Oxide superconductors

Contrasts in critical current

David Caplin

How superconducting are the new high-temperature superconductors? When sufficiently small currents are passed through them, and in the absence of a magnetic field, their resistance is zero (or so low that circulating currents do not decay for days or weeks). But the superconducting transition broadens severely in a strong field (Fig. 1), and the small but finite residual resistance in the long low-temperature tail is a significant obstacle to applications of the new materials. Equivalently, the critical-current densities are disappointingly low (Fig. 2.) If they are to be useful, zero resistance is needed at 77 K (the temperature of cheaply available liquid nitrogen) for large current densities and in high magnetic fields. Conventional superconductors, which of course have to be used at liquid-helium temperatures, show a much more abrupt transition to the resistanceless state, and the contrast between the two groups of materials was the main focus of a recent meeting*.

When the superconducting Bi- and Ti-based oxides were discovered earlier this year, because their transition temperatures (up to 125 K) were significantly further above 77 K than the now 'classical' $YBa_2Cu_3O_7$ ($T_c = 92$ K), there were hopes that their critical-current performance would be significantly enhanced. Unfortunately this appears not to be the case, for reasons that are now beginning to be understood.

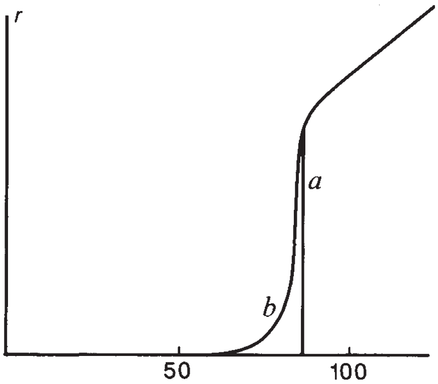

Fig. 1 Schematic resistive transition of $YBa_2Cu_3O_7$ *a*, in zero field; *b*, in a field of 10 tesla. The resistive tail in *b* arises from the motion of magnetic flux induced by the Lorentz force between current and flux; it can be eliminated only by pinning the flux more strongly.

There are two important factors that limit the critical-current density J_c of the new superconductors: the presence of 'weak links' at grain boundaries (and perhaps within grains also); and the weakness of flux pinning. Elegant experiments on thin films of $YBa_2Cu_3O_7$ grown epitaxially on strontium titanate (J. Mannhart, IBM Yorktown Heights) show that although the measured critical currents within a single grain can be extremely high, the inclusion of a grain boundary causes J_c to drop drastically; even misorientations of a few degrees in the *a–b* plane (which should be relatively harmless compared with misorientations with respect to the weakly conducting *c*-direction) bring about a tenfold reduction. Further, the grain-boundary J_cs are about three orders of magnitude more field-sensitive than J_cs in a grain; fields of only a few millitesla suffice to suppress the former.

Why do grain boundaries do so much damage? Some microstructural studies (D.M. Kroeger, Oak Ridge National Laboratory) suggest that there are deviations from stoichiometry on a 10-nm scale, but at an atomic level, the local structure at a grain boundary is certain to differ from that in the bulk. A conventional superconductor is insensitive to these local perturbations because its superconducting coherence length ξ is orders of magnitude greater than interatomic spacings. In contrast, in the new superconductors ξ is little larger than atomic dimensions, so that the grain-boundary region can interpose a layer a few nanometres thick of what is effectively a non-superconductor. A great deal can be learnt from comparing the behaviour of the new materials with that of arrays of conventional superconducting islands connected by weak links (usually a normal metal); because the relevant lengths are much larger, these arrays can be fabricated by microlithographic techniques (P. Martinoli, University of Neuchatel).

One way to circumvent the weak-link problem is to eliminate grain boundaries entirely; carefully grown epitaxial films of $YBa_2Cu_3O_7$ do appear satisfactory in this respect (A. Kapitulnik, Stanford University). Progress is being made also in achieving highly textured bulk materials, with aligned grains up to 10 mm in length, and with J_cs up to 25,000 A cm^{-2} in zero field, dropping by a factor of four or so in 1 tesla (S. Jin, Bell Labs, Murray Hill).

Flux pinning is vitally important because the Lorentz force between the transport current and the flux lines causes the latter to move, so generating a voltage, unless they are pinned. Several experiments have measured the strength of pinning: the time- and field-dependence of the magnetization (Y. Yeshurun, IBM Yorktown Heights); the a.c. susceptibility (R. M. Yandrofski, IBM Yorktown Heights); the form of the low-temperature tail in the resistance (T.T.M. Palstra, Bell Labs, Murray Hill); and the mechanical damping associated with flux line motion (D.J. Bishop, Bell Labs, Murray Hill). Although the numbers that emerge show a broad range, they are all below about 0.1 eV, which is an order of magnitude smaller than in conventional superconductors. Also, it seems that pinning in BiSrCaCuO and TlSrCaCuO systems is a lot weaker than in $YBa_2Cu_3O_7$; perhaps the high density of twin boundaries in the latter is helpful here. General arguments suggest that the shortness of the coherence length leads inevitably to weak pinning. In any case, if the new materials are to be used at liquid-nitrogen instead of liquid-helium temperatures, the 20-fold increase in temperature greatly increases the thermal activation of flux motion.

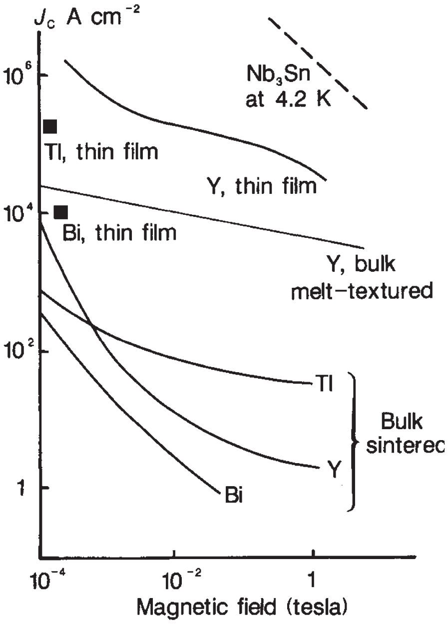

Fig. 2 Summary of recently reported critical current densities at 77 K in the new oxide superconductors. Care is needed in comparing data because of the different criteria used to define the critical current. Y, $YBa_2Cu_3O_7$; Bi, BiSrCaCuO; Tl, TlSrCaCuO of variable compositions. The performance of the conventional superconductor Nb_3Sn at 4.2 K is shown.

Work reported at the meeting shows what can be learnt from two decades of experience with conventional Type II superconductors, but also higlighted the essential differences of the new materials: in the former, structural defects are beneficial — they pin flux; in the latter, they both depress superconductivity and fail to pin flux effectively. Unless ways can be found to overcome the weak-link problem and to pin flux more strongly, the prospects for high-current applications of the new superconductors look poor. ☐

David Caplin is Reader in Physics and Director of the Centre for High-Temperature Superconductivity, Blackett Laboratory, Imperial College, London SW7 2BZ, UK.

---

* *Critical currents in high-temperature superconductors*, Snowmass Village, Colorado, 16–19 August 1988.