HIGH-TEMPERATURE SUPERCONDUCTIVITY

Slim-Look Superconductors Lead the Applications Race

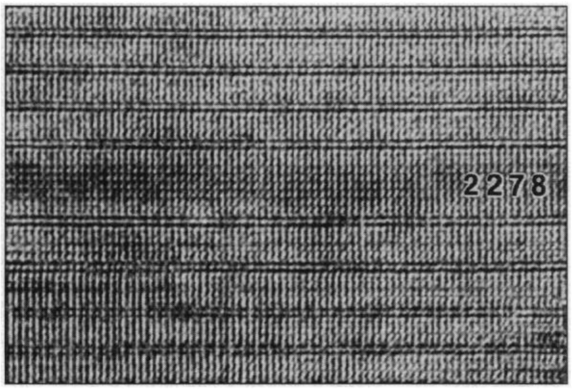
When Georg Bednorz and Alex Müller discovered high-temperature superconductivity (HTS) 10 years ago at IBM's research labs near Zurich, newspapers, magazines, and TV news reports across the world were soon filled with forecasts of super-efficient power lines, trains floating along at unimaginable speeds levitated by superconducting magnets, and swift, silent ships powered by magnetohydrodynamic drives. Chunks of these new ceramic materials, which can conduct electricity free from all resistance at temperatures high enough to require only cheap liquid nitrogen as a coolant rather than expensive liquid helium, would pave the way to the technological future.

A decade down the line, however, many researchers are thinking not of chunks of HTS material, but of thin films. Most of the so-called bulk applications of HTS materials have been relegated to distant dreams by the materials' poor mechanical properties—they are brittle and crumbly—and their inability to carry large currents. But brawn isn't everything: Superconductors have other talents that don't require long wires and coils or high currents. Electronic devices made from HTS ceramics have some remarkable properties, and to make them all you need is a thin layer of the ceramic grown on a rigid substrate of another material to protect it from bending and cracking.

"There are some major advantages of working with thin films, even if you are interested in basic physics," says Ivan Bozovic of Varian Associates in Palo Alto. Growing the ceramics on a substrate lets researchers obtain larger pieces of homogeneous material, without the boundaries between crystals that impede the flow of current. Also, it is much easier to control the composition of the HTS material in a film, for example, by introducing small amounts of other elements. As a result, it is in the form of thin films that HTS materials are finding their way into practical uses, such as super-sensitive magnetic detectors used for medical diagnosis and very narrow-waveband microwave filters for communications.

Researchers have not given up on the bulk applications they once dreamed of; plenty of laboratories are learning how to make HTS materials into flexible wires that can carry high currents. At the moment, however, thin-film research has the edge, but it is not without its own challenges. Thin-film researchers were used to dealing with the materials used in the semiconductor industry: crystalline silicon, metal, or simple compounds such as gallium arsenide. HTS ceramics, in contrast, are made up of four or more different elements, arranged in a complex crystal structure.

To build up these molecular structures, atom by atom and layer by layer, researchers have refined several film-deposition techniques. "We learned to deposit materials that are very complicated in terms of numbers of components, which 10 years ago nobody would have dared making," says Bertram Batlogg of Lucent Technology's Bell Laboratories (formerly AT&T Bell Labs) in Murray Hill, New Jersey, and a director of the Consortium for Superconducting Electronics (CSE), a group of companies and institutions working in the field. By now, he says, "We have lost the fear of making complicated materials because we learned how to deposit them in thin-film form." Indeed, the skills needed to make HTS thin films are now being applied to other thin-film materials, such as magnetic multilayers. Says Malcolm Beasley of Stanford University: "It has profoundly changed the world of people who make films."



Clean connection. Superconducting junction grown by molecular-beam epitaxy with almost atomically perfect interfaces.

I. BOZOVIC, ET AL., JOURNAL OF SUPERCONDUCTIVITY 7, 1, 1994

Films star. The advantages of turning HTS materials into thin films were evident from the start because of the ease and speed with which films can be created and incorporated into devices, says Jan Aarts of Leiden University in the Netherlands. As a result, "if a new HTS material made its appearance, people looked immediately for the possibility of making films," he says.

At first, however, the creation of HTS thin films was a hit-or-miss affair: You put your substrate wafer in a vacuum chamber, inserted the right mix of ingredients as a vapor above it, and waited to see how they settled on the wafer. Such an approach might work for a simple compound, but HTS materials—there are now more than 100 of them—have a layered structure with different constituents in each layer. Researchers wanted to be able to alter the mix of ingredients over time and so control the contents of each layer as it was deposited. Soon researchers were exploring more sophisticated film-deposition technologies, such as sputtering, molecular beam epitaxy, and laser ablation, and refining them for their own needs. To control these processes, they soon began monitoring the growing layers using laser spectroscopy and other methods. "I don't believe anybody is going to build up a serious commercial technology with a simple evaporator and a stopwatch," say Beasley.

One technique that made an early impact was laser ablation (also see Lowndes *et al.*, p. 898). The wafer shares a chamber with several targets, each made of one of the necessary ingredients. As each ingredient is needed, the relevant target is blasted with a laser beam to evaporate off the required amount of that element. "This technique expanded very quickly and became very powerful," says Aarts. "Its great advantage is that it is very fast, especially if you are searching for the right composition and physical conditions."

Oxygen—an essential component in all HTS ceramics—cannot be deposited by laser ablation or evaporation, so researchers have had to find other ways to create the necessary oxide layers. Usually, for the different deposition methods, the oxygen is released into the vacuum chamber at appropriate moments, or the wafer is cooled down and exposed to oxygen to enhance the oxidation process. One elegant solution was pioneered by a team at the Technical University of Munich in Garching. The solid ingredients are placed on tungsten strips in a vacuum chamber and precise amounts of current are passed through the strips to evaporate off just the right amount of each ingredient. The innovation is that the wafer rotates on a turntable that periodically takes it out of the main vacuum chamber into another chamber containing oxygen at a higher pressure, which creates successive oxide layers. The team has produced films of one HTS material, YBCO, on wafers up to 20 centimeters in diameter—the largest in the world—and is now supplying them to Conductus, a U.S. maker of superconducting devices. "We convinced them so well that they copied our machine and have it running now," says the Technical University's Helmut Kinder.

Another technique that is beginning to revolutionize the making of HTS thin films is molecular beam epitaxy (MBE). In this technique, the atoms or molecules to be deposited are evaporated by heating and directed in beams towards the wafer. MBE allows growth of thin films to be strictly controlled—down to the atomic level—by altering the rate of evaporation and interrupting the beam to stop deposition of a particular layer. Jim Eckstein at Varian says that with such MBE systems they can now synthesize the first "artificial" superconductors: "We have mastered this technique to the extent that we are able to synthesize multilayers and even compounds that are metastable, that cannot exist in nature," says Bozovic. "It is really pioneering work," comments Horst Rogalla of Twente University in Enschede, the Netherlands. "This gives us the possibility to 'engineer' the properties of the material."

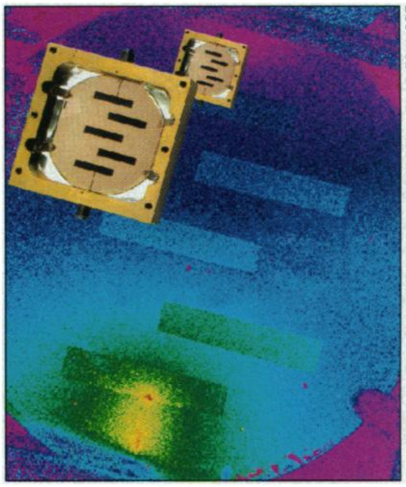
Warmed-up SQUIDs. Once researchers had a certain mastery in making HTS films and integrated circuits, they began making devices, and an obvious candidate was the superconducting quantum interference device, or SQUID—a sensitive detector of magnetic fields and a candidate for the circuits of future computers. SQUIDs have been around since the 1970s, but they had been made from conventional low-temperature superconductors, which have to be cooled to close to zero kelvin.

A SQUID is a superconducting loop made of a thin film deposited on a suitable substrate and incorporating two "weak links," known as Josephson junctions. These junctions get their name from the Josephson effect: If two pieces of superconductor are separated by a thin layer of insulating material, some superconducting electrons can "cheat" and tunnel through the insulator. The current that passes through the insulator is very sensitive to magnetic fields, and the voltage across the junction varies in an unusual way: When the current through the junction is low, the voltage across it is 0 volts, but when it is increased to a certain critical current the voltage suddenly jumps. These well defined "on" and "off" states could suit the junction for use in logic circuits.

Thin-film HTS Josephson junctions at first proved difficult to make, and their performance today is still below that of their low-temperature cousins. A major problem is noise: At the higher temperatures made possible by HTS materials, gremlins known as magnetic vortices—tiny "tornadoes" of magnetic field lines—sneak into the material from outside and move randomly in the superconducting films. "You get a random 'telegraph noise.' If you have a SQUID nearby, the SQUID itself will detect it," says Rogalla.

Researchers are working on two approaches to this problem. Firstly, they are trying to "pin" the vortices in one place. HTS materials used for creating SQUIDs contain imperfections in their crystal structure. These flaws attract vortices and can hold them still and so reduce noise. The second approach is to make very high-quality devices; avoiding imperfections makes it harder for an ambient magnetic field to infiltrate the material. "Just by taking great care when you etch the films ... and by carefully handling the films you can reduce some of the noise associated with the motion of vortices," says John Miller of the University of Houston.

Now that such problems are beginning to be ironed out, researchers are confident that their HTS devices will soon be in widespread use. "With HTS materials at liquid nitrogen temperatures we are now reaching nearly the sensitivity of SQUIDs made from classical materials cooled to 4.2 Kelvin," says Rogalla. Some HTS SQUIDs are now becoming commercially available, and are being put to use measuring the subtle magnetic fields produced by the heart and brain for medical research and diagnosis.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Cold filtered. Superconducting microwave filter warms up above 50 K at full power.

The other talent of Josephson junctions—their ability to adopt two discrete voltage states—has also prompted much research because of the high speed at which the junctions can switch states. "The logic is incredibly fast," says Rogalla. "We are looking at clock frequencies of 100 gigahertz or higher." Such speeds would revolutionize memory chips, allowing computers to access data much more quickly. But researchers have not yet refined their processing techniques sufficiently to make good electrical connections to superconducting films and to make the junctions small enough to cram huge numbers on a chip. The largest HTS memory devices built so far have a capacity in the order of 4 kilobytes, compared to the 4-megabyte chips used in computers today.

The mobile-phone connection. In addition to active devices such as SQUIDs, HTS films are also making major inroads in a second group of applications, so-called passive superconducting devices used to receive or filter high-frequency radio signals. "It was clear to a lot of people very early in the HTS phenomenon that passive radio-frequency will be an early potential application simply because it makes the least demands on the films. A lot of people with foresight saw that," says Beasley.

Superconductors are appealing for carrying microwave signals because currents at microwave frequencies flow not in the bulk of a conductor but in a very thin layer on its outer surface. As all the current is crammed into this small volume, any resistance in the conductor puts up a considerable barrier, so microwave engineers strive to find materials with the lowest possible resistance for their devices. "[HTS] materials do clearly give a performance that you cannot get any other way," says Beasley. As a result, big corporate players such as AT&T soon got involved in passive HTS devices because of their potential importance in communications.

The key devices are superconducting microwave filters, which consist of tiny loops or coils of superconducting films deposited on suitable substrates. The very low resistance of the coils allows engineers to tune them to a very narrow frequency band, so they can, for example, cram a much larger number of communication channels into a given frequency range. Such a filter would sit at the top of a receiving tower for cellular telephone signals, tuning antennas to the right frequency. "This is commercially the most promising application of [HTS] thin films—anything that can be done in the communication business certainly is very important," says Batlogg.

Many researchers believe communications will dominate early uses of HTS materials. "It is the application that currently drives the field," says Bozovic. But as they become more skilled at making thin-film devices and integrating them with other electronics, new uses will emerge. "In the long term we will see really sophisticated circuits that will combine superconducting sensors like SQUIDs, and superconducting digital electronics, with all the processing done on chip. This, I feel, will be the future," says Bozovic. Although this will not be the technological revolution many people originally expected, it will be a revolution nonetheless—a cool and quiet revolution.

–Alexander Hellemans

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