we tried it." The challenge, he says, came in the conception, since his device has no parallel in earlier optical interferometers.

Chu starts by slowing down vaporized sodium atoms and pinning them in place with a net of lasers known as optical molasses. He then releases them through the interferometer in a slow-flowing "atomic fountain." A kind of quantum dissecting mechanism operates on the atoms as they drift by. It begins by administering jolts from two lasers tuned to give the atoms a 50-50 chance of jumping into a second, slightly higher energy state. As a result, the wave representing each atom—technically known as a probability wave—broadens to encompass both states. In a sense, the atom now exists in both states at once. Chu explains that the higher-energy state, having absorbed the impact of two photons, actually careens away from the first one, creating the two wave paths any interferometer requires. During each atom's leisurely passage through the device, its two guises can move several millimeters apart.

Not that you could peer inside the device and see each atom and its doppelgänger. "If you look, you will see it in [only] one state or the other," says Chu. Like Schrödinger's cat, which is both alive and dead but becomes one or the other when its box is opened, the atoms pursue their double existence only in the utmost privacy. But they do give evidence of their duality in the form of the interference pattern that results as the two states of each atom spread out and overlap. The interference pattern takes the form of a periodic distribution of momenta that Chu reads with a third laser.

Chu explains that for measurement applications, the long-lasting separation of the states gives much greater precision. "With slow atoms, there is enough time for the forces you want to measure to act." That advantage has already allowed him to make one measurement of record-breaking precision—of the earth's gravity.

Chu and Pritchard both see wider futures for their atom interferometers. Pritchard, for example, has wondered whether it might ultimately be possible to interfere chunks of matter bigger than atoms. Bigger objects also have a wavelength, he says, but it is even shorter than that of atoms. To give the matter waves enough time to become well-separated, he would have to send them through the device very slowly. The biggest object he could split up through his grating, Pritchard says, would be a tiny speck, containing about 10^{13} atoms. Any bigger, he says, and its travel through the device would exceed the lifetime of the graduate student assigned to carry out the experiment.

■ FAYE FLAM

Shine On, Holey Silicon

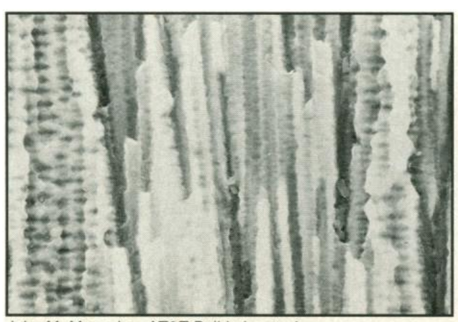
Already famous for its way with electrons, silicon now shows a tantalizing grace with photons.

AN UNEXPECTED GLOW—IN SHADES OF RED, green, yellow, or orange—emanating from silicon wafers in a pair of French and British laboratories might represent the first glimmers of a bright new future for silicon. The colorful display is the first indication that silicon can be induced to emit light. And if silicon turns out to be as good with light as it is with electrons—and that's a big if—the familiar semiconductor could play as large a role in the emerging technology of optoelectronics as it has in the microelectronics revolution. The merger of optical and electronic circuits, which promises more powerful computers, faster communications, new image displays, and a host of other gizmos, could take place in tried-and-tested silicon rather than in more expensive and unwieldy materials.

At least that's the hope raised by the reports of light-emitting silicon presented on 25 April at the spring meeting of the Materials Research Society (MRS) in Anaheim, California. Already, other laboratories are duplicating the light show. And the semiconductor research community is furrowing its collective brow about how the glowing structures displayed at the MRS meeting could possibly work.

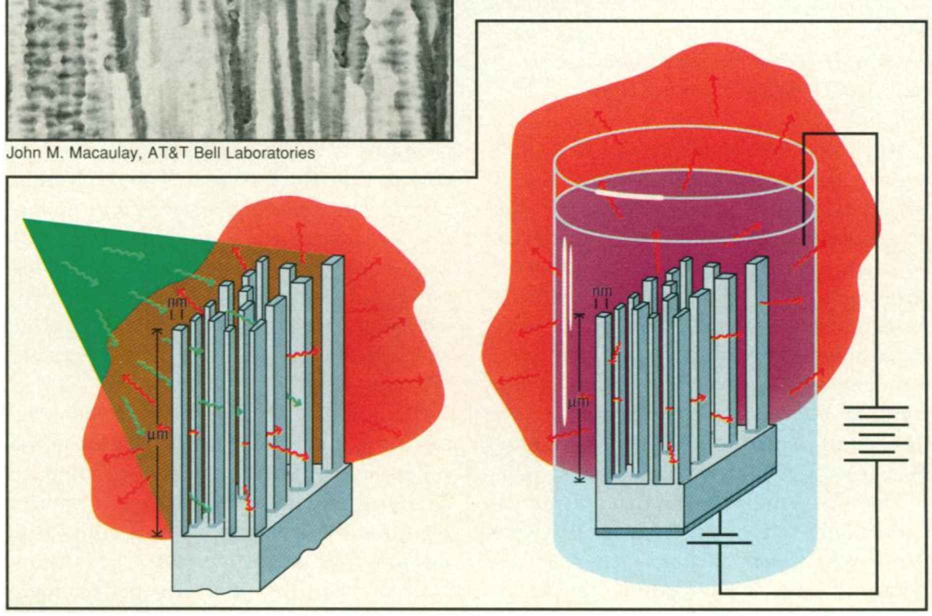
After all, three decades of attempts to turn silicon into an optical material had been littered with enough failures that most investigators simply had relegated light-emitting silicon to the dream heap. "Up to now, the basic physics has been blocking us," says materials scientist John Bean of AT&T Bell Laboratories in Murray Hill, New Jersey. In the face of that seemingly intractable physics (see box), most materials researchers had turned to other light-emitting materials—the so-called III-V semiconductors, made by combining elements from the third and fifth columns of the periodic table. These compound semiconductors launched the first generation of optoelectronic devices—among them the familiar semiconductor lasers and light-emitting diodes—sales of which have already reached about $1 billion a year.

Still, participants in the worldwide effort to shape III-V (and II-VI) compound semiconductors into next century's technologies sometimes indulge in daydreams of light-emitting silicon. If only silicon could be made to emit light efficiently, it would have several immediate advantages over compound semiconductors. For starters, optical devices of silicon would integrate far more easily with standard silicon-based electronic



John M. Macaulay, AT&T Bell Laboratories

Making light. *Etched into a forest of micron-high pillars, porous silicon glows under the influence of light or (when immersed in electrolyte) electric current. An electron micrograph* (left) *reveals the structure of a nonluminous sample of porous silicon.*



circuitry; trying to marry gallium arsenide and silicon in a single chip, researchers say, is like trying to get a three-prong plug into a two-prong socket. And silicon crystals, made of a single, abundant element, are much cheaper and easier to make than compound semiconductors.

In spite of its spectacular light-emitting debut, silicon presents no immediate threat to those specialized materials, but it has put the gallium arsenide research community on alert. "They might lose some sleep over this," says Bean, who several years ago led an unsuccessful effort at AT&T to produce light-emitting silicon structures by creating superfine alloys of silicon and germanium.

How did the European groups apparently succeed where so many others had failed? Brandishing colorful pictures and flashy promotional brochures prepared by business managers, W. Y. Leong of the Royal Signals and Radar Establishment in Malvern, England, told an audience of about 400 at the MRS meeting how he, team leader Leigh Canham, and their co-workers managed it. The secret, he said, was etching silicon into structures so tiny that the electronic behavior of the material is transformed. "We can achieve full-color emission from what we are calling silicon quantum wires," Canham said in an interview. A silicon quantum wire is a pillar-like silicon structure so exquisitely thin that the electrons confined within it can take on different, higher energy states than they can in the larger silicon structures of conventional chips, Canham says.

To make silicon quantum wires, the British scientists build on a process for sculpting silicon invented more than 30 years ago. First, they immerse a silicon wafer in an acidic electrochemical bath, which bores exceedingly small "wormholes" into the wafer. They then chemically etch these pores, enlarging them until they meet one another. The researchers think the process leaves behind an intricate forest of free-standing silicon structures about a micron in height (50 of these end to end would span the cross-section of a human hair) and a few nanometers thick (about 10,000-15,000 times thinner than that same hair).

When the British investigators shine laser light onto the resulting porous silicon, the entire wafer surface glows in a color that depends on the diameter of the silicon wires. The thinner the pillars are etched, the shorter the wavelength of the emitted light becomes, yielding colors ranging from red to orange to yellow to green, Canham says.

This achievement is not a single flash in the pan. R. Romestain of the Joseph Fourier University of Grenoble in France told the MRS meeting how his group also succeeded in wresting light from silicon. Like their colleagues across the Channel, the French group relies on electrochemical and acidic etching techniques to whittle the silicon into nanometer-scale sculptures, which they think might resemble strands of beads—so-called quantum dots—rather than pillars. By bathing the porous silicon in ultraviolet light, the French workers induce it to emit light at wavelengths ranging from near-infrared to oranges and yellows. "The emitted wavelength can be varied by changing the porosity of the porous layer," said Roland Herino, a physicist who works on the project.

The light-induced emission of light announced by both the British and French groups is a tantalizing proof-of-principle. But Romestain startled the Anaheim audience with a hint of an achievement with even larger practical implications: the possibility that silicon can be induced to emit light in response to electric current. He reported that his group's samples gave off light during the etching step, as electrical currents were coursing through the etching bath and the porous wafer. Unfortunately, Romestain added, once the etching process was completed, he could barely drive any current through the silicon, probably because of chemical changes on the silicon nanostructure.

Leong, of the British group, claimed to have matched the achievement. He showed a viewgraph of orange light streaming from a silicon wafer and claimed that the light was produced in response to electrical input. But neither he nor Canham would reveal details because of proprietary interests.

In spite of the uncertainties, researchers in the field are effusive. Electrically triggered light emission, or electroluminescence, is just the process engineers would like to harness for designing all-silicon optoelectronic devices. "People have been dreaming about this for years," notes Pierre Petroff, a quantum wire maker at the University of California in Santa Barbara's Center for Quantized Electronic Structures. "It might mean that eventually light sources integrated directly onto a silicon chip could send signals and talk to another part of a computer or to another computer."

The one-two punch by the British and French groups appears to have moved like-minded researchers to at least contemplate jumping in. "We are talking among ourselves about quickly establishing a porous silicon program," Petroff says.

But he and others counsel caution. Neither team, Petroff points out, has yet presented conclusive evidence that the quantum wires or dots are indeed responsible for the light emission. Rather than resulting from quantum-size effects, for example, the light could stem from impurities left in the pores from the etching steps, Petroff notes.

"This is not the moment of the breakthrough [for light-emitting silicon]," adds quantum-structures maker James P. Harbison of Bellcore in Redbank, New Jersey. "But it is the moment when a lot of people are realizing its potential."

■ Ivan Amato

Putting Some Spark in Silicon

Until the surprise announcement of light-emitting silicon by groups in Great Britain and France (see main text), attempts to get light out of silicon were about as successful as squeezing blood from a stone. The problem is the same electronic structure that accounts for silicon's semiconducting nature.

Semiconductors conduct current when electrons (usually contributed by deliberately implanted impurity atoms) gain an energy boost. The energy carries them from the valence band—the normal energy range—to a higher energy range known as the conduction band, leaving behind positively charged electronic vacancies, or "holes."

A semiconductor can emit light when the electrons cascade back down across the band gap and combine with the holes, releasing energy. The materials now used in optical devices, such as gallium arsenide, have "direct" band-gaps, which means that an electron falling back into the valence band promptly recombines with a hole, releasing the full band-gap energy at once in the form of light. Silicon's band-gap is "indirect," resulting in slow recombination that tends to generate heat rather than light. What's more, the gap is too narrow to generate visible light even when rare, prompt recombinations do occur.

By etching nanometer-scale structures onto silicon wafers, the European researchers suspect they have harnessed quantum effects that transform silicon into a direct-band-gap material like gallium arsenide. This tips the balance in favor of light-emitting recombinations. And the scientists suspect further that they must have increased the width of the band gap—otherwise the material would have glowed only at infrared rather than visible wavelengths.

■ I. A.