MATERIALS SCIENCE

Vertical Lasers Take Aim at New—and Colorful—Targets

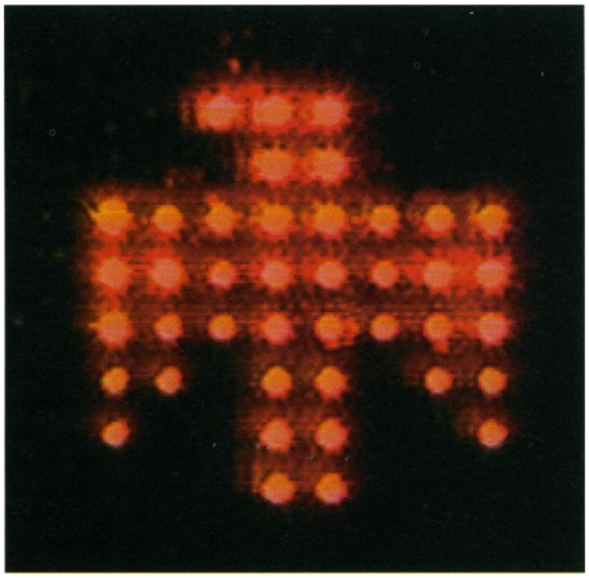
For tiny chip-based lasers, things are looking up. Last November, Motorola became the first company to market a product incorporating a semiconductor laser that shoots light from its top surface. These devices have been hotly desired in the electronics industry because they can easily be made into minuscule, dense arrays, increasing the amount of information they can transmit. Currently most commercial lasers shoot light from the edge of the chip, making it more difficult to combine them into such arrays. Motorola's new device, known as a vertical cavity surface emitting laser (VCSEL), has no such problems. It is part of a system that beams near-infrared light between computers, transmitting data 150 times faster than conventional copper wire connections.

The commercial debut of Motorola's VCSEL is an important milestone, but it's far from the end of the road. VCSEL makers want more of the spectrum than the near-infrared. Red-emitting lasers, for example, can be used to form visible displays, while longer infrared beams are far better suited than other wavelengths for long-distance fiber-optic communication. However, researchers have struggled, mostly in vain, to get VCSELs to emit high-quality beams in these other wavelengths; they require unique combinations of semiconductor alloys, each with its own set of fabrication problems.

Now, however, with the help of new materials and construction techniques—including a way to slap together prefabricated VCSEL building blocks which, according to researchers, shouldn't work but somehow does—scientists are finally beginning to push VCSELs well into the red, the infrared, and even the blue. "There has lately been tremendous progress in the technology" of making VCSELs, says Federico Capasso, a laser researcher at AT&T Bell Laboratories in Murray Hill, New Jersey.

Materials scientists still need to ensure that the substances they are using to fabricate these devices are tough enough to last for years before these latest VCSELs are market-ready. But most researchers see that effort as worthwhile, because the structure of VCSELs brings advantages that make them easier to produce on an industrial scale and test before they are packaged. Says Dennis Deppe, a device physicist and VCSEL maker at the University of Texas, Austin, "There are too many advantages of the device geometry for VCSELs not to be a major player in the future of optoelectronics."

Seeing red. On the face of it, constructing a VCSEL doesn't seem like a daunting task. After all, they are essentially just multilayered stacks of semiconductor alloys. The stacks are configured so that oppositely charged particles—electrons and their positively charged counterparts called "holes"—flow toward the center of the device from electrodes at the top and bottom. This central region, called the optical cavity, holds a series of "quantum wells," traplike structures that confine the electrons and holes, making it easy for them to combine and release energy in the form of a photon. Mirrors—made of dozens of pairs of alternating layers of two different semiconducting alloys—surround the optical cavity; they funnel the electrons and holes into the optical cavity and reflect and amplify the exiting photons into a coherent beam.



Vertical bird. This avian-shaped array is made of semiconductor lasers that shoot red light vertically from their chips instead of from their edges, which is the usual configuration.

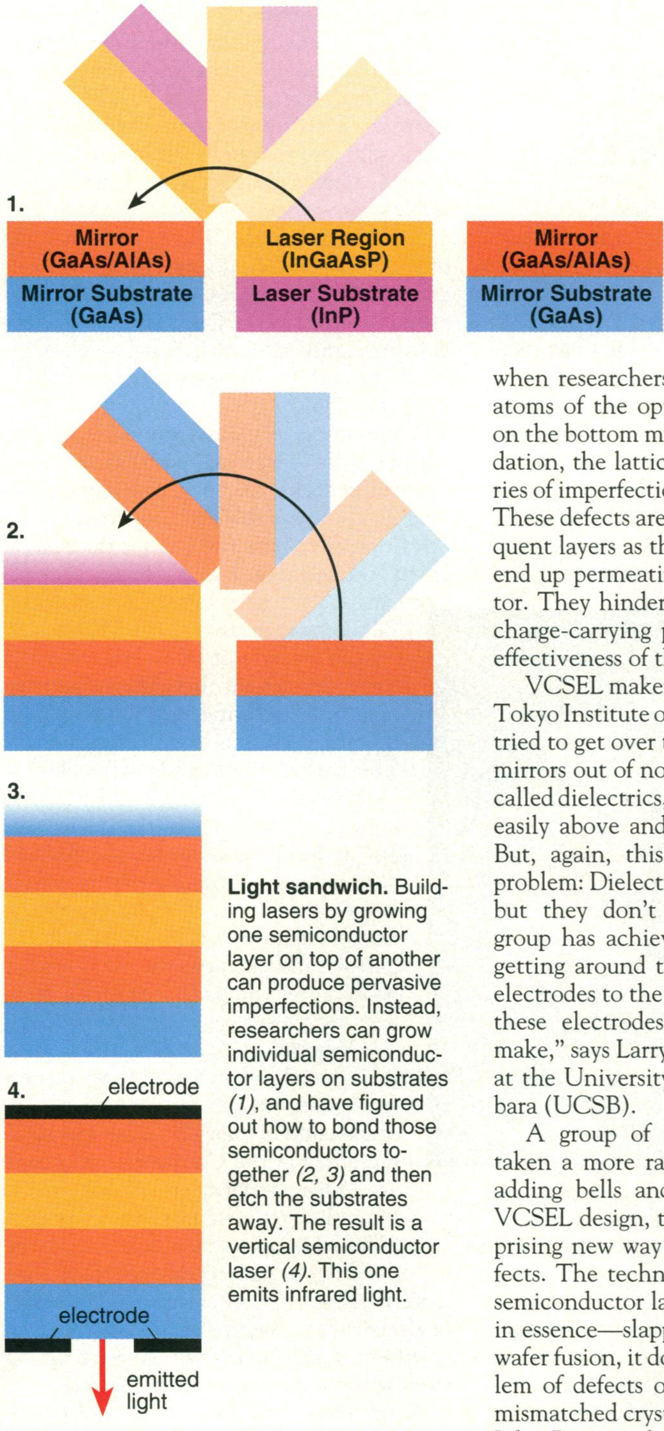
Quantum wells made of different semiconductor alloys produce different wavelengths of light. So by choosing different semiconductor alloys to make—and sandwich—the quantum wells, researchers can, in theory, vary the wavelength of the emitted light. Motorola's near-infrared VCSELs, for instance, use gallium-arsenide quantum wells surrounded by an optical cavity of aluminum-gallium-arsenide. And 2 years ago, Richard Schneider and his colleagues at Sandia National Laboratories managed to get red light out of a VCSEL by making the quantum wells from the semiconductor indium-gallium-phosphide surrounded by an optical cavity made from aluminum-gallium-indium-phosphide.

But changing the alloys created some problems. Much of the energy the researchers put into the devices, unfortunately, produced heat instead of light, and the devices delivered only intermittent light pulses instead of a continuous beam (*Science*, 28 May 1993, p. 1234).

One reason, explains Schneider, is that the new alloys interfered with the ability of charged particles to move through the device. And solving this problem created others. In order to help holes enter the optical cavity, the researchers added magnesium atoms at the top lip of the optical cavity. But doing so meant they also had to add "spacer layers" just below the top of the cavity to prevent these magnesium atoms from diffusing down into it and thereby poisoning the quantum wells. This extra material ended up reabsorbing photons before they could escape as light. The efficiency of the device was also reduced by quantum mechanical peculiarities of the alternating mirror layers, which created resistance to the flow of electrons and holes through the mirrors and required an extra energy boost to get the particles moving from layer to layer.

Over the past 2 years, the Sandia team has developed a number of new techniques to get around these obstacles, and in an upcoming paper to be presented at the Conference on Lasers and Electro-Optics in Baltimore in May, they report considerable success. "Their devices are remarkable given the difficulty of making devices from these materials," says P. Daniel Dapkus, a professor of electrical engineering at the University of Southern California, who is working on making both red and infrared VCSELs.

Schneider and his Sandia colleagues Mary Hagerott Crawford, Kent Choquette, and Kevin Lear improved the ability of charged particles to move through the device by smoothing out the abrupt transitions from one semiconductor layer to another. To do this they used an atom-by-atom deposition technique called metalorganic vapor phase epitaxy. This, in combination with introducing new arsenic-based alloys, allowed them to remove the magnesium from the top of the optical cavity and therefore get rid of the optically fouling spacing layers as well. And in the mirrors, this technique "reduces the resistance by 1 to 2 orders of magnitude," says Schneider. The devices not only turn out red



Light sandwich. Building lasers by growing one semiconductor layer on top of another can produce pervasive imperfections. Instead, researchers can grow individual semiconductor layers on substrates *(1)*, and have figured out how to bond those semiconductors together *(2, 3)* and then etch the substrates away. The result is a vertical semiconductor laser *(4)*. This one emits infrared light.

ILLUSTRATION: C. FABER SMITH

light continuously at room temperature, but do so with an efficiency approaching that of the near-infrared VCSELs.

Sandia's red VCSELs aren't quite ready for the real world yet, however. Now the researchers must make sure the devices are robust enough to last for years, says Schneider. "We're still working on that," he adds.

A better way to build. The challenge of making VCSELs that emit farther in the infrared has been just as daunting. But the potential prize is also great, for these wavelengths are minimally absorbed by glass fibers and are therefore best for beaming information-packed light signals through long-distance fiber-optic telephone cables.

The chief stumbling block here is an atomic mismatch: The best semiconductor alloys for the optical cavity have a different spacing of atoms in their crystalline lattices from the semiconductors used for the mirrors. As a result, when researchers deposit the first layer of atoms of the optical-cavity semiconductor on the bottom mirror that serves as its foundation, the lattice mismatch produces a series of imperfections in the atomic structure. These defects are usually passed on to subsequent layers as they are deposited, and they end up permeating the entire semiconductor. They hinder the free flow of light and charge-carrying particles, undermining the effectiveness of the device.

VCSEL makers such as Kinichi Iga of the Tokyo Institute of Technology in Japan have tried to get over this hurdle by making their mirrors out of non-semiconductor materials called dielectrics, which can be layered more easily above and below the optical cavity. But, again, this solution creates another problem: Dielectrics make adequate mirrors, but they don't conduct electricity. Iga's group has achieved preliminary success in getting around this drawback by attaching electrodes to the sides of their VCSELs. But these electrodes "look pretty difficult to make," says Larry Coldren, a VCSEL expert at the University of California, Santa Barbara (UCSB).

A group of researchers at UCSB has taken a more radical approach. Instead of adding bells and whistles to the original VCSEL design, they have figured out a surprising new way to make it with fewer defects. The technique involves creating the semiconductor layers separately and then—in essence—slapping them together. Called wafer fusion, it doesn't prevent the old problem of defects occurring between the two mismatched crystalline lattices. Rather, says John Bowers, the team leader, it just limits their numbers and confines them to a few atomic layers at the junction where the two mismatched alloys meet.

Bowers, together with his UCSB colleagues Evelyn Hu, Dubravko Babic, and Richard Mirin, grows the mirrors and the optical cavity independently, like open-faced sandwiches, on different substrates well matched to their lattice structure. They then press together the open face of the optical cavity and the open face of one of the mirrors and bake the sandwich together with hydrogen gas in an oven at 650 degrees Celsius. The two faces fuse by forming strong covalent bonds. After using conventional etching techniques to remove the substrate connected to the optical cavity, the researchers then simply repeat the fusion process to attach the second mirror (see diagram). The fewer defects created by this process and the fact that the defects don't extend into the heart of the optical cavity and mirrors allow the device to work, says Bowers.

Indeed, as the researchers report in the 27 February issue of *Applied Physics Letters*, the technique works so well that their devices have set the record for the amount of power they put out. They have also set a record for the minimum threshold of electrical current needed to produce a lasing effect. "It's a thing you wouldn't expect to work," says Olga Blum, who works on far-infrared VCSELs at Sandia National Laboratories in Albuquerque, New Mexico. "But you can't argue with the results."

It doesn't work perfectly, though. Bowers concedes that the devices aren't yet ready for prime time. They currently emit only pulsed light, whereas to be commercially viable they will need to emit light continuously at room temperature. Bowers predicts that "it will just be a matter of time before we solve this problem." And he and other researchers believe that the wafer fusion technique may help make VCSELs feasible in other wavelengths, such as yellow, green, blue, and ultraviolet.

Visions of blue. Even without the help of the wafer fusion technique, however, researchers are beginning to make strides toward creating VCSELs that emit these shorter wavelengths. Lasers that operate at these wavelengths have been a dream of technologists for decades, because the shorter wavelength makes it possible to convey the same amount of information in less space. Thus far, however, efforts to make commercial short-wavelength semiconductor lasers have been stymied for several reasons, not least of which is the unreliability of the materials first used to make the optical cavities. They tend to fall apart after a short period of use.

But in a paper submitted to *Applied Physics Letters*, Asif Kahn and his colleagues at APA Optics in Blaine, Minnesota, report that they have made the first ultraviolet VCSEL using a semiconductor alloy of gallium-nitride. While the APA devices are not electrically powered and must be pumped with another laser to function, researchers such as UCSB's Coldren call the work "promising" because longevity tests of gallium-nitride have shown it to be extremely robust.

Although a lot more work needs to be done on all of these new devices, if the recent pace of progress in VCSELs continues, Motorola's near-infrared devices may soon be in for some colorful competition.

–Robert F. Service