A U.S. Lab Opens Doors To the Nanoworld

The National Nanofabrication Facility is pushing tiny tech to new diminutives—and fretting about its funding future

PRINCETON UNIVERSITY PHYSICIST ROBERT H. Austin had hit a snag in his research on the physics of separating long, chainlike molecules such as DNA as they meander through polymer gels—a process important to biomedical research such as the Human Genome Project. Austin imagined that minute ceramic labyrinths might help him model the molecular obstacle course at the heart of the gel separation process. But his colleagues said such tiny test beds would be impossible to find or make. Undaunted, Austin turned to the National Nanofabrication Facility (NNF), a unique outfit based at Cornell University that specializes in the realm of the ultra-small. After a week at the NNF, he had proved his nay-saying colleagues wrong. With the help of engineers and technicians there, he was on his way home with a handful of meticulously engineered silicon dioxide slabs riddled with micron-sized obstacles and passageways.

Austin's experience is typical. "If you know how to do it, the National Nanofabrication Facility is probably the wrong place to go," remarks Harold Craighead, NNF's director. With $40 million worth of state-of-the-art micro- and nanofabrication equipment, a 14-person staff of trouble-shooting engineers and scientists, a "u-do-it" policy even for nanotech neophytes, and a hunger for outlandish proposals, the NNF has become known as a place to create miniaturized hardware teetering on the edge of impossibility.

In contrast to Japan (see article on page 1304), little in the U.S. nanotechnology effort is centralized. The NNF is an exception: a fully equipped nanotechnology workshop catering to visiting researchers from around the country. Though Cornell is now facing the possibility that the funds for the workshop may go elsewhere after 1992, the NNF wouldn't close its doors but perhaps just change its venue.

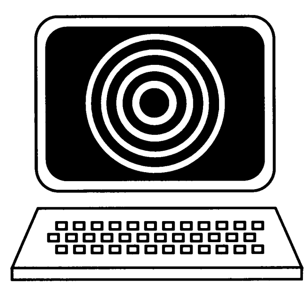
Other labs in university and industrial settings have much of the same equipment. They also present the same scene of moonsuit-clad technicians toiling in white, instrument-laden, clean rooms, fashioning sensors, electronic chips, optoelectronic components, and other miniaturized wonders whose structural complexity emerges only under electron microscopes. But culturally the NNF could be on another planet, says Austin. He had tried out his ideas at other places including the well-equipped AT&T Bell Laboratories an hour or so north of his homebase in New Jersey. "But that was hopeless," Austin says, explaining that most well-equipped facilities with million-dollar machines and secrets to keep have their own projects to run and don't want many outsiders coming in. "When I got to the NNF, they gave me a key to the building."

The same open-door policy that attracts academic researchers like Austin turns off some potential industrial users eyeing proprietary payoff, Craighead admits. But he stands by the NNF's open-air, open-brain philosophy, which he says fosters creativity. "Don't tell us what you don't want to get around," he warns would-be users.

The NNF's work has certainly gotten around. Since the lab first opened its doors in 1978, it has helped thousands of visitors undertake more than 425 projects, which have yielded more than 1500 publications and 400 Ph.D.s. At the moment engineers, students, and scientists from Cornell, other universities, national laboratories, and industry keep the NNF buzzing with more

Step by Step to a Nanodevice

The tiny circuits, lasers, mirrors, and mechanical devices that take shape at laboratories like the National Nanofabrication Facility are built layer by layer, often using higher-resolution versions of the techniques now commonplace in the microelectronics industry. For each layer, engineers transfer a pattern to the surface—usually silicon, gallium arsenide, or some other semiconductor—through a stencil-like mask. Then they etch out the patterned region, deposit new material on it, or modify it with beams of ions. Several iterations of the process yield completed devices: tiny technoscapes sculpted in high relief and criss-crossed with metal connections and regions of varying conductivity. Here are the basic steps of nanofabrication, shown for a minuscule grating—its ridges 250 nanometers apart—designed to deflect a laser beam upward from the surface of a semiconductor laser.

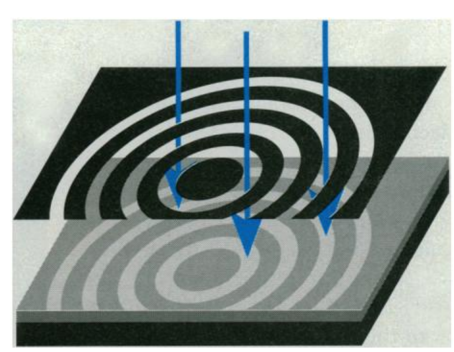


MAKING THE MASKS

It's a little like printmaking writ very small. The masks—each one a stencil defining the features of a device layer—take shape on computer-aided-design (CAD) terminals. A digitally encoded form of the pattern then goes to an electron-beam lithography machine. Using sharply focused electrons, the machine etches the pattern through the shiny metal coating of a glass or quartz mask blank, carving features as small as 200 angstroms or 20 nanometers.

TRANSFERRING THE PATTERN

As a first step in the transfer process, known as photolithography, engineers coat the device blank with a photoresist polymer. When it is exposed to ultraviolet or visible light shining through the mask, the photoresist degrades, making it possible to wash away the polymer from areas not shadowed by the mask. That bares the desired pattern of substrate, leaving it vulnerable to etching, deposition, or doping—the three main ways to convert a blank into a nanodevice.



SOURCES: TURAN ERDOGAN, OLIVER KING, AND DENNIS HALL, UNIVERSITY OF ROCHESTER; MICHAEL ROOKS AND LYNN RATHBUN, NNF. ILLUSTRATIONS: DIANA DEFRANCESCO than 120 active projects.

Among their little works are high-speed microwave devices for satellite communication with components as small as 50 nanometers (equivalent to 500 shoulder-to-shoulder hydrogen atoms); new types of quantum electronic devices including quantum wells, wires, and dots; tiny surface-emitting lasers made up of 1000 concentric ridges of aluminum gallium arsenide, spaced 250 nanometers apart; miniature optical circuits including lasers, waveguides, beamsplitters, detectors, and modulators; even microscopic velcro, meant as a possible alternative to stitches in microsurgical procedures (see *Science*, 22 March, p. 1425).

That range of projects reflects how miniaturization technology has radiated from its starting place in microelectronics, noted Craighead during a National Science Foundation (NSF) workshop held in Washington, D.C., in September to discuss the needs of the microfabrication community. "We've gone from microelectronics to micro-lots-of-things," concurred George Hazelrigg, a deputy director of the NSF division that has been funding NNF.

The notion of a national user facility like the NNF began circulating in the mid-1970s among electronics-oriented "researchers who wanted to get into small structures" but did not have access to the requisite equipment, recalls Edward Wolf, emeritus professor of electrical engineering at Cornell and a former director of the facility. The message reached the NSF, which supplied funds to get the National Research Facility for Submicron Structures, as it was then known, off the ground. In 1988, 10 years after it was established, the facility's name changed to the National Nanofabrication Facility to reflect the trend toward structures on ever smaller scales, Wolf says.

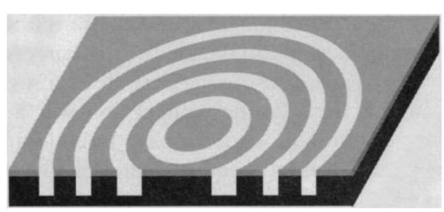
Since its doors opened, the facility has continuously acquired the frontline equipment required for stem-to-stern micro- and nanoengineering. One room is filled with computers for designing structures using CAD (computer-aided-design) software; next door is an environmentally controlled set of laboratories packed with microlithography apparatus, etching chambers, vapor deposition systems, ion milling machines, and—since this fall—a focused ion-beam tool that can fashion features smaller than 25 nanometers. All that wizardry is required to pattern silicon, gallium arsenide, superconducting ceramics, metals, and other materials into tiny shapes and devices. And to scrutinize their handiwork, users can resort to a battery of characterization tools such as electron microscopes, scanning tunneling microscopes, and other devices that probe the nanowares with electrons, light, and other radiation.

NSF has been kicking in $2 million per year in direct grants to help fund this high-tech workshop. The remainder of its $8-million budget comes from fees from users, Cornell University itself, and industrial affiliates. Next year, though, in response to a general decree by the National Science Board last February to keep funding mobile, Cornell's 14-year hold on the NSF funds finally goes up for "recompetition." That means some other research institution could replace Cornell as the NNF's host—a possibility that gives the jitters to some NNF staff and users. "The prospect of review is pretty scary," notes Noel MacDonald, a Cornell electrical engineer who has grown accustomed to having access to the facility for making things like scanning tunneling microscopes on a chip (*Science*, May 31, p. 1252).

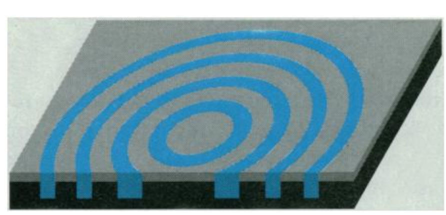
Cornell's jitters may be well founded, because it's facing tougher competition now than in 1978, when it beat 40 contenders for the role as host. Newer microengineering facilities such as the Quantum Electronic Science and Technology Center (QUEST) at the University of California, Santa Barbara, or the Berkeley Sensor and Actuator Center at the University of California, Berkeley, campus could end up giving Cornell a good race for the NSF funds, says Hazelrigg.

Craighead, for one, will fight tooth and nail to keep the facility at Cornell. "What else would I rather do than interact with people who are thinking about things as far out as possible?" he asks. But if Cornell loses its bid, the party won't be over—it will just have moved on. ■ IVAN AMATO

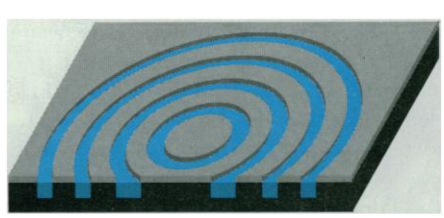
ETCHING
The pattern is chiseled deeper into the blank with techniques such as reactive ion etching or ion milling, which rely on beams of ions to carve the surface.



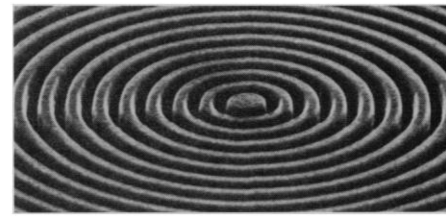
DEPOSITION
Layers of new material—electrodes or other tough ceramic coatings, for example—are built up on the naked substrate by techniques in which atoms are sputtered from a solid target or deposited from a vapor.



DOPING
The exposed areas of substrate are bombarded or bathed with ions to change their electrical characteristics—a critical step in the manufacture of electronic components such as transistors.



INSPECTION AND TESTING
After several cycles of photolithography and fabrication comes the moment of truth, when the engineers take a good look at their handiwork (in this case a laser reflector) with a scanning electron microscope. To probe a device's properties, its makers can pump electrons or photons into it and measure the optical, electronic or other responses with a battery of instruments including oscilloscopes and spectrophotometers. For the finest possible scrutiny of the structure, nanoengineers enlist scanning probe microscopes such as the scanning tunneling microscope and the atomic force microscope.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