The Mod Couple

Wedding silicon and germanium for speed and light

By IVARS PETERSON

The silicon superchip.

Its intricate web of microscopic circuits handles electrons and photons with equal ease. Its optical components amplify light, detect and channel microwave signals or laser radiation, and convert light to electricity or electricity to light. Its electronic transistors switch on and off rapidly enough for high-speed computation.

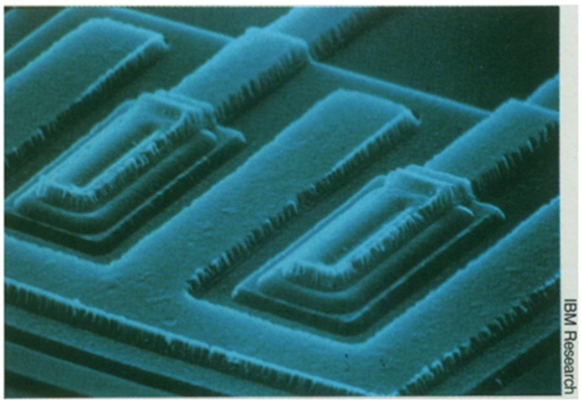
This superchip doesn't exist yet. But a few of the pieces necessary to build it are beginning to settle into place as researchers learn to interweave different types of atoms with silicon to create novel transistors and optical devices.

"It's the ultimate goal of optoelectronics," says Richard A. Soref of Rome Laboratory at the Hanscom Air Force Base in Massachusetts. "But it's a tough problem."

Soref described his vision in the December 1993 PROCEEDINGS OF THE IEEE and in March at an American Physical Society meeting held in Pittsburgh.

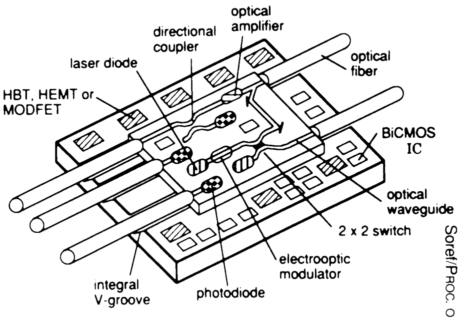
Silicon is the overwhelmingly dominant material in semiconductor electronics. Silicon-based integrated-circuit chips built into digital watches, calculators, computers, stereo equipment, car ignition systems — the list goes on and on — attest to its ubiquity.

One of the most abundant elements on Earth, silicon can be grown on an industrial scale into nearly perfect, ultrapure crystals with no more than 1 in 10 trillion atoms out of place. A remarkably strong material, its surface reacts readily with oxygen to form a stable, high-quality, electrically insulating layer such that vast numbers of microelectronic components can be packed together on a single chip.


IBM Research

Micrograph of an innovative heterojunction bipolar transistor fabricated from silicon and germanium.

At the same time, manufacturing technology has advanced to the point where a typical silicon chip costs just pennies to produce.



Soref/PROC. OF THE IEEE

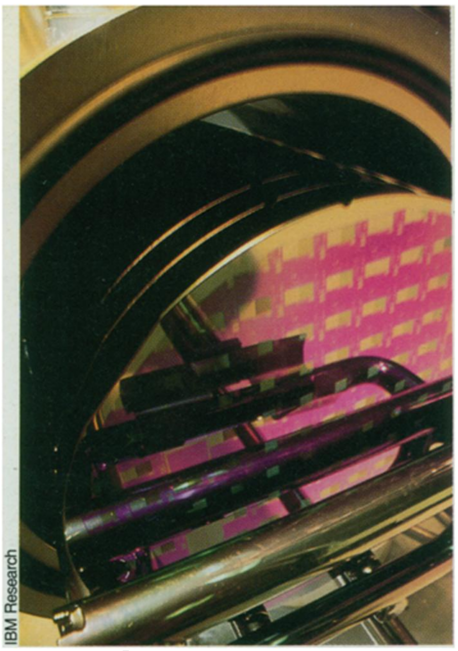
A silicon-based "superchip" would interweave a variety of optical and electronic devices, including lasers and transistors.

This amazing success doesn't mean that silicon-based technology has a free ride into the future. For example, there's a limit to how fast electrons can be pushed through silicon, which determines how rapidly transistors can turn on and off.

One answer to speeding up such devices is to make them smaller, crowding even more components on a chip. But miniaturization can't continue indefinitely. At the very least, the size of atoms sets a fundamental limit.

Silicon suffers an additional disadvantage when it comes to handling light. When conducting electrons in silicon drop to a lower-energy, bound state, the excess energy is converted into phonons, or vibrations of the crystal lattice, rather than photons. In other words, silicon doesn't naturally emit light; therefore, its usefulness for optical devices is severely restricted.

One group of materials, exemplified by gallium arsenide, appears to overcome these silicon deficiencies. Devices made from gallium arsenide and related semiconductors emit light and operate significantly faster than their silicon counterparts.


IBM Research

Baking a silicon wafer.

A decade ago, these advantages looked so strong that some technologists were predicting that Silicon Valley (a strip of high-tech research and business stretching from San Francisco to San Jose, Calif.) would eventually become Gallium Arsenide Gulch. That hasn't happened. Silicon still reigns supreme, though gallium arsenide has established itself as the leader in a few specialized applications.

One drawback has been the difficulty of working with this finicky material, particularly on an industrial scale. It's also tricky to integrate gallium arsenide and its cousins into silicon.

"The problem is that the total investment for silicon infrastructure runs in the hundreds of billions of dollars worldwide," says Abbas Ourmazd of AT&T Bell Laboratories in Holmdel, N.J. "One is very reluctant to abandon that in favor of technologies based on other materials, such as gallium arsenide."

"You can think of silicon as a steamroller that doesn't stop for small animals," he remarks. "Unfortunately, gallium arsenide can be classified as a small animal."

So, if you can't beat silicon at its own game, why not find a way to join the team?

One promising way of overcoming silicon's deficiencies is to mate it with another element, such as germanium. The addition of germanium to silicon can increase the speed at which electrons travel through the semiconductor. It also opens up the possibility of engineering the crystal structure of silicon-germanium alloys to allow these materials to absorb and emit light.

This approach has the advantage of preserving the vast manufacturing infrastructure devoted to silicon while enhancing the performance of silicon-based electronics. "It delivers some of the advantages of gallium arsenide, and it can be integrated into silicon," Ourmazd emphasizes.

The trouble is that although germanium is chemically compatible with silicon, its crystal structure isn't a good match. Germanium atoms naturally settle into an arrangement with atomic spacings about 4 percent larger than those of a silicon lattice.

That doesn't sound like a large discrepancy, but in the world of microelectronics, high performance depends on crystalline perfection. The addition of germanium atoms to silicon distorts or even disrupts the crystal lattice, inducing strain and causing defects. It's like trying to build a neat stack out of a mixture of oranges and grapefruits.

But it's possible to stretch the rules a little. The trick is to keep silicon-germanium layers, deposited atop silicon, as thin as possible. In such a situation, atoms in the first few atomic planes above silicon readily come closer together to match the smaller atomic spacing of the silicon lattice. This introduces strain, but any defects that occur are generally found just at the interface.

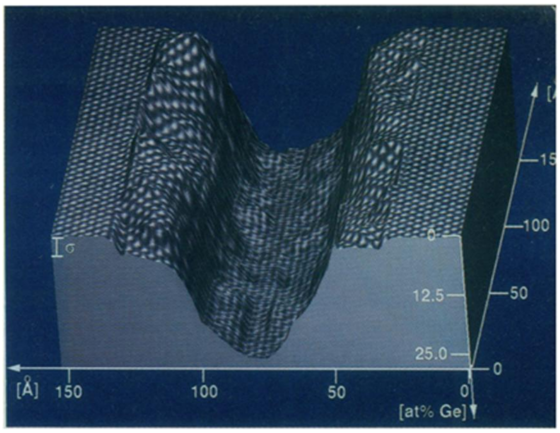
It's also possible to create elaborate sandwiches of alternating layers of silicon and silicon-germanium alloys. By adjusting the thickness and composition of individual layers, these structures can be tailored to exhibit various electronic and optical characteristics.

To produce these finely structured hybrids, researchers generally use a technique known as molecular beam epitaxy. Growing the structures in a high vacuum at a low temperature, they can lay down one layer of atoms after another, achieving a great deal of control over the placement of their atomic building blocks and readily switching from one type of atom to another.

During the 1980s, laboratory investigations of these silicon-germanium structures at AT&T Bell Laboratories, IBM, Stanford University, and other research centers produced rudimentary devices capable of emitting light (SN: 5/9/87, p.294) and prototypes of high-speed transistors that could outperform conventional silicon technology.

One such device was the heterostructure bipolar transistor. The presence of germanium accelerated the motion of electrons across the device, boosting the transistor's speed by roughly 60 percent.

The transistor worked well in the laboratory, setting speed records for silicon technology, but it remained far from useful commercially. There seemed no way of mass-producing these devices at a sufficiently low cost. In particular, molecular beam epitaxy was simply too arduous and slow.



A novel technique—known as quantitative transmission electron microscopy—enables researchers to measure changes in the composition of crystalline solids. In this image, the height represents the germanium concentration across a silicon-germanium quantum well.

C. Kisielowski *et al.*/Phys. Rev. Lett.

The crucial advance occurred at the IBM Thomas J. Watson Research Center in Yorktown Heights, N.Y., where Bernard S. Meyerson and his team developed a chemical vapor deposition process for creating smooth, uncontaminated interfaces between silicon and silicon-germanium alloys.

They found that the presence of hydrogen atoms during the layering of silicon crystals regulates the growth rate and considerably reduces the reactivity of bare silicon. This affords a great deal of control over the manufacturing process, making it easier to introduce the precise amounts of various dopant elements required to turn raw silicon into a transistor.

Last December, IBM announced that it had licensed its pioneering ultra-high-vacuum chemical vapor deposition process to Analog Devices of Norwood, Mass. The two companies plan to design, produce, and market integrated circuits that incorporate silicon-germanium alloys for use in digital telephones and in radios for portable communications.

Finally emerging after nearly 3 decades of research, this represents the first set of commercial products based on silicon-germanium technology. But they're not the only kind of transistors and chips now commonly in use.

Work on silicon metal-oxide chips — like those found in most computers — based on silicon-germanium alloys is not as far along, but there has been some progress. For example, Judy L. Hoyt and her coworkers at Stanford have produced such transistors with electron mobilities significantly higher than those in pure silicon.

These initial results are very encouraging and indicate a strong potential for future integrated-circuit applications, Hoyt says.

Progress toward silicon-germanium optical devices has been slower, but researchers like Soref are encouraged by the success of the heterostructure bipolar transistor. "It shows me that silicon-germanium electronics is leading the way for the entire field," Soref says.

In the case of optics, the chief competitor is gallium arsenide and related compounds, which so far have cornered much of the optoelectronics and photonics market. Nonetheless, researchers at AT&T Bell Laboratories and elsewhere have developed silicon-germanium devices that can serve as photodetectors and waveguides, mainly at infrared and microwave wavelengths.

John C. Bean of Bell Labs in Murray Hill, N.J., and his collaborators are trying to improve light-detection and light-emission capabilities in silicon-germanium, particularly at the microwave wavelengths typically used for communication over optical fibers. They have made some progress in creating structures that enhance the detection of light.

"We certainly see at least the possibility of commercialization, but that's a long way off," Bean says. "It's still very much a research topic."

The prospects of using silicon-germanium alloys for integrating light-handling capabilities directly into silicon remain uncertain. "I would not want to compete on a one-for-one basis with the best that [gallium arsenide] has to offer," Bean says. "But if we can add [silicon-germanium optical devices] to silicon, we can still eat their lunch."

"Some of the limitations of silicon-germanium can be overcome by ingenuity, though it may be difficult," Soref notes. "It will take cleverness, good design, and good engineering." Soref and his colleagues are currently working on two different schemes that may lead to a silicon-based diode laser. Such lasers could find uses in communication, entertainment products, and elsewhere.

Someday, a silicon superchip incorporating both optical and electronic devices may emerge from the laboratory. Silicon-germanium structures are likely to play an important role in achieving this level of integration, but it will take time.

It's not just a matter of devising the necessary components. The resulting chip must be cheaply, efficiently, and conveniently mass-producible on the factory floor. That's one reason it took so long for the heterostructure bipolar transistor to become a commercial product.

At the same time, silicon technology itself keeps getting better and better. "It's a moving target," Soref says.

"There's a tremendous amount of momentum behind silicon technology," Ourmazd adds. "Whether silicon-germanium really manages to deliver performance improvements before silicon gets there is the big question." ☐