ENGINEERING

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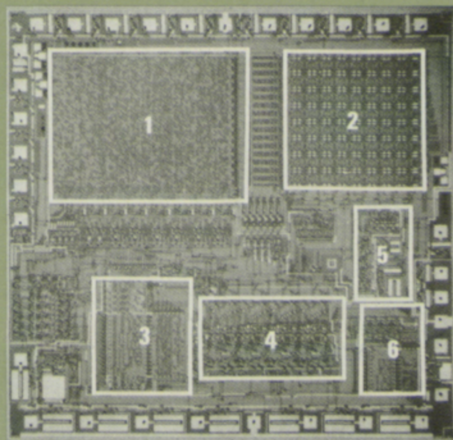

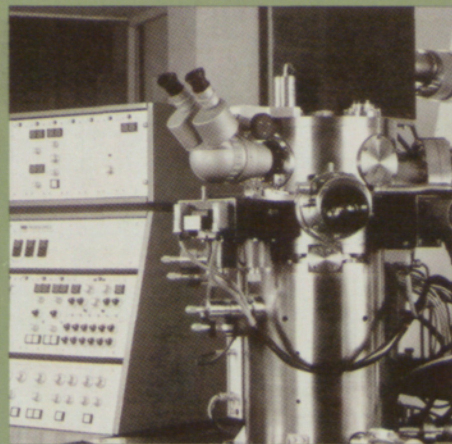

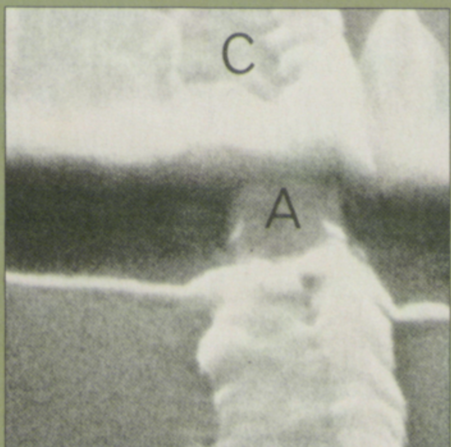

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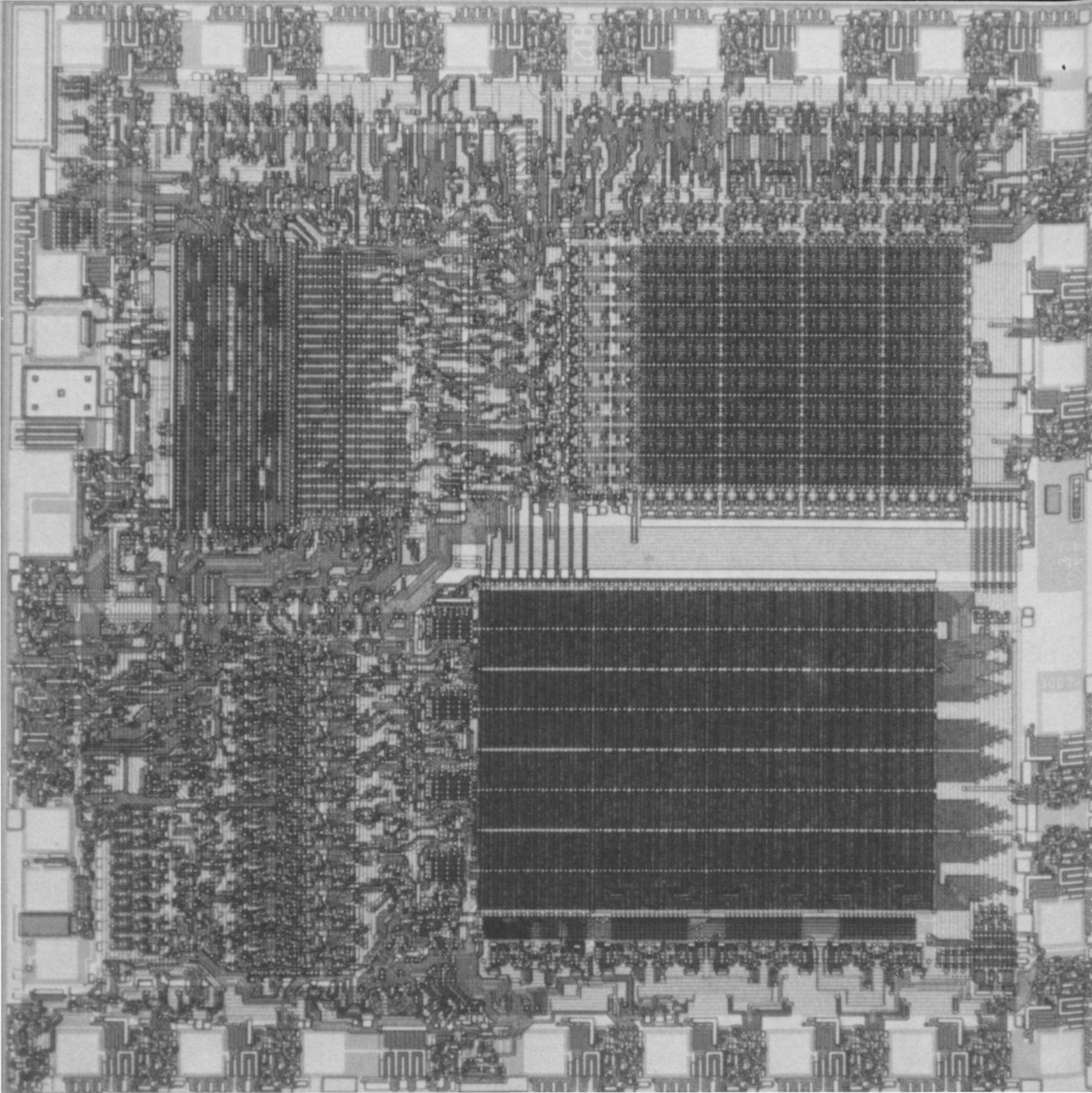
THE NEW SUBMICRON FACILITY



IN THIS ISSUE

The Electronics Revolution and the Potential of the New Submicron Facility at Cornell / 2

Cornell's role as host institution for the National Research and Resource Facility for Submicron Structures is discussed by Joseph M. Ballantyne, professor of electrical engineering and acting director of the facility.

Integrated Circuits: The Expanding Technology of Shrinking Structures / 12

How advances in integrated circuit technology result in lower prices is explained by Jeffrey Frey, associate professor of electrical engineering.

Superconductor Microelectronics: Key to a New Class of Computers / 17

The potential of the Josephson junction and the use of submicron fabrication technology in research on "weak-link" microelectronic devices are discussed by Robert A. Buhrman, assistant professor of applied and engineering physics.

X-Ray Lithography and Microscopy for Submicron Structures / 21

Boris W. Batterman, director of the School of Applied and Engineering Physics, writes about x-ray techniques for the production and examination of submicron structures, and the unique source of x-radiation that Cornell will have.

Introducing Impurity: Ion Implantation and its Role in Microelectronics / 27

Electrical Engineering Professor Charles A. Lee discusses an important technique for the fabrication of integrated circuit components.

A Submicron View of Surfaces and Interfaces / 32

Thor N. Rhodin, professor of applied and engineering physics, looks at some of the equipment to be available in the submicron facility, and how it can be used for the microanalytical characterization of electronic devices and materials.

Register / 41

Faculty Publications / 47

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***Left:* This microcomputer is about a quarter inch square, contains some twenty thousand transistors, and costs about three dollars; with submicron technology, millions of components could be packed onto the same sized chip (photo courtesy Intel Corporation).**

***Outside illustrations (clockwise):* an MOS microcomputer, 0.2 inch on a side (courtesy Texas Instruments, Inc.); part of a STEM, an ultrafine electron probe (courtesy Vacuum Generators Scientific, Ltd.); a scanning electron micrograph of a weak-like device, made at Cornell; and a packaged one-chip microcomputer, approximately actual size (courtesy Intel Corporation).**

THE ELECTRONICS REVOLUTION

And the Potential of the New Submicron Facility at Cornell

by Joseph M. Ballantyne

A revolution in electronics that began more than twenty years ago is about to enter a new phase. Its progress might be compared to the acceleration of a vehicle that was shifted into low gear in the fifties with the introduction of the transistor, went into second gear in the early sixties with the invention of integrated circuits, and is just now shifting into high with the development of a very large-scale integration. We may think that electronics has already permeated our society and penetrated our lives, but even greater changes lie ahead: the shift to overdrive will occur with the introduction of submicron circuit structures.

The key to this revolutionary development is reduction: reduction in the size of electronic structures, and consequently also in cost. The solid-state transistor replaced the bulky vacuum tube. The integrated circuit combined several transistors and other components on a single chip of silicon. More and more components were packed onto single chips as integrated-circuit technology progressed through the stages of medium-scale and large-scale integration. Today designers are talking about very large-scale integrated circuits (VLSI) that will contain on the order of one hundred thousand transistors or other devices, nearly ten times the number of components in the circuits now being used in calculators and other consumer electronic products, and there is no end in sight. Circuits with electrical conductors of submicron widths may ultimately make it possible to place perhaps ten million components on a single chip.

HANDY SUMMARY OF UNITS

Meters (m)	Microns (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

The shaded area shows the region to be emphasized in programs at the submicron facility. Atomic distances are of the order of Angstrom units.

The consequences of this new phase of miniaturization are enormous. In addition to integrated circuits, many other kinds of electronic devices will also benefit from size reduction; these include microwave transistors and diodes, superconducting bridges and logic elements, components in integrated optical systems, acoustic wave devices, and components for memories and displays. Potential applications range through the entire field of communications, from space vehicles to local telephone systems. Integrated circuits containing larger numbers of smaller components will make possible a new order of high-speed, high-capacity computers. Consumer products like pocket calculators and word-processing typewriters will become more accessible and their capabilities will increase manyfold. New applications, perhaps including some not yet conceived of, are sure to be introduced.

Cornell has a special interest in the electronics revolution, and a special function. Researchers here have contributed to the new developments for many years, and now the University is

"A new generation of instruments is required, and a new array of techniques."

assuming an important role in the latest surge of activity: The National Research and Resource Facility for Submicron Structures, the first of its kind in this country, is being established at Cornell's School of Electrical Engineering under a \$5-million, five-year contract with the National Science Foundation. Cornell will become a center for researchers in various areas of electronics and physics that are related to the science and technology of fabrication on the submicron scale.

GOALS AND PROBLEMS IN SUBMICRON FABRICATION

The fabrication and replication of integrated circuits is one important concern of the new facility. One goal in fabrication is to pack as many components as possible onto each chip; the way to do this is to generate and reproduce circuit patterns with very small geometries. Much of the activity in the laboratory will focus, therefore, on the production or replication of circuit patterns with submicron features.

A measure of the size of a circuit is the linewidth used for the electrical conductors. The chips now used in calculators and other large-scale integrated circuits have linewidths of approximately 5 microns (5 millionths of a meter). For very large-scale integrated circuits (VLSI), it will be necessary to produce, on a routine basis, chips with lines only 2 microns wide. This appears to be quite possible: already techniques exist for producing lines only 0.5 micron wide, and lines 0.1 and even 0.01 micron in width have been produced in research laboratories.

Reduction in size to the submicron scale is accompanied by special problems, however. The basic reason is that optical techniques are not adequate for the fabrication or analysis of structures with dimensions smaller than about one micron because the wavelengths of light are not short enough to give adequate spatial resolution. It becomes necessary to utilize beams of electrons, ions, or x-rays. A new generation of instruments is required, and a new array of techniques.

For example, it might be necessary to make a chemical analysis to detect the presence of certain impurities in the material of an electronic device with submicron dimensions. For this purpose, it would be desirable to analyze a sample 0.01 square microns in area and 10 Å (an Angstrom unit is one-ten thousandth of a micron) deep. Since such a volume would contain on the order of 10^7 atoms, and an impurity concentration of one part per million or less can be important, the task would be to detect the presence of just ten atoms of the foreign substance in the tiny sample. Instruments capable of such high resolution and analytical sensitivity do not now exist.

Another type of problem arises from the fact that as dimensions shrink to the submicron region, the physics for treating the motion of electrons or other charge carriers becomes different. As the dimensions of electronic devices approach the distances over which electrons and other charge carriers are scattered, the scattering mechanisms no longer limit device performance in the same way they did previously.

Some of these special problems are discussed in more detail in subsequent articles in this issue.

Table I
CORNELL MEMBERS OF THE SUBMICRON FACILITY AND THEIR RESEARCH INTERESTS

Applied Physics	
Boris W. Batterman	*X-ray and neutron diffraction, synchrotron radiation*
Robert A. Buhrman	*X-ray and electron beam lithography, ion beam processing, superconducting devices*
Thor N. Rhodin	*Physics and chemistry of semiconductor interfaces*
Benjamin M. Siegel	*Electron and ion sources, optics and lithography*
John Silcox	*Microscopy and microanalysis with electron probes, electronic structure*
Chemical Engineering	
Ferdinand Rodriguez	*Polymer resists*
Chemistry	
George H. Morrison	*Microanalysis, ion microscopy, ion microprobe studies*
Electrical Engineering	
Joseph M. Ballantyne	*Electron lithography, semiconductor growth and devices for integrated optics*
G. Conrad Dalman	*Microwave devices and circuits*
Lester F. Eastman	*Semiconductor growth, molecular beam epitaxy, microwave semiconductor devices*
Jeffrey Frey	*Microwave transistors and integrated circuits, physics and technology for VLSI*
Charles A. Lee	*Ion implantation and lithography, molecular beam epitaxy, material and device physics*
Ross A. McFarlane	*Ultraviolet lasers, laser annealing*
Chung L. Tang	*Holography, devices for integrated optics, nonlinear optics*
Materials Science and Engineering	
Dieter Ast	*Amorphous metals*
Edward J. Kramer	*Strain and displacements in solids, superconductor flux pinning*
Arthur L. Ruoff	*Ultrapressure research, x-ray lithography, electron lithography, mechanical properties*
Physics	
Albert J. Sievers	*Granular metal films, surface wave spectroscopy*

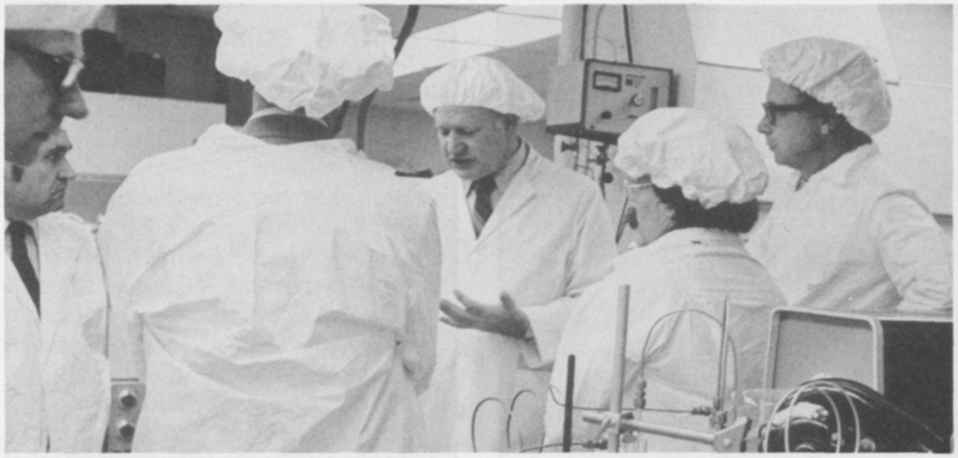
A NATIONAL LABORATORY: THE NEED AND THE RESPONSE

A problem of another kind encountered in the development of submicron structures is the result of an unfortunate relationship:

$$\frac{1}{\text{size of pattern features}} => \$ \text{ for lithographic equipment.}$$

Because of this, it has become increasingly difficult for workers in universities across the country to participate in a practical way in research on state-of-the-art electronic devices or on fundamental problems that may limit the application of these small devices. It became apparent that academic researchers need access to expensive high-technology equipment for producing very small structures. In 1976 NSF responded by organizing a series of regional workshops to explore the feasibility of establishing a national laboratory, open to academic investigators and others in the scientific community across the country, that would provide facilities for constructing and analyzing patterns with submicron dimensions. The overwhelming consensus of opinion was that there should be such a center, and subsequently NSF invited proposals for the establishment of the National Research and Resource Facility for Submicron Structures.

In seeking its selection as the host institution, Cornell was in competition with most of the major research universities in the country, as well as leading government and nonprofit laboratories. It had much to offer, however. With well developed graduate and postgraduate programs in relevant fields, Cornell has an excellent "built in"



The submicron facility is visited by scientists from all over the country. Here Lester F. Eastman, Cornell professor of electrical engineering, explains the process of liquid-phase epitaxial growth of III–V compounds to visitors to the clean laboratory in Phillips Hall. This group was among 101 delegates who attended a symposium on the facility last October. In addition to 54 university scientists, the delegates included representatives of industrial laboratories, as well as of NSF.

capacity to train engineers and scientists. It has a community of researchers in many areas of science and technology related to the central concerns of the national facility, and there is widespread interest in the project on campus (as indicated, for example, by the list in Table I of people who participated in preparing the Cornell proposal). Cornell's conception of the national facility is, in fact, quite broad, emphasizing basic research in physics and materials science as well as technology development. In addition, there is substantial financial support from the University, largely in the form of laboratory space made available; this includes both existing rooms suitably renovated and new areas to be constructed. All these factors may have contributed to Cornell's strength as a candidate for designation as host institution.

GOALS OF THE LABORATORY AND THEIR IMPLEMENTATION

The official goals of the facility, as set forth in the Cornell proposal, are:

(1) to promote and carry out research to advance the art of submicron fabrication technology and to train engineers and scientists in the field;

(2) to provide a resource for the academic community to use to fabricate advanced devices or research structures which require submicron dimensions;

(3) to stimulate innovative research by investigators outside the electrical engineering device community whose work can benefit from use of the facility or will shed light on fundamental physics or materials problems that affect or limit the application of submicron technology; and

(4) to keep the technical community apprised of the capabilities of the facility and the work done in it.

In keeping with the first objective, it is expected that an active community of researchers, including a number of resident Ph.D. candidates, will be established at Cornell. Their work will be in various areas of fabrication technology, including, but not necessarily limited to, the technology of electron and ion beams, sources, and lenses; pattern replication, involving the use of ion and photon (including x-ray) beams; the development of hardware and software for pattern generation; investigation of properties of resist materials and their interaction with beams; and the development of processing techniques for submicron structures.

As implied by the second goal, a number of scientists—perhaps half of all who use the laboratory—will be from institutions other than Cornell. First priority will go to representatives of academic institutions, but investigators from government, nonprofit, and industrial laboratories will also be eligible to participate as resident researchers. An orientation program and staff assistance will be organized to help visitors make effective use of the facilities. In addition, collaboration between resident and nonresident scientists will be encouraged.

The third goal will be met by making the facility available to researchers in areas other than electrical engineering. The list in Table I of Cornell members of the facility and their research interests gives an idea of the breadth of programs relevant to the mission of the laboratory.

Edward Wolf Named Director

Recently named director of the new National Research and Resource Facility for Submicron Structures at Cornell is Edward D. Wolf, an expert on submicron technology and surface chemical physics. He will also be professor of electrical engineering.

Wolf had been at Hughes Research Laboratories since 1965, most recently as senior scientist and section head in the Electron Device Physics Department. His work there included the development of new high-resolution electron-beam techniques for diagnostics and computer-controlled microfabrication of devices and circuits. His experience also includes three years at Rockwell International Science Center, where he conducted fundamental studies on the adsorption, diffusion, and surface reactions of cesium fluoride on tungsten by field emission microscopy. He has also worked with scanning electron microscopy at the University of California at Berkeley.

Wolf received the Ph.D. in physical chemistry from Iowa State University in 1961, and then served as a research associate at Princeton University. He was graduated magna cum laude from McPherson College in 1957.

He has published widely in professional journals and has given papers at professional meetings around the world. He is a fellow of the Institute of Electrical & Electronics Engineers and a member of the Electron Microscopy Society of America, the Microbeam Analysis Society, the American Physical Society, and the American Association for the Advancement of Science.

Wolf

MAKING PROGRAM AND BUDGET DECISIONS

The technical programs of the facility are expected to fall into the three categories alluded to previously: (1) research to improve the technology for fabricating small structures; (2) the application of submicron technology to the fabrication of electronic devices or other research structures; and (3) investigation of fundamental physical problems that may limit the performance of devices with submicron dimensions. The allocation of resources among proposed programs and among investigators from the Cornell faculty and elsewhere will be made by a program committee acting on guidelines established by the policy board. Both of these groups comprise approximately equal numbers of people from Cornell and from other places.

The program committee (see Table II) includes nine members elected for three-year terms by members of the facility (any senior researcher who is a regular user of the facility can become a member). The committee also in-

TABLE II. **CURRENT MEMBERS OF PROGRAM COMMITTEE**

J. M. Ballantyne, *acting director of the facility; professor of electrical engineering, Cornell University*

B. W. Batterman, *professor and director, School of Applied and Engineering Physics, Cornell University*

A. N. Broers, *IBM fellow; manager, Photon and Electron Optics Department, IBM T. J. Watson Research Center*

W. S. C. Chang, *professor and director, School of Engineering and Applied Science, Washington University*

E. R. Chenette, *section head, Electrical Sciences and Analysis, Division of Engineering, NSF*

G. C. Dalman, *professor and director, School of Electrical Engineering, Cornell University*

L. F. Eastman, *professor of electrical engineering, Cornell University*

T. H. Henderson, *professor and director of graduate study in electrical engineering, University of Cincinnati*

C. A. Lee, *professor of electrical engineering, Cornell University*

P. R. McIsaac, *associate dean of engineering and professor of electrical engineering, Cornell University (chairman of the committee)*

R. F. W. Pease, *supervisor, Electron Beam Exposure Group, Bell Telephone Laboratories*

A. L. Ruoff, *professor of materials science and engineering, Cornell University*

B. M. Siegel, *professor of applied and engineering physics, Cornell University*

E. D. Wolf, *senior scientist and section head, Electron Device Physics Department, Hughes Research Laboratories* cludes as nonvoting members the facility director; a representative of NSF; and Cornell's dean of engineering, director of the School of Electrical Engineering, and director of the School of Applied and Engineering Physics.

The policy board comprises the director of the facility, Cornell's vice president for research, the dean of engineering at Cornell, a Cornell faculty member elected by the program committee, and four representatives of other institutions.

Administration of the facility is the responsibility of the director.

The facility's budget for the first year is $2 million, most of which is being spent on capital equipment. In subsequent years, the annual budget will be about $750,000, which is to finance additional capital equipment, maintain the equipment and make it available without cost to qualified academic users, support a small central staff, and support a core of research that is considered important to the facility's goals.

Resources available for this core research effort will be about $250,000 a year. Most of this will be allocated to programs—primarily those directed by Cornell faculty members—that will advance the technology for producing submicron structures. It is evident that $250,000 is a very small amount to be divided among the number of people on and off the Cornell campus who have research interests related to submicron technology, and it is expected, therefore, that most of the funding for research carried out at the facility will come from grants awarded by various agencies directly to individual investigators. The role of the facility will be to provide the capital resources these investigators need.

Table III

EQUIPMENT CAPABILITIES AT THE CORNELL FACILITY

Pattern Generation

Computer-Aided Design System: *Interactive design and drawing digitizing capability. Resolution of 1 part in 10^9.*

Electron-Beam Pattern Generator: *Resolution of 0.2 micron or better in a 1 mm X 1 mm field. Adjacent fields stitched together with 0.3 micron accuracy. Pattern size up to 4″ dia. Multi-layer registration to 0.3 micron.*

Experimental STEM Pattern Generator: *Resolution about 100 Å or better over small field.*

Holographic System: *Generation of high-accuracy optical gratings with periods 0.1 micron or greater.*

Pattern Replication

X-Ray Lithography Systems: *Low-intensity sources for pattern resolution 100 Å or better. Synchrotron radiation (available in 1980) for fast exposure, with resolution of 0.1–0.2 micron.*

Optical Proximity and Contact Aligner: *Resolution of 1 micron over 3″ diameter wafer.*

Optical Projection Aligner: *Resolution of 0.7–1 micron over 1/4″ X 1/4″ area. 10X reduction. Noncontact printing with 5X5 step-and-repeat matrix.*

Materials Preparation and Thin Films

Liquid Phase Epitaxy Systems: *Layers of III–V compounds 0.1–10 microns thick over 2 cm^2 area.*

Vapor Phase Epitaxy System: *GaAs layers over 2 cm^2 area.*

Molecular-Beam Epitaxy System: *Layers of III–V compounds with thickness control down to 100 Å.*

Thermal and Electron-Beam Evaporators.

DC and RF Sputtering Systems: *Up to 6″ diameter targets and substrates; up to three materials sequentially. Sputter etching.*

Ion-Beam Deposition and Milling System: *4″ diameter beam. Up to four materials sequentially. Etching.*

Doping

Hot Tube Diffusion Systems: *2″ diameter wafers.*

Ion Implantation System: *300 KeV, all elements in periodic table. 3″ diameter wafers. 600 KeV for doubly-ionized species.*

Device Processing

Thermal Oxidation Tube.

Wire and Die Bonders.

Wet Chemical Processing Stations.

Plasma Etching System.

Diamond Scriber.

Wire and Diamond Saws.

Device and Structure Analysis

Scanning Electron Microscope: *70 Å resolution. Energy dispersive x-rays. Up to 3″ diameter samples.*

Scanning Transmission Electron Microscope: *3 Å resolution. Elemental analysis by energy-loss spectroscopy.*

Scanning Auger Spectrometer: *Resolution of 0.1–0.2 micron lateral, 10 Å depth. Sensitive to 1 part in 10^3. Computer-controlled analysis. Depth profiling.*

Ion Microprobe: *Resolution of 1 micron lateral, 10 Å depth. Sensitivity up to 1 part in 10^7. Computer-controlled analysis. Depth profiling.*

Surface Profilometer: *Depth resolution to 100 Å. Lateral scan to 3 cm.*

Scanning Optical Microprobe: *Areal resolution less than 1 micron. Wavelengths 1.06 to 0.33 micron.*

Optical Microscopy.

Equipment and laboratories already in use at Cornell will become part of the new facility for research on submicron structures.

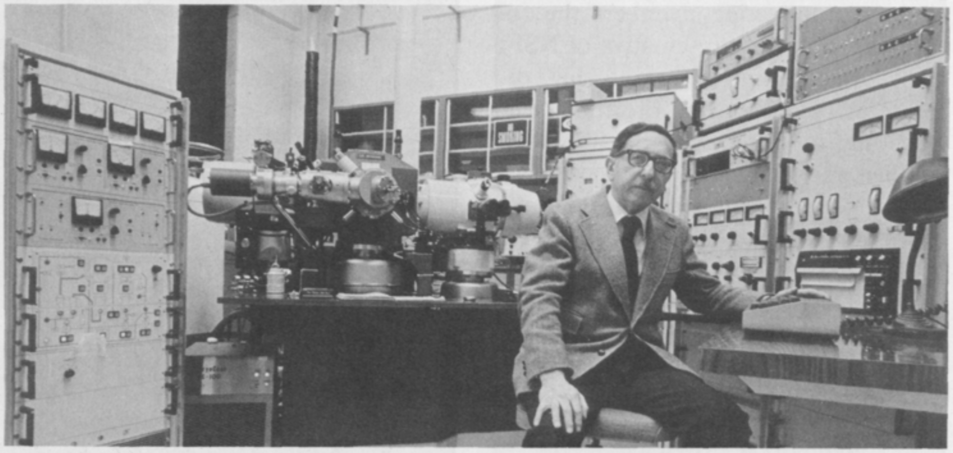
1. Chemistry Professor George H. Morrison uses a CAMECA ion microprobe in his study of the surface composition of semiconductor materials and devices. With this instrument, it is possible to perform chemical analysis with sensitivity up to one part in 10^7. The instrument can be used to chart a profile of the concentration of an element with spatial resolution of about one micron and depth resolution of 20 Angstroms.

2. The clean laboratory in Phillips Hall will be used in part for submicron studies during Phase I of the laboratory development program. Here Timothy J. Maloney (foreground), a postdoctoral associate last year, instructs a student in techniques of photolithography.

3. Ira Benson, a graduate student working with Professor Ballantyne, uses a scanning optical microprobe for analysis of semiconductor materials and devices.

4. Benson adjusts the sample position in a multiple-mask electron-beam evaporation system, which is used for sequential deposition of patterned thin-film layers.

1



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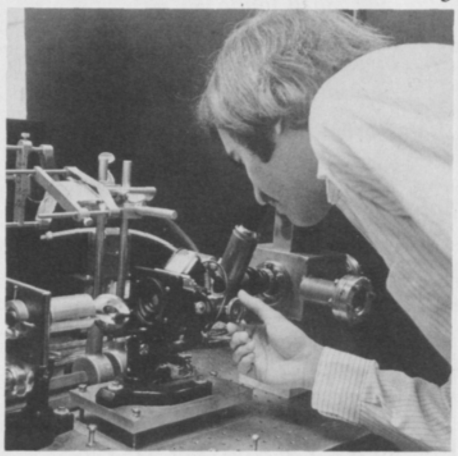

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2

FOURTH-FLOOR PHILLIPS, HOME OF THE FACILITY

The location of the laboratories and offices associated with the submicron facility is on the fourth floor of Phillips Hall, the main building of Cornell's School of Electrical Engineering. When it is completed, the facility will occupy more than 12,000 square feet of space and could accommodate twenty or more visitors from other institutions.

In Phase I of the laboratory's development, the facility will operate in existing laboratories and in additional space renovated for the installation of special equipment. The laboratories already functioning include the clean rooms that were set up recently to facilitate the long-standing Cornell research and development program on semiconductor devices (a program that includes the fabrication of components by the growth of epitaxial layers).

In Phase II, a 6,000-square-foot fourth-floor addition to the south wing of the building will be made available, along with some additional renovated

Figure 1

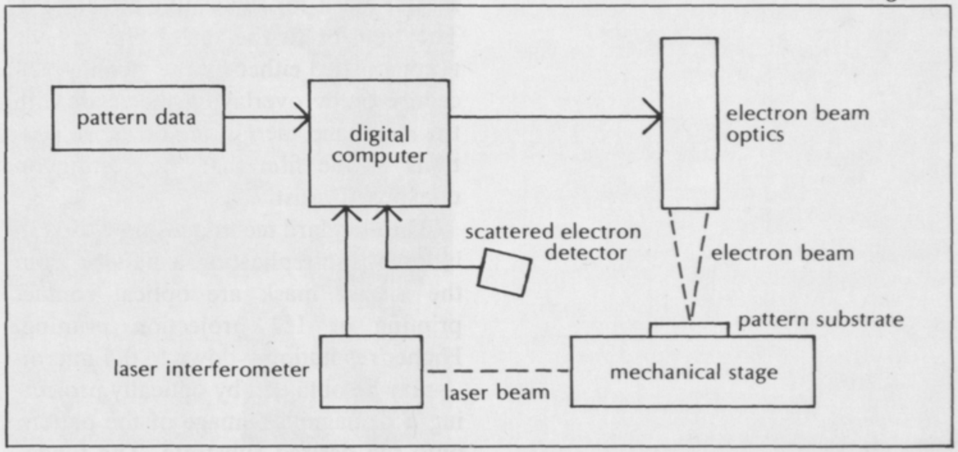


Figure 1. Schematic of an electron-beam pattern generator. Data generated on a separate computer are fed via magnetic tape into the pattern generator's computer, which exercises closed-loop control over the positions of the electron beam and mechanical stage. The positions of the beam and stage are known to the computer because of the feedback supplied by the scattered-electron detector and the laser interferometer on the stage.

A typical electron-beam pattern generator is shown in the photograph below the figure. The electron optical column is at left, above the box containing the laser interferometer, scattered-beam detector, and mechanical stage. The control computer is at right. This is system EBMF–11, of Cambridge Instruments, Ltd.

rooms. The new space will house the permanent clean laboratory of the facility. The Phase II construction, budgeted at more than $850,000, will be funded by private donors. It is hoped that it will be completed by the fall of 1979.

TECHNIQUES AND EQUIPMENT FOR SUBMICRON WORK

The major technological areas to be investigated and some of the main pieces of equipment that will be placed in the facility are summarized in Table III. Some of the instruments and techniques are discussed in other articles in this issue.

The central function of the facility is pattern generation and replication. The complex patterns used in submicron lithography are generated on a computer-aided design station that can digitize drawings or be used in an interactive mode with a television display. The system produces a magnetic tape containing the digitized information, and this is used in the electron-beam pattern generator to control the movement of the electron beam. The pattern is written by the beam in an electron resist, which is a material that undergoes molecular changes when it is bombarded with electrons. Most resists are polymers that undergo either cross linkage or bond scission when they are irradiated, and therefore the irradiated portions exhibit different solubility characteristics than the unexposed regions. The resist that gives the best known resolution is a form of the common plastic, Lucite; its resolution limits have not been measured, but are known to be below 500 Å. Lucite is a *positive* resist because it undergoes a reduction in molecular weight under irradiation; after irradiation, the exposed, lower-molecular-weight portions can be preferentially dissolved in a developing solution.

Once the pattern is written in the electron resist, it may be transferred to the underlying substrate by chemical or plasma etching, or it may be transferred onto a thin metal film and used as a master mask for replicating the pattern. The transfer to the metal film can be accomplished either by the etching procedure or by overlaying the resist with the metal and then lifting off those portions of the film that are resting on unexposed resist.

The standard techniques now used in industry for replicating a pattern from the master mask are optical contact printing or 1:1 projection printing. Higher resolution—down to 0.5 micron —may be obtained by optically projecting a demagnified image of the pattern onto the desired substrate. The fundamental limit of this optical reduction technique is the diffraction limit imposed by the optical wavelength, but this can be reduced to very small values by utilizing short-wavelength x-rays. (This very promising technique is discussed by Professor Batterman.)

The resolution of patterns generated with the scanning electron beam is limited by the scattering of the electrons in the resist and substrate materials. While the electron beam can have a very small diameter, 100 Å or less, the electrons—with typical energies of about 20 keV—have a scattering range in most resist and substrate materials on the order of 0.5 micron (5,000 Å). Because of this scattering, electron-beam pattern generation is not very useful in fabricating features that are spaced closer than about 0.3 micron. This limitation may be overcome by using either short-wavelength x-rays, which do not backscatter, or ions to expose the resist. Although ions scatter at large angles, just like electrons, they lose energy much more rapidly, so that a typical distance travelled by a scattered ion is only 0.01 micron.

"Cornell will become a center for researchers in . . . fabrication on the submicron scale."

An example of an ongoing Cornell project that will benefit from submicron fabrication technology is the development of a tunable semiconductor laser. Shown with the instrument is George Metze, graduate student in electrical engineering. The research is sponsored by Professors Ballantyne and C. L. Tang.

Not only the generation of patterns, but also the analysis of structures made from them, are dependent on the resolution that can be achieved with the energizing beam. It is evident that the technology of producing, focusing, and manipulating electron, ion, and x-ray beams is of central importance.

THE SIGNIFICANCE OF THE NEW FACILITY

The establishment of the national submicron facility represents a new venture for the Engineering Division of NSF: it is the first centralized research laboratory to be sponsored by that division. And although in other fields of science, such as high-energy physics and astronomy, there has been long experience with large centralized research facilities, the new laboratory at Cornell is the first in the area of solid-state devices. If it is successful, there is a high probability that other such centers will be established, for there is great need for laboratory facilities for university people working with submicron structures.

This first facility will have a substantial impact on the research programs of a significant number of academic and perhaps also nonacademic scientists. For example, the Institute of Electrical & Electronics Engineers will hold its first Workshop on Very Large Scale Integration at Cornell in June; production engineers and researchers, primarily from industry, will gather to exchange views on the state of the technology and how production methods can be adapted to the manufacture of integrated circuits with submicron dimensions.

It is important, though, to put the scope of the program into perspective by comparing its $5-million, five-year budget with the expenditures of industrial companies and other governments for research and development in the same area. For example, over the same five-year period, IBM reportedly expects to spend about ten times the amount of the new facility's budget. The Japanese government and five Japanese companies have established a cooperative laboratory for the development of very-high-density integrated circuits and are planning to put $250 million over the next five years into the venture, which is now in its first year. (Similar laboratories are being established in Great Britain, France, and Germany.) Of course, the emphasis at the Cornell facility will not be to try to duplicate the work being done in industry, but rather to explore more fundamental and long-range approaches.

From the viewpoint of Cornell, the presence of this facility ensures that submicron structures will be a major research area at the University and its College of Engineering. The facility provides an exciting focus for the work of a score of faculty members and gives students the stimulating opportunity to work in a field with seemingly limitless possibilities, a field in which research results may find widespread application in practical devices that will have an impact on our everyday lives.

Joseph M. Ballantyne, professor of electrical engineering, coordinated the preparation of Cornell's proposal for the establishment of the National Research and Resource Facility for Submicron Structures and is serving as acting director of the facility.

His current research in the area of submicron technology includes electron-beam lithography and the development of integrated optical devices, such as semiconductor lasers and detectors. He has also directed research in tunnel-injection devices, solar cells, far-infrared and photoelectric spectroscopy of solids, solid-state microwave detectors, and the growth of semiconducting crystals. In 1970–71 he spent a sabbatic leave at Stanford University conducting research on internal and external photoemission as a National Science Foundation senior fellow.

Ballantyne came to Cornell in 1964 after completing his doctoral study in electrical engineering at the Massachusetts Institute of Technology. He did his undergraduate work at the University of Utah, earning baccalaureate degrees in both mathematics and electrical engineering in 1959.

His experience includes summer work and consulting in various areas of semiconductor, ferro-electrical, magnetic, and optical materials and devices. Companies and laboratories he has worked with include Westinghouse, Hercules Powder, Lincoln Laboratory, Sandia, Materials Technology, General Telephone and Electronics, IBM, Battelle Memorial Laboratories, Cayuga Associates, Laux Market Research, American Optical, and the U.S. Army at Fort Monmouth.

He is a senior member of the Institute of Electrical & Electronics Engineers and a member of the American Physical Society.

INTEGRATED CIRCUITS

The Expanding Technology of Shrinking Structures

by Jeffrey Frey

The smaller their features, the less they cost. That is the principle behind the research and development effort in integrated circuits that is going on around the world and here at Cornell.

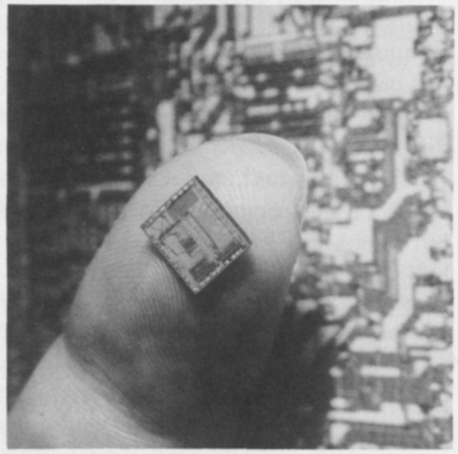
Quite simply, the smaller the size of the structures on a single circuit, the larger the number of functions that can be accommodated in a given area—and the smaller the cost per function. The next generation of integrated circuits will have structures with submicron dimensions, as suggested by the name of the new National Research and Resource Facility for Submicron Structures that was established recently at Cornell. Research conducted here will contribute directly to the compression of integrated circuits and therefore to reductions in their cost.

These results are generally thought to be a good thing. They will make possible, for example, computers that are faster and larger, as well as computers that are cheaper and smaller; more economical transmission of data; inexpensive closed-loop control of automobile efficiency and emissions; implantable devices to help the blind perceive their surroundings; more reliable washing machines; wireless portable telephones; and electronic transmission of mail. All this technological advancement should also give a boost to the American economy in an increasingly competitive international market.

INDUSTRIAL PRODUCTION OF INTEGRATED CIRCUITS

To understand the relationship of the new Cornell facility to the industry, we need to understand what integrated circuits are, how they are produced, and why size is such a crucial factor.

A monolithic integrated circuit, designed to perform a specific operation, is a collection of transistors, resistors, and capacitors, all made within a single piece of silicon and interconnected by a pattern of thin aluminum or gold. The individual components are formed by changing the properties of the silicon in selected regions by doping—the incorporation of controlled concentrations of impurities. Each integrated circuit, or chip, occupies a very small area: in the near future, chips only about one-quarter inch square will contain more than one hundred thousand electronic components. The components themselves are also very small: with today's technology, an integrated bipolar transistor might occupy an area of three-millionths of a square inch.



The actual size of a one-chip microcomputer is shown in this photograph of the Intel 8748.

Integrated circuits are produced in very large batches. Thousands of identical chips are fabricated at the same time

Figure 1

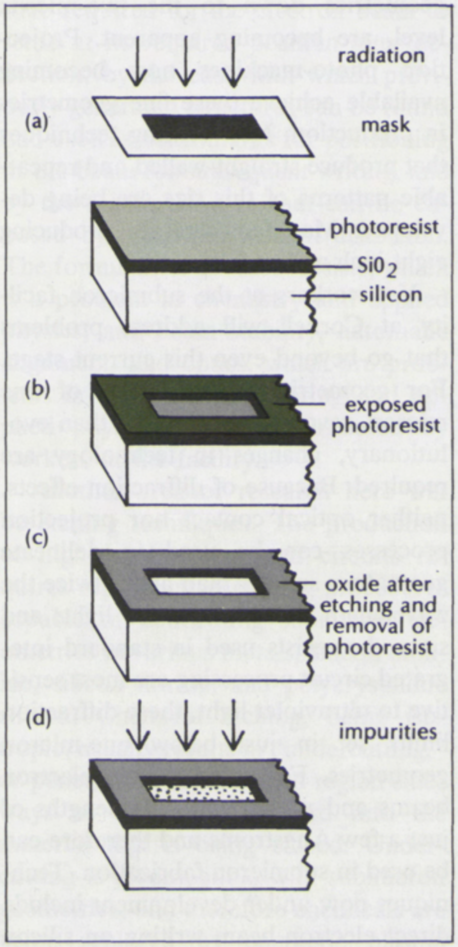


Figure 1. Simplified diagram showing steps in current procedures for fabricating circuit components on a silicon chip.

(a) The silicon wafer is oxidized, forming a layer of SiO_2 glass, and then coated with a thin photosensitive film called a photoresist. A mask carrying the desired pattern is placed over the photoresist, which is then exposed to ultraviolet light.

(b) Development of the photoresist removes those portions that have not been exposed.

(c) The oxide layer in these now unprotected regions is removed by an etching process. Then the remaining photoresist material is removed, leaving an oxide layer with "windows" to the silicon substrate.

(d) The circuit component is fashioned by introducing a controlled concentration of impurities through the window by diffusion or ion implantation. The oxide layer shields the silicon where impurity doping is not desired.

These steps illustrate current procedures. When geometries become submicron, modifications must be introduced. For example, ultraviolet light cannot provide great enough resolution and x-rays, electron beams, or ion beams are required for exposure of suitable resists. Beams of electrons or ions can be used either with masks or to write the pattern directly on the wafer. Diffusion may be replaced entirely by more controllable ion-implantation techniques.

Steps similar to those shown are also used to create connections between the circuit elements. The complete process of manufacturing circuits includes the design and fabrication of the series of masks that are needed for the various fabrication steps. Mass production methods allow the simultaneous manufacture of many individual circuits, each containing thousands of components.

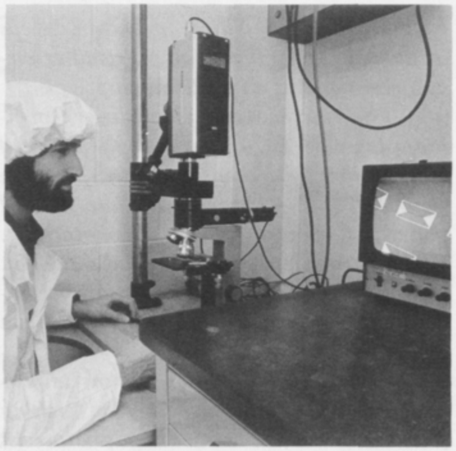
on a single wafer of silicon, usually three or four inches in diameter. This wafer is cut apart after all processing steps and some testing have been completed, thus separating the individual chips. Up to one hundred wafers may be processed in a single batch with the use of procedures that are independent of the size or complexity of the individual circuits on them.

The cost of processing a single wafer, regardless of its overall size or the size of the chips on it, is roughly one hundred dollars; therefore, the cost of each working chip on that wafer goes down as the yield of acceptable chips goes up. Since yield is a function of area-dependent conditions such as defect density in the single-crystal silicon wafer or the extent of dust contamination, the cost per chip goes down with the size of each chip. Alternatively, the cost per function of a circuit goes down as the number of functions that can be incorporated on a chip of a given size is increased.

THE TECHNOLOGY NOW AND ITS NEW DIRECTIONS

The individual devices on silicon chips are made by altering the properties of the substrate. This is done not only in specified areas, but also at particular depths; the properties of the silicon must be controlled in three dimensions. Local control is achieved by using silicon dioxide—which is easily grown on the silicon—to mask against the selective addition of impurities; the oxide covers the silicon everywhere but where the properties are to be changed. In simple terms, the current procedure is to cut a hole where the impurities must have access to the silicon by etching through the silicon dioxide. The area in which the hole is to be cut is determined by a photographic process—contact printing, usually—which itself results in a hole being cut in a light-sensitive, acid-resistant film called a photoresist. Where the resist is removed, after exposure to ultraviolet light, the oxide can be etched; where the oxide is etched, the impurities can enter the silicon. The metal patterns for interconnections or the gates of field-effect

A microwave FET (field-effect transistor) with a micron-sized gate is viewed on the TV screen by Steve Kratzer, a graduate student working with Professor Frey. The laboratory is in the "clean room" area in Phillips Hall.



transistors are created in a similar fashion. Various combinations of masking, exposure, etching, doping, and deposition permit the fabrication of complex, many-layered circuit chips.

Many technological improvements have been made in recent years. Contact printing is being supplanted by the projection of the desired patterns onto the wafer; with this process, the cost of the photomasks (masters for the on-wafer image) is reduced because the masks need not touch the wafer and therefore last longer. As a means of introducing the required impurities, ion implantation has supplanted diffusion, giving greater control of the distribution of impurities with depth and, since high diffusion temperatures can be avoided, resulting in more perfect crystalline properties. Improved working environments have contributed to the reliability of the manufactured products; in modern clean-air rooms, the concentration of dust can be reduced to a level of less than one hundred particles per cubic foot of air.

These advances have reduced the size of circuit structures, increased the density of components, and allowed the manufacture of circuit chips with a larger physical size. Ten years ago the minimum width of a line that could be defined on an integrated circuit chip was about ten microns; today it is about five. The number of components per chip has doubled every year since the early sixties, rising from about thirty transistors in a 1964 bipolar logic gate to about one hundred thousand memory elements and transistors in a 1978 65,536-bit memory. In the past decade, chips have increased in size from about a tenth to about a quarter of an inch on a side. Large-scale production has also been aided by increases in the size of wafers; during this same period, they have gone from one to four inches in diameter. Concurrently, the cost per function has declined: for example, from 0.5 cent per bit for a 1,024-bit memory in 1973 to about 0.08 cent per bit for a 16,384-bit memory in 1978. (The 65k-bit memory is not yet in production, but its cost should be about 0.02 cent per bit.)

The most recent advances in integrated circuit technology, producing geometries down to the two-micron level, are becoming apparent. Projection photo-machines now becoming available achieve these fine geometries in production. New etching techniques that produce straight-walled and repeatable patterns of this size are being developed. Manufacturers are producing eight-inch wafers.

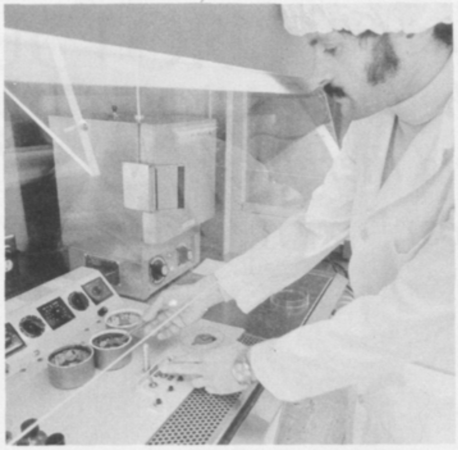
Yet workers at the submicron facility at Cornell will address problems that go beyond even this current stage. For geometries of the order of one micron, revolutionary, rather than evolutionary, changes in technology are required. Because of diffraction effects, neither optical contact nor projection processes can be used to delineate geometries smaller than about twice the wavelength of the exposure light; and since the resists used in standard integrated circuit processing are most sensitive to ultraviolet light, these diffraction limits set in just below one-micron geometries. Fortunately, both electron beams and x-rays have wavelengths of just a few Angstroms and therefore can be used in submicron fabrication. Techniques now under development include direct electron-beam writing on silicon wafers and x-ray replication of master patterns generated originally by electron-beam writing (see the article by Boris W. Batterman).

INTEGRATED CIRCUIT RESEARCH AT CORNELL

At the new submicron facility, research will include projects aimed at increasing the throughput of wafers for direct-writing systems and also the accuracy and precision of beam positioning for the direct writing of patterns on wafers. Throughput is affected by the sensitivity of the electron-beam resists used, by the time required for the electron beam to settle at its required position after deflection, by the ease with which previously generated structures can be found and used as benchmarks for positioning of the beam for subsequent writing, and by the maximum area that can be exposed by the beam without distortion. The formulation of "fast" resists, which is a problem in chemistry and applied physics, and beam stability, automatic alignment, and optics, which are problems in electrical engineering and applied physics, will be considered by workers at the facility.

Another area of research here will be etching techniques. The production of high-density integrated circuits requires reproducible etching procedures capable of delineating submicron geometries in various metals, silicon dioxide, silicon nitride, and polycrystalline silicon. Chemical etching, being isotropic, usually results in "undercutting," or penetration of an etched region sideways as well as downward into the material that is being etched. Undercutting is incompatible with submicron geometries, and therefore chemicals are being replaced by energetic plasma particles for etching operations. The new processes, called ion milling or plasma etching, are only imperfectly understood. Questions exist as to what the etching reactions actually are and how much wafer damage they cause. Researchers here can be expected to investigate these questions.

The doping of semiconductors by the diffusion of impurities also involves a form of undercutting, in the sense that diffusion, like chemical etching, is isotropic and will occur transversely as well as downward. Ion implantation, with its high-energy directed ion beams, does not produce much transverse spread and therefore may be superior to diffusion techniques in the manufacture of submicron devices. Implantation has the additional advantage of being an easily reproducible process, since it is dependent on the electrical parameters of beam current and accelerating voltage. Furthermore, it can be used as diffusion cannot: to modify the electrical charges at the interface between the surface of a silicon wafer and a layer of silicon dioxide, for example, or to dope compound semiconductors such as gallium arsenide. Ion implantation is already an important process in integrated circuit manufacture; its use in the fabrication of devices with submicron structures will be studied at the new facility (see the article by Charles A. Lee).



Professor Frey, shown in the clean laboratory, demonstrates some of the techniques for integrated circuit fabrication. In the top photograph, he is applying the photoresist film. Next he is placing wafers in a furnace for the ion-diffusion process. In the bottom photograph, he is using a bonding machine to fasten the gold wires that will connect a chip to the "outside world."

The physics of submicron-sized devices is another important area of the research program. Interesting phenomena, now largely unexplained, have been noticed in prototype submicron-sized devices. Premature breakdown and excessive leakage current are two of the deleterious effects that have been

"Research conducted here will contribute directly to the compression of integrated circuits and therefore to reductions in their cost."

observed. In submicron devices, very large electric fields can exist, even if the voltages applied to their terminals are only of the order of one volt; and under the influence of these fields, electrons may not behave in an easily predictable fashion. Techniques previously used by Cornell researchers to describe phenomena occurring, for example, in submicron-gate microwave field-effect transistors may prove applicable to these effects in other devices with submicron dimensions.

Other approaches to the development of the science and technology of integrated circuits will surely be pursued at the facility, for it is planned as a national resource, open to all workers for research, consultation, or discussion. Here at Cornell we expect to be in the midst of research activity that will facilitate the transition to quantity production of integrated circuits with submicron geometries.

The level of today's best integrated circuit technology is epitomized by the Intel 8021 microcomputer, shown on the inside front cover; its twenty thousand transistors on a chip about one-quarter inch square provide internal and external control logic, clock timing, a programmable read-only memory, random-access data-storage memory, and input/output ports to a keyboard, a television display, a line printer, or a floppy-disk unit. The chip costs about three dollars. With new submicron integrated circuitry, the same sized chip could be furnished with millions of bits of memory for about the same price. For well under one hundred dollars, plus the cost of a modest-sized cabinet, it may soon be possible to acquire a computer equivalent to Cornell's large, multipurpose computer, an IBM 370.

Jeffrey Frey, associate professor of electrical engineering, developed Cornell's integrated circuits laboratory for teaching and research. His own research is mainly in the area of microwave semiconductor devices and methods, and includes both theoretical and practical studies.

Frey received his undergraduate education in electrical engineering at Cornell, earning the B.E.E. degree (with distinction) in 1960. He did his graduate work at the University of California at Berkeley, receiving the M.Sc. in 1963 and the Ph.D. in 1965. During his graduate years, he was a Howard Hughes fellow, and was employed as a technical staff member at the Hughes Research Laboratories. After completing his doctorate, he spent a year as a technical staff member at the Watkins-Johnson Company, and then a year as a NATO postdoctoral fellow at the Rutherford High Energy Laboratory in England. From 1967 to 1969 he remained in England, working on ion-implantation technology as a research associate with the United Kingdom Atomic Energy Research Establishment at Harwell. He was appointed to the Cornell faculty in 1970.

Frey's activities here have included work with the Program on Science, Technology, and Society on studies of the societal implications of inexpensive microwave solid-state devices, and of technical aspects of the widespread use of portable telephones.

He has served as a consultant to Cayuga Associates, an Ithaca-based firm for research and development in semiconductor devices, to the National Patent Development Corporation, and to the U.S. Air Force. He is a member of the Institute of Electrical & Electronics Engineers and of several honorary societies, including Tau Beta Pi and Sigma Xi.

SUPERCONDUCTOR MICROELECTRONICS

Key to a New Class of Computers

by Robert A. Buhrman

The small, high-speed, high-capacity computers of the future probably will owe their superior performance to a microscopic electronic element called a Josephson junction, a "weak link" between superconductors in an electronic circuit. Superconductor computer circuits are under intensive development at the present time, and prototypes of a half-dozen other superconducting electronic devices with Josephson junctions have already been produced.

How to achieve even better device performance through improved Josephson junctions is one of the chief concerns of current superconductor electronics research, and a problem that we are studying at Cornell. The indicated approach is the use of submicron fabrication techniques to produce Josephson junctions that are even smaller than the ones now being made.

THE ORIGIN OF A NEW AREA OF ELECTRONICS

The physical basis of superconductor electronics is the so-called superconducting state exhibited by many metals when they are cooled to temperatures within five or ten degrees of absolute zero. The most striking characteristic of this state is that there is no resistance to the flow of electricity; but there are, in addition, several other unusual phenomena associated with superconductivity—phenomena that make possible the new types of high-performance electronic devices.

Modern superconductor electronics had its beginnings in 1962, when Brian Josephson made two rather startling predictions that later (in 1973) won him the Nobel Prize in physics. These predictions, which were subsequently experimentally verified in great detail, concerned what would happen when two superconductors were connected together.

In essence, the first prediction was that when the connection was made, a small dc electrical current could flow between the superconductors with no resistance. Unlike a current in a single superconductor, the maximum possible amplitude of this supercurrent could be modulated periodically by very small applied magnetic fields. This has become known as the dc Josephson effect.

If a current greater than the maximum possible supercurrent is caused to flow, the connection begins to act much like a normal resistor: the dc supercurrent disappears and an electrical voltage appears across the connection. Josephson's second prediction applied to this situation. The prediction was that while the dc supercurrent would now be zero, there would be an ac supercurrent oscillating back and forth between the two superconductors. The frequency of this oscillating supercurrent would depend directly on the electrical voltage across the connection and on some fundamental constants of nature. The relation is that for every additional microvolt (10^{-6} volt) that appears across the connection, the frequency of oscillation increases by 485 megahertz (10^6 hertz). This oscillation, which can continue to frequencies greater than 10^{13} hertz, is known as the ac Josephson effect.

TECHNIQUES FOR MAKING JOSEPHSON JUNCTIONS

These Josephson effects are obtained only when the connection, or Joseph-

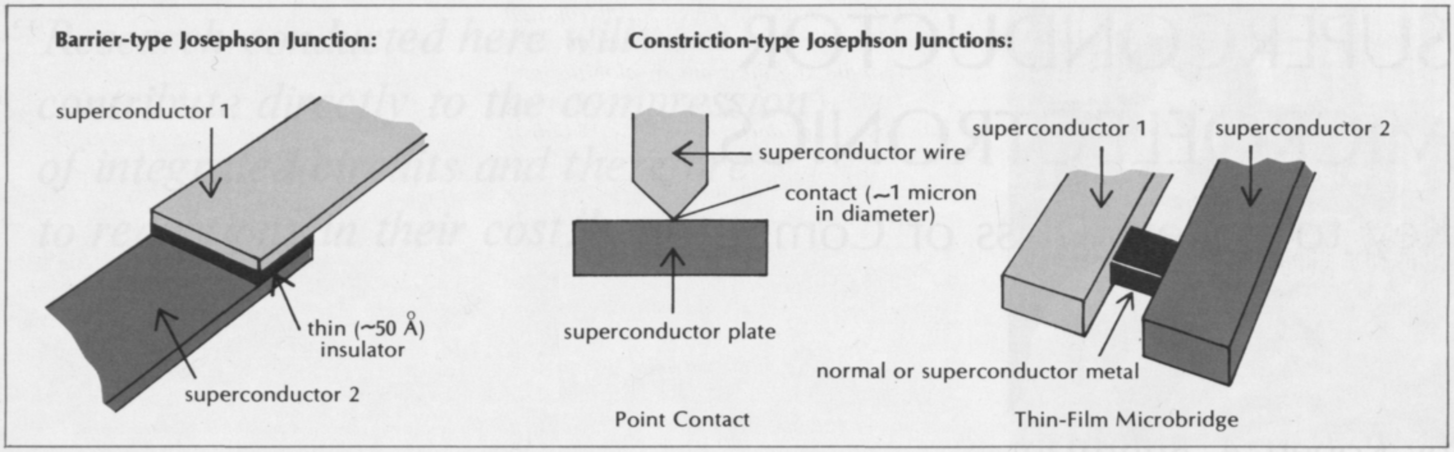


Figure 1. A schematic representation of the different types of Josephson junctions. The point contact gives very good electronic response but is not reliable. Future advances in superconductor microelectronics will be made with either barrier junctions or thin-film microbridges.

son junction, between the superconductors is properly formed. This is usually technically difficult. There are basically two approaches (see Figure 1).

One technique is to produce a sandwich-like structure in which an oxide layer or a semiconductor layer separates two superconductor films. If the barrier layer is sufficiently thin—less than 50 Angstroms (50 x 10^{-6} centimeters) for an oxide layer, and somewhat thicker for a semiconductor—electrical currents can pass through the layer and the Josephson effect can occur. The oxide version is the original Josephson junction.

The alternative approach is to join the two superconductors through a severely constricted metallic bridge made of either superconducting or normal metal. If the lateral dimensions of this bridge are of the order of one micron and if it is less than about one micron long, then Josephson effects will be exhibited. The classic example of this kind of Josephson junction is the point contact made by touching one superconductor to another. A more reliable and useful version is produced by forming a thin-film bridge between two thick superconducting films.

At the present time, the oxide barrier junctions are the most readily produced and widely used. The materials that are usually employed in fabricating them are not particularly rugged, however, and consequently there are some long-term stability problems with some versions. The oxide junctions are also characterized by a large shunt capacitance which acts to slow the response of the junction, limiting its performance in some applications and making it unsuitable for others.

To avoid capacitance limitations completely, it is necessary either to produce oxide junctions with cross-sectional areas of the order of one square micron, or else to use the very small microbridge configuration. Both alternatives, particularly the latter, place heavy demands on present-day microfabrication technology. For example, in our work with microbridges of normal metal, we have found that even junctions with all dimensions as small as 0.2 micron are not small enough for best performance. It may be that not all types of junction will require such high resolution, but it is clear that future improvements in the performance and reliability of Josephson devices, and the integration of these devices into complex circuits, depend heavily on the development of advanced submicron fabrication and on advanced thin-film materials research.

DEVICE APPLICATIONS OF JOSEPHSON EFFECTS

A wide range of electronic devices that utilize the dc and ac Josephson effects can be produced. Those that have already reached or passed the stage of prototype development include magnetometers, voltmeters, voltage-tuned microwave oscillators, microwave and millimeter wave mixers, and infrared detectors, as well as digital computer

Figure 2

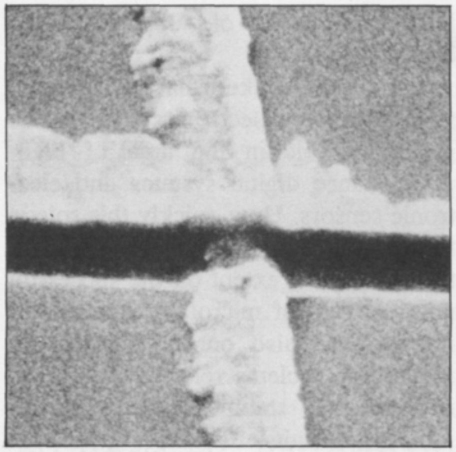


Figure 2. A scanning electron micrograph of a thin-film microbridge junction. The superconducting films are of niobium and are 1,500 Å thick. These films are separated by a gap (dark color) about 2,000 Å wide, which is bridged by a narrow copper strip. This junction was formed by electron-beam lithography and ion-beam etching. The white material in the micrograph is chemical residue from the lithography process; while undesirable, it does not affect the electronic properties of the junction. (This junction was formed at Cornell by John M. Warlaumont, a graduate student. See also page 35.)

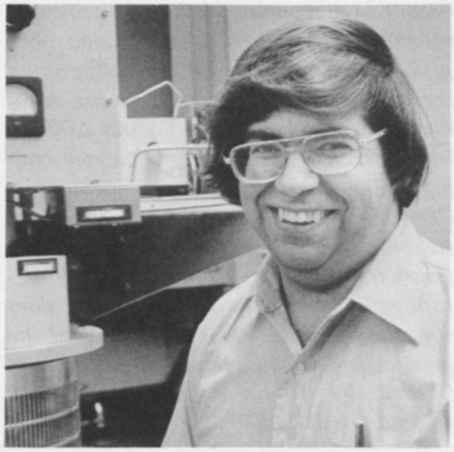
Below: This digital pattern generator, which drives a scanning electron microscope, was used to fabricate the junctions prepared by Professor Buhrman and his students. Shown with the instrument is Jason Lo, a graduate student in materials science and engineering.

elements. These superconducting devices are characterized by exceptional performance that matches or, in most cases, far exceeds what can be obtained with more conventional semiconductor electronics. Further advances in superconductor device performance, based in large part on the application of new developments in microfabrication, appear imminent.

The most successful application of the Josephson phenomena so far is the superconducting magnetometer, a device that can measure magnetic fields as small as one-trillionth (10^{-12}) of the magnetic field of the earth. This is by far the most sensitive magnetometer in existence, and further improvements are quite possible. It is finding application in a number of fields, including geophysical and biomedical research. In the latter case, the instrument is being employed to map and monitor the magnetic fields of the heart and brain.

While specialized electronic instruments such as the superconducting magnetometer or the infrared detector will continue to be developed and improved in the coming years, it seems certain that in the future the greatest impact of superconducting devices will be in the area of digital electronics. Digital devices based on the Josephson effect have two characteristics—ultrafast switching times and ultralow power consumption—that together make feasible the construction of digital systems of unparalleled speed and computational power. Switching times (to go from the zero to a nonzero state) of less than 10 picoseconds (10^{-11} seconds) have been measured for single Josephson junctions. Yet the power consumption of an individual junction can be less than one microwatt. Because of this very low power level, it is possible to place Josephson junctions very close together without encountering major problems of heat removal. Thus, time delays in the transport of signals from one junction to another in a digital logic operation can be minimized. One criterion for the quality of a digital device is the product of the switching time and power consumption; and by this criterion, the Josephson junction is superior by orders of magnitude to its closest semiconductor competitor.

Because of the potential of Josephson junctions in digital applications, there is currently a large-scale research and development effort underway in this area at IBM and, to a lesser extent, elsewhere. The main objective is to produce an extremely powerful computer for applications that require very rapid computation. Other objectives include the production of very-high-speed analog-to-digital converters for the direct acquisition of microwave signals which could then be processed by the Josephson computer.



"... devices based on the Josephson effect ... make feasible ... digital systems of unparalleled speed and computational power."

While such systems will not be fully developed for a number of years, major advances have already been made. IBM recently announced the production of experimental versions of integrated digital circuits with switching times of the order of 50 picoseconds, and also a 2,000-bit Josephson memory circuit with an access time of 7 nanoseconds. These times are about a factor of ten shorter than the times that can be obtained with the best semiconductor systems now commercially available.

The experimental devices produced thus far constitute only the first step in the development of a complete, full-scale superconductor computer. Nevertheless, they represent an impressive accomplishment. These results have been achieved, moreover, with the use of current state-of-the-art fabrication linewidths, which are much greater than one micron; the developmental work has not begun to take full advantage of the much smaller intrinsic size limitation of Josephson devices. The eventual development of a satisfactory production capability in submicron linewidths will greatly improve the already excellent performance of superconducting digital systems.

It seems most likely that in the future, superconductor electronics will play an important role in the area of high-performance digital systems and electronic sensors. How quickly this role is filled and how large it becomes depend to a very great extent on the successful advancement of microfabrication technology, and also on the solution of materials problems related to the fabrication and stability of Josephson-junction circuits. It is for just such purposes that the submicron facility is being established at Cornell. It is our expectation that in the coming years, workers at this facility will make valuable contributions to the eventual establishment of a successful superconductor electronics technology.

Robert A. Buhrman became assistant professor of applied and engineering physics after receiving his Cornell doctorate in 1973. His specialty field is solid-state and low-temperature physics; his current research on Josephson junctions is discussed in this article.

Buhrman received his undergraduate education at The Johns Hopkins University, earning the B.E.S. degree in engineering physics, with honors, in 1967. He held an NSF fellowship during his graduate study at Cornell, and served as teaching assistant and as research assistant in the School of Applied and Engineering Physics. At Johns Hopkins he was an assistant in space science and in computer science. His experience also includes a summer with the U.S. Army Materiel Command in research on fluids.

He is a member of the American Physical Society and Tau Beta Pi.

X-RAY LITHOGRAPHY AND MICROSCOPY FOR SUBMICRON STRUCTURES

by Boris W. Batterman

A small beryllium window in the high-energy storage ring now being built at Cornell's Wilson Synchrotron Laboratory may prove to be a valuable accessory to the new submicron facility here. Through this window we expect to obtain x-rays suitable as a source for reproducing and examining structures with dimensions as small as a tenth of a micron.

To understand the value of x-rays in work with submicron structures, it is necessary to understand the spatial relation between such structures and the probes used to examine or create them. Any microprobe process is limited by the wave nature of the probe itself: the ultimate resolution will always be comparable to the wavelength of the probe. With an optical source, such as in an optical microscope, features with dimensions in the range of a micron (10,000 Å) are the smallest that can be resolved. This is because the light rays are diffracted outside of the geometrical trajectories when the structure being created or examined is comparable in size to the wavelength of the beam.

In microscopy, improved resolution is obtained by using electrons rather than photons for the incident beam. Although electrons are *matter* rather than electromagnetic radiation, it has been amply demonstrated experimentally that matter has wave properties and that these wave properties are related to the energy of the matter particles. In an electron microscope, wavelengths associated with the electron beam can be as small as several hundredths of an Angstrom, almost a million times less than the length required for one-micron resolution.

Electrons are also ideal for probing and creating submicron structures. Techniques for electron-beam writing of circuit patterns utilize the well established technology for spatial control of electron beams, coupled with sophisticated techniques for optical pattern design. There are problems with direct electron-beam writing, however. It is an expensive procedure from a technological point of view: since the system writes the pattern point by point, the throughput is severely limited. Furthermore, the apparatus is very expensive.

This is why the use of x-rays is an important consideration in the development of submicron technology. These rays, with wavelengths in the 100 Å to 1 Å range, can be used to create fine-line structures rapidly from an electron-beam-written mask in a process called x-ray lithography. They can also be used, as we shall see, to delineate microstructures in the related process of x-ray microscopy.

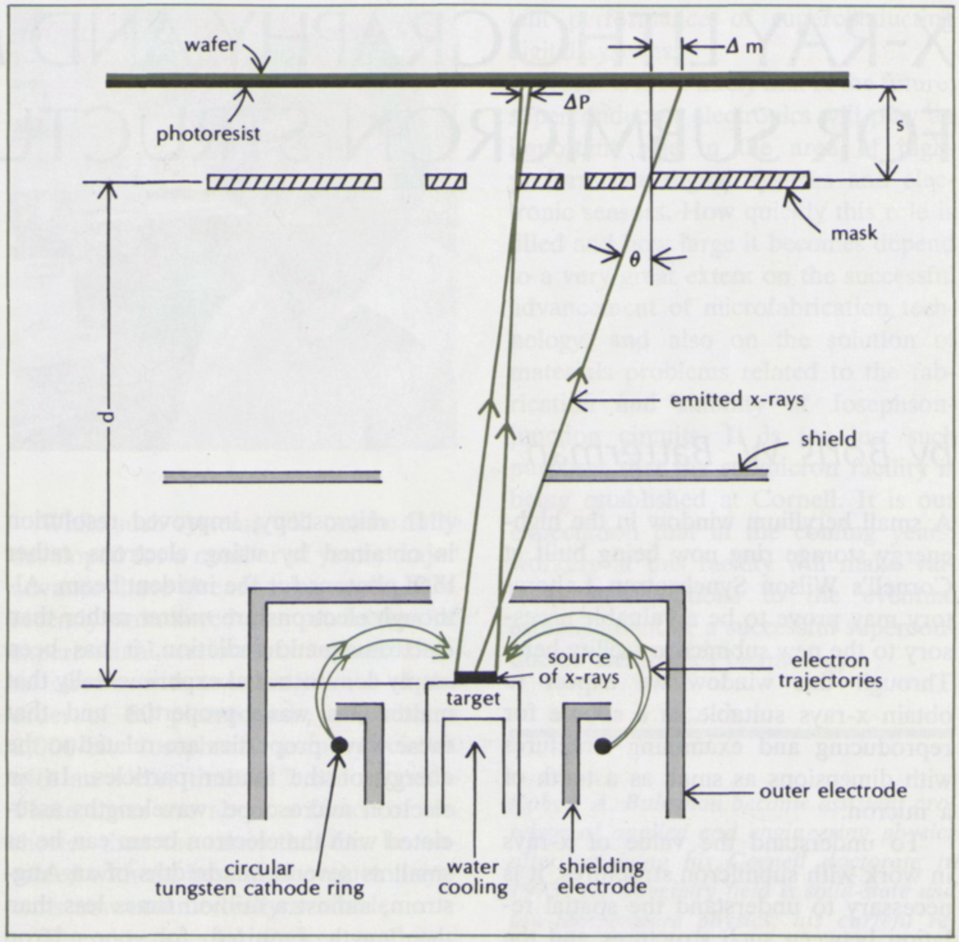
X-RAY LITHOGRAPHY FOR PATTERN REPLICATION

One of the most important applications, and our immediate concern at Cornell, is the development of these x-ray techniques for use in the fabrication of submicron structures.

In simplest terms, the electron beam device creates a line structure in a material (gold, for example) that is opaque to x-rays. Where a line has to be written, the gold is removed: the electron beam exposes a photoresist coated on the gold film, the resist is developed, exposing the gold where the beam has written, and then the gold is selectively removed. After this mask

Figure 1. Schematic of a conventional x-ray lithographic setup. The electron gun in the lower portion of the figure uses electrons from a ring cathode; these are focused on a water-cooled target (carbon, aluminum, or copper, for example) to produce fluorescent x-rays. The source of x-rays is circular with a diameter of 1–2 millimeters. The emitted x-rays strike the wafer–photoresist sandwich. Two types of distortion are illustrated: penumbral broadening, ΔP, due to finite source size; and geometrical distortion, Δm, due to nonaxial x-rays passing through the mask at angle θ.

Figure 1



has been constructed, a shadow of the structure is projected by x-rays onto a photoresist deposited on an appropriate semiconductor substrate, and the wafer is subjected to further development and processing.

The advantage of the x-ray lithographic technique is that the mask, which is difficult and expensive to produce, needs to be written only once; replicas are made rapidly in a one-shot mode using a wide-area x-ray beam. The x-rays are used in a manner that is similar to the way light is used in conventional techniques; the advantage is that the shorter wavelength of the x-rays allows the creation and imaging of structures in the 0.1 to 0.01 micron range (1,000 – 100 Å), whereas light is limited to structures with dimensions greater than about a micron. A schematic of the x-ray lithographic technique is shown in Figure 1.

The electron-beam-written mask must be supported on a substrate that is transparent to x-rays. The mask material itself must be thick enough to be a high absorber of x-rays, or there will be very little contrast in the projected image of the mask. After the projected image falls upon the substrate (PMMA—polymethylmethacrolate), the resist is developed by dissolution of the areas that have been exposed to the x-ray beam, and then chemical treatment and evaporation techniques are applied to create the submicron structure on the wafer.

In principle, the mask can be kept separated from the wafer in order to prolong the life of the mask by avoiding mechanical abrasion. In practice, however, several complications arise. Since the size of the x-ray beam is finite, the shadow of any edge is broadened by an amount, ΔP, as shown in Figure 1; this is known as penumbral broadening. It is related in a simple geometrical way to the distance, s, separating the wafer and mask, to the distance, d, from the source to the mask, and to the source size. There is an additional distortion due to the fact that the x-rays may arrive at the mask at an angle, θ; this gives rise to a so-called geometrical distortion, Δm. Both of these distortions can be eliminated by having a very small source

Figure 2

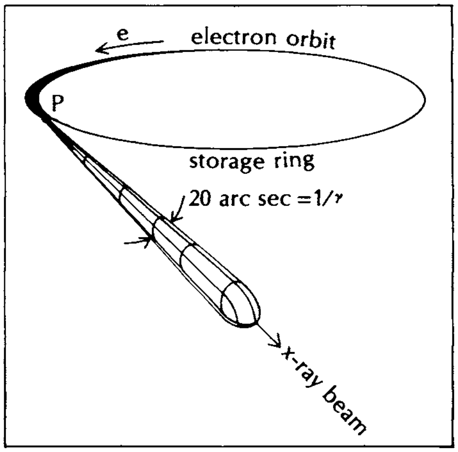


Figure 2. Synchrotron x-ray emission. The cone angle of the radiation emitted when the electron is at point P is γ^{-1} = (rest energy / electron energy). For a 5-GeV electron, γ^{-1} = (0.5 / 5,000) ≈ 20 arc sec. Over the entire orbit, the x-ray beam sweeps out a sheet of x-rays in the plane of the electron orbit.

at a very large distance, but then the brightness of the beam must be correspondingly high.

Another consideration is that it is highly desirable to have steep walls between the substrate lines in many device applications. This so-called high aspect ratio can be achieved if the incident beam of x-rays is made nearly parallel (as from a far-away source) and if there is substantial penetration of the resist. The high penetrating power of x-rays, as compared with light beams, in the low-atomic-number photoresists makes x-ray lithography ideal for the purpose of obtaining high aspect ratios.

THE ADVANTAGE OF SYNCHROTRON X-RAYS

The source shown in Figure 1 is a conventional x-ray generator. The circular cathode produces electrons by thermionic emission, and after acceleration by an approximately 4-KV potential difference, these electrons are focused onto the target. The target can be aluminum, copper, or any other metal whose fluorescence x-rays produced by the incident electron beam will match the properties of the x-ray resist.

The ideal source, as I have suggested, would have to be much brighter than the beam produced by a conventional source. In optical terms, the brightness increases as the source size and the divergence of the rays get smaller. Fortunately, there is an x-ray source with these properties: it is the x-radiation that is produced as a byproduct in high-energy particle accelerators and is just now coming into its own. This is the source we plan to tap from the new Wilson Laboratory storage ring (called CESR).

Figure 2 shows the trajectory of an electron that is travelling in a synchrotron at essentially the velocity of light and with an energy of, say, five billion electron volts (GeV). In such a circular orbit, a charged particle is constantly accelerating centripetally, and this centripetal acceleration causes the charged particle to radiate in the electromagnetic spectrum. When the particle energy is as high as 5 GeV, much of this radiation takes place in the ultraviolet and x-ray regions. A feature that makes this x-radiation particularly useful is that it is highly focused in the instantaneous direction of the travelling particle; in fact, the divergence of the cone of radiation being emitted by an electron travelling at 5 GeV corresponds to only 20 seconds of arc. Thus, a highly parallel beam of x-rays leaves

"...we expect to be able to do x-ray lithography and microscopy with resolution of 0.1 micron."

Figure 3

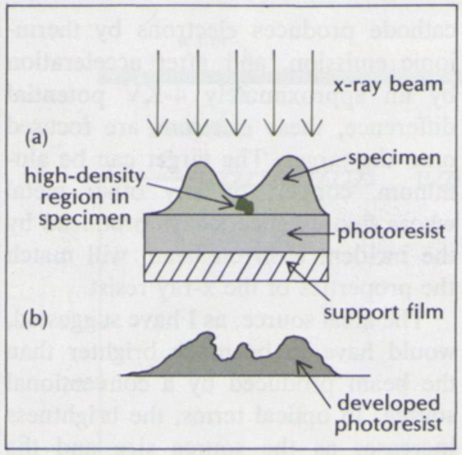


Figure 3. X-ray microscopy. (a) The specimen placed on a photoresist is irradiated by an x-ray beam. (b) The developed photoresist has a surface profile related to the absorption path through the specimen.

the synchrotron orbit during high-energy experiments. This beam could be brought out to a working area by channeling it down a tangential pipe.

Such a source is ideal for the x-ray lithography I have described. Because of the high collimation and the small source size (a fraction of a millimeter in the horizontal and vertical directions), penumbral and geometrical broadenings would be negligible even at distances of several tens of meters. In fact, one could afford to place the x-ray mask farther from the wafer (distance s in Figure 1) so that wear and tear on the mask could be reduced considerably. The most attractive feature of this radiation, though, is that it is more intense by many orders of magnitude than the x-radiation produced by the conventional source of Figure 1. For example, an exposure with a conventional system with an aluminum target might take ten to twelve hours with current x-ray resists; with x-rays from a synchrotron, the time can be reduced to the order of minutes.

One might expect that the highest resolution in x-ray lithography would be attained by using x-rays of the shortest wavelengths. This is not the case, however, because of a different kind of broadening that occurs upon interaction of the incident ray with the photoresist. When x-rays enter the polymer of the resist, electrons, called photo-electrons, are ejected from the resist molecules. Such a photo-electron has an energy equivalent to the difference between the energy of the incident photon and the binding energy of the electron in the resist molecule. Since the binding energy is typically of the order of electron volts, and the energy of an x-ray of, say, one Å is approximately 12 kilovolts, the photo-electron would be ejected with almost 12 kilovolts of energy. Because of this large kinetic energy, such a photo-electron has a large straggling range in the resist. Therefore, although the incident point of the initial photon is very well defined, the damaged area of the resist will be much larger. The effect is to reduce the definition of the submicron structure. The best resolution will come about when the photo-electron range is no bigger than the diffraction broadening due to the wavelength of the incident x-rays. It turns out that in the currently popular PMMA resist, a photo-electron range of about 50 Å is created when the incident photon is from an x-ray of wavelength about 50 Å (this corresponds to an energy of about 250 electron volts). Thus, the ultimate resolution in this type of system will be about 50 Å.

50-ANGSTROM RESOLUTION BY X-RAY MICROSCOPY

In a very dramatic piece of work by E. Spiller and collaborators at IBM, a resolution of 50 Å in an x-ray resist has been demonstrated. In this case, the technique would be better described as x-ray microscopy, for the purpose is to image an object by x-ray absorption.

This x-ray microscopy is similar to x-ray lithography, with the mask replaced by the object itself. In the examples illustrated in Figure 3, a biological diatom is placed on top of a photoresist and a supporting substrate. The x-ray beam incident on the object suffers different attenuation in different portions of the object (as in medical x-ray pictures, in which the contrast is due to differential absorption by the various structures of the body). In this case, the wavelength is chosen so that the beam will be attenuated rather strongly in the object, with variations in the absorption producing a corresponding projected differential exposure in the photoresist. When it is developed, as shown in Figure 3, the photoresist has a profile that corresponds to the absorption paths in the specimen. To see the x-ray image, one plates the developed photoresist with a very thin metallic layer, of the order of

Figure 4(a)

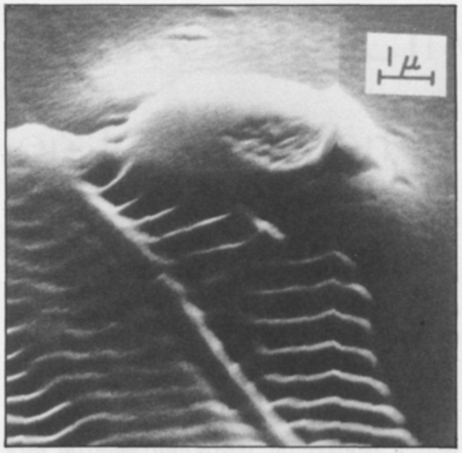


Figure 4(b)

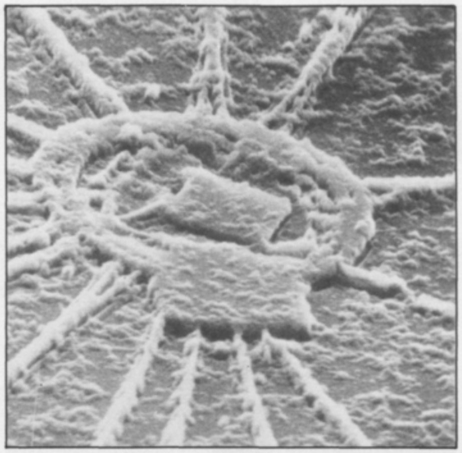


Figure 4(c)

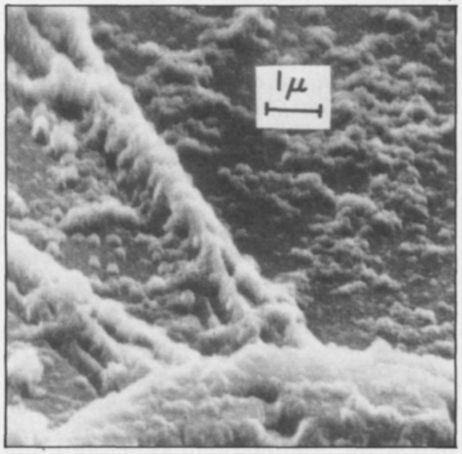


Figure 4. X-ray replicas of diatoms. The exposed resist is coated with a very thin metallic layer and is then viewed with a scanning electron microscope. Figure 4(a) was taken with a conventional source, such as the one diagrammed in Figure 1, with use of a carbon target emitting K x-rays with a wavelength of 45 Å. Distance s in Figure 1 was 15 centimeters and the exposure time was 20 hours. Figures 4(b) and 4(c) are different portions of the same specimen, with the exposure made with synchrotron radiation at the facility DESY in Hamburg, Germany. The source was 40 meters distant and the exposure time was 10 minutes. Note that details smaller than 0.1 micron (1,000 Å) in diameter are visible. (These figures were supplied by Dr. E. Spiller of IBM and were published in Science *191:1172 (1976). Authors of the article are E. Spiller, R. Feder, J. Topalian, D. Eastman, W. Gudat, and D. Sayre.)*

Figure 5(a)

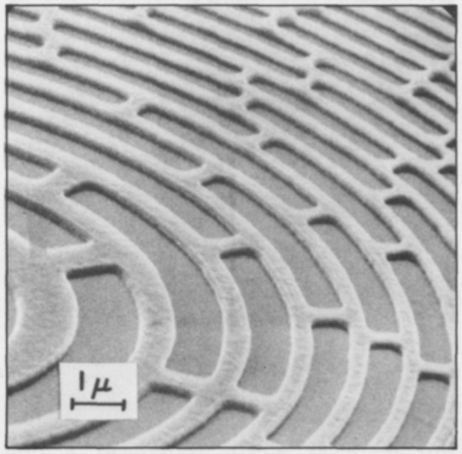
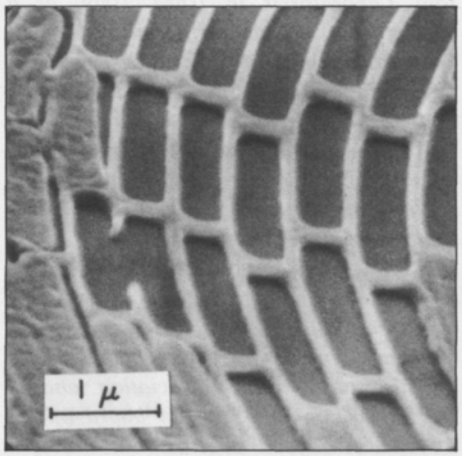


Figure 5(b)



Figures 5(a) and 5(b). Replicas of a Fresnel zone plate made of 0.1-micron-thick gold and exposed with synchrotron radiation. The smallest linewidths are 700 Å. [After Spiller et al., J. Applied Physics *47:5450 (1976).]*

Figure 6

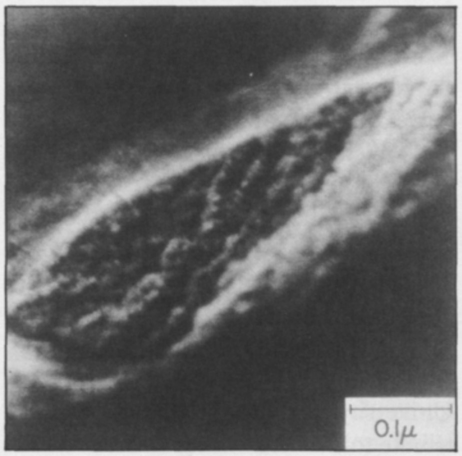


Figure 6. A replica showing about the highest resolution obtained to date in x-ray microscopy. It is a replica of frog retinal pigment epithelium taken by Spiller and collaborators (see Figure 4 for authors) and published in Science *197:259 (1977). The exposure time was 15 minutes and the wavelength of the synchrotron radiation was 30–44 Å. The marker (0.1 μm) shows 1,000 Å. Details of 100-Å dimension are clearly visible. The very fine detail is probably due to the metallization process used in coating the exposed resist.*

10 Å or less, and then views the plated resist with a scanning electron microscope. Figures 4, 5, and 6 are examples of x-ray lithographic pictures taken with a beam from the synchrotron in Hamburg, Germany. Note that a structure of about 100 Å is clearly resolvable.

USING SYNCHROTRON X-RAYS FOR SUBMICRON RESEARCH

The high-energy storage ring at Cornell's Wilson Synchrotron will contain circulating electrons with energies in the range of 4 to 8 GeV. This will produce a copious source of x-rays of high intensity and collimation for use in our submicron research. The major disadvantage of the physical arrangements, as specified in the current plans, is the use of the beryllium window in the storage ring. This window will cut out the longer-wavelength radiation; x-rays with wavelengths greater than 6 Å will be severely attenuated. Still, the photoelectron straggling produced in the photoresist by 6 Å rays is below 1,000 Å or 0.1 micron, so that even with our present limitation of a beryllium window, we expect to be able to do x-ray lithography and microscopy with resolution of 0.1 micron. This resolution is well beyond the technical capability of current semiconductor technology. We expect to explore x-ray lithography and microscopy using not only the conventional source described in Figure 1, but also the more exotic synchrotron radiation.

Cornell is very fortunate to have both a national center for submicron structures and a laboratory for synchrotron radiation. This combination puts our University in a unique position to contribute to new technologies.

Boris W. Batterman, director of the School of Applied and Engineering Physics at Cornell, has been a member of the applied physics and materials science and engineering faculties since 1965. As reflected in this article, his current research centers on x-ray and neutron diffraction for examination of the atomic structure of solid materials.

Batterman was educated at the Massachusetts Institute of Technology, earning the S.B. degree in physics in 1952 and the Ph.D., also in physics, in 1956. Before joining the Cornell faculty, he was a member of the technical staff at Bell Telephone Laboratories. He has served as a consultant to the Inland Steel Corporation, the Aerospace Corporation, and Stanford University, as well as to the Bell laboratories.

In 1953–54 Batterman was a Fulbright scholar at the Technische Hochschule in Stuttgart, Germany. In 1971–72 he spent a year's leave at the international Euratom Laboratories in Ispra, Italy, as a recipient of Guggenheim and Fulbright fellowships.

At Cornell he is associated with the Materials Science Center and has served on the executive committee of that laboratory. He has served also as graduate faculty representative in applied physics and on a number of policy, fellowship, and admissions committees. He is a fellow of the American Physical Society and a member of the American Society for the Advancement of Science and the American Crystallographic Association, and he has served on the editorial board of the Journal of Crystal Growth.

INTRODUCING IMPURITY

Ion Implantation and its Role in Microelectronics

by Charles A. Lee

Microelectronics and the revolutionary changes it is effecting in our lives have been made possible by the development of two fundamentally important techniques: photographic and electron-beam lithographic mask fabrication (discussed by others in this issue), and ion implantation. Advanced lithographic techniques make it possible to produce integrated circuits containing upward of a quarter of a million devices on a single chip. Ion implantation is an important process in the fabrication of the diodes and transistors that compose the active devices in these circuits.

Why is ion implantation so important? The reason is that semiconductor devices of microscopic size require the presence of minute, closely controlled amounts of impurities. The implantation technique provides a way of introducing the needed ions into the semiconductor substrate with precise control of dosage, purity, and depth.

EARLY DEVELOPMENT OF THE TECHNIQUE

One of the first researchers to use ion implantation in the fabrication of semiconductor devices was Russell S. Ohl, who reported on the properties of "ionic bombarded silicon" in 1952. I had the pleasure of visiting his laboratory in 1954 to examine his implantation apparatus. Compared with those in common use today, it was a very rudimentary machine, consisting of a tall glass cylinder, several inches in diameter, with a silicon target as the cathode at one end and the anode at the other end. When a gaseous hydrocarbon was introduced into the evacuated cylinder and a discharge struck between the electrodes at a potential of about 10 kV, high-velocity carbon ions became embedded in the silicon. The inclusion of the carbon ions considerably improved the properties of point-contact-detector diodes that Ohl was making.

That same year, 1954, William Shockley and I had started work on a diffused-base transistor. This device required the diffusion of only 10^{13} donor impurities per square centimeter to a depth of one micron from the surface, a requirement that was very difficult to meet with the technology available at that time. Shockley, however, recognized the capability of ion implantation for fabricating such thin, lightly doped transistor base layers, and he was farsighted enough to file a patent on such a technique that same year.

FIRST APPLICATIONS OF ION IMPLANTATION

During the next ten years, there were only sporadic reports concerning ion implantation, but by 1964 a sufficient amount of exploratory work had been done to reveal its potential as an important fabrication tool. Although the importance of ion implantation became generally acknowledged, it was for some time regarded as an expensive laboratory technique. Two important device applications changed this picture. One was the use of an implant for adjusting the gate potential in a metal-oxide-semiconductor (MOS) device, and the other was the use of an implant concentration graded in depth to make a hyperabrupt tuning diode. Both of these devices required such precise impurity doses that only ion implantation could be used. After this

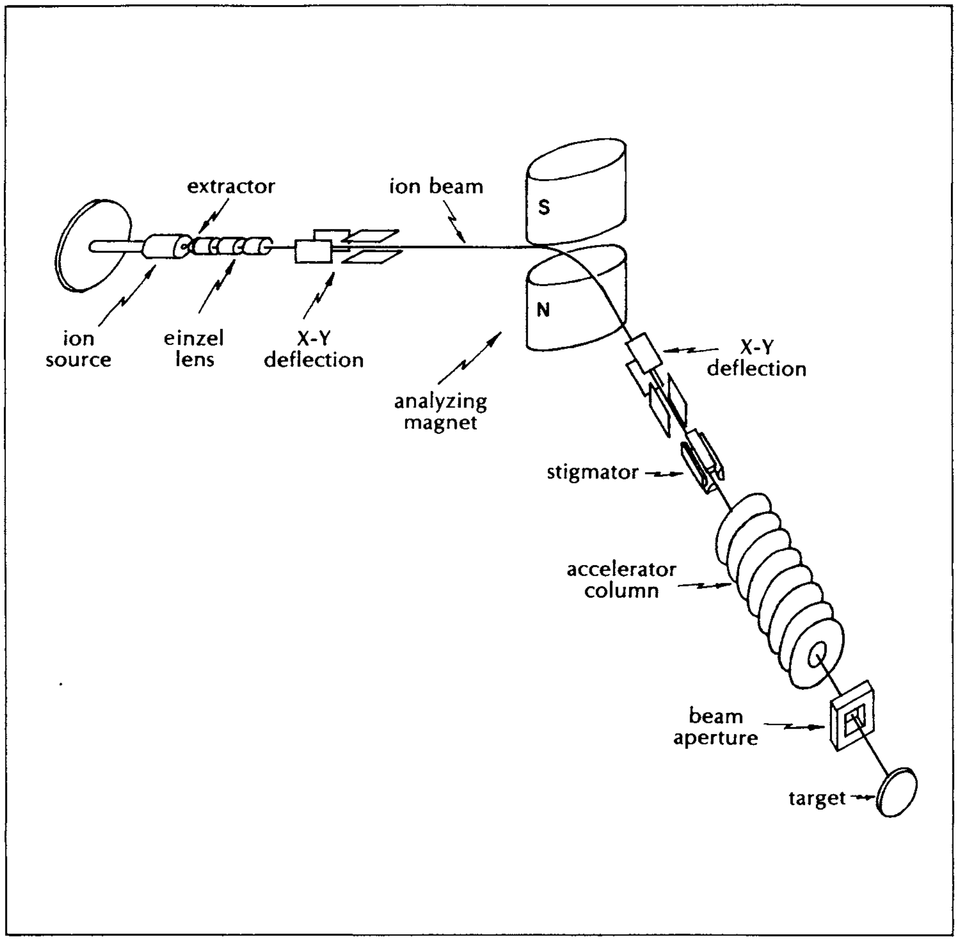


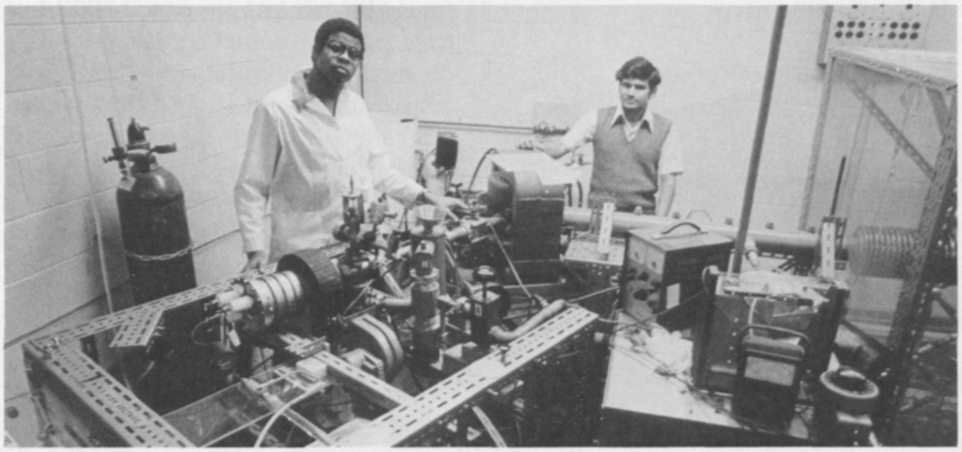
Figure 1. Schematic of the ion implantation machine at Cornell.

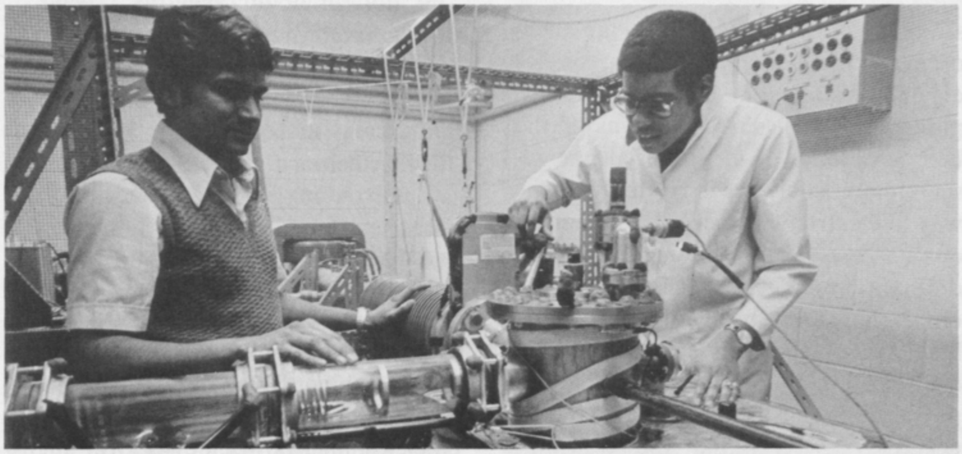
introduction of ion implantation into manufacturing, its economic potential was quickly realized; it was because of this technique that the manufacturing yield of integrated circuits with thousands of transistors and diodes could be increased dramatically. At the present time, ion implantation is utilized not only in research, but also on a large scale in production.

HOW AN ION IMPLANTER WORKS AND WHAT IT CAN DO

In simple terms, an ion implantation machine consists of an ion source, a magnetic field, and an ion accelerator. In the ion source, an intense arc is formed in a low-pressure stream of a gaseous compound containing the desired element or isotope. The resulting plasma is extracted as a narrow beam of ions and is passed through a uniform magnetic field whose magnitude can be adjusted so as to focus a beam of the desired ionic species at an aperture on the far side of the magnet. After passing through this aperture, the ions are accelerated through a potential in the range of a few tens of kilovolts to about 200 kV, and reach velocities of the order of 10^8 centimeters per second. Finally, they strike a target (the semiconductor substrate) and embed themselves in the first few thousand Angstroms of the surface layers.

An understanding of the importance of the process can be gained by examining some examples of what can be accomplished with it. Suppose we consider two of the semiconductor devices I have mentioned. In the diffused-base transistor, the base region has to contain 10^{13} impurities per square centimeter, distributed to a depth of one micron; this works out to be an impurity density of only ten parts per million. The hyperabrupt tuning diode requires a dose that is a factor of ten smaller; if the impurity dose is to be controlled to 0.5 percent or less, the doping mechanism must be able to control the impurity density to a few parts per billion. To use chemical means to exclude undesired impurities while introducing precise amounts of specific, electrically active impurities is a frustrating, nearly impossible task. With





The ion implanter currently in use at Cornell was developed over the years by electrical engineering faculty and students. In the upper photograph, graduate students Gary Harris (left) and Aditya Gupta are shown with the ion source. The lower photograph shows the target chamber.

ion implantation, however, magnetic selection excludes unwanted impurities to a degree that is extremely difficult to attain by chemical methods, and the dose can be controlled easily by regulating current and exposure time. For example, with a target current of 10^{-6} amperes scanned over a wafer two inches in diameter, an exposure of only 3.2 seconds will give a dose of 10^{12} particles per square centimeter. This exposure time can be readily increased by a factor of ten by stopping down the beam. In fact, the dose may be accurately controlled to a few thousand atoms per square centimeter if that is necessary.

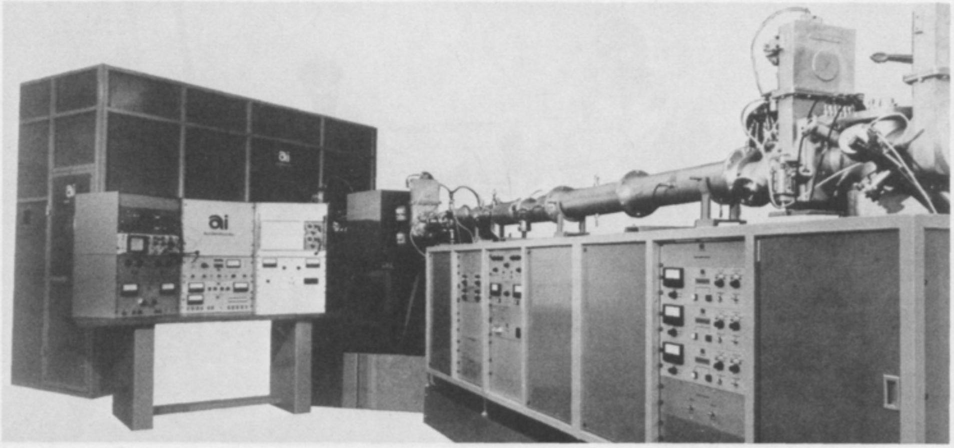
The depth of the implant may be controlled, of course, by varying the acceleration potential of the ions. Furthermore, with modern lithographic techniques, the implanted areas of the substrate can be defined with an accuracy of a quarter of a micron. This degree of precision may be more vividly conceived of and appreciated if it is recalled that the thickness of a human hair is some 60 to 70 microns.

CORNELL WORK ON ION IMPLANTATION

The first construction of an ion implanter at Cornell was started by Professor Lee MacKenzie in 1966. After he left the University the following year, I continued the construction of that first machine, completing it in 1969. From 1972 to 1974, Professor Jeffrey Frey and I collaborated on the construction of a new machine, reusing some parts of the first one. A new ion source and a new target chamber were designed and built, a new analyzing magnet was acquired, and the high-voltage source was upgraded from 100 to 200 kV. This machine has been used in research for the past four years and is now once again in the process of being upgraded, this time by the addition of a new ion source and some improvements to the source vacuum system.

In general, our research on ion implantation centers on the lattice location of implanted impurities, their electrical activity, and the annealing of the inevitable damage to crystalline structure that occurs when highly energized ions

"... it was because of this technique that the ... yield of integrated circuits ... could be increased dramatically."



A new commercially built ion implanter will be available in the submicron facility at Cornell. The instrument pictured is manufactured by Accelerators, Inc.

strike the target surface. Although much of the work is done on plain, single-crystal substrates, and the effect of implantation is measured in terms of the bulk properties of the material, the research almost always is related in some way to electronic devices. For example, one's interest in the interaction of two different implanted species would include the effect this interaction might have on device performance. Or in developing a process for annealing implantation damage, one would be concerned with retaining the transport properties of the material that are required for optimal device performance. Current projects at Cornell reflect these aims and approaches.

For example, one of my graduate students and I are studying secondary ionization rates and the time dependence of the avalanche process in very narrow junctions made by ion implantation. This work has relevance to junction photomultiplier structures for optical communications and also to Read diodes that can be used as amplifiers and sources at microwave frequencies.

Another project in which I am involved, along with Professor G. Conrad Dalman and a graduate student, Aditya Gupta, is the construction of complementary silicon Read diodes. This work is aimed at understanding how to make efficient, high-power devices for high-power linear amplifiers. Although such devices have been made from gallium arsenide, the performance of silicon diodes has been comparatively poorer, and there is as yet no satisfactory explanation of the difference.

A third very interesting project, on laser annealing of ion implantation damage, is just getting started in a collaborative effort by Professor Ross A. McFarlane, myself, and two graduate students. The intriguing aspect of this research is that a laser pulse lasting only 20 nanoseconds can raise the surface temperature of the semiconductor to 1,000° C or more and virtually completely anneal the lattice disorder, even though classical diffusion processes do not seem to be able to account for the reordering of the crystal within this time and at this temperature. The technique being developed should prove to be of great technological importance because an implanted wafer can be annealed *in situ*. There is the added possibility of localizing the annealing with suitable masks, a technique that should provide greater flexibility in the construction of complex integrated circuits.

Several projects involving ion implantation are under consideration for inclusion in the program of the new facility for submicron technology. Professor Frey is interested in fabricating microwave field-effect transistors with ion implantation; Professor Arthur A. Ruoff and Dr. Mool Gupta are interested in implantation in diamond for their high-pressure studies of materials; and Professor Benjamin M. Siegel and I are collaborating on ion-beam lithography.

Projects such as these illustrate how we at Cornell have developed and utilized the most innovative techniques in our research on solid-state devices. Ion implantation has been a crucial technique in the development of integrated-circuit and device technology, and will remain one of the foundations for the development of future generations of such devices. With the establishment of the new facility for submicron structures at Cornell, we foresee a great expansion of effort and accomplishment.

Charles A. Lee, professor of electrical engineering, has conducted research in the physics of electronic devices since the early years of their technological development. He is the coinventor of the diffused base transistor, which is now a basic component in solid-state electronic equipment. He collaborated in the first experimental realization of the Read diode, which is now the most efficient solid-state microwave source operating above the frequency limit of present-day transistors, and he is also responsible for developing much of the theory of Read avalanche devices. At the present time he is using ion implantation in his research on submicron structures.

Lee earned the B.E.E. degree at Rensselaer Polytechnic Institute in 1944 and the Ph.D. in physics at Columbia University in 1954. After a postdoctoral year at Columbia, he joined the Bell Telephone Laboratories for research on physical electronics and semiconductors. He came to Cornell in 1967.

Lee is a consultant to several industrial research laboratories, and has served as a reviewer and editor. He is now a member of the American Physical Society, the Institute of Electrical & Electronics Engineers, and the honorary societies Sigma Xi and Tau Beta Pi.

A SUBMICRON VIEW OF SURFACES AND INTERFACES

by Thor N. Rhodin

The smaller an object is, the more significant are the characteristics of its surface atoms. In an electronic device fabricated on the submicron scale, about one out of every three hundred atoms is on the surface. The physical and chemical behavior of these surface atoms over very small dimensions can be critical to the engineering usefulness of the device.

The nature and location of atoms on and near the surface are extremely sensitive to the materials and methods used to fabricate a microelectronic device, and also to the chemical, electrical, magnetic, and thermal conditions under which it is to operate. It is therefore of the greatest importance in a laboratory for research on submicron structures to be able to probe the compositional and spatial characteristics of these atoms on the microscopic scale. Fortunately, major advances in diagnostic instruments have occurred in the last few years, and equipment available in the new National Research and Resource Facility for Submicron Structures at Cornell will enable researchers to analyze surfaces over dimensions as small as several hundred atomic distances and at depths corresponding to a few atomic layers.

INSTRUMENTS FOR STUDYING SUBMICRON FEATURES

Any analytical method used should preferably meet two important criteria: it should be sufficiently sensitive, and it should be nondestructive to the material. In addition, it is advantageous if the method can be used in conjuction with other diagnostic techniques.

Instruments and analytical tools that employ beams of electrons, ions, or x-rays are able to meet these criteria, and are proving very useful in achieving the microcharacterization of small electronic devices.* The three most important properties to be defined are the atomic composition, the spatial arrangement, and the electronic structure of atoms at both external and internal surfaces, as well as in the bulk of the sample. The many ways in which such beams can be used are indicated very schematically in Figure 1. General features that may be noted are: (1) the excitation produces a response that may be the same or different in nature from that of the stimulating beam; (2) the excitation may be either reflected by the target or transmitted, and may or may not permanently alter the surface; and (3) the momenta and energetics of the reflected radiation can be used to characterize the microscopic nature of the solid.

Three of the most useful instruments of this kind are the scanning Auger microprobe (SAM), the scanning electron microscope (SEM), and the scanning transmission electron microscope (STEM). It is significant that these particular instruments can be used not only for diagnostic testing, but also to study problems of fabrication *in situ;* that is, in the same environment as the diagnostic testing. Since all three will

**A good discussion of unique analytical methods is given by J. P. Hobson in "The Relationship of Solid Surfaces to Vacuum Science and Technology," in* Proceedings of 6th International Vacuum Congress, Japan Journal of Applied Physics, *supplement 2, part 1 (1974).*

Figure 1

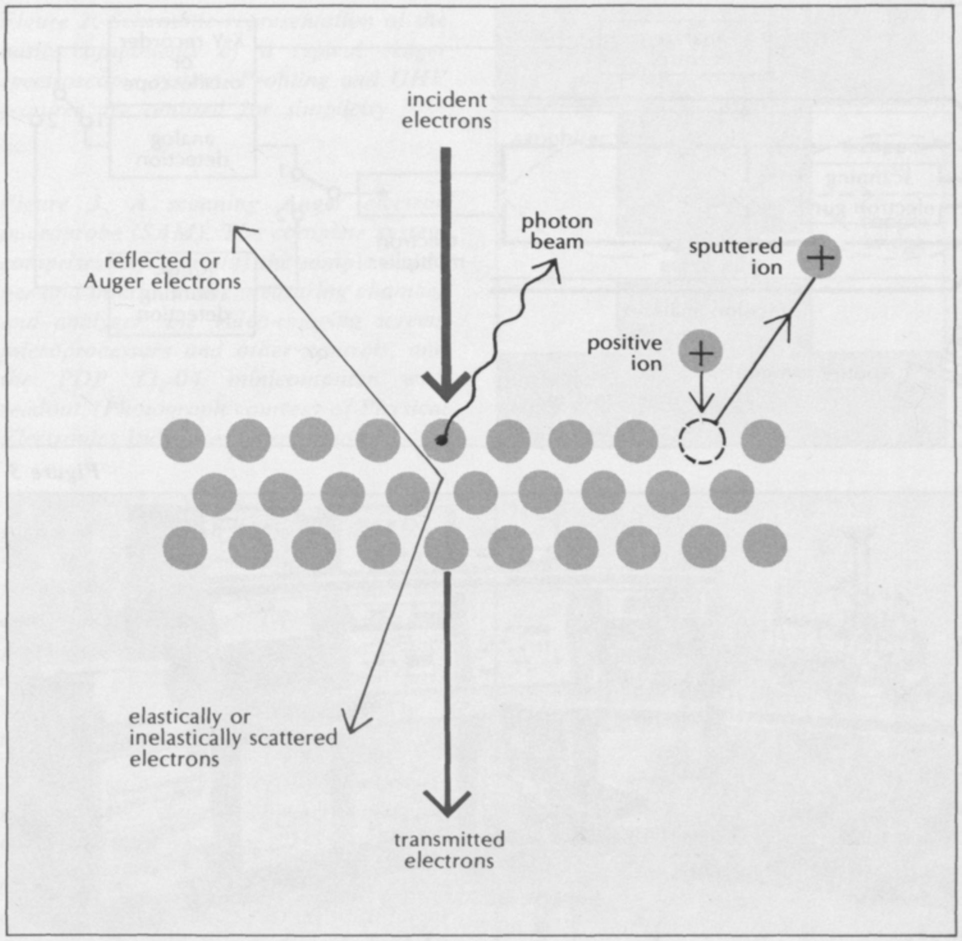


Figure 1. Schematic representation of some of the modes by which electrons and ions interact with an ordered solid surface to give information on surface and bulk properties on a microscopic scale.

be put into operation very soon in the submicron facility at Cornell, it is appropriate to consider how they can be utilized.

HOW SAM IDENTIFIES AND COUNTS ATOMS

The primary function of scanning Auger analysis is to determine the elemental composition of the first few atomic layers of a solid. Information about surface composition is essential for work with submicron structures because of the importance of surface phenomena; information about the outermost atomic layers is important because these can be very different in composition from even the first few thousand atomic layers.

Scanning Auger microscopy is based on the principle that when high-energy electrons impinge on a solid surface, they can excite secondary electrons of much lower energy; the energy and intensity of these secondary electrons are then used to identify and count the number of atoms in an extremely small volume of the sample. In the SAM, the incident electron beam is in the 5–50 keV range, the secondary electrons are in the 1–1,000 eV range, and the size of the test volume is about 10^{-17} cubic centimeters (a spot about 1,000 Å in diameter with an "electron skin depth" of 3–20 Å). The instrument operates in ultrahigh vacuum because the extremely high sensitivity of the method requires careful control of the surface condition.

With this instrument, quantitative chemical analysis can be achieved, within an uncertainty of about 10 percent, for most of the elements in the

Figure 2

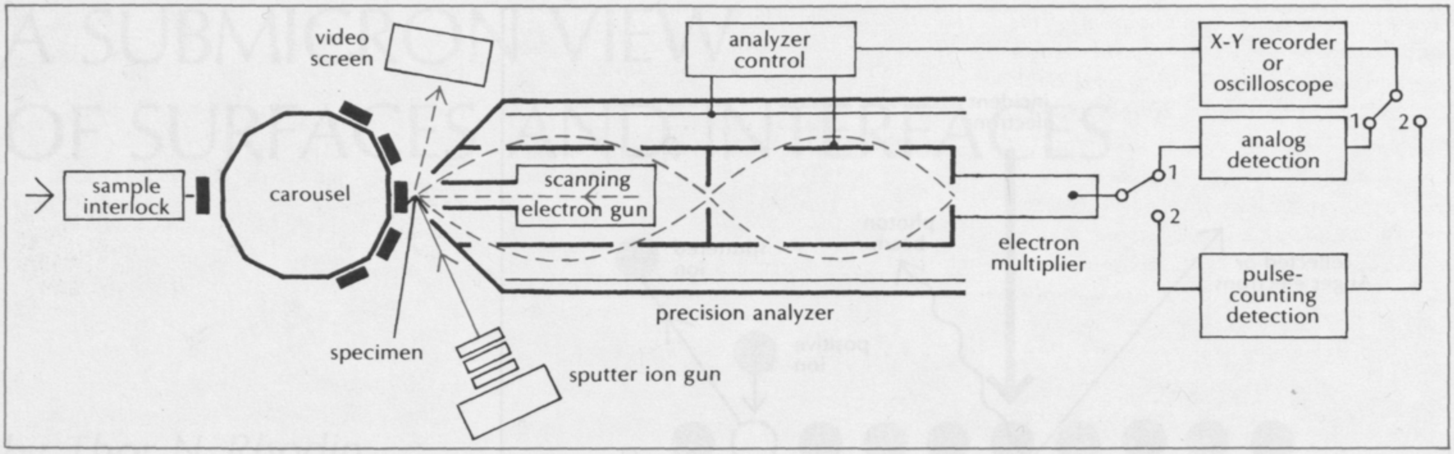
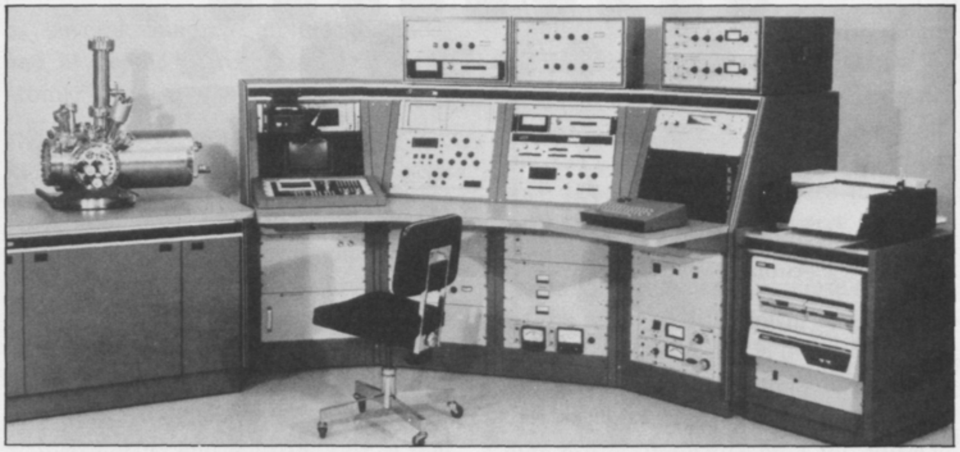


Figure 3



periodic table.* In addition, chemical information on the submicron scale can be obtained for some elements through analysis of Auger peak shapes or peak shifts.

A typical Auger system is shown schematically in Figure 2 and in the Figure 3 photograph. The essential components—a sample holder, a high-energy scanning electron gun, and a precision electron-energy analyzer—can be augmented by additional features that substantially extend the usefulness of the instrument. For example, equipment for spatial imaging permits direct correlation of specific features of composition with spatial changes in surface structure (see Figure 4). With a gun for sputter ion bombardment, ion-beam milling can be used to identify as many as six elements and produce a compositional profile normal to the surface. An auxiliary testing chamber and transfer stage makes it possible to perform electrical, chemical, and thermal tests on the sample without removing it from the UHV system. A minicomputer and microprocessor interfaced with the Auger system greatly increase the speed, scope, and quality of the analytical information.

The SAM at Cornell will be used in three modes, to obtain energy scans, line scans, and Auger maps. An *energy scan,* produced by driving the electron detector between two energies, pro-

**The chemical spatial resolution usually is limited by the lateral distribution of backscattered electrons, which in turn depends not only on the probe size, about 1,000 Å, but also on the energy of the Auger transition, the primary probe energy, the angle of incidence of the electron probe, and the composition and surface topography of the specimen. (Characterization of surface topography is one of the main sources of uncertainty in advancing quantitative SAM analysis below the submicron range.) For a good discussion of the potential of the instrument, see N. C. MacDonald and C. T. Hovland, "The Scanning Auger Microprobe: A Review," in* Proceedings of 8th International Conference on X-ray Optics and Microanalysis and 12th Annual Conference of Microbeam Analysis Society *(1977), p. 64a.*

Figure 2. Schematic representation of the basic components of a typical Auger spectroscopic system. Profiling and UHV features are omitted for simplicity.

Figure 3. A scanning Auger electron microprobe (SAM). The complete system comprises (left to right) the sample chamber and interlock, the measuring chamber and analyzer, the video-imaging screen, microprocessors and other controls, and the PDP 11–04 minicomputer with readout. (Photograph courtesy of Physical Electronics Industries Corporation.)

Figure 4. Surface structure and composition in the submicron range as revealed by a combination of spot Auger analysis and spatial imaging. The illustrations pertain to a superconducting weak-link device in which a sapphire (Al_2O_3) base is overlaid first with copper and then with niobium.

(a) Schematic diagram of the structure of the weak-link device. The area analyzed is indicated in color.

(b) Scanning electron micrograph (SEM) of the spot under study. Areas of different surface composition are characterized by spot Auger analysis as shown in (c). A copper bridge crosses the approximately 2,500 Å gap in the niobium overlayer.

(c) Auger electron spectra of the areas labeled A *and* C *in the SEM photograph.* A *contains copper and* C *is mainly niobium. (The spectrum for area B, corresponding to the sapphire base, is not shown.)*

The SEM photograph and Auger elemental scans were obtained with an Auger microprobe, model HB50A, courtesy Vacuum Generators Scientific, Ltd. The weak-link device was furnished by Cornell Professor Robert A. Buhrman.

Figure 4(a)

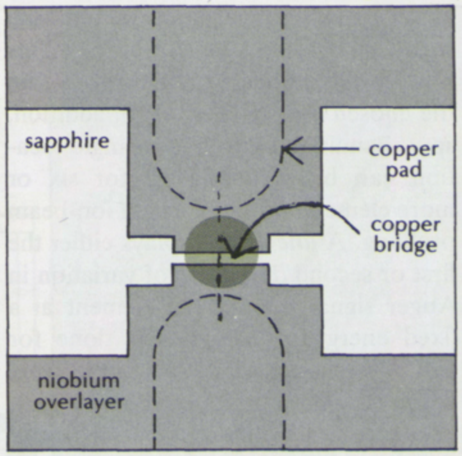


Figure 4(b)

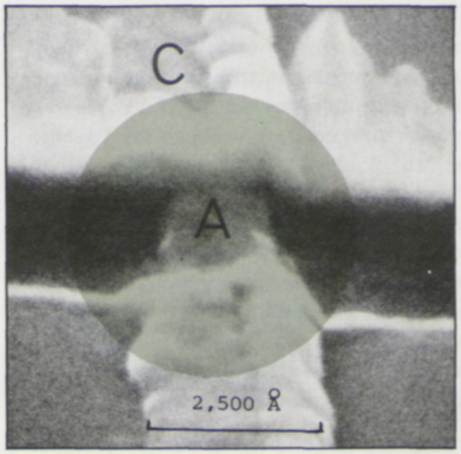
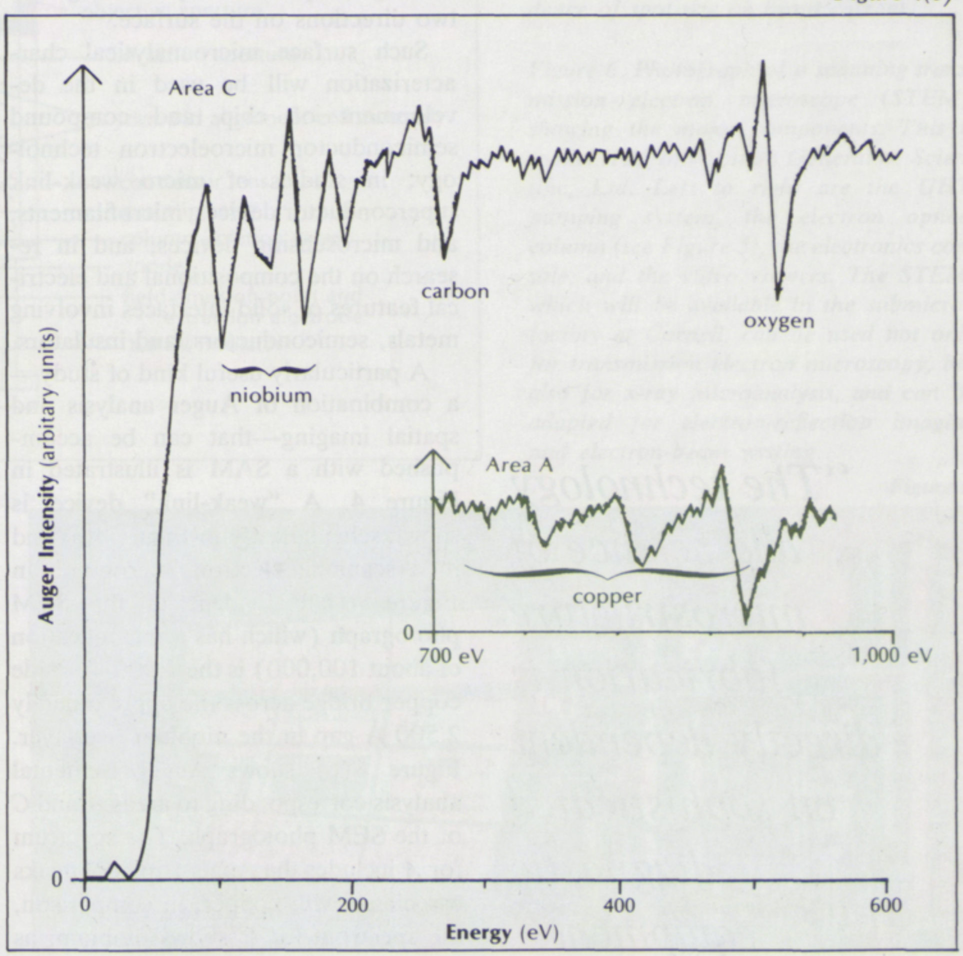


Figure 4(c)



"The technology and science of microstructure fabrication is directly dependent on sophisticated diagnostic equipment."

vides a dN/dE (variation of intensity with energy) spectrum for all elements that exhibit Auger excitations within the chosen energy interval. In addition, spot scanning in depth at a single location can be accomplished for six or more elements with the use of ion-beam profiling. A *line scan* displays either the first or second derivative of variation in Auger signal for a given element at a fixed energy; usually this is done for one element per scan. An *Auger map,* which is a contour plot of concentration of a single element over the surface of the target, is produced by scanning over two directions on the surface.

Such surface microanalytical characterization will be used in the development of chip and compound semiconductor microelectron technology; in studies of micro weak-link superconductor devices, microfilaments, and microsensing devices; and in research on the compositional and electrical features of solid interfaces involving metals, semiconductors, and insulators.

A particularly useful kind of study—a combination of Auger analysis and spatial imaging—that can be accomplished with a SAM is illustrated in Figure 4. A "weak-link" device is shown schematically in Figure 4(a) and in a scanning electron micrograph in Figure 4(b). Evident in the SEM photograph (which has a magnification of about 100,000) is the 1,000–Å–wide copper bridge across the approximately 2,500 Å gap in the niobium overlayer. Figure 4(c) shows Auger elemental analysis corresponding to areas *A* and *C* of the SEM photograph. The spectrum for *A* includes the Auger triplet of peaks associated with copper; in comparison, the spectrum for *C* shows niobium, as expected, and also contamination from carbon and oxygen. This example clearly shows how chemical composition can be effectively defined for a specific surface area with a resolution better than 2,000 Å.

DIRECT SPATIAL IMAGING BY SEM MICROPHOTOGRAPHY

Direct spatial imaging of surfaces in the electron reflection mode can be accomplished at a much higher level of performance with a scanning electron microscope (SEM) designed specifically for that purpose. With its superior electron optics, such an instrument has excellent capabilities for characterization and fabrication studies.

The advantages of SEM are first, that it is very convenient for the routine observation of surface topography down to a spatial resolution of 70 Å under normal operation; and second, that it can be used for electron-beam exposure work at spatial dimensions down to 1,000 Å if beam blanking and external access to the scanning system are provided. In addition, electron-beam lithography can be carried out on this instrument for the preparation of submicron structures that do not require the high precision of a special electron-beam-writing machine. Accessories can be added to facilitate supplementary microanalytical measurements, including x-ray microprobe analysis and cathode luminescence observations.

The high-performance SEM planned for the Cornell submicron facility is intended primarily for the examination of surface topography of fabricated structures, but it will be a very useful all-around instrument for microanalytical and possibly fabrication operations.

Figure 5

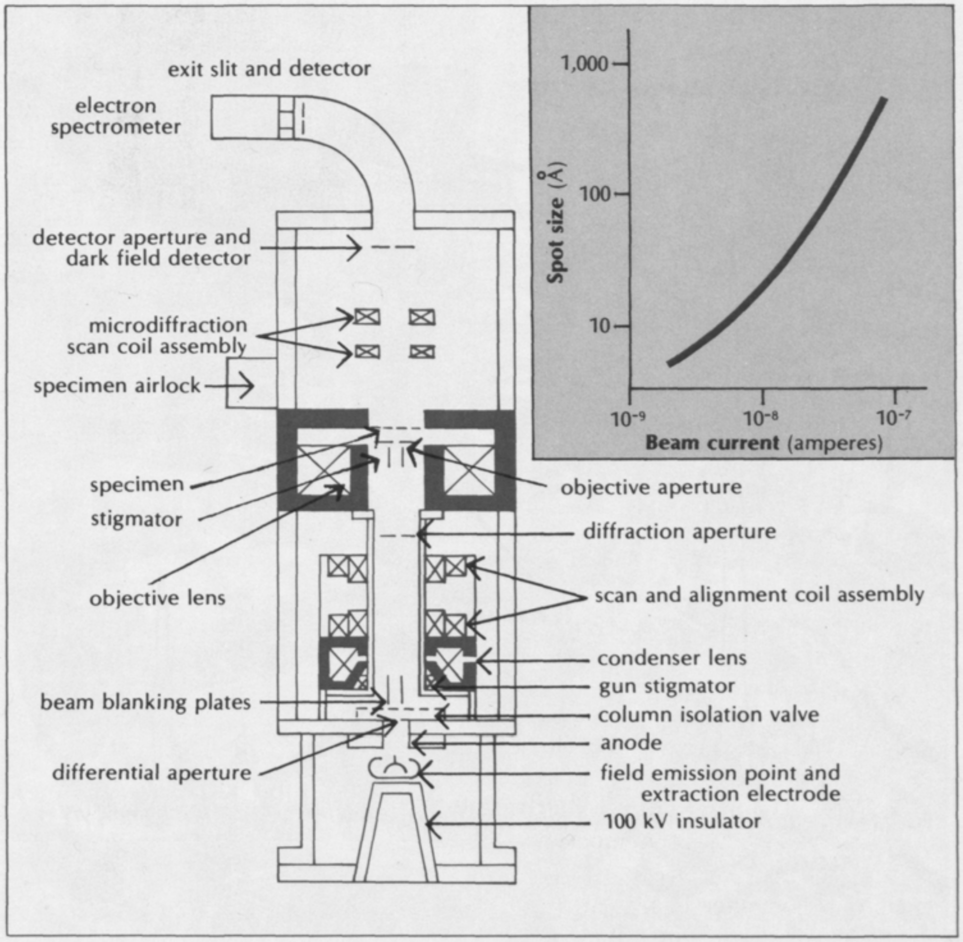
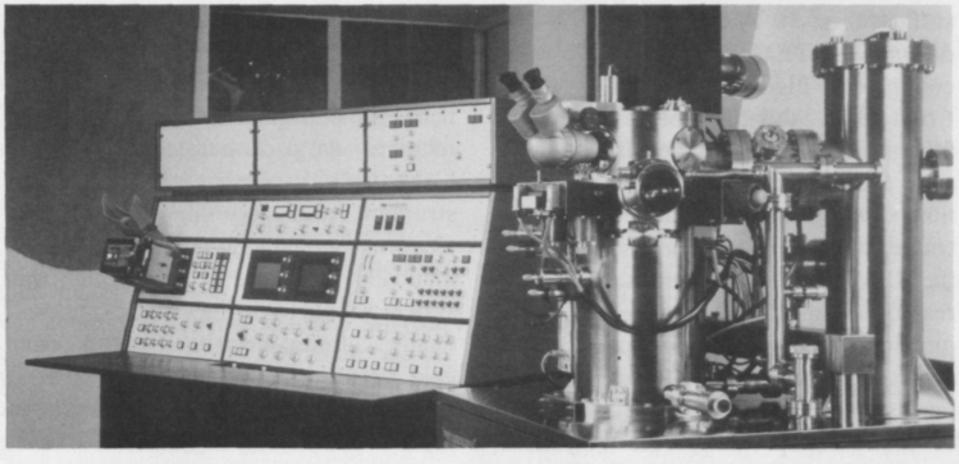


Figure 5. The electron optical column of a scanning transmission electron microscope (STEM). The schematic refers to model HB5 of Vacuum Generators Scientific, Ltd. The system, which utilizes the high-intensity, small-diameter probe provided by the field emission gun, produces transmission imaging at a resolution of 2 Å, and x-ray microanalysis of regions as small as 50 Å in diameter. Its high performance depends to a large degree on the high current density of the electron beam, combined with the spatial and electronic stability of the field emission gun.

The inset shows the logarithmic dependence of spot size on beam current.

Figure 6. Photograph of a scanning transmission electron microscope (STEM), showing the major components. This is model HB5 of Vacuum Generators Scientific, Ltd. Left to right are the UHV pumping system, the electron optical column (see Figure 5), the electronics console, and the video viewers. The STEM, which will be available in the submicron facility at Cornell, can be used not only for transmission electron microscopy, but also for x-ray microanalysis, and can be adapted for electron-reflection imaging and electron-beam writing.

Figure 6



THE STEM: AN ELECTRON TRANSMISSION INSTRUMENT

The SAM and the SEM depend for their usefulness primarily on the energy and intensity characteristics of a beam of electrons *reflected* from the target. A third very powerful microanalytical instrument that will be part of the Cornell facility—the scanning transmission electron microscope (STEM)—depends primarily on the energy and intensity properties of an electron beam *transmitted* through the sample.

Figure 7

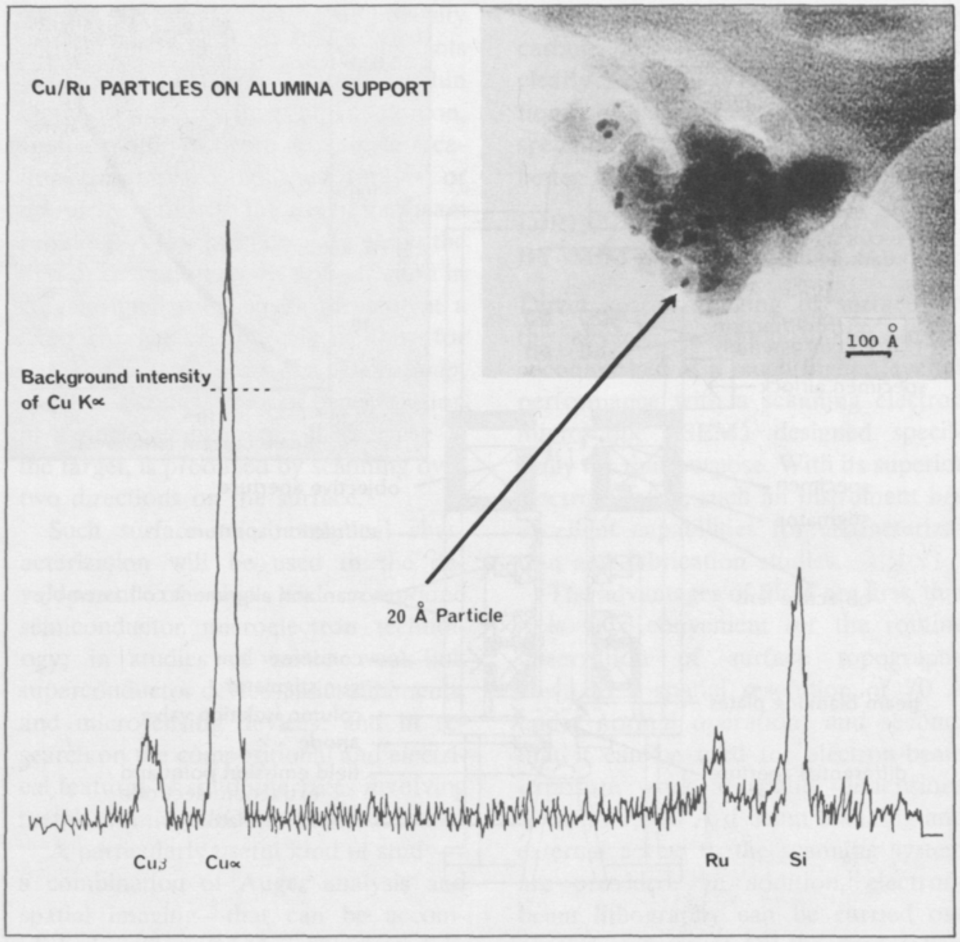
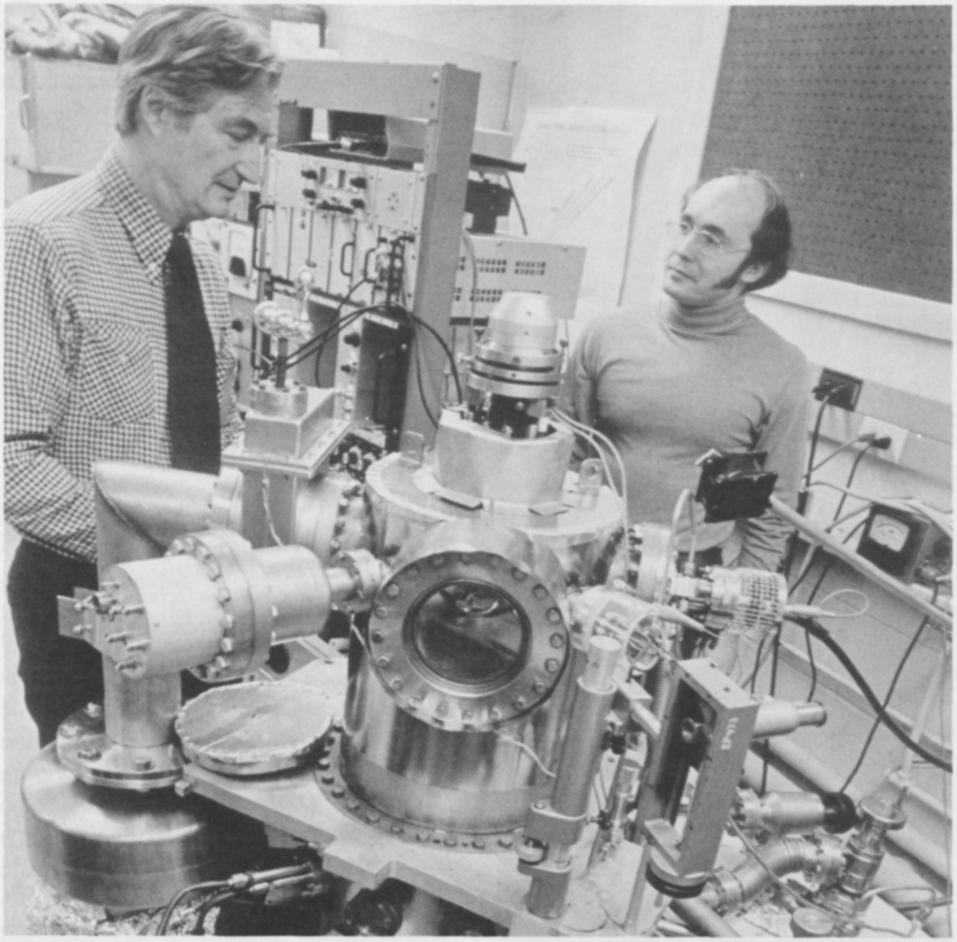


Figure 7. An example of sensitive chemical analysis of a submicron surface area using STEM spatial imaging in combination with x-ray microanalysis. The x-ray fluorescence spectra shown were obtained from a copper–ruthenium particle, about 20 Å in diameter, on an amorphous alumina support. The spectra show the presence of copper and ruthenium, along with silicon contamination. The spatial location of the particle in the micrograph (inset) is indicated by the arrow. (Courtesy of Vacuum Generators Scientific, Ltd.)

The STEM is an instrument of great versatility that combines excellent transmission electron microscopy with sensitive x-ray microanalysis of chemical composition. The instrument, which is essentially an ultra-fine electron probe, is capable of providing micrographs with a lattice-fringe resolution better than 2 Å, and x-ray microanalysis with sensitivity corresponding to a target mass as small as 10^{-19} grams or a surface area 50 Å in diameter. In addition, the STEM can provide a highly collimated, high-current-density electron beam suitable for exploratory lithography studies at the highest possible spatial resolution. With the addition of an appropriate reflection cartridge, the STEM can be used also in the SEM mode to obtain imaging with resolution in the 30-Å range in conjunction with x-ray microanalysis of high spatial resolution. Despite its versatility and complexity, the system can be made to operate in the very low pressure range of 10^{-8} to 10^{-9} torr. While the STEM is a rather sophisticated electron microscopic instrument, it has the additional advantage of being relatively easy to operate.

The basic component of the instrument is a very high-performance electron optical column, shown schematically in Figure 5. Essentially, this system is able to distinguish among elastically scattered electrons (annular dark field detection), inelastically scattered electrons, and those electrons that have experienced zero energy loss.

A major advance in analytical microscopy has been achieved in this instrument by interfacing the transmission electron microscope with the x-ray detection system. It is a good example of the effective combination of high-performance spatial imaging with sensitive microchemical analysis. An illustration of how this technique can be applied is given in Figure 7, which shows the x-ray fluorescence spectra from a single 20-Å copper–ruthenium particle on an amorphous alumina support, together with a micrograph that locates



Professor Rhodin (at left) is using electron spectroscopy under ultrahigh vacuum conditions for detailed study of the photon-excited emission of electrons at metal–semiconductor and oxide– semiconductor interfaces. The photoelectron spectrometer pictured here is being used by Wesley Capehart, a graduate student, to measure the influence of surface molecules on the angle-resolved photoemission of electrons from a nickel single-crystal surface.

the particle on the surface under examination. The x-ray spectra show the presence of copper and ruthenium, along with silicon contamination.

Although the x-ray signals are sensitive to the chemical composition of very small regions on a surface, there is another phenomenon very promising as an analytical tool in the electron microscope: transmission inelastic electron scattering, or electron energy loss spectroscopy (ELS). The nature and uses of this phenomenon have been under study at Cornell for several years under the direction of John Silcox.* The utilization of inelastic electron scattering depends on the fact that when fast electrons pass through matter, the amount and distribution of the energy they lose is dependent on the characteristics of the material through which they pass; information on elemental composition for targets as small as 10^{-21} grams may be obtained, in principle, from the energy spectrum of these transmitted electrons. The fine structure in the spectrum also can yield useful information about local atomic and valence-electron structure. This aspect of analytical electron microscopy is still in an early stage of development, however, and there are some instrumental and physical problems that may limit the sensitivity and applicability of the technique.* Nevertheless, ELS has the potential of becoming a very powerful microanalytical chemical technique at the 10-Å level. We expect it to play an increasingly important role as it

**See J. Silcox, "Inelastic Electron Scattering as an Analytical Tool," in* Scanning Electron Microscopy, Proceedings of the Workshop on Analytical Electron Microscopy, *vol. 1 (1977), p. 393. Also, see J. Silcox, "The Chemical Nature of Atoms," in* Engineering: Cornell Quarterly *12(3) (1972):2–9.*

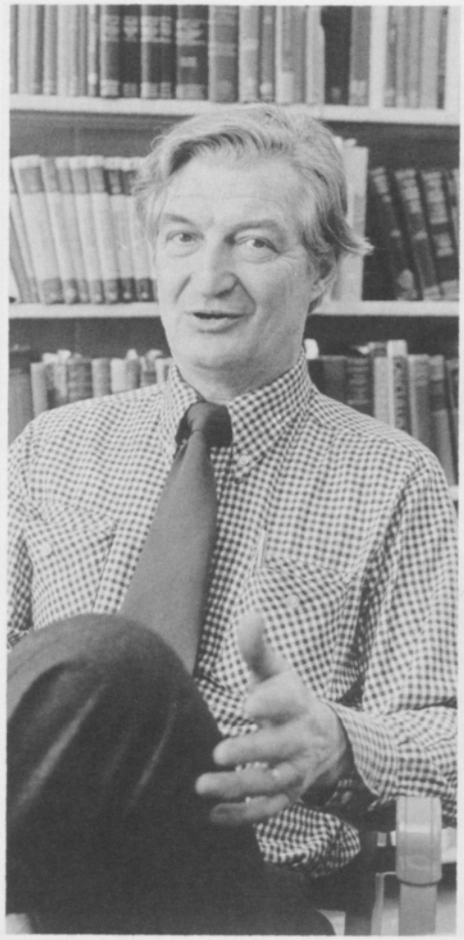
**See M. Isaacson, "Some Thoughts on Electron Energy Loss Spectroscopy (ELS) within the Electron Microscope: Where Does It Stand and Where Is It Going?" in* Proceedings of 8th International Conference on X-ray Optics and Microanalysis and 12th Annual Conference of the Microbeam Analysis Society *(1977), p. 18a.*

becomes necessary to monitor the performance of microelectronic devices over smaller dimensions—at the 1,000-Å level and below.

THE HEART OF THE SUBMICRON FACILITY

The technology and science of microstructure fabrication is directly dependent on sophisticated diagnostic equipment. In fact, instruments employing microbeams of electrons and x-rays have been developed recently for the very purpose of implementing research on submicron structures.

The three powerful electron-beam instruments I have described — the SAM, the SEM, and the STEM— together will constitute an important microcharacterization resource for the national submicron facility at Cornell. They will be applied to technological problems in the fabrication of practical devices, as well as to research in the associated basic physics, chemistry, and metallurgy. Overall, they will provide information on microstructure and composition that is not accessible to the same degree by any other means.



Thor Rhodin, professor of applied and engineering physics, is actively contributing to the development of the new submicron facility at Cornell with special attention to the microcharacterization of solid surfaces and to the physics and chemistry of compound semiconductor interfaces. His current research centers on the nature of electron excitations and transport at solid surfaces and the relation of these phenomena to chemical bonding and reaction on metals.

Rhodin joined the Cornell faculty in 1958 after five years as a member of the research faculty of the Institute for Study of Metals at the University of Chicago, and seven years on the scientific staff of the Engineering Research Laboratory of E. I. duPont de Nemours and Company. He has also been a Senior National Science Foundation research fellow at Cambridge University and a visiting professor at the Massachusetts Institute of Technology. In 1975 he was awarded a NATO Senior Fellowship in Science for study and lecturing at the Physical Chemistry Institute of the University of Munich, Germany, and at Chalmers Technical University in Gothenberg, Sweden. He was also a visiting professor in the Japanese Society for Promotion of Science program in 1976.

He holds the B.S. degree in physical chemistry from Haverford College (1942), and the A.M. (1944) and PhD (1946) in chemical physics from Princeton University. He is a member of the American Physical Society, the American Vacuum Society, and the American Association of University Professors. At Cornell he serves as chairman of the Graduate Professional Program Committee of the College of Engineering and is a member of the Fellowship Review Board of the Graduate School.

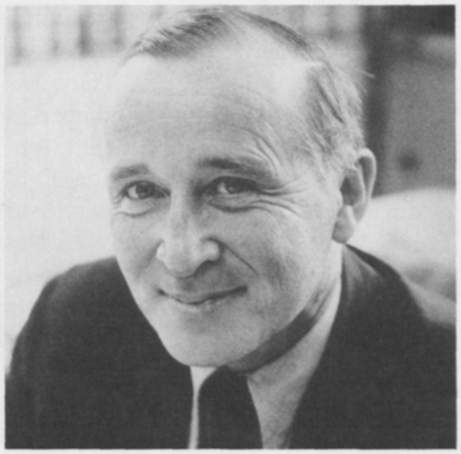
REGISTER

Cranch Accepts WPI Presidency After More Than Five Years as Engineering Dean Here

Edmund T. Cranch, sixth dean of the College of Engineering here and a Cornellian since his undergraduate years, will become the twelfth president of Worcester Polytechnic Institute this summer.

Cranch's thirty-four year association with Cornell began in 1943 when he entered the Navy V-12 program after completing two years at the Newark College of Engineering. He was graduated with a baccalaureate degree in mechanical engineering in 1945, received the Ph.D. in mechanics, mathematics, and physics in 1951, and then joined the faculty as an assistant professor of mechanics and materials. By 1956 he was a full professor and head of that department. In 1962 he became a professor in the Department of Theoretical and Applied Mechanics and served as chairman of that group from 1966 to 1968. Since 1967 he has served in the College administration, first as associate dean for graduate study and research and then, since 1972, as dean.

In the Cornell engineering deanship, Cranch succeeded Andrew Schultz, Jr., who returned to teaching as professor of



operations research and industrial engineering after nine years (1963–72) as dean. Others who preceded him as dean of the College were Dexter S. Kimball (1921–36), Herman Diederichs (1936–37), S. C. Hollister (1937–59), and Dale R. Corson (1959–63).

At WPI, in Worcester, Massachusetts, Cranch will head a science and engineering institution that was established the same year as Cornell University, in 1865, and is about the size of the Cornell College of Engineering.

In addition to his engineering teaching and administrative service at Cornell, Cranch has participated in educational and policy-making activities at the University level. In 1970 he was elected to a five-year term as a faculty member of the Board of Trustees, and for four years served on the board's executive committee. In the early 1970's he was chairman of the President's Special Committee on Long-Range Financial Planning. He has worked also in the area of minority affairs: he served on a 1968 presidential commission on racial disturbances and in the period 1974–76 he was chairman of the University's Committee on Special Educational Projects (COSEP). Other University groups with which he has worked have been concerned with the ROTC program and the residential environment at Cornell. Last year he was appointed Cornell representative to the Ivy Policy Committee, an advisory group to the Council of Ivy Group Presidents.

Cranch has contributed to the development of academic and research programs in a number of areas. He has been a member of the faculties in engineering physics and mechanical engineering, as well as materials and mechanics. As dean, he has helped organize and advance programs in many areas of research and instruction. He has served on the executive committees of the Materials Science Center, the Center for Applied Mathematics, the Center for Water Resources and Marine Sciences, and the Center for Environmental Research. He was a member of the Geological Sciences Evaluation Committee prior to the reorganization of that department in the early 1970's. He was the principal instigator of a project proposal on "Environmental Quality and Societal Needs" that resulted in a quarter-million-dollar grant to Cornell from the NSF, and he has served as director of the Program on Policies for Science and Technology in Developing Nations, a program that received funding of three-quarters of a million dollars from AID.

Cranch's activities during his years at Cornell have included scientific research as well as educational development and administration. His research interests include the dynamics of shells and wave propagation in solids, and he has published a number of papers on these subjects. He spent sabbatic leaves conducting research at Stanford University as an NSF faculty fellow, and at the Swiss Federal Institute of Technology in Zurich as a senior postdoctoral fellow. He is an author of a text on engineering mathematics and has served as a reviewer for two professional journals in the field of applied mechanics.

He has also maintained affiliations with industrial organizations throughout his career. He spent a year at the Bell Telephone Laboratories after completing his Navy service, and since his appointment to the Cornell faculty has served as a consultant to a number of industrial firms, including Lincoln Laboratory, the Cornell Aeronautical Laboratory, General Electric, Bausch & Lomb, IBM, Ohaus Scale, and the Electromechanical Corporation. He is a member of the boards of directors of a number of industrial, educational, and business organizations.

Cranch has participated also in national professional activities. He has served on the National Academy of Engineering Panel on the Role of U.S. Engineering Schools in Development Assistance, as a member of the Task Force on Organization Study of the American Society for Engineering Education, and of the New York State Rural Development Advisory Council. He is a fellow of the American Society of Mechanical Engineers and a member of several other professional societies, as well as the honoraries Tau Beta Pi and Sigma Xi.

He is married to the former Virginia Harrison and has three grown children.

An alumnus of Worcester Polytechnic Institute who has been a close Cornell associate of Edmund T. Cranch throughout his years as engineering dean reflects on Cranch's appointment to the WPI presidency. Donald F. Berth, *now director of engineering development for the College of Engineering at Cornell, has been at the College since 1962. He holds the B.Ch.E. and M.Ch.E. degrees from WPI.*

■ Thirty-four years at Cornell. For an undergraduate from New Jersey, the move to the University here was hardly what he had anticipated. It was the Navy that sent Ed Cranch to Cornell for the wartime V-12 program, and for the beginning of what turned out to be a remarkable and possibly unique career at the College of Engineering. It is a thorough Cornellian that Worcester Polytechnic Institute has chosen for its new president.

For those of us at the College and the University, this is a time for reflection on what Ed Cranch has done for us. I would like to participate in this reflection, for my association with him has extended throughout his years first as associate dean and later as dean. Any individual's assessment is bound to be incomplete, for no one man sees the total person or is aware of the full chronicle of events in the course of a career. Thus, what follows are impressions formed over the years of my association with him.

When Ed Cranch became dean of engineering, he brought to a tough job the qualities of an unassuming manner, openness, attentiveness, and kindness. It is truly remarkable that after almost six years as dean, those qualities remain

1

Looking back with Edmund T. Cranch. 1. Here he is as a high school baseball player. 2. As Cornell mechanical engineering undergraduates, Ed and his roommate Robert L. Dwight (now at Westinghouse in Baltimore) built this "Dwightmobile." 3. Ed completed college in the Navy V-12 program. 4. His graduate and early faculty research involved work on stresses in pressure vessels. (Before this testing, Ed had climbed inside to attach strain gauges while safety patrol officers stood by.) 5 and 6. Later he served as chairman of the Department of Theoretical and Applied Mechanics, as associate dean, and then as dean.

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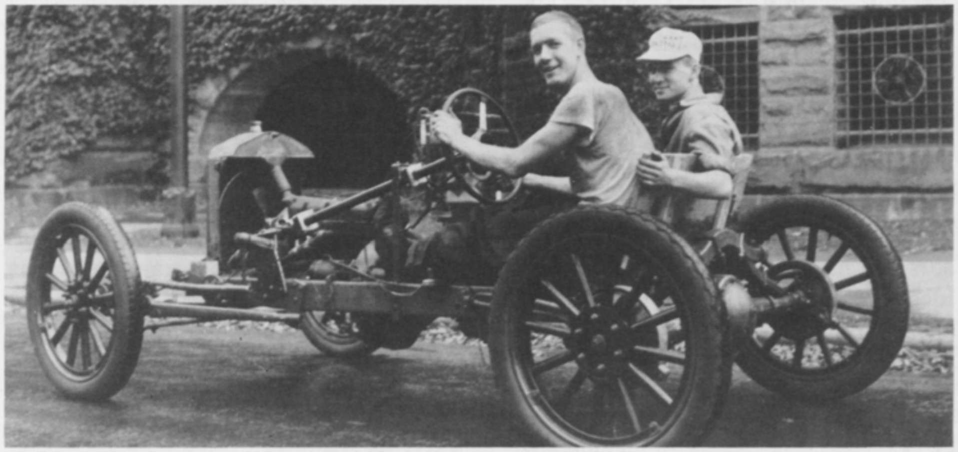

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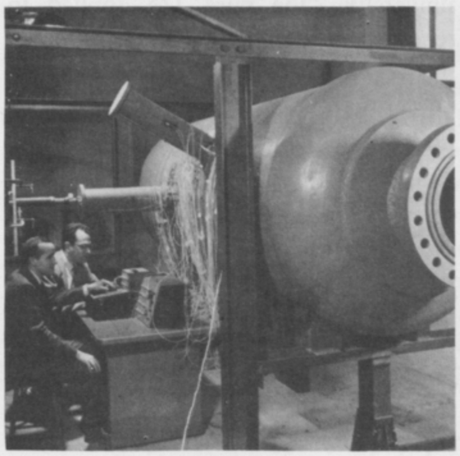


intact. He makes people feel significant; colleagues, University administrators, alumni, secretaries—all seem to appreciate his personal qualities as well as his professional ones. It is rare to encounter a man cast in a leadership role who seems so at peace with himself and, by extension, with others.

Of course, openness and accessibility can be a liability. Ed's willingness to share his time with others has never been measured in the manner of an efficiency expert. He is not a man to be rushed by anyone: I have sometimes "needled" him by claiming he tells time with a calendar rather than with a clock. As dean he showed an uncanny skill in privately ranking priorities and giving his reflective and measured attention to the most important things first, sometimes to the dismay of those who presented low-priority questions or problems. He has an underlying courage and toughness. His decision-making has been thorough, rational, resolute. Still, he respects the opinions of others; as dean he rarely formulated key decisions without seeking advice.

When Ed became dean in December, 1972, the College was in good shape. Its research program was flourishing, the students' educational options were broad, and the quality of the undergraduates was high. What the College needed were: more senior faculty members of national stature; selective improvement of the graduate program, particularly in areas of great national significance; better financing of the Master of Engineering degree program; and a greater synergism between departments that could lead to new directions in both research and instruction. (This latter idea, incidentally, is a favorite one at Cornell: the diversity of resources offers great possibilities for innovation, though too often the surface is hardly scratched.) The challenge was that all of this had to be undertaken in a new era of fiscal constraint. Ed had to say *no* more often than his predecessors had had to, and not infrequently to ideas of merit. His criterion seemed always to be the long-range educational benefit—how to best prepare Cornell engineering students at all levels to assume professional leadership. One of his favorite comments was that in any university, "the pure (as applied to teaching, research, service) drives out the applied," and he worked hard to keep his College a center for *engineering* and *applied* science.

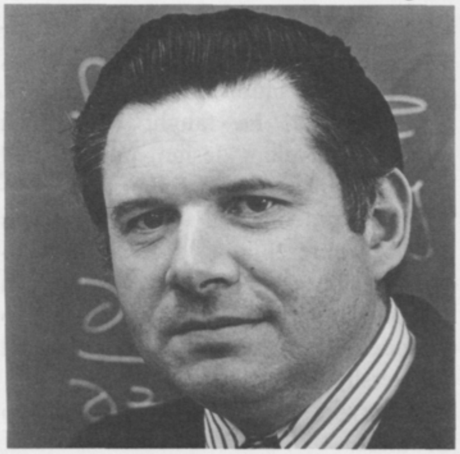
One of Ed's chief contributions to the College was to bring fresh leadership to several of the departments and schools. With his help and support, both recognized and good younger people (often from within the University) were selected for departmental leadership. With the infusion of funds and new faculty appointments, Ed helped put a modern geological sciences department on its feet, and he helped add new vigor to the faculty and programs, especially in chemical, electrical, and environmental engineering, and materials science and engineering. In addition to these efforts for specific departments and schools, there was a project of special importance to him: a strengthening of the overall Master of Engineering program. Like his predecessor, Ed believed that the *professional* thrust of this program not only benefitted the students, but also served the long-range interests of the College. Cornell engineering has had a long-standing reputation for the excellence of its professional preparation of graduates, but this is an aspect of the educational program that requires sustenance from "on top," especially with a faculty largely characterized by vigorous research interests and efforts. Not the least of Ed's contributions to the M.Eng. program was in the area of finance; he worked hard to obtain funding for this, as well as for other programs and facilities, and he was very effective.

Many people at Cornell probably know Ed Cranch mainly as the author of the "Report of the Advisory Committee on Financial Planning" (known as the Cranch Report), which was written just before he became dean. Or they will remember him as chairman of the University's Committee on Special Educational Projects, which had to cope with problems connected with Cornell's program for the education of minority students. In both these areas, the issues were complex, difficult, and controversial, and seemed to be "no win" situations for these committees and especially for their chairman. Ed Cranch accepted these assignments, and others as well, out of a well-rooted loyalty and affection for Cornell. Those who knew him were not surprised by his calmness in the storms, coupled with a strong adherence to his convictions.

By nature a private rather than a public man, Ed Cranch enjoys working in a one-on-one mode. Those who come in direct contact with him are generally impressed not only by his manner, but by his memory for people, facts, events —everything. It is perhaps evidence of his attentiveness and care. And, of course, some people at Cornell have come to know Ed Cranch more personally. They know, for example, about his regard for hockey that began in his student days and still keeps him on the ice as a skater as well as in the stands as a fan. Perhaps encouraged by his wife, Virginia (a Russell Sage graduate and former nurse), he maintains a surprisingly vigorous conditioning program; even during this winter's heavy snows, the Cranches were out there regularly shoveling their driveway. Acquaintances also know about Ed's regard for things old: he is an avid collector of antique furniture and Oriental rugs; and until the equilibrium between rust and metal shifted toward almost pure rust recently, he could be seen riding around in a late-1950's car.

Cornell is fortunate to have "landed" that young seaman so many years ago. His substance, style, and service will leave a lasting imprint here. Now WPI has chosen wisely. I am confident that Ed and Virginia Cranch will make an enduring contribution to my alma mater.—DFB

Gallagher



Gallagher Named Dean at Arizona

Richard H. Gallagher, professor and chairman of the Department of Structural Engineering, has accepted the deanship of the College of Engineering at the University of Arizona, effective in July. At Arizona he will head a college with five departments and about sixteen hundred undergraduate and more than three hundred graduate students.

He brings to his new position a background of experience not only in university teaching, research, and administration, but also in professional engineering. Before joining the Cornell faculty in 1967, he worked for seventeen years as a structural engineer, twelve of them with the Bell Aerosystems Company. He was employed also by the Civil Aeronautics Administration and Texaco, Inc., and has been a consultant to Bell, IBM, Ford, and Union Carbide. He is a licensed engineer in New York State.

Gallagher has written many papers and books on finite element analysis, his specialty field. *Finite Element Analysis Fundamentals,* a text published by Prentice Hall in 1975, has been translated into Japanese, German, and French. *Matrix Structural Analysis,* with Gallagher and his Cornell colleague William McGuire as coauthors, will be published in the near future by John Wiley. In addition, Gallagher has served as coeditor of the *International Journal for Numerical Methods in Engineering.*

In 1973-74 he spent a leave as a Fulbright fellow in Australia and as a visiting professor at the University of Tokyo and the University of Wales. His professional activities at the international level also include organizing and chairing symposia on the use of computers in structural design and analysis.

He holds baccalaureate and master's degrees in civil engineering from New York University, and the Ph.D. in structural engineering from the State University of New York at Buffalo. He is a member of a number of professional societies in civil, structural, and aeronautical engineering.

York

Robert York

■ The School of Chemical Engineering lost one of its long-time faculty members with the death of Robert York, professor, on January 7. He had been a member of the faculty here since 1956.

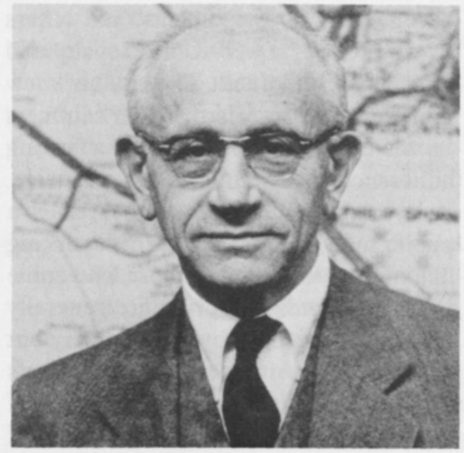
York came to Cornell from the Monsanto Chemical Company, where he was assistant director of the General Development Department. Prior to his twelve-year employment at Monsanto, he had spent nine years on the faculty of the Carnegie Institute of Technology.

He received the B.S. and M.S. degrees in mechanical engineering from the University of Tennessee in 1933 and 1934, respectively, and the Sc.D. in chemical engineering from the Massachusetts Institute of Technology in 1938. He was registered as a professional engineer in Pennsylvania and Missouri, and during his academic career served as an engineering consultant to several chemical manufacturing firms. He was a member of the American Institute of Chemical Engineers, the American Chemical Society, and the Association of Cost Engineers.

At Cornell he taught courses in process and plant design, process and development economics, thermodynamics, and patents. In addition, he was faculty representative for the professional master's degree program in chemical engineering. His activities also included membership in the Cornell University Senate.

Survivors include a sister and two brothers.

Sporn



Philip Sporn

■ Philip Sporn, former president of the American Power Company and a member of Cornell's Engineering College Council since 1958, died on January 23 on the way to his office in New York. He was eighty-one.

Sporn was born in Austria and emigrated to this country at the age of eleven. He was graduated from the Columbia University School of Engineering with a B.S. degree in electrical engineering in 1917, and joined the American Gas and Electric Company system in 1920. Ultimately he became president of the parent company and its subsidiaries, and after his retirement in 1961, served on the board of directors. During his retirement years, he was also an adviser to the Government of Israel, serving as chairman of the Israel Sea Water Conversion Commission.

Sporn was known as one of the foremost contributors to electrical engineering technology in the United States. A comment by John F. McManus, associate dean at the Cornell College of Engineering, attributed to Sporn a "large and inspirational vision of the role of engineering and technology, and of education, in meeting the needs of society and in advancing its well-being."

Among the honors he received are the 1954 Charles A. Coffin Medal and the 1956 John Fritz Medal. He was a member of the National Academy of Sciences and the National Academy of Engineering, and a fellow of the Institute of Electrical & Electronics Engineers, the American Society of Mechanical Engineers, and the American Society of Civil Engineers. He received honorary doctorates from ten institutions.

Among his special activities at Cornell were the sponsorship of a prize for excellence in freshman teaching, and three lectures on electrical power research that he gave in the Cornell University Lecture Series of 1965.

He is survived by his wife, several children, and grandchildren.

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The New Submicron Facility

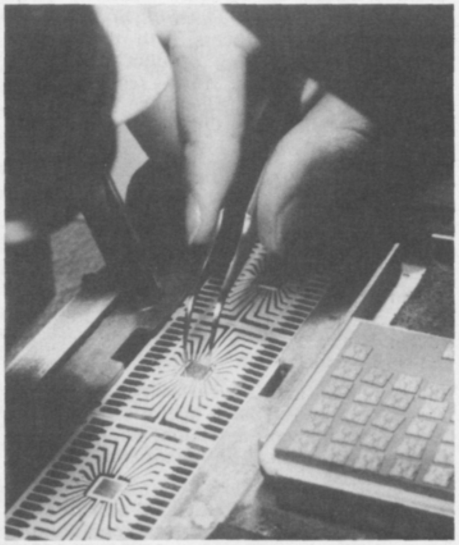
In this issue we explore the microscopic world of electronic devices with submicron dimensions, an area now under intensive technological development both in this country and abroad. Such structures represent a new generation of electronic devices and will have a major impact on the computer and communications industries, and probably on others as well. Their development and production require new instruments and techniques, however, and a deeper understanding of the surface phenomena of materials; and we are pleased that Cornell will have a special role in the national effort to acquire the necessary technical capability and knowledge.

The new National Research and Resource Facility for Submicron Structures, located at Cornell, was established by the National Science Foundation in recognition of the importance of having significant research on submicron structures undertaken at academic institutions as well as in industry. This is a high-technology area that requires a large capital investment in highly sophisticated equipment and in controlled-atmosphere laboratory space, and very few universities could afford the necessary facilities.

The selection of Cornell as the host institution was based primarily on the excellence of existing research programs here and the merit of the proposal drawn up by our faculty committee. Cornell already had outstanding programs in microwave and optical semiconductor devices, for example, and in materials science (as exemplified by the Materials Science Center). The scope and extent of Cornell's present and proposed projects in the area of submicron structures is suggested by the research interests of professors who will be using the facility (see page 4), as well as by the articles in this issue. The research objectives of the Cornell members and of the facility as a whole encompass the three areas of fabrication techniques, the properties of devices with submicron structures, and the physics of related materials problems.

The location of the facility here gives Cornell and its College of Engineering the opportunity to become the national academic leader in the field of submicron structures. Students and faculty members will benefit not only from access to facilities normally beyond the means of a university, but also from the unusually good opportunity to interact with research groups from university, government, and industrial laboratories across the country. Congruently, the success of the venture will be judged not only by the quality of the research accomplished, but also by the effectiveness of the facility as a resource center and as a training ground for scientific and technical leaders in a growing industry.

Achieving a successful combination of research, resource, and educational capability in an important, rapidly developing technology is both a challenge and a unique opportunity for the faculty, staff, and students associated with the new facility at Cornell.—The Editor



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