Silicon devices: LED there be light

Silicon is king of the electronics world. Virtually every kind of semiconductor device can be made from this material. The one exception has been a device that emits light. For example, while silicon has enabled all sorts of calculations to be performed on hand-held calculators, only gallium arsenide – which makes up the light-emitting diodes (LEDs) in the calculator's display – has allowed the numeric inputs and outputs to be illuminated.

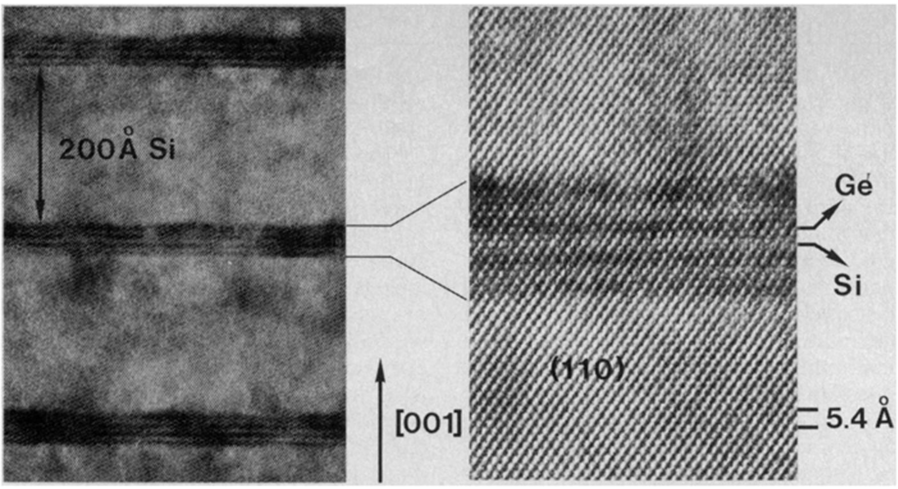
But if papers presented April 22 at the Anaheim, Calif., meeting of the Materials Research Society are any indication, silicon's exclusion from the light-emitting club may be soon challenged.

Researchers from AT&T Bell Laboratories have developed a technique enabling them to construct novel artificial crystals that could soon lead to the first silicon-based light-emitting devices. If they succeed, says Kevin J. Malloy, a program manager for electronic materials at the Air Force's Office of Scientific Research in Washington, D.C., who attended the meeting, "they will open up a whole host of optical and electronic applications that were previously reserved for gallium arsenide."

What's more, because their technique gives the researchers remarkable control over the small-scale structure of crystals, it will allow them to custom-tailor the properties of a great variety of materials in addition to silicon, and to create crystals that have never before appeared in nature.

Gallium arsenide naturally emits light because it has what is known as a direct-energy band gap: When free, conducting electrons drop to a lower-energy, bound state, they transfer their energy directly to light. In contrast, the band gap of bulk silicon is indirect: The energy given up by electrons is largely converted into phonons, or vibrations of the crystal lattice.

The AT&T researchers have discovered how to change the electronic structure of silicon in a way that may allow optical transitions to occur more easily in the material. They use a conventional technique called molecular beam epitaxy, but they grow their crystals in an unusually high vacuum and at low temperatures, and they are able to meter out, atom by atom, the material that gets deposited on the crystal. This gives them a great deal of control over the placement of the atomic building blocks, so that they can construct crystals one atomic layer at a time. The growth and study of these crystals have been conducted by Joze Bevk, Thomas P. Pearsall, Leonard Feldman and John Bean at Murray Hill, N.J., Abbas Ourmazd at Holmdel, N.J., and their colleagues.



A. Ourmazd/AT&T Bell Laboratories

These images, taken with a transmission electron microscope, show a crystal containing alternating rows of germanium and silicon, each four atomic layers thick. The germanium-silicon part is highlighted in the magnified image to the right. Each tiny sphere in the images represents a pair of atoms.

By alternately depositing layers of silicon and germanium atop a thicker silicon substrate, they have constructed crystalline films in which the atomic constituents vary over the unusually small distances of one or two atomic layers. "When crystals are grown with most conventional techniques, it's hard to grow anything thinner than a few hundred atomic layers," says Pearsall.

His group can make crystals several layers thick that consist of, for example, alternating rows of two atomic layers of germanium and two of silicon. At this small scale, the researchers are altering the structure of the unit cell, which is the smallest collection of atoms that contains all the properties of the bulk material; normal unit cells for silicon and germanium are four atomic layers high.

The properties of the new crystals, says Pearsall, are different from those of bulk silicon, bulk germanium and germanium-silicon alloys made by mixing the two elements together.

Pearsall says his group has experimentally determined that the artificial ordering of atoms has produced new, strong optical transitions that lie 0.7 to 2.0 electron-volts (eV) above the bound state. This does not mean, however, that the crystals will emit light: There is an indirect energy transition lying 0.1 eV below the lowest optical transition, and because this indirect transition occurs at a lower energy, it is more likely that electrons would lose their energy to phonons than to light. Still, this is much closer to being a direct-band-gap material than the bulk materials; the lowest direct transition in a 50 percent silicon, 50 percent germanium alloy, for example, occurs at 2.6 eV.

With some guidance from Sverre Froyen at the Solar Energy Research Institution in Golden, Colo., and his colleagues (who presented the results of their theoretical calculations on the new materials at the Anaheim meeting), the researchers think they may be able to get even closer. Bevk says the key factors for creating new energy levels and for controlling where the indirect band gap lies are the order, periodicity and amount of strain in the crystal on the atomic level.

AT&T's materials are strained because the lattice constant – the natural distance between atoms in a crystal – of silicon is smaller than that of germanium. Since the silicon substrate sets the lattice constant for the rest of the crystal, the germanium atoms are squeezed together closer than they would be naturally in a pure germanium crystal. Unfortunately, says Pearsall, this compressive strain on the germanium causes the indirect band gap to be the lowest-energy feature. "If we could make the strain tensile instead of compressive," he says, "it would force this indirect band gap to go up in energy, greatly improving the chances of getting light out of the crystal."

Pearsall and Froyen think they can do this by using different substrates, such as germanium or a silicon-germanium alloy. In these cases, the silicon atoms would then be put under tensile strain. "Producing these samples is probably not going to be any more difficult than producing the samples we've worked on so far," says Bevk.

If he and his colleagues succeed, they will have found a way to cut down on the costs and times of producing light-emitting devices. "By processing just one 6-inch silicon wafer alone," Pearsall says, "I could make enough LEDs to satisfy all the needs of [AT&T] for probably four or five years."

Gallium arsenide is still more of a laboratory technology than a production technology, he says. It would take about a week to make 20 to 30 working LEDs from one gallium arsenide wafer; with one 6-inch silicon wafer, over 1 million devices could be produced in a day, he notes.

Having silicon light devices would also cut down tremendously on the costs and time involved in connecting gallium arsenide LEDs to silicon integrated circuits. These assembly costs, Pearsall notes, are "very expensive. You'd really like to have everything on one little chip of silicon."

In addition to making silicon LEDs, the researchers envision a variety of other uses, including nonlinear optical devices for handling light in fiber optics and in making silicon solid-state lasers. Since their technique is not limited to silicon and germanium, many other potential applications are possible, they say, such as making better superconductors.

"I would expect that in every case when you take a material that is homogeneous and change it into something that has a dramatically varying atomic or chemical potential over only a few angstroms, you will see spectacular properties because you'll be exaggerating the normal forces that exist in most materials," says Pearsall.

But for now most of these ideas must wait until the researchers' understanding of the technique and its implications develops more fully. "In a way we're like children now," says Ourmazd. "We've discovered a new game and we're trying to learn the rules." — *S. Weisburd*

Getting the picture in the infrared

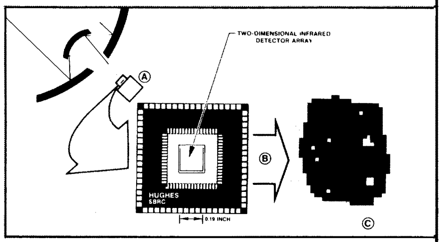
In the film "Wolfen," special effects give the audience a view of the world through the eyes of a pack of superwolves, whose eyes presumably can sense and image infrared. Now astronomers have something similar, devices to put on telescopes that can make an image with infrared radiation analogous to what human eyes do with visible light. The first of these infrared array detectors are being applied to telescopes belonging to the National Optical Astronomy Observatories (NOAO).

Previously astronomers working in the infrared had to build up pictures of the sky by "rastering," or measuring the infrared brightness of the sky, point by point, realigning the telescope for each point. The new detectors operate like human eyes, as well as like photographic plates and charge-coupled devices (CCDs) that visible-light astronomy uses, making an image of a portion of the sky all at once. Furthermore, according to NOAO, they do it with greater sensitivity and resolution than infrared has ever had before.

Like CCDs also, the new infrared imagers involve the latest photoelectric technology and were originally developed for military and intelligence uses. (As Albert Fowler, the NOAO engineering manager for this project, puts it, astronomy doesn't have the money it takes to fund state-of-the-art infrared. The Defense Department does.)

The new detectors replace the single infrared sensor used in rastering with an array of indium antimonide sensors about the size of a flake of confetti. The array is mounted on a silicon microchip that reads out the data and sends them to a computer system, called the Image Reconstruction and Analysis Facility, that draws the picture. These sensors are as much as 100 times as sensitive as the ones they replace.

So far, the new array detectors have been used with the 50-inch and 84-inch telescopes at the Kitt Peak National Observatory near Tucson, Ariz. "For many applications at these wavelengths [1 to 5 microns]," says Frederick Gillett, a Kitt Peak astronomer who is project scientist on the infrared-detector team, the 50-inch telescope has thus become "the most powerful infrared telescope in the world." However, he sounds eager to get the detectors on a 4-meter-class telescope. Such a coupling will produce "an altogether new game," he says. "You can carry out observations you wouldn't have dreamed of doing in the past."



Sensor (center) at focus of telescope makes image (right) via computer.

NOAO

Among the areas of astronomy in which infrared of this range is particularly useful are: searches for areas where new stars are forming; searches for dark companions, either planets or brown dwarf stars, bound to visible stars; surveys of redshifts and therefore distances of other galaxies; investigations of the center of our own galaxy, which is obscured in visible light but comes through in infrared; and studies of the planets of our own solar system. "The second night we had this array, we imaged the rings around Uranus," Gillett says.

The Santa Barbara Research Center, a subsidiary of Hughes Aircraft, developed the arrays. Of the four now in existence, one will soon go to the Cerro Tololo Inter-American Observatory at La Serena, Chile. Eventually the 50-inch, 84-inch and 4-meter telescopes at Kitt Peak and the 50-inch and 4-meter telescopes at Cerro Tololo will get them. — *D.E. Thomsen*

Worldwide progress in ozone talks

Thirty-one nations meeting in Geneva last week agreed in principle to freeze and eventually reduce the production of some chemicals that attack stratospheric ozone. At issue are chlorofluorocarbons (CFCs) — synthetic compounds used in refrigeration, foam production and other products. These chemicals are thought to deplete stratospheric ozone, which shields life on earth from harmful ultraviolet radiation (SN: 11/15/86, p.308).

The proposed protocol, says Richard E. Benedick, the U.S. representative to the recent Geneva talks, is a "landmark international agreement. It's the first time the countries of the world are in the process of agreeing to take an action to control potentially dangerous chemicals before there's actual evidence of damage."

For several years, the United Nations Environment Programme has been shepherding the negotiations of protocols, or specific schedules of international CFC controls, under the Vienna Convention for the Protection of the Ozone Layer. Benedick says he is optimistic that a final protocol agreement will be concluded this year. A diplomatic meeting is scheduled to take place in Montreal this September.

According to Benedick, the protocol draft calls for a 1990 freeze of the production of at least two CFCs, CFC-11 and CFC-12, at 1986 levels. It then proposes a 20 percent production cut in 1992 and gives signatories the option of voting for an additional 30 percent cut in the late 1990s. Delegates still have to negotiate an exact timetable and which specific chemicals are to be included in the final agreement.

Benedick says the working text is consistent with the three principles expounded by U.S. representatives going into the talks: a near-term freeze, a long-term reduction of production levels of up to 95 percent and periodic reevaluations in light of emerging scientific data.

The United States, which has been one of the countries pushing for tighter international CFC controls, banned the nonessential use of CFCs in aerosols in 1978. On May 1, the Environmental Protection Agency (EPA) was scheduled to announce whether additional U.S. regulations are warranted. (EPA had agreed to consider further controls as part of a settlement in a suit brought by the Natural Resources Defense Council.) But last week EPA and NRDC together asked for an extension of the deadline so that discussions between the two parties could continue. According to an EPA spokesman, the agency also did not want to jeopardize the international negotiations with any new unilateral U.S. policy. — *S. Weisburd*