the solar system as a whole, as well as the insights that other planets can provide into understanding *our* planet. Its recommendations include surface landers and sensor networks on all the rocky planets of the inner solar system—Mercury, Venus, the moon, and Mars—together with samples returned from all but Mercury; orbiters and atmospheric probes for all the gas giant planets of the outer solar system—Jupiter, Saturn, Uranus, and Neptune—as well as an orbiter for icy Pluto; landers for Jupiter's moon Io and Saturn's moon Titan; and rendezvous/sample-return missions to a variety of comets and asteroids. The board also recommended that Mars, as the most Earth-like of the planets, should be the subject of more extensive investigation and perhaps even human exploration—but only as a supplement to the baseline program, not as a substitute.

■ **Solar system space physics.** The board emphasized a better understanding of the physics of the sun, and of the processes that link solar variability to phenomena on the earth. Among its recommendations are high-resolution x-ray and ultraviolet telescopes to study the small-scale phenomena on the surface of the sun that are thought to play a critical role in generating solar flares and the solar wind; a solar probe mission to carry instruments to within 2 million kilometers of the sun's surface; a high-speed interstellar probe that would reach the edge of the sun's magnetosphere within 10 years; and new instrumentation for large-scale monitoring of the earth's magnetosphere.

■ **Astronomy and astrophysics.** The board pointed out that space offers unique opportunities for large imaging interferometers, in which orbiting arrays of optical, infrared, or radio telescopes would combine their beams to form images of distant galaxies and quasars that are hundreds of times sharper than those of the Hubble Space Telescope; and for individual telescopes with very large collecting areas—say a 16-meter optical telescope, or an imaging gamma-ray telescope—that could gather in scarce photons by the bucketful. The board also called for a new high-resolution cosmic-ray spectrometer using superconducting magnets.

■ **Fundamental physics and chemistry.** The board saw many opportunities for high-sensitivity tests of general relativity and gravity, using techniques such as laser ranging to reveal the effects of low-frequency gravity waves on the position of spacecraft. Also addressed was the possibility of studying the small-scale behavior of matter under conditions of weightlessness—the "materials processing" research that NASA has advanced as a major rationale for its multi-billion dollar space station. The board agreed that there is interesting work to be done in this area. However, the report pointedly noted that very little is really known about the basic scientific questions, "[and] until these are answered, there does not seem to be any way to structure a rational program of materials processing in space."

■ **Life sciences.** Among the most urgent areas in this field, assuming that the nation eventually decides to attempt a manned lunar base or a manned expedition to Mars, is space medicine. Top priorities are a better understanding of how weightlessness degrades bone and muscle, what kind of shielding astronauts would need in the interplanetary radiation environment, and what it would take to build a reliable "ecosystem" for recycling wastes on missions of long duration.

The latter recommendations notwithstanding, one very clear undercurrent at the symposium, and in the report itself, is the community's abiding bitterness at NASA's manned space program. As pointed out by NASA's Fisk, himself a space plasma physicist, the agency's science programs have always gotten plenty of money, "but we weren't allowed to spend it wisely." Researchers were required to use the shuttle whether they needed the manned capability or not—and then to watch their missions multiply in costs because of the endless and finally catastrophic delays in the shuttle. Not surprisingly, they now tend to be deeply suspicious that the same thing will happen again as NASA keeps pushing for its space station.

Thus, the report's strongest recommendation: a call to make science "an objective no less central to the space program of the United States than any other." It was left to the reader to decide whether this meant that space science should somehow be separated from NASA. But for his part, said Donahue, "I think the possibility should be discussed."

■ M. MITCHELL WALDROP

Turning Down the Heat on Thin Films

Superconducting thin films will be essential to any practical application of superconductivity to microelectronics. Scientists have now succeeded in putting these thin films onto silicon, which is the base element in most integrated circuits.

RECENT ANNOUNCEMENTS and publications indicate that superconductivity researchers have made an important breakthrough in processing high-temperature superconductors. Teams at several labs across the country have found ways to make thin films of superconducting yttrium-barium-copper-oxygen at significantly lower temperatures. Although the breakthrough may not have the drama or media appeal of discovering yet another record-setting superconductor, it could have just as much practical importance in the long run.

Thin films are the key to what many experts see as one of the most valuable applications of high-temperature superconductors: use in integrated circuits and computers. Since integrated circuits are made by laying down thin layers of different materials and etching those materials in different patterns to form electronic circuits and components, researchers have been working on molding the high-temperature superconductors into thin films for over a year.

There has been some success in this work. Researchers have made very high quality thin films out of not only the Y-Ba-Cu-O compound but also the recently discovered thallium-based superconductors. The problem is that these films had been made under conditions that would not transfer well to semiconductor manufacturing.

To integrate superconducting thin films into existing semiconductor technology, the films need to be placed on silicon, which is the basic material on which almost the entire semiconductor industry is based. But the techniques for making superconducting films, while successful with specialized base layers, or substrates, broke down in the presence of silicon. The problem was that the temperatures used in the processing were too high.

The processing techniques for making a superconducting thin film vary, but they have certain steps in common. The substrate must be heated and bombarded with atoms or molecules of the materials that will make up the superconducting layer. Then once the thin film condenses onto the substrate, the material generally needs an oxygen treatment at 850°C or higher to transform it from a non-superconducting form to one that is superconducting.

Unfortunately, if this is done on a silicon substrate, the high temperatures in the processing cause the superconductor to react with the silicon molecules, changing the composition of the thin film and killing its superconductivity. Until recently, the only good superconducting thin films were made on substrates, such as strontium titanate or sapphire, that do not react with the superconducting film at such temperatures.

Now several groups have succeeded in putting superconducting thin films on silicon substrates by lowering the temperatures used in processing. Although the quality of these films is still not as good as those on other substrates, it is improving rapidly as researchers experiment with ways to modify the processing technique.

Researchers at the University of Texas were among the first to report superconducting thin films on silicon. Using a technique called electron beam evaporation and keeping the temperature of the substrate at a relatively cool 540°C, and also avoiding the extra step of annealing the thin film after it was deposited, the group produced samples that lost electrical resistance at 68 K. Alex de Lozanne, the physicist who led the group, said he believed this to be at the time the highest critical temperature ever produced in thin films on silicon. (Thin films of the yttrium-barium-copper-oxygen material de Lozanne used have critical temperatures as high as 92 K on other substrates with other processing techniques.)

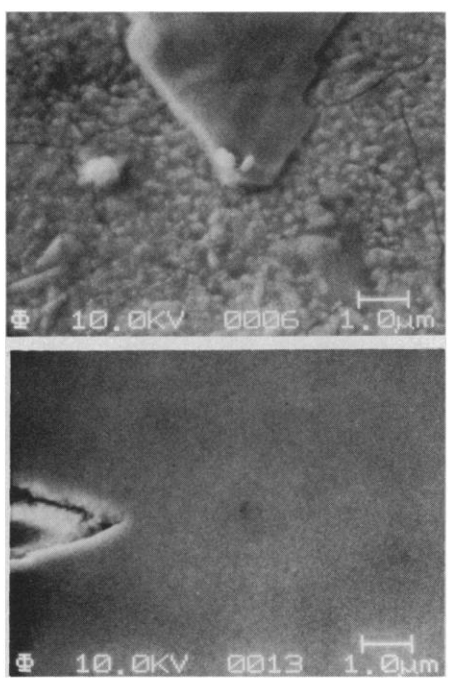
Wen Lee and colleagues at IBM Almaden Research Center announced similar results with a different method shortly after the University of Texas group. With the temperature of the substrate at 650°C, the IBM team used a method called magnetron sputtering to produce thin films on silicon that lost resistance at 76 K. And at Bell Communications Research (Bellcore), scientists used a laser vaporization technique that kept the temperature of the substrate around 600°C and produced a thin film that became superconducting at 67 K. Venky Venkatesan at Bellcore noted that the temperatures were measured at the substrate holder and that the temperatures on the substrate surface, where the thin film was being deposited, were actually much lower.

The key to all three techniques was keeping the substrate at a temperature low enough that the silicon did not react too much with the thin film as it was being deposited. The IBM group found, for example, that heating the substrate holder to 700°C instead of 650°C considerably degraded the superconductivity of the film, reducing its critical temperature from 76 K to less than 50 K.

On the other hand, reducing the processing temperature past a certain point also extracts a price. The IBM results showed the critical temperature dropped to about 60 K when the substrate holder was heated to only 600°C.

Despite the success with thin films on silicon, they still fall far short of superconducting thin films on friendlier substrates. With high-temperature processing, yttrium-barium-copper-oxygen films on strontium titanate lose resistance at 92 K, and several labs say they can get films nearly as good on strontium titanate using a much lower processing temperature.

De Lozanne, for instance, reports films on strontium titanate made with a substrate temperature of 570°C that have critical temperatures up to 84 K, and Bellcore is getting temperatures near 90 K. Venkatesan at Bellcore said his group is making thin films on strontium titanate that are nearly perfect crystals, even at substrate temperatures of 650°C and lower. A group at the State University of New York at Buffalo has reported an 85 K critical temperature on a strontium titanate substrate from a process with temperatures as low as 580°C. And researchers at Cornell University have made thin films on yttria-stabilized zirconia with a critical temperature of 86 K via a process at 625°C.



A thin film *made with Bellcore's low-temperature technique (below) is much smoother than one made at higher temperatures. The spot on the low-temperature surface was created on purpose to help focus the microscope.*

In addition to the relatively low processing temperatures, the techniques developed by these different groups carry a bonus: The thin films were superconducting as they were deposited on the substrate and did not need an extra annealing step, where the film is heated and cooled in the presence of oxygen. With earlier processing methods, the thin film as first deposited onto the substrate was not superconducting and had to be annealed.

One further plus is that at least some of the low-temperature processing techniques produce thin films with much smoother surfaces than the high-temperature methods. Venkatesan said high-temperature processing produces "rough surfaces and huge cracks that look like the Grand Canyon when viewed through a microscope." Such a surface makes it difficult to form the tiny patterns used in electronic circuits because the cracks may cause breaks in the individual components. "Our technique produces the smoothest surface I am aware of—bumps of less than 100 angstroms, compared with 5000 angstroms for high-temperature annealed superconductors," Venkatesan said, although he added the technique does not get such results consistently.

But despite the success of the low-temperature techniques and the ability to put superconducting thin films on silicon, several barriers remain to practical application. The thin films on silicon still do not have nearly as high critical temperatures as do bulk materials or thin films on other substrates, nor can the films on silicon carry nearly enough current to be useful in most applications, such as interconnects on computer chips. Wen Lee at IBM Almaden said it will be difficult to increase the critical temperature of these films because of the mismatch between the silicon and the Y-Ba-Cu-O superconductor. Not only do their crystalline structures not align well, but their thermal properties differ, so that one shrinks more rapidly than the other when cooling, creating a large strain at their interface. This strain leads to cracking, which limits the quality of the film.

Paul Grant, also at IBM Almaden, summed it up by noting that a number of serious problems—and probably a number of years—remain before IBM can expect to use high-temperature superconducting components in its computers. "The outlook is cautionary right now," he said, "but we're working hard to overcome them [the problems]." ■ ROBERT POOL