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Critical current anisotropy in high-T_c superconductors

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Using grain-aligned samples, we have investigated the anisotropy of the superconducting critical current in three different copper oxide superconductors. At low temperatures there are large anisotropy differences between the materials, but at higher temperatures we find that the anisotropy is both small and roughly material independent. This result suggests that a small *intrinsic* critical current anisotropy may exist in high-T_c superconductors.

In conventional type-II superconductors, the critical current density J_c is an *extrinsic* property being controlled by a variety of structural defects. However, magnetic measurements on $Y_1Ba_2Cu_3O_{7-\delta}$ have shown[1-6] that J_c is strongly anisotropic, raising the possibility that the critical current is controlled in some way by the material's anisotropic structure. Unfortunately, the present experimental situation does not permit any clear physical conclusions to be drawn. Critical current anistropy data on the copper oxide superconductors has remained restricted to $Y_1Ba_2Cu_3O_{7-\delta}$, and there are serious qualitative and quantitative disagreements between different reports. If $J_{c\parallel}$ and $J_{c\perp}$ are the critical current densities obtained with the magnetic field lying parallel and perpendicular to the **c** axis, respectively, we define the critical current anistropy as $\gamma_J=(J_{c\parallel}/J_{c\perp}-1)$; at low temperatures and low fields, values of γ_J between 0.5 and 43 have been reported.[4,5] Some workers find large increases[1,4] of γ_J as the temperature increases, while others find that γ_J decreases.[3,5,6] In the work reported here, we have retained the standard magnetic technique for evaluating γ_J, but have used grain-aligned[7] samples rather than single crystals. The systematic data we have obtained provide the first indication that a small *intrinsic* critical current anisotropy may exist in high-T_c superconductors.

We chose the following materials as representative of three of the families of copper oxide superconductors: $La_{1.85}Sr_{0.15}CuO_4$, $Y_1Ba_2Cu_3O_{7-\delta}$, and $Tl_2Ba_2Ca_2Cu_3O_{10+\delta}$. In the following we represent their formulas by the abbreviations La-Cu-O, Y-Cu-O, and Tl-Cu-O, respectively. (We note in passing that we have not yet succeeded in obtaining aligned single-phase samples of any representative of the bismuth family). Grain-aligned samples were prepared in a manner described previously[7] and sample characteristics are noted in Table I. The resistive T_c values were obtained on the materials in sintered form prior to grinding down into small ($\sim 10\,\mu$m) grains. These grains were mixed in epoxy which was then cured in the indicated magnetic field at room temperature. This procedure produces uniaxial **c**-axis alignment which was checked using x-ray rocking curves. The full angular widths at half maximum (FWHM) recorded in Table I indicate good grain alignment in all cases. The samples were all single phase, as judged by x-ray-powder patterns, although the T_c for Tl-Cu-O suggests the presence of some 1:2:1:2 intergrowth.[8]

The magnetization for all our samples was studied in both principal directions as a function of field and temperature using a commercial superconducting quantum interference device (SQUID) susceptometer. The data obtained for two of the materials (La-Cu-O, Tl-Cu-O) were very similar but displayed a sharp contrast with those for Y-Cu-O. Figure 1 displays the full hysterisis loops at $T=4$ K for Y-Cu-O and at $T=5$ K for Tl-Cu-O. The data for Y-Cu-O are similar to those obtained previously on a different (grain aligned) sample[7] but there is a clear qualitative difference between them and those for Tl-Cu-O. Application of the Bean model[9] allows us to estimate a (field-dependent) anisotropy $\gamma_J(H)$ using

$$\gamma_J(H)=\left[\frac{\Delta M_{\parallel}(H)}{\Delta M_{\perp}(H)}-1\right] \tag{1}$$

where $\Delta M(H)$ is the difference, at field H, between the magnetizations obtained with the field increasing and decreasing. As $H\rightarrow 0$ the value of γ_J is about six for Y-Cu-O but close to one for the other two materials. A similar distinction exists for the field dependence (as shown in Fig. 2). For Y-Cu-O, γ_J increases with field, in agreement with single-crystal data.[1] By contrast, for the two

TABLE I. Sample properties.

Property	La-Cu-O	Y-Cu-O	Tl-Cu-O
T_c (K) ($R=0$)	34.5	91	118
Packing fraction (%)	30	16	10
FWHM (°)	3.0	2.2	1.8
Curing field (kOe)	50	50	94

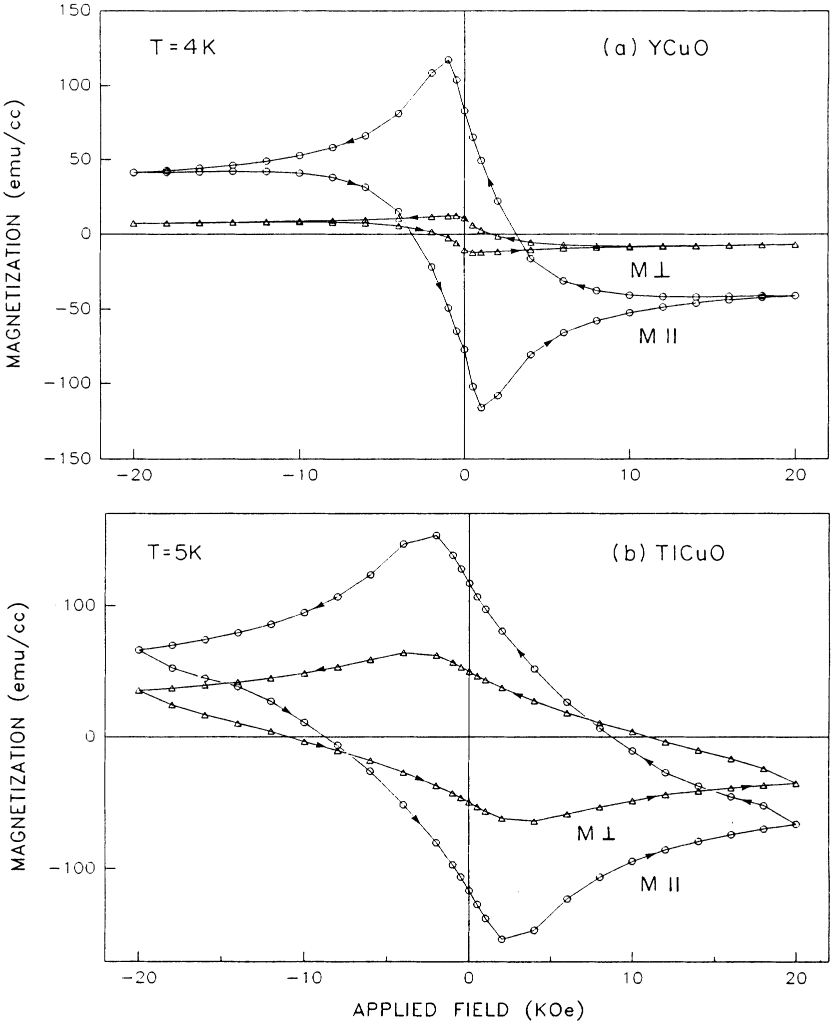

FIG. 1. (a) Magnetization hysteresis loops for $Y_1Ba_2Cu_3O_{7-\delta}$ at $T=4$ K and (b) $Tl_2Ba_2Ca_2Cu_3O_{10+\delta}$ at 5 K. In each case, $M_{\parallel}$, $M_{\perp}$ are the magnetizations observed with the field parallel and perpendicular to **c**, respectively.

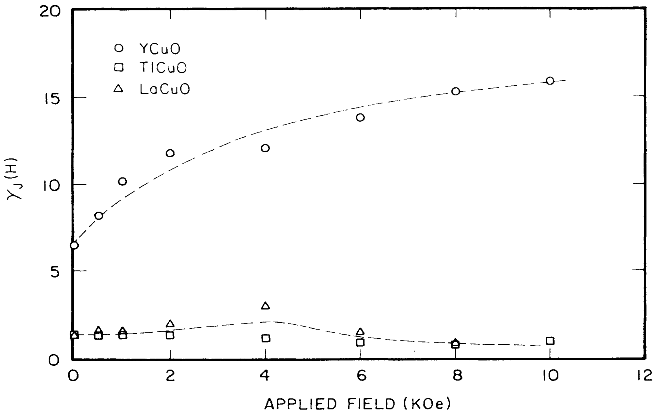

FIG. 2. Field dependencies (at $T=5$ K) of the critical current anisotropy γ_J (defined in the text), for the three copper oxide superconductors studied. The two dotted lines are to guide the eye.

other materials, γ_J become smaller at higher fields. In view of these qualitative distinctions at low temperatures, the similar behavior observed for $\gamma_J(0)$ at higher temperatures (Fig. 3) is striking. (We note that it was not possible to obtain data in the regime $t > 0.6$ and $H > 0$ because J_c itself decreases very rapidly with field and temperature.)

Before discussing the possible significance of the data in Fig. 3, it is appropriate to consider some possible experimental complications. It is known[1] that single-crystal magnetization values decay with time, presumably due to some type of flux-creep process, and so we have examined this decay in our grain-aligned materials by studying the time dependence of both $\Delta M_{\parallel}(0)$ and $\Delta M_{\perp}(0)$ for all our samples. After setting the field, five observations of both quantities were made with an interval of 4 min between each observation. Both $\Delta M_{\parallel}(0)$ and $\Delta M_{\perp}(0)$ were observed to decrease with time *but with a similar decay constant* so that $\gamma_J(0)$ was sensibly independent of time. In fact, for all three materials, over most of the temperature range ($t < 0.8$), the changes in $\Delta M_{\parallel}$ and $\Delta M_{\perp}$ for the whole 16 min period were ~10% but the associated change in $\gamma_J(0)$ was ~1%. In two instances, the measurements were extended to ~10 h and a further change of ~10% noted in the $\Delta M(0)$ values, but again only ~1% in $\gamma_J(0)$. The situation for $t > 0.8$ is less clear cut, both because flux creep becomes more severe and because the measurements themselves are more difficult, owing to the small size of both $\Delta M_{\parallel}$ and $\Delta M_{\perp}$. However, since $\gamma_J(0)$ was always observed to *decrease* with time, we think that the two data points for $t > 0.8$ in Fig. 3 provide reliable *upper bounds* to the $\gamma_J(0)$ values at those temperatures. In summary, for $t < 0.8$, the $\gamma_J(0)$ data in Fig. 3 are thought to represent equilibrium values to a few percent while for $t > 0.8$ the values are thought to represent good upper bounds: We also note that the actual shape of the hysterisis loops in Fig. 1 do not resemble the Bean-model predictions which are more nearly matched by the single-crystal data.[1-6] However, the original Bean model ignores the equilibrium magnetization, which is size independent. By contrast, the contribution of the irreversible magnetization scales with sample size and dominates single-crystal magnetization data, which is, therefore, reasonably well fitted by the original Bean model. The relevant size for our samples is that of the grains which is only ~10 μm and the contribution from the equilibrium magnetization is evidently not negligible. Nonetheless, in these circumstances, ΔM still provides the appropriate measure for estimating[10] the critical current.

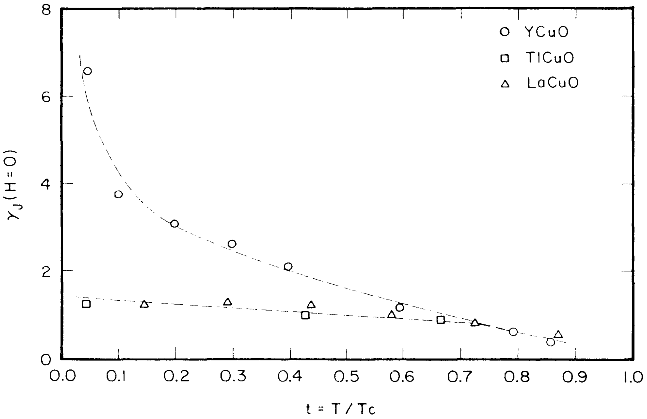

FIG. 3. Zero-field critical current anisotropy γ_J ($H=0$) as a function of reduced temperature for the three copper oxide superconductors studied. The two dotted lines are to guide the eye.

The main contribution of this work is the experimental data shown in Fig. 3, but we note here some possible implications. First, the crystal structure of Y-Cu-O is orthorhombic while that of Tl-Cu-O is tetragonal. The presence of {110} twinning plane in Y-Cu-O has already been suggested as a major source of critical current anisotropy.[11] This idea is supported by the low γ_J value we observe for Tl-Cu-O, since tetragonal materials can have no {110} twin planes. La-Cu-O is also orthorhombic but we note that the orthorhombic distortion[12] is significantly less than in Y-Cu-O. Although La-Cu-O twin boundaries have not been studied extensively, they appear to be less well-developed[13] than in Y-Cu-O. The low γ_J value for La-Cu-O may, therefore, not prove to be inconsistent with the idea that twin planes are an important source of critical current anisotropy, but much more work will be needed to firmly establish this point. The most interesting feature of our data is the (small) material-independent anisotropy we observe for $t > 0.6$. The small coherence length (~10 Å) in the copper oxide materials certainly raises the possibility of flux-pinning mechanisms that operate on a much smaller length scale than in conventional superconductors. As a frankly speculative suggestion, the observed high-temperature anisotropy may, therefore, be due to a (weak) lattice-pinning mechanism that reflects the major structural anisotropy between the two principal crystallographic directions.

In conclusion, we have obtained critical current anisotropy data for three copper-oxide materials. Above a reduced temperature of ~0.6 they exhibit a universal behavior. This result provides the first indication that a small intrinsic critical current anisotropy may exist in high-T_c superconductors.

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