

HIGH- T_c THIN FILMS AND ELECTRONIC DEVICES

Only five years after the discovery of high-temperature superconductors, researchers have succeeded in developing a variety of useful circuits and devices using thin films of these new materials.

Randy Simon

A worldwide effort to develop high-temperature-superconductor thin films and electronic devices began within weeks of the initial discovery in early 1987 of superconductivity above liquid-nitrogen temperature. The ensuing period has seen remarkable progress, spurred by innovations in deposition technology, materials characterization and device design. Prospects for practical electronic applications of superconductivity have driven the development of high-temperature-superconductor thin-film technology at an unprecedented pace. After five years researchers in the field have surmounted many of the initial hurdles in developing the new materials, and they are now working toward the first practical implementations of high-temperature-superconductor electronic technology.

The applications of superconducting thin films range from those requiring only single layers of superconductor—such as simple interconnects, infrared sensors and many passive microwave devices—to those based on complex multilayer circuit processes—including more sophisticated interconnect applications; SQUID (superconducting quantum interference device) magnetometers (see figure 1); and Josephson integrated circuits. Thus, the development of high-temperature-superconductor electronic technology requires developing considerably more than the superconducting films themselves. It also entails the development of a multilayer device technology that encompasses dielectric and normal-metal films, and most significantly, the development of active devices in the form of Josephson junctions.

So far, progress in all the essential areas of high-temperature-superconductor thin-film technology has been substantial. There have already been laboratory demonstrations of all the single-layer applications listed

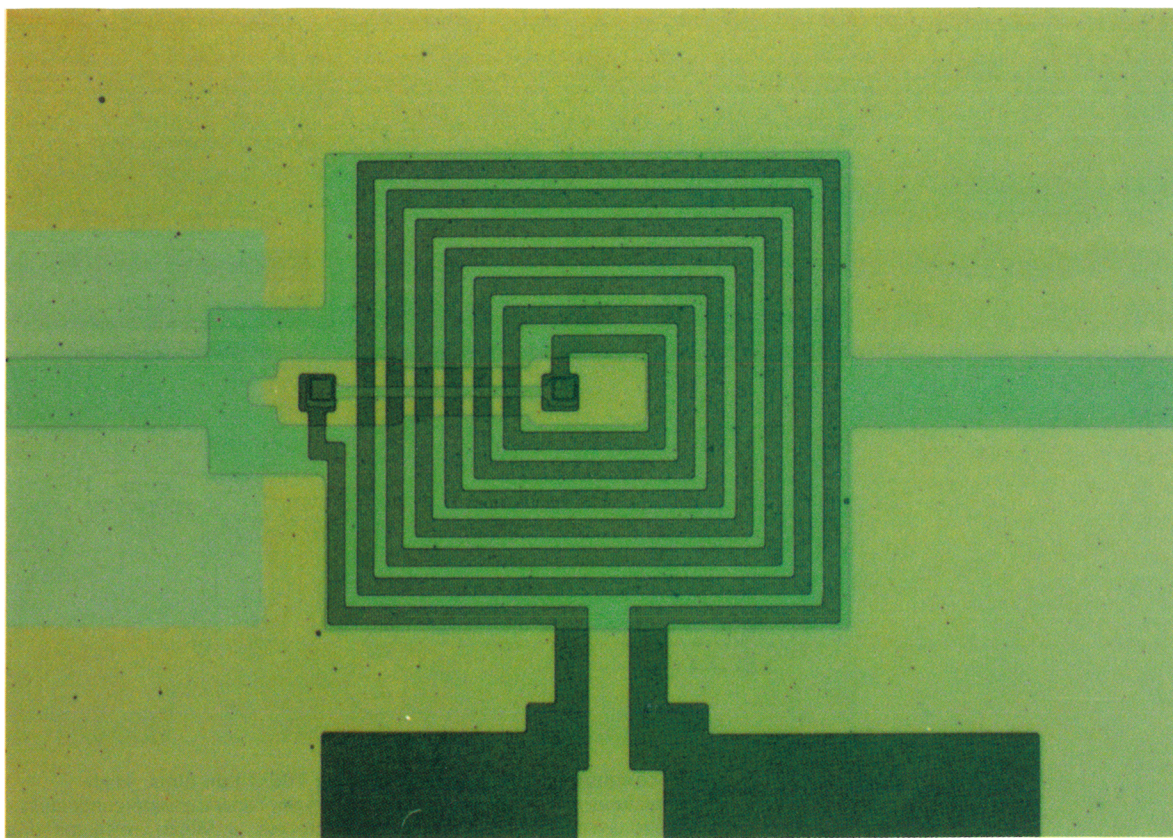
above; multilayer applications are now under development.

Making the new superconductor thin films

The high-temperature-superconducting cuprates and the other new oxide superconductors were first synthesized by ceramic techniques—typically, the mixing, grinding and baking of powdered reagents. The resulting samples were suitable for identifying the presence of new superconducting phases but bore little resemblance to practical materials such as thin films or wires. Single-crystal samples of cuprate superconductors have provided much of our understanding of their fundamental properties but are far too small for practical applications. Thus, as soon as these new materials were identified, researchers began working to try to make them into thin films and useful bulk conductors. Producing films was thought to be a simpler task than fabricating practical wires from complex oxide materials, and this has proved to be the case. As a result, electronic applications are widely believed to be closer to implementation than wire-based, large-scale applications.

Existing thin-film conventional superconductor technology is based on relatively simple materials that can be made with relatively unsophisticated growth processes. The important materials for conventional superconductive electronics—lead in earlier days, niobium today—are rather forgiving with respect to crystalline quality, substrate choice and compatibility with associated materials, but these materials only superconduct in the 7–9-K range. The evolution of niobium nitride (with a T_c of 16 K) as a third-generation superconductive circuit material has been hampered by both its material properties (high growth temperatures) and some of its superconducting properties (for example, its large penetration depth). Nevertheless, it is a cubic (rock salt or B1) crystal containing only two elements and is therefore a far more simple system to develop than any of the high-temperature superconductor oxides. The erstwhile high-tempera-

Randy Simon is director of research and development at Conductus Inc, in Sunnyvale, California.



YBCO sQUID magnetometer fabricated by Conductus Inc integrates high- T_c superconductor bi-epitaxial Josephson junctions and a multiturn flux transformer for the first time. **Figure 1**

ture superconductors of the A-15 family—those having a beta-tungsten structure, with critical temperatures in the 20-K range—share some of the complexities of the oxides, and these materials have never been developed into integrated circuits.

The prospect of superconductor applications at the much higher temperatures afforded by the cuprates has stimulated a development effort of unprecedented magnitude. Yet these efforts to develop high-temperature-superconductor devices have faced a unique set of challenges. The superconducting cuprates are highly anisotropic, layered compounds containing from three to five metallic elements plus oxygen, and their properties are highly sensitive to crystal structure and oxygen content. In addition, the constituent elements and perhaps even the superconducting materials themselves are highly reactive with a variety of other materials. This reactivity severely limits the choice of substrates and associated materials (dielectric and normal-metal layers) for making multilayer circuits. Because crystallization occurs only at elevated temperatures (600–900 °C), cuprate superconductor films must be made at very high temperatures (above 700 °C) or at least must be annealed in oxygen at high temperature. Furthermore, the likelihood of forming other equilibrium phases of the cuprate compound is sensitive to temperature and oxygen (and in some cases even heavy-metal) vapor pressure. All these factors conspire to make thin-film development a difficult task.

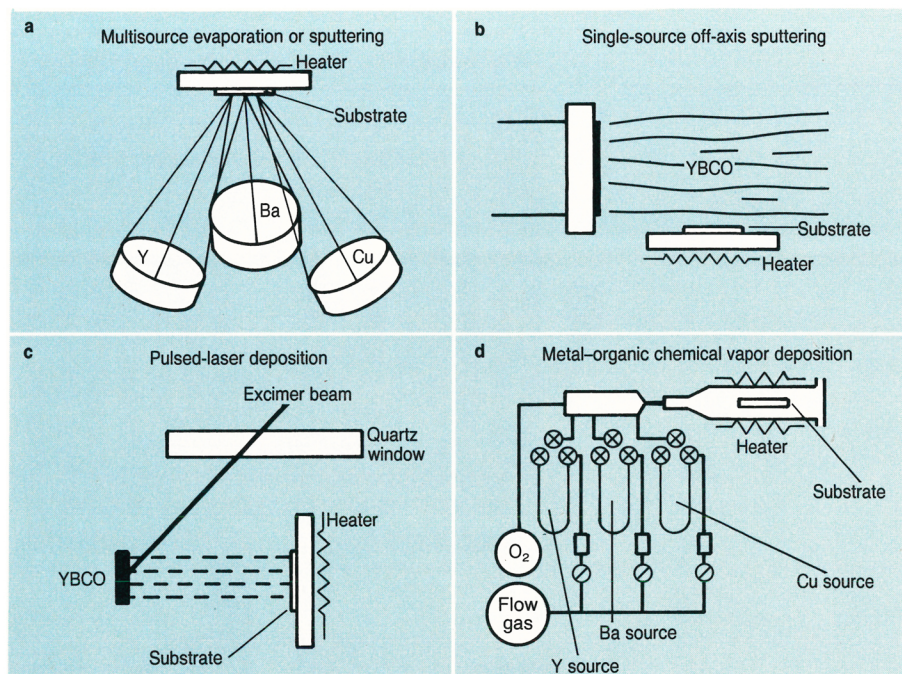
Apart from the materials science issues, there are aspects of the electronic properties of cuprate superconductors that may differ in important ways from those of conventional superconductors. While the basic properties of the cuprates have been well understood for quite some time, there is no consensus on the nature and origin of

electron pairing in the superconducting cuprates. The mechanisms for flux pinning and the sources of magnetic noise in these materials are not understood. Furthermore, the very existence of the energy gap in the electronic density of states—a fundamental parameter in the Bardeen-Cooper-Schrieffer theory of superconductivity—is controversial for the cuprates. Nevertheless, despite a diversity of unfinished business for physicists and materials scientists, deposition of high-quality high-temperature-superconductor thin films has become a routine task in numerous laboratories around the world.

YBCO films

The first compound found to superconduct above 77 K and the most widely studied of the new superconducting materials is $\text{YBa}_2\text{Cu}_3\text{O}_7$ (or YBCO), known as “1-2-3” for the ratio of its atoms. Researchers learned their first lesson about the highly anisotropic superconducting cuprates from this material: Optimum superconducting properties can only be obtained from samples with a high degree of crystalline order and phase purity. In the course of learning this lesson, researchers have deposited YBCO thin films using every available means of physical vapor deposition, as well as a variety of chemical vapor-phase and liquid-phase techniques. Even after four years of study, new deposition methods continue to be explored. Nevertheless, the research community has settled upon a handful of techniques for the overwhelming majority of its work.

One can make YBCO thin films from independent sources of the three cations or from a single source composed of the superconducting compound, or at least a stoichiometric mixture of its constituents (see figure 2). Single-source techniques have the virtue of simplicity. In



Four common techniques for depositing YBCO thin films. High temperatures and a sufficient amount of oxygen allow the superconducting phase to crystallize during the deposition process. **a:** Metals are sputtered or evaporated from separate sources onto a heated substrate. **b:** To produce stoichiometric films, a stoichiometric YBCO target supplies material to a heated substrate that is situated outside the sputtering plasma at right angles to the sputter gun. **c:** A high-energy laser pulse vaporizes from a stoichiometric YBCO target a small quantity of material, which deposits onto a heated substrate. **d:** Organic precursor compounds bearing the required metal atoms are heated, and an inert gas mixed with oxygen transports the resultant vapors into a reactor vessel containing a heated substrate, onto which the vapor is deposited. (Adapted with permission from *Solid State Technology*, September 1989, page 141.) **Figure 2**

fact, the most widely used deposition techniques today are sputtering and pulsed-laser deposition, both of which use sintered YBCO disks as target material. Other popular techniques include metal-organic chemical vapor deposition and multisource evaporation—in which the barium source is in the form of BaF_2 . Multisource evaporation techniques require an elaborate post-deposition procedure to produce the superconducting phase. An advantage of the evaporation technique¹ (see figure 2a) is that deposition takes place at room temperature, greatly simplifying processing. In contrast, the *in situ* techniques—in which the superconducting phase crystallizes during deposition—require growth temperatures from 650–760 °C. Even higher growth temperatures are needed in the case of metal-organic chemical vapor deposition.

Sputtering (a process by which atoms are evaporated from a cathode target by bombardment from a gas plasma) has long been the workhorse technique for deposition of conventional superconductor thin films. Many of the early studies of YBCO films were based on sputtering from three metallic targets, but sputtering from a single source is a simpler and more reliable process. However, conventional sputter geometries do not yield stoichiometric films from stoichiometric target materials, because negative ions produced by the sputtering process can preferentially remove freshly sputtered material from the substrate and alter the stoichiometry of the film. To reduce this effect, novel sputtering schemes have been developed in which

the substrates are positioned outside of the sputtering plasma. One of these—the off-axis technique² (see figure 2b)—has become a standard technique in many research labs; enhancements have enabled its use for coating 5-cm wafers with good film uniformity.³ A drawback of this technique is that it has extremely slow deposition rates: Typically only a few tens of nanometers of YBCO are deposited in an hour.

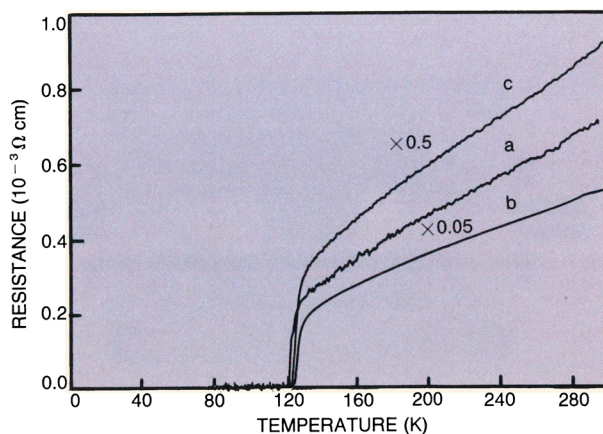
While sputtering is a standard method for depositing a variety of materials, pulsed-laser deposition—a much faster technique than off-axis sputtering—has gained acceptance specifically for making oxide superconductor thin films⁴ (see figure 2c). This technique is well suited to the stoichiometric deposition of complex oxide materials and multilayers, and the availability of reliable, high-power pulsed lasers has made it practical for use in many laboratories. In the early days the technique was limited by the evaporant plume diameter to depositions of about a centimeter wide, but pulsed-laser deposition is now being scaled up for coating wafers (commonly 5 cm in diameter); schemes to translate or rotate substrates allow much larger films to be produced by this technique.

The properties of YBCO films produced by all techniques are slowly converging toward what may be their practical limits. High-quality thin films are nearly single crystal in character as a result of epitaxial growth on lattice-matched substrates. Such films have critical temperatures as high as 92 K and critical current densities

of 5×10^6 amps/cm² at 77 K and $2-4 \times 10^7$ amps/cm² at 4 K. These critical currents exceed those obtained for single-crystal specimens, perhaps because of the presence in the films of point defects, which enhance flux pinning. However, high current density in YBCO requires both electrical transport along the copper-oxygen layers and samples whose grains are fully oriented in the plane of the substrate. The presence of high-angle grain boundaries reduces critical currents. In-plane misorientation and grain boundaries have even more pronounced effects on the high-frequency properties of the films. Of particular interest is the high-frequency surface resistance of the films, a property that determines the performance of microwave components such as filters and resonators. YBCO films with good in-plane orientation⁵ exhibit 10-GHz surface resistances as low as 10–20 micro-ohms at 4 K and below 300 micro-ohms at 77 K. The high-temperature values are consistent with the expectations of conventional models (derived from the BCS theory) for the electromagnetic response of superconductors, but the low-temperature residual resistances are still orders of magnitude greater than theory predicts. However, such predictions assume the presence of a large energy gap, whereas the existence of an energy gap of any size in the high-temperature superconductors is controversial. A complete description of the nature of the high-frequency losses in YBCO remains to be elucidated.

The best YBCO films have been deposited on lattice-matched perovskite substrates such as SrTiO₃ and LaAlO₃. LaAlO₃ has dielectric properties that may be acceptable for high-frequency applications, but it is not an ideal substrate because of anisotropy associated with a structural phase transition. MgO substrates yield excellent films, but this material has less-than-ideal mechanical properties and is hygroscopic. More recently, buffer-layer technology has made it possible to produce good films on conventional substrates such as silicon⁶ and sapphire⁷: A thin, crystalline layer of SrTiO₃, yttria-stabilized zirconia or MgO deposited epitaxially on the substrate wafer permits the growth of high-quality YBCO films by reducing chemical reactions and providing a template for epitaxial growth (and even allowing in-plane orientation). There are concerns about such issues as anisotropy in sapphire, but buffer-layer technology may provide the best means of obtaining useful substrates for high-temperature-superconductor applications, particularly those that require large-area films.

Although the best superconducting properties are observed in YBCO films in which the current-carrying copper-oxygen layers lie in the plane of their substrates (so-called c-axis films), there are reasons to grow films with other orientations. Under suitable conditions, it is now possible to grow films that are “a-axis oriented”⁸—that is, films in which the copper-oxygen planes are normal to the substrate. Such films allow the maximum coherence-length direction and strongest critical-current direction to be normal to the substrate rather than along its plane. This orientation may be desirable or even necessary for vertical device structures such as sandwich tunnel junc-



Resistive transitions for $\text{Ti}_2\text{Ba}_2\text{Cu}_3\text{O}_{10}$ films show zero resistance above 120 K on three different substrates: LaAlO_3 (a), MgO (b) and Y-ZrO_2 (c). (Data courtesy of W. Y. Lee, IBM Almaden.) **Figure 3**

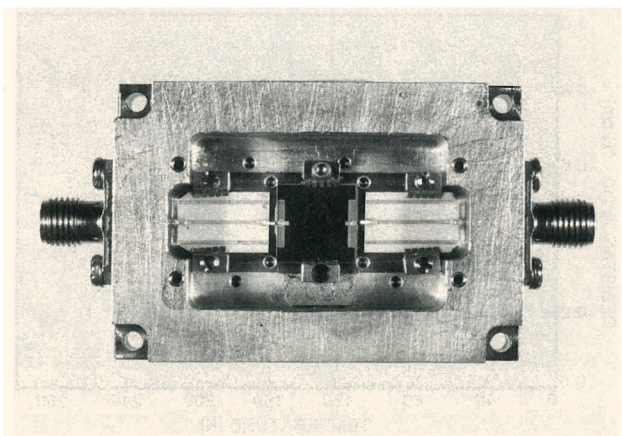
tions. In this regard there have been remarkable demonstrations of controlled deposition technology in the form of superlattices containing multiple cuprate-film layers.⁹

Other oxide superconductor films

YBCO is not the only oxide superconductor being developed in thin-film form. There is great interest in materials with higher critical temperatures and even in some materials with lower critical temperatures. Cuprates based on bismuth and on thallium exhibit superconductivity above 100 K; the thallium compound ($\text{Ti}_2\text{Ba}_2\text{Cu}_3\text{O}_{10}$, or TBCCO), with three copper-oxygen layers, has a critical temperature of 125 K, as shown in figure 3. However, the bismuth and thallium cuprates have even more elements and a greater number of secondary phases than does YBCO. As a result it is very difficult to produce films with nearly ideal properties.

Much of the research on bismuth cuprates has been done in Japan, where the materials were first discovered. Growth of bismuth cuprates by *in situ* techniques is a fairly recent development. To date, the properties of bismuth films and the development of deposition processes do not compare with those of YBCO films. Despite the fact that bismuth-based high-temperature-superconducting wires have exhibited the highest critical current densities reported for any cuprate (although these current densities were measured on samples with lower critical temperatures), even nearly-single-crystal bismuth films generally have lower current densities than epitaxial YBCO films. One exception to this observation is a report¹⁰ in which high critical currents were measured in sputtered films. In any case, another drawback to the bismuth system is that it is extremely difficult to grow thin films of the highest- T_c phase. There has been some success in doping lead into the bismuth-strontium-calcium-cuprate compounds to stabilize the higher- T_c phase, but bismuth-based superconducting thin films with T_c above 100 K are very rare. In fact most of these bismuth films superconduct at a lower temperature than do YBCO films. As a result, these materials continue to receive only minor attention, at least outside of Japan.

The thallium-based cuprates have a somewhat different story. Thin-film synthesis of superconductors with critical temperatures above 100 K has been successful; at least one lab¹¹ routinely makes films with T_c of 120 K.



4.8-GHz YBCO microstrip resonator
fabricated by Superconductor Technologies Inc is one of the microwave devices that has been made from single-layer high-temperature-superconductor thin films on substrates. **Figure 4**

The big stumbling block with thallium superconductors is control of stoichiometry, primarily because of the volatility of thallium-based oxides at cuprate growth temperatures. As a result there are still no *in situ* processes for TBCCO films, and they must therefore be crystallized by elaborate (and often proprietary) post-annealing processes. The properties of the resultant films can be quite good, particularly with respect to microwave losses. The higher T_c of TBCCO gives it an intrinsic advantage at 77 K over YBCO; if a particular application requires 77 K or higher temperatures, thallium superconductors may be the materials of choice.

There appear to be some important differences between TBCCO and YBCO films. Grain boundaries in TBCCO films appear to have very different (and more benign) properties than those of YBCO, particularly with respect to their effects on current transport. The critical currents of TBCCO films can be high, although not as high as those of YBCO films, even at 77 K. This may be due to intrinsically lower flux pinning. However, a real advantage for the thallium-based system is that the critical current of polycrystalline TBCCO films can be orders of magnitude higher than that of YBCO films of comparable structure. On the other hand, of the epitaxial films, YBCO has a clear edge. In contrast, the microwave surface resistance of thallium films at 77 K (and certainly above) is very competitive with that of YBCO, although the power dependence of this property is still inferior.

Apart from these considerations, whether thallium superconductors become significant for electronic applications may depend on the development of a deposition technology that produces smoother films and does not require high-temperature post-deposition processing. The most significant devices and structures of superconductive electronics are based on multilayers containing several superconducting films, dielectrics and other materials. Unless a thallium multilayer technology is developed, many important applications may be precluded.

Thin films of the first discovered cuprate superconductors— $\text{La}_{2-x}\text{Ba}_x\text{CuO}_4$ and $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ —have also been studied but have not attracted the attention of applications-oriented researchers because of their lower critical temperatures. The highest-temperature superconductor that is not a copper oxide compound—

$\text{Ba}_{1-x}\text{K}_x\text{BiO}_3$, or BKB—has become the focus of a growing research effort. The BKB superconductor—with a 30-K T_c —is a cubic, isotropic material and appears to be a conventional BCS-type superconductor, based on studies of the characteristics of tunnel junctions composed of BKB electrodes.¹² While the problems associated with producing high-quality BKB thin films are considerable (the transport properties of today's films are still poor), the potential payoffs for Josephson circuit technology appear to be high.

Microwave thin-film devices

Passive microwave devices such as filters and resonators were among the first successful demonstrations of high-temperature-superconductor thin-film applications (see figure 4). The virtue of such structures is that they can be made from single-layer films on substrates. The performance of microwave components made from superconducting films benefits from surface resistances much lower than those of components made from ordinary metals. Simple high-temperature-superconductor microwave devices are in fact the first thin-film components to be offered for sale in the marketplace. A variety of these microwave devices will be placed in Earth orbit and tested for "space-worthiness" in 1992 as part of an experiment being conducted by the US Naval Research Laboratory.¹³ (See the article by John Rowell on page 22.)

While the performance of simple high-temperature-superconductor filters and resonators has been impressive, the insertion of high-temperature-superconductor technology into real systems will require larger-scale implementation in terms of both the size and number of devices. As 5-cm film technology matures, larger microwave structures, such as delay lines, beam-forming networks and filter banks, become viable. This technology will undoubtedly require improved substrates (or substrate-buffer-layer combinations) that avoid problems with losses, structural irregularities and anisotropy. Researchers have used YBCO and thallium cuprate films to produce good microwave devices, but more advanced high-temperature-superconductor microwave technology will require multilayer technology to produce more sophisticated structures.

Josephson junctions

The key element of superconductive electronics is the Josephson junction—that is, any device structure that allows two regions of superconducting film to weakly couple. (Such a device is called a "weak link.") Although the device of choice traditionally has been the sandwich tunnel junction made from a superconductor-insulator-superconductor (S-I-S) trilayer, to date there has been no demonstration of a cuprate superconductor Josephson junction using the S-I-S geometry. Because of their properties, the cuprate superconductors present challenges in fabricating and perhaps even using such junctions.

The current-voltage characteristics of tunnel junctions are determined by the electronic density of states in the superconductor electrodes that form the junctions.

The high-temperature-superconducting cuprates may well have fundamentally different electronic properties than conventional superconducting materials. For example, as mentioned above, there has been no indisputable evidence of a conventional energy gap in the cuprates. Tunneling measurements on cuprate films and single crystals have revealed reproducible current-voltage characteristics, but those characteristics are certainly not much like those seen in conventional superconductors. Without an energy gap, Josephson tunnel junctions would not have two well-defined voltage states and thus would not be able to operate as hysteretic switching devices. If this is the case, there may be no intrinsic advantage to using tunnel junctions as Josephson devices.

Apart from fundamental physics issues, the practical challenges associated with fabricating cuprate Josephson tunnel junctions are daunting. In this type of device, the superconducting order parameter in each electrode of the junction must have nearly bulk magnitude and lateral uniformity within a coherence length of the tunneling interface. This characteristic length, anisotropic in the cuprates, is only about 20 Å in the favorable directions. This means that producing working junctions will require superb control of material properties on the scale of an individual unit cell. Such practical constraints, in addition to the possibility that fundamental properties may limit the desirability of cuprate tunnel junctions, have led the research community to focus on a variety of alternative Josephson devices.

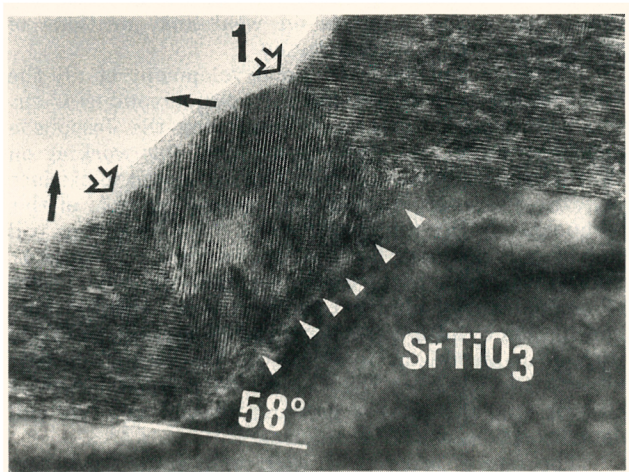
There is a rich history of successful techniques for fabricating Josephson devices, and many of these techniques have now been applied with a fair amount of success to the new materials. Researchers have obtained good results from a diverse set of weak-link Josephson devices in the past few years. However, the earliest cuprate Josephson devices were not made by design: Early cuprate films contained natural weak links in the form of grain boundaries. Using only rudimentary lithographic techniques, researchers could easily isolate a small number of such grain boundary junctions and demonstrate SQUIDS. However, the presence of grain boundaries scattered throughout these films also contributed high levels of noise to the SQUIDS and made them unsuitable for practical applications. The evolution of thin-film deposition technology gradually eliminated most grain boundaries and with them, the inadvertent Josephson junctions. The availability of high-quality films therefore necessitated the development of deliberately engineered Josephson devices.

A "classic" Josephson geometry that has yielded reasonable results has been superconductor-normal-superconductor microbridges. These S-N-S devices can either be made as planar or multilayer devices. Many of the junctions studied to date have used noble metals—silver or gold—as the normal-metal layer. The growth conditions needed for making cuprate films do not allow the fabrication of sandwich junctions that contain noble metals, so researchers have either used single-layer geometries, discontinuous step edges filled in with noble metal¹⁴ or devices containing only one cuprate electrode.

More recently, low-carrier-density normal layers such as $\text{PrBa}_2\text{Cu}_3\text{O}_7$ and Nb-doped SrTiO_3 have been used to make S-N-S junctions.¹⁵ Another standard geometry used for high-temperature-superconductor junctions has been the edge junction, in which Josephson coupling is obtained between two films that meet at an exposed edge of one of the films through either an insulating barrier¹⁶ or a normal metal.¹⁷ This geometry simplifies the fabrication of multilayer junctions, particularly for producing small-area devices.

Because naturally occurring grain boundaries in cuprate films are known to act like Josephson junctions, there has been a great deal of creative work to produce artificial grain boundaries in the films. A successful effort of this sort involved creating a substrate grain boundary by fusing together two substrate crystals with different orientations.¹⁸ A YBCO film grown across such a bicrystal has a clean grain boundary. This technique¹⁹ has been used to produce low-noise SQUIDS that operate at temperatures as high as 87 K. Of course the junctions are limited to the location of the boundary in the fused substrate. Comparable junction results have been achieved by growing films made up of large grains with 45° tilt boundaries.²⁰ Suitable patterning of such films results in devices that contain only a few such boundaries, but there is little chance of extending the technique to complex circuits.

Another successful technique for inducing grain boundaries in high-quality films consists of growing the film over a sharply etched step in a substrate.²¹ In the process of making two abrupt orientational changes the film develops grain boundaries, as shown in figure 5. The step-edge technique provides a high-yield process for making



YBCO step-edge Josephson junction, shown in a cross-sectional transmission-electron-micrograph, exhibits 90° grain boundaries at the edges of the step. (Courtesy of A. Braginski, Forschungszentrum Jülich.) **Figure 5**

junctions and SQUIDS, and in principle can be extended to producing complex circuits.

Very recently, another technique to artificially induce grain boundaries has been developed. By growing appropriate thin buffer layers on sapphire substrates, one can precisely control the in-plane orientation of YBCO films. In this "bi-epitaxial junction," a 45° tilt boundary forms where a YBCO film crosses an underlying thin MgO layer, which closely simulates the structure of the bicrystal junction described above. In this case, however, junctions can be produced at arbitrary locations on the wafer.²² The yield of working devices for this junction process is quite high, and the noise for SQUIDS is encouragingly low. The requirements for many practical applications can already be met with these devices.

With respect to these cuprate Josephson devices in general, a number of unresolved technical issues remain. Perhaps foremost among these concerns is gaining an understanding of the nature of the Josephson coupling in the junctions and the extent to which junction properties can be controlled. The characteristic voltages in cuprate devices are rather low for reasons that are not understood. The low-frequency noise levels in SQUIDS—while approaching useful levels—is still higher than ideal and also not understood. The prospects for enhancing the performance of high-temperature-superconductor junctions will depend on furthering our understanding of the devices themselves.

There is a continuing interest in the application of YBCO devices at 77 K. It is unclear whether any YBCO device will be of practical value at this temperature; it may be too much to ask of any Josephson device for it to function at more than 80% of its T_c ! This is particularly true for circuits, but SQUIDS have noise problems that are exacerbated by diminishing signal levels at 77 K. With its higher critical temperature, TBCCO may offer greater hope for use in 77-K devices. Of course, even if we had conventional Josephson junctions at 77 K, the power consumption associated with increased gap voltages and the larger currents needed to overcome noise might reduce the intrinsic advantages of large-scale Josephson digital circuits. These and other issues continue to be explored. The physics of high-temperature-superconductor Josephson junctions is a rich field of study that may well extend beyond the confines of earlier device designs. In any event, the recent progress on weak-link junctions of several types is quite encouraging.

Progress continues on the development of all the building blocks of high-temperature-superconductor circuit technology. Apart from developing the Josephson junctions themselves, many groups are now working on the multilayer technology that will be needed to produce integrated circuits. A relatively simple example of this technology is the flux transformer—the multitrans coil that couples magnetic flux into SQUIDS (shown in figure 1). Fabricating this structure involves patterning two layers of superconductor film that are electrically isolated from one another by a dielectric layer and connecting the layers through an opening in the dielectric. These tasks exercise most of the technology that is needed for superconductive circuits, and there are a growing number of successful demonstrations of such structures.²³

The rate of progress in high-temperature-superconductor microelectronic technology development has been remarkable compared to that of almost any other advanced material technology. Both thin-film-deposition technology and device processing are evolving rapidly. Much of the effort has been devoted to incorporating the new materials into the design of conventional superconducting devices and structures. The unique characteris-

tics of oxide superconductors have made this task difficult, but in the long run these seemingly intractable properties may provide opportunities for creating entirely new devices and structures. Recent work on a flux-flow transistor²⁴ is an example of how potential drawbacks of high-temperature-superconductor materials can be exploited for electronic devices. Only five years after the discovery of the first high-temperature-superconductor materials, we are in the process of demonstrating a variety of useful circuits and devices.

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