Magnetic characterization of rare-earth barium cuprate superconductors

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We report magnetic characterization of barium rare-earth cuprate superconductors to determine critical current densities as a function of rare-earth constituent. A vibrating sample magnetometer was used to measure M-H loops for fields to 15 kOe of oriented single crystals. Critical current densities are insensitive to rare-earth constituent despite the magnetic moment on the rare-earth ion. Values of critical current densities in the a-b plane vary from $\sim 3\times10^5$ A/cm^2 at 10 K to $\sim 2\times10^4$ A/cm^2 at 77 K. Anisotropy in the critical current density in the a-b plane and perpendicular to this plane was a factor of 2 in a $Ba_2YbCu_3O_7$ crystal at $T=38$ K. Aluminum impurities lower critical currents but also reduce the superconducting transition temperature.

Discovery of superconductivity at temperatures above the boiling point of liquid nitrogen in $Ba_2YCu_3O_7$ and its rare-earth analogs[1-5] suggests a number of potential uses for these materials, including wire for lossless electrical transmission and interconnects in microcircuitry. Such uses require these oxides to carry reasonable supercurrent densities. First measurements of critical current densities were made on ceramic samples and relatively low values were found, $\approx 10^3$A/cm^2 at 77 K with zero applied field.[3] Two factors influence the values obtained in ceramic samples. First, the critical current density in ceramics is determined by both the intrinsic behavior of the material and by intergrain effects including grain boundary resistance. The measurement is further complicated in $Ba_2YCu_3O_7$ which has an anisotropic structure. Recently, measurements of electronic anisotropy were carried out on single crystals of $Ba_2YCu_3O_7$.[6,7] Critical current densities of 3×10^6A/cm^2 are measured in the a-b plane, the high conductivity plane, at 4.2 K with low applied magnetic fields, but are reportedly an order of magnitude lower perpendicular to this plane. Vortex pinning in perfect single crystal is typically small, so these values may represent lower limits to critical current densities obtainable in cuprate perovskites. Indeed, critical current densities in excess of 10^5A/cm^2 have recently been reported in epitaxial films of $Ba_2YCu_3O_7$ on strontium titanate substrates at 77 K.[8]

In addition to yttrium, a number of trivalent rare-earth metals form perovskite phases of formula, $Ba_2MCu_3O_7$, with superconductivity onsets in excess of 90 K.[4,5] Since many of these rare-earth ions carry large local moments, we have measured critical current densities as a function of temperature in single-crystal samples of several barium rare-earth cuprate perovskites to determine whether substitution of rare-earth ions for yttrium affects critical current densities. We have also studied the influence of aluminum impurities, which substitute for copper on Cu—O chains,[9] on critical current densities as a function of temperature.

Single-crystal samples of $Ba_2MCu_3O_7$, $M=$Y or trivalent rare-earth metal were grown from partially melting CuO-BaO-M_2O_3 mixtures as described previously.[10] Crystals grow as platelets with the c axis normal to the basal plane. Crystals measuring approximately $1\times1\times0.1$ mm^3 were selected for this study. Superconducting transition temperatures of crystals were measured on an ac susceptibility apparatus.

The magnetization as a function of field was measured using a vibrating sample magnetometer with a field range of ±15 kOe. To obtain the critical current from the magnetization data, we used the Bean model.[11] Most of the measurements were made with the applied field (H) parallel to the c axis, so that for the Bean model the thin rectangular platelet approximated a disk with a diameter taken as the average of the two large dimensions. For H parallel to the c axis the superconducting currents flow in the a-b plane. Typical results are shown in Fig. 1, where we plot M as a function of H at 25 K for a $0.9\times0.8\times0.1$ mm^3 sample of $Ba_2HoCu_3O_7$. Before the magnetization data were recorded, the applied field was cycled through ±15 kOe. The magnetization was then measured with increasing H, starting at $H=0$. After a complete loop was recorded, a minor loop from about 4.5 to 10 kOe was recorded. The M-H loop shown in Fig. 1 very closely approximates the shape predicted by the Bean model.[11] At temperatures below about 10 K, the maximum field of 15 kOe was insufficient to produce M-H loops readily interpreted on the basis of the model. Similarly, at higher temperatures the loops increasingly deviated from the expect-

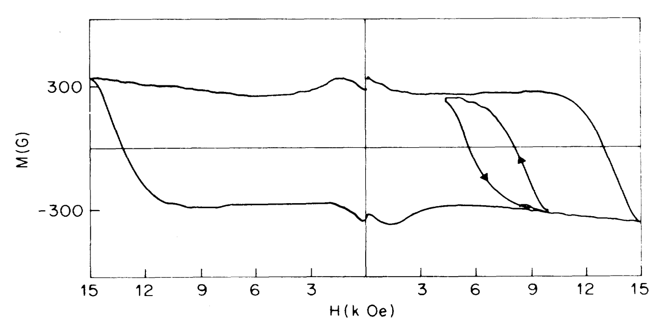

FIG. 1. The magnetization M as a function of applied field H at 25 K for a $0.09\times0.08\times0.01$ cm^3 platelet crystal of $Ba_2HoCu_3O_7$ with $\mathbf{H}\parallel\hat{\mathbf{c}}$.

ed shape. Therefore, the magnetization data were interpreted to yield critical current values only in the temperature range from about 10 to 80 K. The Bean model gives $J_c = 30\Delta M/D$ (J_c in A/cm^2, ΔM in gauss, and D in cm), where ΔM is the magnetization difference for increasing and decreasing fields and D is the diameter of the disk.

We evaluated ΔM at 9 kOe and plot the values obtained this way for various samples as a function of temperature in Fig. 2. These results show that, with the exception of the Er-Al sample, measured values cluster along a line from 4–6$\times 10^5$A/cm^2 at 10 K to 1–3$\times 10^4$ A/cm^2 at 80 K. These results are very similar to those reported for $Ba_2YCu_3O_7$ crystals by Crabtree *et al.*[7] and Dinger *et al.*[6] In addition, similar behavior of J_c in polycrystalline $Ba_2YCu_3O_7$ samples is observed if it is assumed that the currents flow only within a grain and not across grain boundaries. In that case, in the expression for J_c in terms of ΔM and D, the sample diameter D is replaced by the average radius of the grain.

Impurities may act as pinning centers resulting in higher critical current values, and aluminum has been shown to substitute for copper on the Cu–O chains believed critical to superconductivity in these materials.[9] However, in the Er-Al crystal, $Ba_2ErCu_{3-x}Al_xO_7$, $x \approx 0.1$, essentially the same value of J_c is found at low temperatures as in the undoped material, but J_c falls off more rapidly with increasing temperature. This behavior may be accounted for by the fact that the Er crystal has a somewhat lower T_c than the other samples because of the aluminum incorporation.

The $Ba_2YbCu_3O_7$ samples was also measured with the applied magnetic field in the plane of the platelet ($\mathbf{H}\perp\hat{\mathbf{c}}$ axis). Since these crystals are twinned in the *a-b* plane, the field is then along an average of the *a* and *b* axes in the plane and the circulating currents flow along the *a*,*b* axes and a shorter length along the *c* axis. For this geometry, the Bean model for a slab of thickness D is applicable. Then, $J_c = 20\Delta M/D$. At 38 K for $\mathbf{H}\parallel\hat{\mathbf{c}}, J_c = 1.6\times 10^5$ A/cm^2, and for $\mathbf{H}\perp\hat{\mathbf{c}}$, $J_c = 8.3\times 10^4$A/cm^2, indicating that at this temperature, at least, the apparent anisotropy in J_c is relatively small. Earlier measurements of the anisotropy in J_c (Refs. 7 and 8) reported a higher degree of anisotropy; an order of magnitude rather than the factor of 2 seen in this study. However, as noted above, the shape of available crystals introduces uncertainties into this measurement, and differences between earlier values for anisotropy and those reported here may reflect differences in the treatment of the measured data.

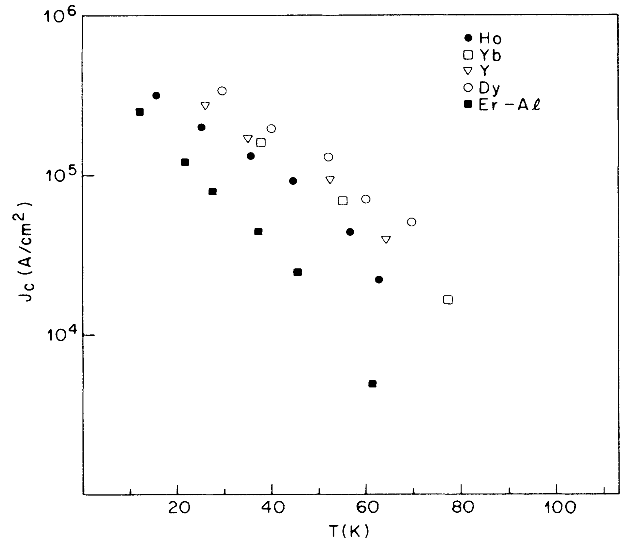

FIG. 2. Temperature dependence of the critical current density J_c at 9 kOe obtained from magnetization measurements such as shown in Fig. 1. The samples are $Ba_2MCu_3O_7$ single crystals with **H**∥ to the *c* axis, M = Ho, Yb, Y, Dy, and Er. The Er sample is substitutionally doped with Al on the Cu–O chains.

The observed small anisotropy of J_c with crystal orientation indicates that the limited critical current densities found in ceramic samples cannot, in a straightforward way, be accounted for by a postulated crystallographic anisotropy in J_c. Of course, this particular explanation for limited critical current densities in ceramic samples was already suspect on a number of different grounds such as the field dependence. In addition, we find that rare-earth (M) substitutions in $Ba_2MCu_3O_7$ do not affect critical current densities and thus fail to clarify the mechanism that limits J_c values in ceramic samples.

In conclusion, we have shown that not only is the intrinsic property T_c independent of M in $Ba_2MCu_3O_7$ single crystals, but so is the extrinsic property, J_c. This observation implies that if the value of J_c is determined by the number, spacing, and strength of pinning centers, these pinning centers are not sensitive to the lanthanoid constituent.

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