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Behavior of critical currents in Bi-Pb-Sr-Ca-Cu-O/Ag tapes from transport and magnetization measurements: Dependence upon temperature, magnetic field, and field orientation

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We have measured the dependence of the transport critical-current density on magnetic field and temperature of a high-J_c Bi-Sr-Ca-Cu-O/Ag tape sample. At low temperature, $J_c > 10^4$ A/cm^2 extends to high fields as previously reported by several groups. For $T > 20$ K and with the applied field parallel to the c axis, J_c declines precipitously with increasing field and temperature, reflecting the properties of intragranular pinning. The variation of J_c with the angle between B and the tape normal is consistent with a two-dimensional model of the vortex lattice. Independent determination of J_c by magnetic hysteresis measurement shows rough agreement with transport J_c's at low fields but falls below by a factor that increases with increasing field and temperature. This can be accounted for by a model for thermally activated flux motion.

Recent progress[1,2] with Bi-Sr-Ca-Cu-O/Ag tapes produced by the oxide-powder-in-tube process has achieved critical-current levels of interest for high-field applications at low temperatures, $T < 20$ K. Most significant is the fact that these current densities at high magnetic fields indicate the suppression of weak links in a polycrystalline material processed in a manner amenable to continuous production of long conductors. Microstructural studies have shown a strong correlation between high current densities and the presence of a highly-c-axis-textured, platelike morphology.[1] This has suggested the "brick-wall" model, recently developed by Bulaevskii *et al.*,[3] in which currents flow predominantly along the CuO_2 planes and transfer between grains across large-area Josephson junctions. These authors have developed the model to account for the low-temperature J_c-B characteristic of a rapid decrease at low fields followed by a high-J_c plateau extending to fields > 25 T. Whereas this model describes the low-temperature behavior well, for $T > 20$ K the experimental results[4] generally show a strong field and temperature dependence previously observed in single crystals[5] and epitaxial films[6] of Bi-Sr-Ca-Cu-O. A pronounced anisotropy develops in which J_c decreases rapidly with the magnetic field aligned along the crystallographic c axis, while it remains relatively field independent for fields lying in the CuO_2 planes. The stronger pinning for the in-plane orientation has been attributed to "intrinsic pinning"[7] provided by severe depression of the superconducting order parameter between the planes. The weaker pinning for the c-axis orientation appears to be correlated[8,9] with the degree of anisotropy of the compound and may reflect a transition to two-dimensional (2D) pinning. These intrinsic mechanisms have been advanced to account for the magnetic and transport characteristics of materials that are dominated by intragranular properties and are not determined primarily by current transfer across grain boundaries as envisioned in the brick-wall model.

The present investigation was undertaken to study the temperature, magnetic-field, and field-orientation dependence of the critical-current density of a high-J_c Bi-Sr-Ca-Cu-O/Ag tape to provide a more complete picture of the complex behavior at $T > 20$ K. Results are presented from both transport and magnetic hysteresis measurements in order to probe a range of time scales (voltage sensitivities). Although we have observed qualitatively similar behavior on several tapes, we present data taken on a tape that had J_c at 77 K and a zero applied field of 1.6×10^4 A/cm^2.

Samples were produced by the conventional oxide-powder-in-tube (OPIT) process. Oxide powder with a stoichiometry of $Bi_{1.8}Pb_{0.3}Sr_{1.9}Ca_{2.0}Cu_{3.1}$ was produced by pyrolysis of a nitrate solution. The oxide powders were then packed into a silver billet and formed into a tape that was 2.5 mm wide and 0.2 mm thick using conventional deformation techniques. The sample was heat treated for about 150 h at temperatures between 805 and 830 °C in 7.5% O_2–92.5% Ar with two intermediate room-temperature pressings. The final dimensions of the monofilament tape were 3.0 by 0.16 mm^2 and the core was 0.08 mm thick.

Transport J_c measurements were performed over the temperature range 20–77 K in a flow cryostat in magnetic fields up to 8 T. A section of tape 2.0 cm in length was attached with vacuum grease to a copper block containing a calibrated carbon-glass thermometer. Tests with a second thermometer in direct thermal contact with the sample showed negligible heating for currents less than 30 A. A voltage criterion of 0.5 μV/cm was chosen to define I_c from the I-V curves. $J_c(B,T)$ was determined in this manner with the magnetic field aligned normal to the tape surface, which was the direction of the crystallographic c axis for these highly textured tapes. A second set of J_c measurements was made with the sample immersed in liquid nitrogen in a horizontal applied magnetic field. Rotation of the sample probe axis allowed determination of the dependence of $J_c(B,T)$ on the angle between B and the c axis over the ranges 64–75 K and 0–1.0 T.

Magnetic M vs H measurements were carried out on a segment of tape from the same sample used in the transport measurements in a Quantum Design SQUID magnetometer. A 3-cm scan was used and the field was swept in a no-overshoot mode.

Figure 1 shows the transport $J_c(B)$ results for B parallel to the c axis at several temperatures. At the lowest temperature, 20 K, J_c, after an initial drop at low fields, remains relatively field independent at about 2×10^4 A/cm^2 to beyond 6.0 T. The zero-field values were not measured at the lower temperatures because of sample heating at currents in excess of 30 Å. At the higher temperatures the steep initial fall is generally followed by a less steep, roughly exponential decline with increasing magnetic field. As the temperature increases the rate of decline increases rapidly. At 77 K, J_c drops below 100 A/cm^2 at a field less than 1.0 T. This is in contrast to the more commonly reported results for B perpendicular to the c axis, where $J_c > 10^4$ A/cm^2 has been seen[1] at 1.0 T and 77 K. At 35 K our data for B parallel to the c axis shows $J_c > 10^4$ A/cm^2 for fields out to 3.0 T which may be of interest for some applications. The rapidly increasing anisotropy with increasing temperature and field makes it imperative that c-axis aligned results be reported to give an accurate picture.

In Fig. 2 we show the variation of I_c with angle between B and the c axis at 75 K and at the low field of 0.05 T. The cusplike form, near 90° has been seen previously[6] in epitaxial thin films of Bi-Sr-Ca-Cu-O and in artificially layered films of Y-Ba-Cu-O compounds in which very thin layers of Y-Ba-Cu-O are separated by nonsuperconducting material.[10] The solid-line fit through the data assumes that the measured J_c-B for B aligned with the c axis describes the data for an arbitrary angle with B replaced by its c axis component. This is shown more convincingly in Fig. 3 where data at 64 K taken over a range of fields 0.01–1.0 T is shown plotted as a function of $B\cos\theta$. It is clear from the superposition of all the data onto a single universal curve that the c-axis component of B alone determines the critical current and that the tape behaves as if transparent to the in-plane component. Similar results have been recently reported by Flukiger *et al.*[2] for Bi-Sr-Ca-Cu-O/Ag tape material.

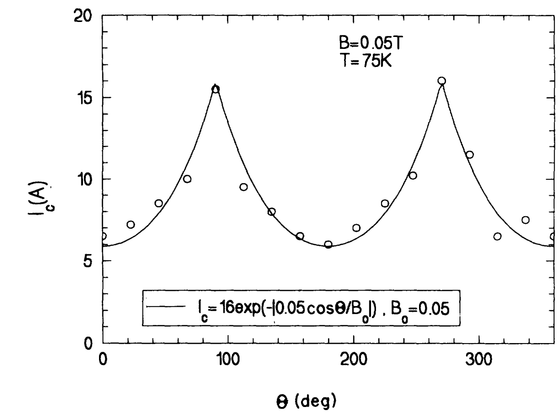

FIG. 2. Transport I_c of the Bi-Sr-Ca-Cu-O/Ag tape at 75 K and in an applied field of 0.05 T as a function of the angle between B and the tape-normal direction. The solid line is a plot of the function shown in the box and represents a fit to $J_c(B)$ data for B parallel to the tape normal, but with B replaced by $0.05\cos\theta$.

Figure 4 shows M-H hysteresis loops at 7 and 35 K measured on a 3.5-mm length of tape cut from the sample used in the transport measurements. The 7-K loop shows an initial rapid fall, followed by a plateau extending beyond 5 T, similar to the low-temperature transport results. At 35 K the low-field drop is followed by a steady decrease to a reversible behavior for $B > 3.0$ T, giving the loop an unusual triangular shape. In using the Bean model to derive J_c values from these loops we have utilized the form appropriate for an orthorhombic shape,[11] $J_c = 20\Delta M/a(1-a/3b)$ A/cm^2, where ΔM is the width of the loop in emu/cc, a is the width, and b the length of the

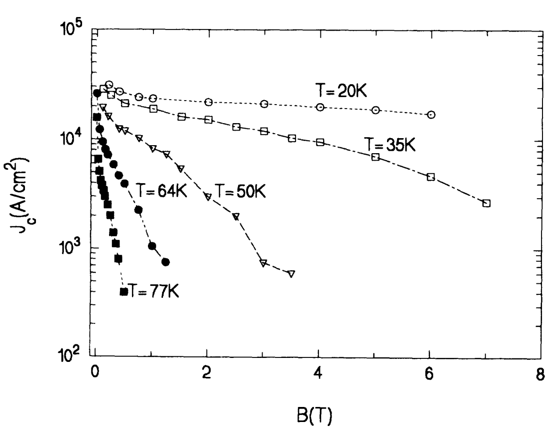

FIG. 1. Transport J_c of the Bi-Sr-Ca-Cu-O/Ag tape determined from I-V curves with a 0.5 μV criterion as a function of magnetic field B along the c axis at several temperatures.

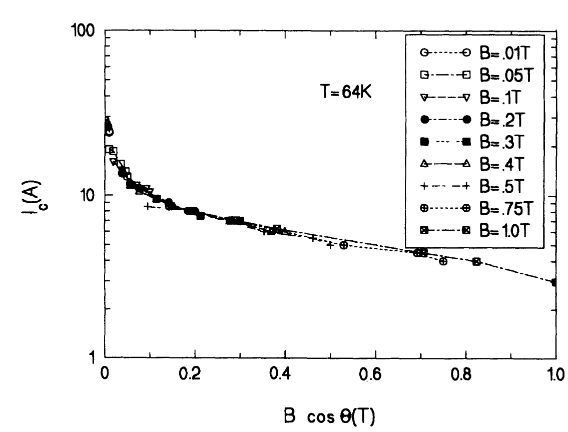

FIG. 3. A plot of I_c vs $B\cos\theta$ at $T=64$ K for several different values of B. The lines connect data points for the same B.

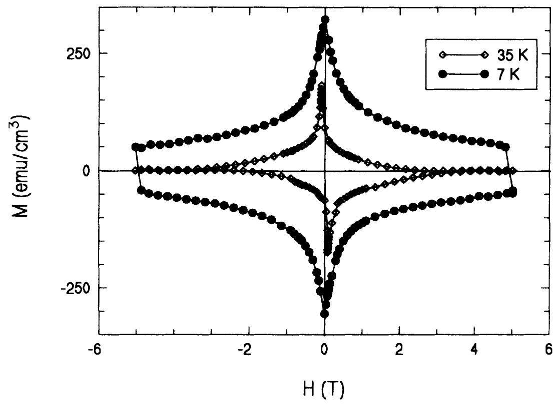

FIG. 4. Magnetization M vs H curves for the Bi-Sr-Ca-Cu-O/Ag tape measured at 7 K and at 35 K, with H along the c axis.

sample in cm. The results of this determination for $T=20$ K are shown in comparison with the transport measurements in Fig. 5(a). Although surprisingly good agreement is obtained from these two measurements at low fields, the magnetization results are lower by a factor that is an increasing function of magnetic field. In Fig. 5(b),

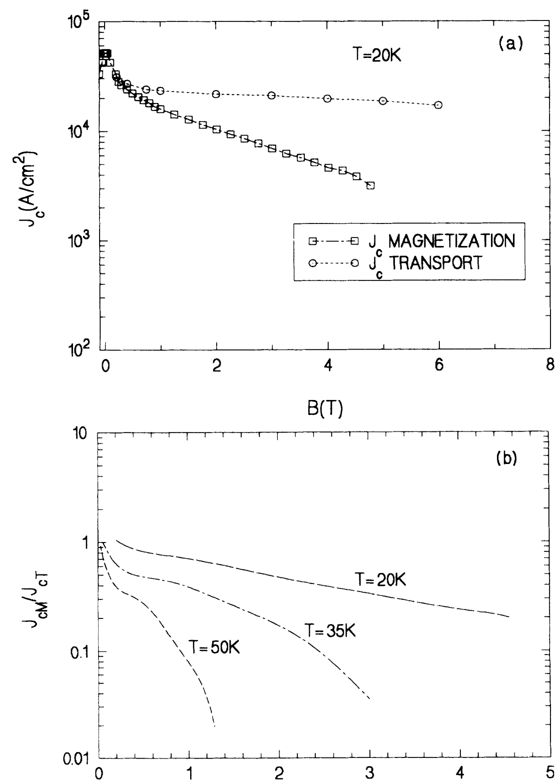

FIG. 5. (a) Plots of J_c vs B at 20 K obtained from transport and from magnetization measurements. (b) Plots of the ratio J_{cM}/J_{cT} of critical-current densities from magnetization and from transport measurements vs magnetic field for several temperatures. B is along the c axis.

we plot the ratio J_{cM}/J_{cT} of critical-current densities determined by magnetic and by transport measurements, respectively, as a function of magnetic field for three temperatures. As is apparent, this ratio increases both with field and temperature. At 35 K the magnetic J_c is more than an order of magnitude smaller for fields above 2.5 T. The fact that these measurements probe very different time scales and voltage sensitivities is essential to understanding this discrepancy.

Textured polycrystalline Bi-Sr-Ca-Cu-O tape materials present some challenging features for the interpretation of experimental results. The combination of relatively strong intergranular coupling and weak intragranular pinning creates a possibility for confusion particularly at high temperatures and fields where their effects upon J_c may be comparable. The success of the brick-wall model[3] in describing the low-temperature J_c-B characteristic, in which a high-J_c plateau extends to very high fields >25 T, suggests that at low temperature intragranular pinning is more than adequate to sustain high J_c and that J_c is determined by the physics of intergranular current transfer. Even at 20 K, as seen in Fig. 1, a weak dependence on B is maintained. However, by 35 K a strong decline with B is developing similar to that observed in single crystals and thin films. The continuing collapse of J_c with increasing B and T suggests that intragranular pinning is now determining $J_c(B,T)$, rather than intergranular current transfer. Although the roles played by such phenomena as flux lattice melting, 3D-2D transitions and "thermal smearing" of pinning potentials is still controversial,[12,13] there is now general consensus that anisotropy plays a decisive role in determining the temperature and field dependence of pinning and of J_c. This is reflected for Bi-Sr-Ca-Cu-O in an irreversibility line that remains below 2 T until the temperature drops below 35 K.[5] Added support for the interpretation that our high-temperature results in Fig. 1 represents the behavior of intragranular pinning is provided by the angular data, Figs. 2 and 3. These results agree quite well with predictions based on the "pancake-vortex" model[14] and with experimental results on single crystals, thin films, and artificially layered superconductors. It is not obvious how a brick-wall grain-boundary model could account for this high-temperature angular dependence.

In attempting to understand the differences between the magnetic and transport determinations of J_c summarized in Fig. 5(b), it is important to take into account the different levels of voltage sensitivity represented by the two measurements. The magnetization measurement is made on a slow time scale, over 60 s following the setting of the external magnetic field. During this period, rapid flux creep allows relaxation of the flux profile away from the critical state by an amount that is a strong function of temperature and field. We measured the rate dM/dt for a number of temperatures and fields and found it generally to be <0.01 emu/ccs for the time scale of interest. We will report the results of relaxation measurements separately. For the sample that we used for these measurements this maximum rate of decay would produce an electric field at the sample surface $<10^{-10}$ V/cm. By contrast, it is the nature of the transport measurement to continue increasing the current until the electric field criterion is reached, in this case 0.5 μV, nearly four orders of magnitude higher than in the magnetic measurement. Assuming in both cases that the voltages are generated by thermally activated flux motion, the different current densities required to generate these voltage levels can be derived from a knowledge of the dependence of the activation energy $U_{\rm eff}$ on current density, J.[15] Generally, $V \propto dM/dt \propto \exp[-U_{\rm eff}(J,B,T)/kT]$, where $U_{\rm eff}$ is a monotonically decreasing function of current density, field, and temperature. Recent theoretical work based on collective pinning and vortex glass models have derived expressions for $U_{\rm eff}(J)$ that vary with the assumed dimensionality of the vortex lattice and with J/J_c, where J_c is the critical-current density. Vinokur, Feigel'man, and Geshkenbein[16] showed that the expression: $U_{\rm eff} = U_0 \ln(J_c/J)$ "is an exact result for the case when the vortex motion is controlled by intrinsic pinning in a layered system with the field parallel to the layers and provides a good approximation for the creep activation barrier in the single-vortex creep regime, thus giving a quite realistic description for activation barriers in a wide range of temperatures and magnetic fields." In a separate study we find that our experimental results for Bi-Sr-Ca-Cu-O materials can be fit quite well with this logarithmic form for $U_{\rm eff}$ over a wide range of J near J_c. Using this in the expression for the voltage results in $V=(J/J_c)^{U_0/kT}$.

This implies that two experiments probing different voltage levels V_1 and V_2 will generate these voltages at current densities with a ratio $J_1/J_2=(V_1/V_2)^{kT/U_0}$. Taking into account the monotonically decreasing dependence of U_0 on B and T provides a qualitative explanation of our results comparing J_c's obtained from transport and from magnetization measurements summarized in Fig. 5(b).

We have measured the dependence $J(B,T)$ of the transport critical-current density on magnetic field and temperature of a high-J_c Bi-Sr-Ca-Cu-O/Ag tape sample. At low temperature the results are similar to those reported by a number of groups, showing a high-J_c plateau extending to high fields, a behavior recently explained by the brick-wall model of percolative current flow through large area grain junctions. However, for $T > 20$ K and with the field aligned along the crystallographic c axis, J_c declines precipitously with field and temperature, as is generally seen in single crystals and epitaxial films, and ascribed to the properties of intragranular pinning in this highly anisotropic compound. At high temperatures, 64–75 K, we measure an angular dependence for J_c consistent with a two-dimensional model of the vortex lattice in which J_c depends only upon the c-axis component of B. Independent determination of J_c by magnetic hysteresis measurement shows rough agreement with the transport J_c's at low fields but falls below them by a factor that increases steadily with increasing temperature and field. This discrepancy can be explained as a result of the different voltage levels sampled in the two experiments and the dependence of the activation energy for thermally activated flux motion on J.

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