High-transport current density up to 30 T in bulk $YBa_2Cu_3O_7$ and the critical angle effect

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Measurements of the dc *transport* critical current of oriented-grained $YBa_2Cu_3O_7$ have been made using high quality Ag contacts and a high-current sample mount. The critical-current density J_c at 77 K for mutually perpendicular current and magnetic field B in the *a,b* plane is 8 kA/cm^2 at 8 T, decreasing gradually to 3.7 kA/cm^2 at 20 T, and remaining over 1 kA/cm^2 out to 30 T. High magnetic field measurements of J_c as a function of the angle θ of B with respect to the *c* axis are also reported. In contrast to earlier results at lower fields ($\leqslant 3$ T) the measurements reported here in high fields reveal a J_c vs θ curve with a *head-and-shoulders* shape, consisting of a sharp peak ("head") $< 5°$ wide for B parallel to the CuO_2 planes, and a wide (30° at 9 T, for example) shoulder region on either side of $B \perp c$ axis, where the transport J_c remains high and constant. Beyond the shoulder region, however, the transport J_c decreases sharply, giving rise to the concept of a *critical field angle* for application design, defined by the minima in $d^2J_c/d\theta^2$ at the edge of the shoulders.

The achievement of high-*transport* critical currents in *bulk* high T_c superconductors at high magnetic fields is crucial to many applications of these new materials. Bulk sintered high T_c superconductors, however, have transport critical current densities J_c that are usually severely limited by weak links at magnetic fields above ~ 1 mT.[1] The new melt growth process[2–4] offers the potential to minimize this problem and enable high-critical-current densities at high fields and temperatures to be obtained. Unfortunately, transport J_c data reported on these materials has been limited to low fields (< 1 T)[2–6] and plagued by both contact heating problems[4,7] and sample motion under the influence of the Lorentz force, which causes premature quenching of the sample.[7] As a result the reported transport J_c values represent only a lower bound, with the "real" transport J_c still being unknown.[3] A calculated J_c from magnetization measurements has been reported in many cases, but it is the *transport* J_c (not the *calculated* J_c that can differ greatly depending on geometric uncertainties) that is the practical parameter for most applications. Pulsed transport measurements have been reported to avoid the contact heating problem,[2,4,5] but these have been only at low magnetic fields (< 1 T) and have the added complication that the measured J_c may be affected by transient flux relaxation effects.[8]

The low-contact-heating J_c results reported here at 77 K for field along the *a,b* planes in bulk oriented-grained $YBa_2Cu_3O_7$ are more than triple those previously reported at low fields and extend to much higher magnetic field. As shown in Fig. 1, transport J_c along the *a,b* planes was 8 kA/cm^2 at 8 T, decreasing gradually to 3.7 kA/cm^2 at 20 T, and remaining over 1 kA/cm^2 out to 30 T, all at liquid-nitrogen temperature. To our knowledge, these are the highest dc transport J_c reported for bulk $YBa_2Cu_3O_7$ at 77 K at high magnetic fields. The data demonstrate for the first time that high transport J_c can be obtained in bulk $YBa_2Cu_3O_7$ at magnetic fields up to 30 T *at liquid-nitrogen temperature* (well above the irreversibility field that is typically quoted as about 6 T for $YBa_2Cu_3O_7$ at 77 K for field along the *c* axis).[8–10] Such J_c' s at this high field level have not been obtained in the Bi- and Tl-based high T_c systems at liquid- nitrogen temperature because of the strong thermally activated flux creep at 77 K in these material systems.[11–13]

At a lower temperature of 4.2 K, the critical current exceeded the current capacity (200 A) of our vapor-cooled current leads, and so we are able to determine only a lower bound for the transport J_c of bulk $YBa_2Cu_3O_7$ at 4. 2 K of > 22 kA/cm^2 at 30 T. To our knowledge, even this lower limit is the highest transport J_c reported for bulk $YBa_2Cu_3O_7$ at 4.2 K at high fields. These data suggest that in the intermediate temperature range between 20 and 40 K the transport J_c at high fields over 30 T may well reach practical levels (above 10^4 A/cm^2). These results bode

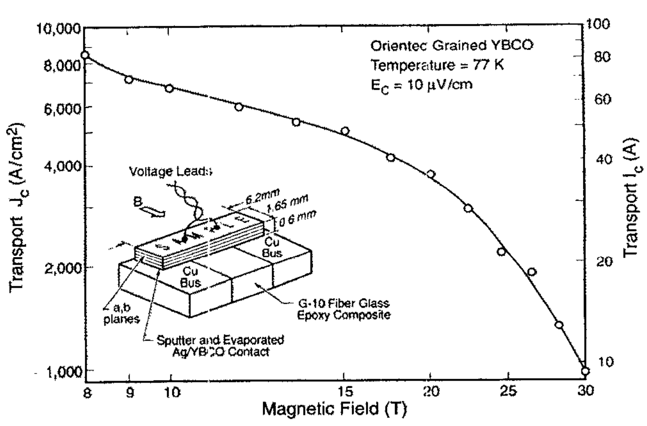

FIG. 1. Transport critical current density J_c vs magnetic field for bulk oriented grained $YBA_2Cu_3O_7$ at liquid-nitrogen temperature with $B \perp c$ axis. Inset shows the measurement geometry and sample holder.

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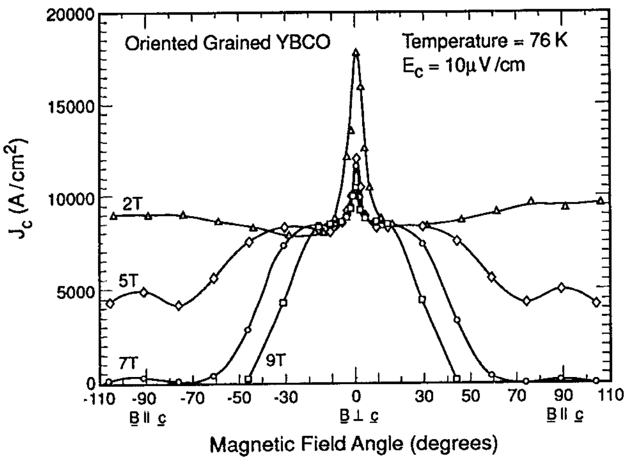

FIG. 2. High-field transport critical current density dependence on the angle between B and the c axis in bulk $YBa_2Cu_3O_7$ at liquid-nitrogen temperature.

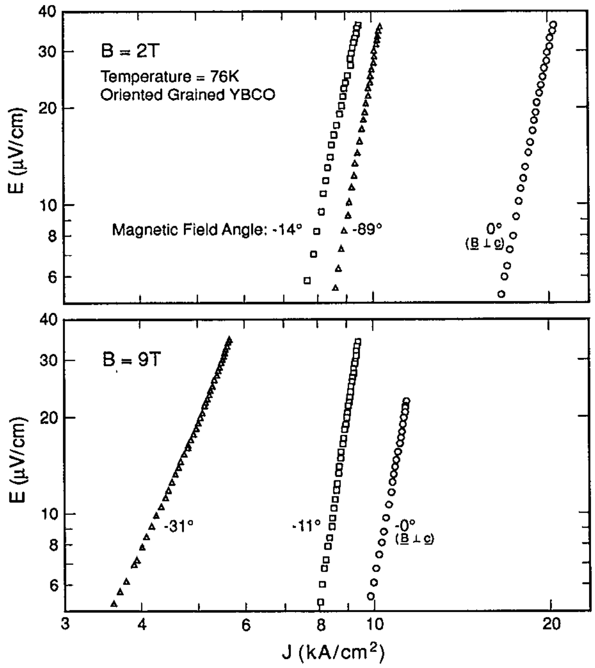

FIG. 3. Logarithmic electric field vs current density (log E-log J) curves as a function of the angle of B with respect to the c axis (0° corresponds to $B \perp c$ axis). The log E-log J curves show no positive curvature within the shoulder region, but change to positive curvature where J_c drops rapidly on either side of the shoulders, indicating the onset of significant flux creep at that critical field angle.

well for high-temperature superconductor applications such as current leads operating between liquid-nitrogen and liquid-helium temperature. They also provide motivation for the difficult task of developing long length conductors of such superconducting material for high-temperature magnet applications.

The first high magnetic field measurements of the transport J_c at 76 K as a function of the angle of B with respect to the c axis are also reported. Unlike earlier reports on thin-film $YBa_2Cu_3O_7$ samples at 77 K at lower fields,[14] we observe at high fields the formation of a J_c versus angle (J_c-θ) curve with a head-and-shoulders shape. The curve consists of a relatively small, narrow [< 5° full width at half maximum (FWHM)] peak (head) for $B \perp c$ axis and a relatively wide shoulder region of high, nearly constant J_c. As shown in Fig. 2, the width of the shoulder region (about 30° wide at 9 T, for example) is greater than might be expected from the field-angle measurements reported earlier and cannot be explained by a spread in the c-axis orientation for this sample, which was quite narrow (less than 1° wide rocking curve at half maximum, as described below). This unexpectedly wide shoulder region is important from the standpoint of enabling practical design of high-field superconducting magnets at high temperatures. The drop in the transport J_c on either side of the shoulder region is quite precipitous, however, making it useful to introduce the concept of a *critical field angle* for application design. For this head and shoulders formation, we define the critical angle by the minima in $dJ_c^2/d\theta^2$ at the edge of the shoulders ($\pm 15°$ at 9 T, for example).

As shown in Fig. 3, the electric-field versus current-density (E-J) curves in the shoulder region have a log E-log J characteristic with no positive curvature, so that flux creep can be excluded if we assume that in the flux-creep regime, the electric field is proportional to sinh J/J_0, which always shows positive curvature.[15] On the other hand, at the critical field angle at the shoulders the transport J_c starts to drop very rapidly and the E-J curve changed shape to a positive curvature log E-log J characteristic (see the $-31°$ E-J curve at 9 T), indicating the onset of significant flux creep.[15]

The small narrow peak in J_c right at $B \perp c$ axis we believe to be a remnant of the intrinsic pinning peak reported in thin-film $YBa_2Cu_3O_7$ at lower temperatures and fields.[14,16] At these higher temperatures and fields, however, the coherence length, which determines core pinning, becomes quite long, and thus, the angular region where the whole flux-line length is interacting with the weak superconducting region between the Cu-O planes becomes very narrow with increasing field.

The samples used in these measurements were fabricated using a liquid-phase processing method described in detail elsewhere.[17] In this process, sintered bars of $YBa_2Cu_3O_x$ were melted vertically at 1100 °C for 10–15 min to decompose the compound into Y_2BaCuO_5 and liquid. The melt is then cooled slowly through the peritectic transformation temperature at a rate of 1–2 °C/h from 1025 to 925 °C. This resulted in the crystallization of plate shaped $YBa_2Cu_3O_x$ grains oriented over a length of 10–15 mm and a width of 5–10 mm. Following the liquid phase process, the samples were annealed in oxygen for 24 h at each of 500 and 400 °C. No secondary phases such as CuO and $BaCuO_2$ were detected between grains. However, Y_2BaCuO_5 precipitates are found embedded within the long grains. X-ray pole figure and rocking curve measurements have been performed on the same sample. Figure 4 displays a rocking curve obtained about the 005 peak.

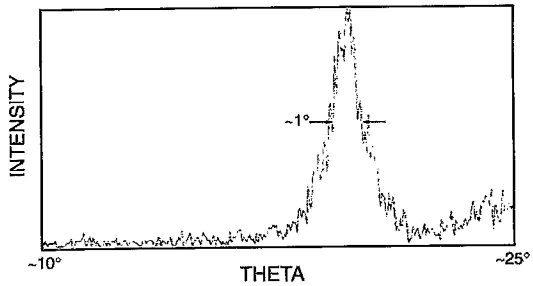

FIG. 4. X-ray rocking curve about the 005 peak from a sample prepared by the liquid phase process, showing a c-axis angular spread of 1° full width at half maximum.

From this figure, a c-axis spread of 1° (FWHM) is observed.

Samples used in the critical current measurements were cut from the melt-grown bars by a diamond saw and dry polished to dimensions of approximately $6\times1.7\times 0.6$ mm. The measurements were carried out with the samples immersed directly in either liquid nitrogen or liquid helium. An electric field criterion of 10 μV/cm was used to determine the critical current.[18] On cycling the field between 8 and 30 T, the critical current was reversible to within the experimental precision of $\pm5\%$.

High quality current contacts were made using relatively thick (~7 μm) silver pads formed by sputter etching the $YBa_2Cu_3O_7$ surface, sputter depositing about 1 μm of silver, and evaporatively depositing the balance of the silver. Afterward, the silver contact pad was annealed in oxygen for 1 h at 550 °C. Further details of the contact fabrication method are described in Refs. 19 and 20. Contact resistance was measured in a separate four-terminal measurement and found for the two contacts to be 9.5 and 9.9 $\mu\Omega$, respectively, at 77 K and 0 T. At 8 T the contact resistances rose only about 5%. The contacts had an ohmic voltage-current characteristic, and their resistance fell 20%– 30% on cooling to 4.2 K, indicating a metallic (as opposed to semiconducting) behavior. At 4.2 K, the contact resistivity increased about 40% between 8 and 30 T, but was still only about 10 $\mu\Omega$ at 30 T.

The sample holder was designed to withstand the high Lorentz forces accompanying these measurements, over 6 kN/m (34 lb/in.) at 30 T, as well as minimize sample strain introduced by differential thermal contraction between the sample and holder. For the high-field data, the magnetic field B was applied perpendicular to the c axis ($B\perp c$) with a 30 T hybrid superconductor/Bitter magnet. Alignment was within about 5°, which was probably close enough to $B\perp c$ to be at least within the J_c shoulder region described above.

In summary, low-contact heating measurements of the transport critical current of oriented grained $YBa_2Cu_3O_7$ have been made with high quality Ag contacts and a high-current sample mount. The results of these measurements provide the first direct demonstration that high-transport J_c can be achieved in bulk high T_c superconductors at high magnetic fields up to 30 T at liquid-nitrogen temperature for magnetic field oriented along the CuO_2 planes. The dependence of J_c on magnetic-field angle has a head-and-shoulders shape about $B\perp c$ axis above 2 T at liquid-nitrogen temperature, with a relatively wide angular region (30° at 9 T, for example) where the transport J_c remains high and constant. Above a critical field angle at the edge of the shoulders, significant flux creep begins and the transport J_c decreases sharply, giving rise to the concept of a critical field angle for application design.

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