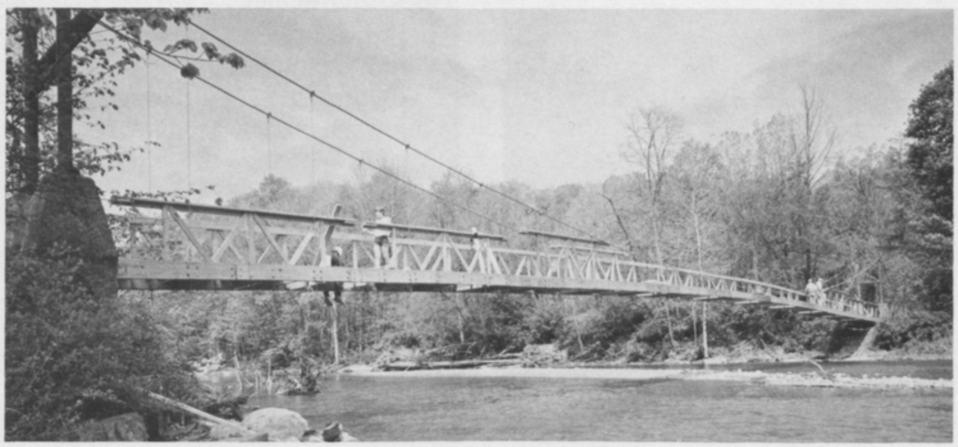
A suspension footbridge over scenic Fall Creek just above the Cornell campus is the unusually appropriate legacy of this year's civil engineering students. Built by the student chapter of the American Society of Civil Engineers as the group's annual community service project, the bridge is a sturdy and handsome example of engineering design and construction, as well as a symbol of the interrelationship between college and community. Even before completion, it won local acclaim and national recognition for the student organization.

The bridge was inaugurated May 27, during graduation weekend, in a ribbon-cutting ceremony attended by scores of bridgebuilders, their parents, friends, fellow students, and wellwishers from Cornell and the Ithaca area.

Located just above the Flat Rock area on Forest Home Drive, across from the Floriculture and Ornamental Horticulture Test Garden Facility, the bridge provides access to a network of trails extending from the Cornell Golf Course to the agricultural fields in Varna. Part of the Finger Lakes Trail System, these footpaths are used by bird watchers, wildflower fanciers, cross-country skiers, and joggers.

Actually, the new footbridge is a replacement for one that was washed out by the flood of October 28, 1981. Built in 1936, the old bridge had hung only a short distance above the water, and when trees piled up against it, the cables snapped. Within days of the collapse, Cornell Plantations began receiving phone calls asking when it would be replaced. The ASCE members were able to adopt the project because of a $10,000 gift from Mrs. Eva Howe Stevens, an Ithaca resident who is the widow of former Law School Dean Robert S. Stevens. Additional funds were provided by Cornell Plantations and the University's Department of Maintenance and Service Operations.

The bridge is the third in a series of community service projects undertaken by the ASCE chapter. The others were the building of a pavilion in



Robert H. Treman State Park in 1981–82 and the design of a recreation park for Eastern Heights.

The bridge project was coordinated by students Bryan D. Clark, president of the ASCE chapter; Rick Crum, chief designer; Douglas Neal, financial manager; and Mark Ehlen, construction manager. About sixteen students were involved in the computer aided design, and twenty worked at prefabricating sections of the deck, which were built in the George Winter Laboratory for structural engineering. The Department of Maintenance and Service Operations then implemented student plans for new steel towers on the concrete abutments of the old bridge, replaced the old cable anchorage, and hung new cable according to the specifications. Finally, more than fifty students installed the hangers and decking, using a trolley that rode along the cables.

There were some problems, of course. One was the time constraint: the bridge had to be finished before the students dispersed at the end of the school year. Cables thicker than necessary were chosen because they could be delivered immediately, but then they could not be put in place until high water from the spring runoff had subsided enough for heavy equipment to cross the stream. As time began to run out and costs continued to mount, the students learned how much a successful construction project depends on good administration. Bryan Clark worked such long hours trying to keep the project on schedule that he lost his voice and had to communicate by scribbling notes on a pad. Much of the work force was

Below: A high point of the inauguration ceremony was the cutting of a white ribbon stretched between the abutments on the Forest Home Drive side of the bridge. The students shown are (left to right) Bryan Clark, David Worsley, Robin Ackerman, Richard Crum, Sean Killoy, Paul Rooney, Mark Ehlen, and Douglas Neal.

Professor O'Rourke, speaking at the inauguration of the bridge, quoted from "Little Gidding," the last of T. S. Eliot's Four Quartets:

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

lost when classes ended and all the students except graduating seniors went home. But those still in town worked frantically, taking advantage of a few days toward the end of May when it finally stopped raining. They barely managed to finish the decking and put up the railings by the time of the opening ceremony.

The bridge is 180 feet long and five feet wide. The decking and railings are designed to flex in response to the weight of pedestrians and the action of the wind, and are connected to the abutments with springs. The cables dip steeply from the towers at each end, and the deck rises in a slight curve. The intersection of the two parabolas—one acute, the other gentle—gives the bridge a very graceful appearance.

The students were especially happy to learn, just a few days before the inauguration of the bridge, that they had won the 1983 Robert Ridgway Award of the ASCE as the outstanding student chapter. Bryan Clark said he felt that the award recognized not only the suspension bridge, but the dynamism that has characterized the Cornell chapter since the presidency of Marshal Case Haggard in 1980–81. Haggard was killed the summer after his graduation, while serving in the Peace Corps in Nepal.

The afternoon of the opening ceremony was cool but not rainy; the sun shone fitfully. Bush honeysuckle bloomed near the concrete abutments; a smell of fresh paint wafted from the steel towers. Nearly everyone in the crowd seemed to have a camera. Clark welcomed the visitors and then introduced Thomas D. O'Rourke, former faculty adviser tó the chapter, who said that the bridge was "both a gift and a discovery": a gift to those who would use it and a discovery for those who built it. The students, he said, had made a new discovery of basic engineering principles and the elements of cooperative enterprise. He quoted T. S. Eliot to the effect that such truths are timeless, but always fresh to those who encounter them for the first time. John Kingsbury, acting director of Cornell Plantations, recounted the history of the project and thanked those who had been involved: the Stevens family (Mrs. Stevens, who is 91, was unable to be present, but other members of the family were there); the students, and Maintenance and Service Operations. Provost W. Keith Kennedy called the span "Cornell's answer to the Brooklyn Bridge," whose 100th anniversary had been celebrated earlier in the week; he regretted that there were no fireworks to celebrate with. Finally, James M. Gossett, who is currently the faculty adviser to the chapter, smashed a champagne bottle on the concrete abutment, and Bryan Clark and the seniors who had worked on the project cut a white ribbon with a sheath knife.

As people began walking onto the bridge, someone asked, "How many people will it hold?" Anthony Ingraffea, the structural engineering professor who was technical adviser for the project, gave a fitting professional opinion: "All of us." A keg of beer was tapped, congratulations were exchanged, and the bridge was officially open.—D. P.

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 three-month period December, 1982 through February, 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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Solar and Fuel Cells and the Hydrogen Economy

Hydrogen-Economy buffs should take special note of the two feature articles in your provocative Spring, 1983 issue. If the theoretical efficiencies projected by Professors Lewis and Cocchetto can be attained for both the bacteriorhodopsin (BR) process and for the fuel cell, prospects for the full-blown development of the hydrogen-economy alternative will be improved substantially.

The relationship between the BR pigment and the highly saline solutions in which the bacteria that produce it grow suggests an intriguing new possibility for large-scale, solar-to-electric-energy conversion using BR solar cells directly coupled to fuel cells. The essential requirement is a large body of salt water near a desert: Utah's Great Salt Lake, for example.

Assuming an eventual 48 percent net overall efficiency (60 percent and 80 percent for the BR and fuel cells, respectively) and an insolation conservatively taken as 300 watts per square meter, a calculation shows that 800 square miles of desert along Salt Lake could provide about 100 GW of continuous electric power, or approximately 20 percent of our present total national installed generating capacity. (The power would be continuous because stored hydrogen could be released to the fuel cells during the dark hours.) The fuel cells would also produce about 140 million gallons of fresh water daily, and release some 85 billion BTU per hour. Net annual water loss would be about one percent, assuming no direct return to the lake. The large, nearby electric-energy market could be served conveniently by high-voltage a-c and d-c transmission lines.

What we have here is potential for a new, *clean,* $50 billion-a-year industry!

Simpson Linke
School of Electrical Engineering
Cornell University
Ithaca, New York

Kudos for the Quarterly

...I want to congratulate Cornell on the excellence and value of the publication *Engineering: Cornell Quarterly.* I receive this publication on a regular basis and it has assisted me in making effective contacts with Cornell faculty on research programs of interest to my company. It was the way I first heard about the Cornell Manufacturing Engineering and Productivity Program (COMEPP), a program we will be exploring.

R. D. Wismer
Director, Technical Center
Deere & Company
Moline, Illinois

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