IBM Superconductor Leaps Current Hurdle

Passage of more than 1 million amperes per square centimeter through oriented, crystalline films erases any doubts about low critical currents in the 90 K ceramic superconductors

FOR those interested in the practical applications of superconductors, the critical current density is most often the all-important property. The critical current density is the maximum a superconductor can carry before returning to its normal metallic state. By demonstrating that the new rare earth–barium–copper–oxygen superconductors can carry substantial current densities, researchers at the IBM Yorktown Heights laboratory have now removed one of the major question marks hanging over these compounds.

In experiments with oriented, crystalline (epitaxial) films on crystalline substrates, the researchers passed current densities of more than 10^6 amperes per square centimeter at 4.2 K (liquid helium temperature) and 10^5 amperes per square centimeter at 77 K (liquid nitrogen temperature). The latter value, which is an improvement by a factor of 100 over that previously attainable, is particularly important because the prospect of operating with liquid nitrogen as the refrigerant is what has caused all the excitement over these superconductors.

Although the IBM achievement plainly demonstrates that the superconductors are not intrinsically limited to a low critical current, it is not so obvious how relevant epitaxial thin films on strontium titanate substrates are to many of the large-scale applications foreseen for high-temperature superconductors, such as electric power generation, storage, and transmission.

However, the ability to reproduce the films on silicon substrates would open the way to their use in microelectronics. Often mentioned as a likely first such application for superconductors are high-speed interconnects on and between chips in a computer. Although the current in an interconnect with a diameter of about 1 micrometer is not so large, the current density can be about 10^5 amperes per square centimeter. Farther in the future is an ultrahigh-speed computer made entirely of superconducting chips, although this may require that someone first invent a superconducting device that functions like a transistor. Josephson junctions switch like transistors but have no gain, which places stringent requirements on the uniformity of device performance.

Researchers have ascribed the low current densities generally obtained in both bulk and thin-film specimens of the rare earth–barium–copper–oxygen compounds to the boundaries between crystallites (grains) of polycrystalline superconducting material. The grain boundaries might not be superconducting, for example, but the so-called proximity effect allows superconducting currents to flow from grain to grain through the boundaries, if the currents are not too large. Some evidence for this explanation comes from Brookhaven National Laboratory and from the Karlsruhe Nuclear Research Center in West Germany, where investigators used a magnetic technique to deduce that the current density in the grains of finely ground powders was about ten times higher than in sintered bulk ceramic, where current must cross grain boundaries.

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One way to avoid this limitation is to eliminate the grain boundaries, and this is what the IBM group, which included Praveen Chaudhari, Robert Laibowitz, Roger Koch, Thomas McGuire, and Richard Gambino did for an yttrium-containing compound. Their method is electron beam evaporation, which is also being used by other groups working on superconducting thin films.

In short, separate electron beams evaporate material from yttrium, barium, and copper targets in a vacuum system with a low oxygen pressure of 10^{-3} to 10^{-5} torr. Metal vapor atoms and oxygen deposit on a heated substrate, forming a film. A strontium titanate substrate heated to 400°C has given the best results so far. The deposited films with thicknesses ranging from 0.3 to 2 micrometers were characterized by very small grains and no superconductivity. However, heating the film to a high temperature from 900° to 1000°C in oxygen had two effects. It caused the growth of large grains up to 1 centimeter or so in diameter, and it converted the compound into a superconductor with a critical temperature of 90 K.

Getting the method perfected to achieve such spectacular results required considerable insight into how the film was growing. Just 2 weeks before the IBM announcement of high current densities, for example, Koch described a nearly identical process to a meeting of materials researchers, but could only report grain diameters less than 0.1 millimeter and current densities 1/100 of those now achieved.

In addition to eliminating nonsuperconducting grain boundaries, the IBM researchers say that one other factor may play an important role in the high critical current densities. Theorists and experimentalists alike have speculated that the 90 K superconductivity in these compounds is associated with electrons flowing through linear chains of copper and oxygen atoms that run in only one direction through the crystal structure, so that the material is highly anisotropic. In the epitaxial films, the chains are parallel to the substrate. Moreover, within a single grain, the chains would be continuous, and their ability to carry large currents would be maximized as compared to polycrystalline materials with discontinuous chains running in several directions.

Some support for the importance of anisotropy comes from within IBM, where Tim Dingen, Tom Worthington, Bill Gallagher, and Bob Sandstron have also been able to make freestanding single crystals up to 400 micrometers thick. From measurements of both the lower critical field and current, they concluded that the values of these quantities were ten or more times lower in the direction normal to the axis of the crystal than parallel to it.

The IBM results point up an interesting difference between traditional metallic superconductors and the ceramic rare earth–barium–copper–oxygen compounds. In the past, to obtain high critical currents, materials scientists have had to engineer arrays of defects, including grain boundaries, into their superconductors. Very roughly speaking, the defects prevent the high current from driving the superconductivity out of the material by "pinning" it in place (flux pinning). What causes flux pinning in the ceramic superconductors is not known for sure, but the IBM researchers have evidence for a different kind of pinning center than grain boundaries. ■

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