High-transport current density up to 30 T in bulk YBa$_2$Cu$_3$O$_7$ and the critical angle effect

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Measurements of the dc transport critical current of oriented-grained YBa$_2$Cu$_3$O$_7$ 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 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 $\theta$ of B with respect to the c axis are also reported. In contrast to earlier results at lower fields ($< 3$ T), the measurements reported here in high fields reveal a $J_c$ vs $\theta$ curve with a head-and-shoulders shape, consisting of a sharp peak ("head") $< 5^\circ$ wide for B parallel to the CuO$_2$ planes, and a wide ($30^\circ$ at 9 T, for example) shoulder region on either side of Blc 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 $\sim 1$ mT. The new melt growth process 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) and plagued by both contact heating problems and sample motion under the influence of the Lorentz force, which causes premature quenching of the sample. As a result the reported transport $J_c$ values represent only a lower bound, with the "real" transport $J_c$ still being unknown. 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, but these have only been at low magnetic fields ($< 1$ T) and have the added complication that the measured $J_c$ may be affected by transient flux relaxation effects.

The low-contact-heating $J_c$ results reported here at 77 K for field along the $a,b$ planes in bulk oriented-grained YBa$_2$Cu$_3$O$_7$ 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$_2$Cu$_3$O$_7$ 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$_2$Cu$_3$O$_7$ 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$_2$Cu$_3$O$_7$ at 77 K for field along the c axis). 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.

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$_2$Cu$_3$O$_7$ 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$_2$Cu$_3$O$_7$ 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 ($> 10^4$ A/cm$^2$). These results bode...
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$_2$Cu$_3$O$_y$ samples at 77 K at lower fields, we observe at high fields the formation of a $J_c$ versus angle ($J_c$-$\theta$) 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 $B_{lc}$ 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, 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.

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. 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.

The small narrow peak in $J_c$ right at $B_{lc}$ axis we believe to be a remnant of the intrinsic pinning peak reported in thin-film YBa$_2$Cu$_3$O$_y$ at lower temperatures and fields. 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. In this process, sintered bars of YBa$_2$Cu$_3$O$_y$ were melted vertically at 1100 °C for 10–15 min to decompose the compound into Y$_2$BaCuO$_5$ 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$_2$Cu$_3$O$_y$ 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$_2$BaCuO$_5$ 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.
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 $6 \times 1.7 \times 0.6$ mm. The measurements were carried out with the samples immersed directly in either liquid nitrogen or liquid helium. An electric field criterion of 10 $\mu$V/cm was used to determine the critical current. On cycling the field between 8 and 30 T, the critical current was reversible to within the experimental precision of ±5%.

High quality current contacts were made using relatively thick (~7 μm) silver pads formed by sputter etching the YBa$_2$Cu$_3$O$_y$ 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 $\mu$Ω, respectively, at 77 K and 0 T. At 8 T the contact resistances rose almost by 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 $\mu$Ω 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 ($B_{lc}$) with a 30 T hybrid superconductor/Bitter magnet. Alignment was within about 5°, which was probably close enough to $B_{lc}$ 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$_2$Cu$_3$O$_y$ 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-field $J_c$ 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 $B_{lc}$ 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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18. For these data, the difference between the electric field and the offset criterion was small, so the electric-field criterion was used because of the high noise-to-criterion ratio inherent to the analysis of hybrid-magnet data: J. W. Ekin. Appl. Phys. Lett. 55, 905 (1989).