Pass the Plasma, . . . Please

Some engineers and scientists are working out new collaborative strategies to speed technological progress

By ELIZABETH PENNISI

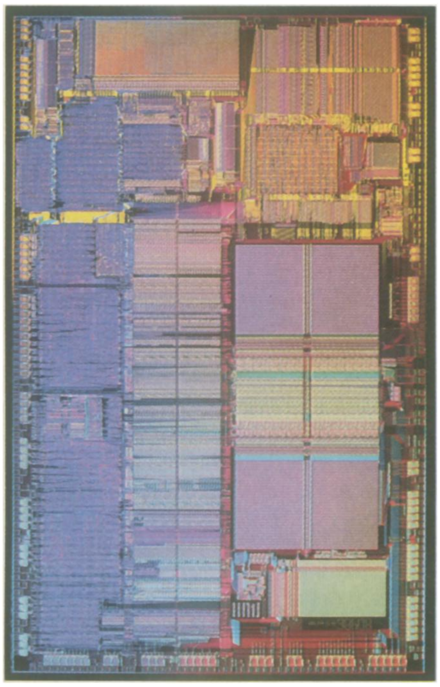
Fifteen years ago, no one could have predicted that physicist James Roberts and chemical engineer Harold Anderson — researchers separated by 2,000 miles and vastly different disciplines — would one day confer almost weekly on what experiments they should perform and then on their results. Or that fusion scientist Joseph L. Cecchi would work with engineers to improve the performance of factory equipment.

But today such interdisciplinary collaborations are occurring ever more frequently — not only between individuals, but also between companies, universities and government agencies as they try to keep pace with rapidly changing technologies.

This new way of conducting research demands that experts with very different perspectives come to the proverbial table and learn a new etiquette as well as the languages of colleagues from other fields. As with teenagers sitting down to dinner with their parents and younger siblings, communication can be strained — so much so that some would prefer to keep quiet. But just as families often find the effort worthwhile, many researchers have decided that such exchanges must occur if the United States is to regain its high-technology leadership, especially in microelectronics. "We had better get together and coordinate — from the fundamental research through the commercial idea," says Roberts, a physicist at the National Institute of Standards and Technology (NIST) in Gaithersburg, Md. "We have to all work together just like the Japanese are working together."

Semiconductors represent one area where such teamwork has become critical and where researchers, the U.S. government and industry have changed their work habits to spur technological growth. By focusing on specific problems and crossing disciplinary boundaries, these players can make progress faster than ever before.

Anderson, Roberts and Cecchi have applied their diverse backgrounds to plasma processing, an increasingly important step in the making of computer chips. And many researchers believe that collaboration could serve as a model for spurring progress in other technologies.


Intel Corp.

Modern computer chips pack in millions of transistors, up from several thousand components per chip 20 years ago. To pack components in so tightly, manufacturers need ever better production technologies.

Hot, gaseous collections of approximately equal numbers of positive ions and negative electrons, plasmas form when gases are heated to more than a few thousand degrees Celsius or subjected to an intense burst of energy. Though scientists have studied plasmas for almost a century, so many chemical reactions occur within them that these ionized gases still defy understanding.

The increasingly intricate circuitry in computer chips has driven designers of the better chips to harness plasmas. These reactive gases etch away silicon or other materials during semiconductor manufacturing. Initially, chip designers and manufacturers tailored chips without really knowing what goes on during the etching process. No longer. To mass produce more complex, precisely etched chips, companies need a better understanding of plasmas.

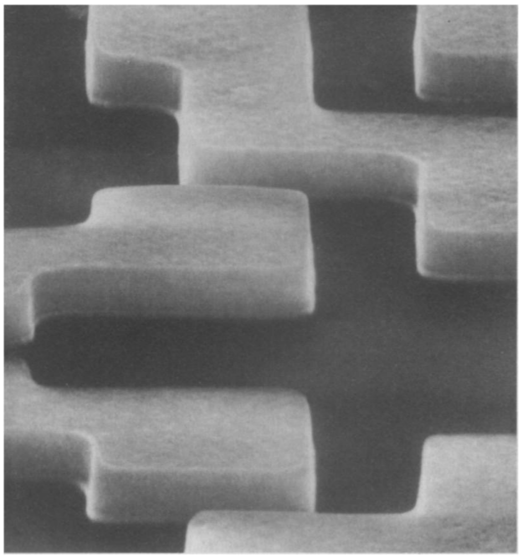
That means scientists, not just chipmakers, must get in the act — and get their act together. So beginning four years ago, Cecchi, a physicist at Princeton (N.J.) University who had used plasmas in developing fusion for energy, signed on with SEMATECH (Semiconductor Manufacturing Technology), a national program that seeks to accelerate advances in microelectronics manufacturing. One year later, chemical physicist James B. Gerardo of Sandia National Laboratories in Albuquerque, N.M., Roberts and several other scientists started investigating inconsistencies in research results involving plasmas. Their efforts led to the development of a new vessel for studying these plasmas.

These collaborative attempts — one a grassroots effort and the other, SEMATECH, designed as more of a top-down program — reflect the changing nature of the nation's research enterprise as investigators respond to what many perceive as an economic crisis.

"Electronics is an enormous force in society," says Cecchi. "It's the thing that's most shaping the world we live in."

Semiconductors lie at the core of laptop computers, VCRs and virtually all modern electronic devices. Once the world's leading producer of semiconductors, the United States lost 2 percent of the market annually between 1980 and 1989. That represents a $1 billion annual loss in gross national product (GNP), according to the Austin, Tex.-based SEMATECH. Now six of the world's top 10 semiconductor manufacturers are Japanese, and national security analysts worry about the United States' increasing dependence on foreign suppliers for weapons and other vital equipment (SN: 2/21/87, p.117).

Regaining lost ground will not be easy. Technologies propelling the volatile and vigorous microelectronics industry change so fast that companies barely recover their development costs before their products are obsolete. This rapid technological turnover puts added pressure on scientists and engineers to



Applied Materials, Inc.

This image, taken through a scanning electron microscope, shows the narrow, 1-micron-wide trenches etched by plasma during processing. When designers began squeezing in more components, they made it necessary for trenches to be closer and therefore more important for their sides to be straight.

streamline and reduce the costs of technology transfer. Researchers find they must pay closer attention not only to improving the chip but also to refining how the chip is made. And increasingly, this has meant companies must revamp how they do business.

Two decades ago, companies treated technology like a baton to be handed off from scientist to development manager to scale-up and manufacturing engineers and finally to promotion and sales departments in a relay race to market. "Today it's much more like a basketball game," says engineer Frank P. Carrubba, director of Hewlett-Packard Laboratories in Palo Alto, Calif. "The hand-off process is a lot different," with technology passing back and forth between all these players as they make their way down the court to score with consumers.

But policymakers face an uphill battle as they encourage people and companies to become better team players. "In the United States, we have a little bit of this pioneers' spirit, this cowboy spirit," says Karl H. Zaininger, president and chief executive officer at Siemens Corporate Research, Inc., in Princeton, N.J. "We want to do it alone."

Adds electrical engineer Terry R. Turner, a SEMATECH program manager in Austin, "Our very competitive nature has almost put us at a disadvantage relative to some of our international competition."

Computer chips are miniaturized circuits on silicon wafers often no bigger than a fingernail. Over time, engineers have worked to steadily shrink a chip's size and increase its capabilities. Through three decades, designers have squeezed in more and more electronic components — from about 4,000 twenty years ago to roughly 12 million today. The minimum size of each feature, line or space on a chip, generically referred to as line width, has also shrunk dramatically — from 24 microns to just 0.8 micron, which is about 1 percent of the width of a typical human hair. These changes are analogous to squeezing a street map of the entire United States onto an area that could once hold only the street map of a small city.

"As things got smaller, people had to look for a different way to etch," says Chris Daverse, a SEMATECH physicist.

Enter plasma processing. Able to etch atom by atom — at least in theory — plasmas offer unparalleled precision. They can not only etch straight down through material without drifting sideways, but also discriminate between silicon and silicon-oxide targets — so one gets etched and not the other. Alternatively, plasmas can deposit material onto chips, again with great precision. However, the more demanding the job, the more likely that the plasma will damage a chip.

In plasma etching, a technician mounts a silicon wafer inside a vacuum chamber and injects a gas. An electrical current passing between two plates, or electrodes, in the chamber will ionize the gas, causing some molecules to break apart and let go of electrons. The resulting plasma includes reactive atoms that bind and remove silicon from the wafer's surface.

Hundreds of other chemical reactions occur at the same time, complicating the etching process. This confusing activity makes it all but impossible for scientists to figure out what is going on and for engineers to fine tune their equipment.

Though adjusting the pressure inside the vacuum chamber, the distance between the electrodes, the flow rate of the gas or the size of the current all affect the process, no one can predict just what the change will be. "The chemical and physical processes that are going on are not well enough understood to make reasonable advances," says NIST's Roberts. "Much more must be known about the plasma and semiconductor interface — where the rubber meets the road, so to speak."

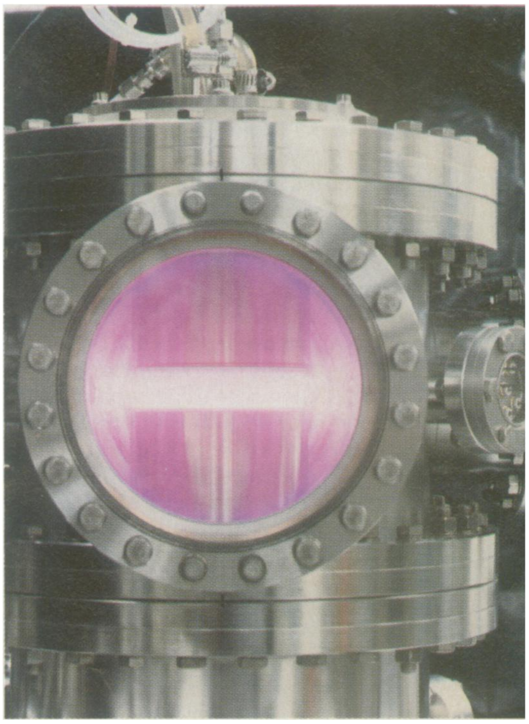
"The whole technology is so empirical, it's not based on good science," adds physicist G. Kenneth Herb of AT&T Bell Laboratories in Allentown, Pa. Furthermore, no two machines — not even identical models — work exactly alike. "It's becoming increasingly difficult to control the process," Herb says. "It's becoming more of an art than a science."

These issues bog down innovation. Much to the chagrin of scientists, engineers have for years tended not to worry about how something worked — so long as it worked. But to turn out products more efficiently than their Japanese competitors, U.S. chip manufacturers now worry they will indeed have to advance what is today only a cursory understanding of plasma etching.

Companies eventually hope to rely on plasma etchers that run on automatic pilot, with computer-based monitors adjusting manufacturing conditions. For these improvements, SEMATECH members find the old engineering approach to innovation just doesn't work well anymore. "Traditionally, we've treated them as a black box," explains Turner. "But there's a limit to how far you can drive that technology by turning knobs."

To date, scientists have not helped advance plasma etching much. One reason is that most plasma physicists have focused on stellar and interstellar plasma. But more importantly, those scientists who did concentrate on Earth-based plasmas never really studied the same plasmas.

Though plasma-generating reactors may seem simple enough, small differences in their designs radically altered the gaseous milieu they created and, consequently, its properties. Because



Sandia National Labs.

By studying a glowing plasma in the GEC Reference Cell, scientists understand better how plasmas etch and deposit materials during the manufacture of computer chips.

even the simplest measurements by plasma scientists in different labs didn't agree, "there was no consistency from one lab to another," Gerardo says.

Yet "plasmas are so complex, and understanding them is such a large problem that it's really beyond the capability of any one individual or research lab," notes Harold M. Anderson at the University of New Mexico in Albuquerque.

In 1988, scientists attending the Gaseous Electronics Conference (GEC) in Minneapolis began to address the inconsistencies in their results by sketching out plans for what they hoped would become a standard plasma-research reactor. It proved no easy task. For instance, no one could settle on what the reactor should look like or on how to build it. Few even thought that problem could be solved, Gerardo now recalls.

But judging by the turnout of researchers attending this meeting, he says, "clearly a lot of people agreed we did have a problem." And during the course of the meeting, more and more people became convinced that developing such an instrument was worth a try. So after the meeting, several participants formed a committee to design the GEC Reference Cell. One year later, the first models were finished.

Initially, the cell's developers established a set of standard tests to ensure that each reference cell operated uniformly and as expected. But when scientists at Sandia, AT&T Bell Labs, the Wright-Patterson Air Force Base in Ohio, the University of New Mexico and NIST ran identical tests, they got widely varying results.

It turns out that even though the cells were identical, the electrical devices that powered them were not. "Nobody ever thought power supplies would affect the plasma, but that really shows how touchy the system is," says Roberts. The research teams are now considering adding a filter between the reactor vessel and power source to ensure the same current reaches all cells.

Two dozen scientists now work with these cells and another 75 have shown interest in them. The investigators include modelers, scientists who try to characterize plasma processing through mathematical equations. Done right, a model can issue predictions that guide researchers' efforts to improve plasma etching. Other researchers plan to use the reference cell to invent process-control devices — systems that will provide feedback to ensure that etching operations proceed according to plan. Overall, Gerardo expects the new reference cell "to bring order to a chaotic area of technology and science."

Roberts says the reference cell's prospect for generating solid technical answers to questions about plasmas excites most of these scientists. He, however, thinks the cell's development will ultimately yield much more. "The whole idea was to get members of the community to act together," he explains. And this project is indeed serving "as a focal point, as a glue to hold the community together."

On a grander scale, SEMATECH — a national experiment in collaboration, begun in 1987 by the federal government and 14 leading U.S. semiconductor manufacturers — holds out the promise of boosting U.S. semiconductor technology ahead of Japan's. SEMATECH's goal is to have in production by the mid 1990s fine-detail computer chips with lines 0.35 micron wide, down from today's standard of 0.8 micron. Toward that end, the U.S. government is kicking in $100 million a year, matching an equal amount from the companies, to fund research and development of better manufacturing techniques.

Previously, antitrust laws made it difficult for U.S. companies to collaborate. Now about 240 people from SEMATECH's 14 member companies work side by side at the consortium's facilities in Austin. Typically, researchers spend two years there, periodically filling in their home laboratories on the progress underway. That and regular meetings between and among consortium members keep the information flowing. "The consortia approach is changing the way people do research," says Turner.

Toward this end, SEMATECH also promotes collaborations between industry and academic experts, such as Cecchi. With $10 million a year, SEMATECH supports 11 "centers of excellence." One, a collection of five university and industry research centers in New Jersey, focuses on the development of new etching systems and a better understanding of plasma chemistry. Another, in New Mexico, is developing measurement tools for monitoring production steps, including plasma processing of semiconductors.

These centers encourage basic researchers to apply their talents toward solving manufacturing problems. Anderson, for example, pursues promising leads on how to monitor plasma automatically during wafer processing. One approach he's investigating links a sophisticated, high-resolution video camera — sensitive to a very broad range of wavelengths — to a computer. When gas ionizes, its various constituents emit energy at different wavelengths. The camera and computer identify not only where these constituents are in the chamber but also what they are. As a result, researchers can determine whether a plasma's reactive atoms are spreading uniformly across the wafer and etching evenly.

Ten miles away at Sandia National Laboratories, physicist Philip J. Hargis Jr. has taken another tack in monitoring the distribution of important plasma constituents in the processing chamber. Using lasers, he induces a fluorescence from the plasma components. The intensity of the fluorescing atoms signals their concentrations.

If perfected, such plasma-monitoring systems could improve quality control in the mass production of semiconductors. But first scientists must ensure that monitors see what is really there. And the new reference cell lets them compare data from these different techniques.

To keep academics talking to their SEMATECH sponsors and to speed the transfer of knowledge, SEMATECH also pairs industry engineers with scientists in a mentor program. "The mentor has an obligation to stay in close communication with the researcher and make sure what he's doing is relevant," Turner explains. As mentor to some GEC Reference Cell researchers, Turner has already seen this effort pay off.

"Right now, we're in the process of making improvements in the way we measure power," he explains. Previously, the instruments measured electrical power where it was generated. But along the way, the power cable absorbs some current. Recent investigations have shown that those minor power losses can significantly alter the energy available to ionize the gas. So changing where the current is measured should lead to improved control over plasma etching, Turner says.

For their part, scientists seem to appreciate having the industrial mentors, says Turner, and "are responding very favorably. They want their work to be used."

Cecchi, for example, talks proudly about a patent pending for a coupler between the plasma reactor vessel and a microwave power source. This coupler will eliminate the need for operators to stand by and constantly adjust incoming power levels. "It would not have come about naturally had we not known what it means to put a better plasma reactor on the manufacturing floor," says Cecchi.

No one calls these collaborations a panacea. Already, new ways of ionizing plasmas make the present GEC Reference Cell outdated for some studies. And some modelers complain that this reactor is too complicated for their use. Finally, keeping lines of communication open between people in distant laboratories takes a lot of work.

Nevertheless, Cecchi, Roberts, Anderson and others see many benefits to becoming team players and working with other scientists and engineers. "In the past we would have looked at each other as rivals; who was going to get to the discovery first," Anderson explains. "Now we realize we all look better if we work together." □