Transport critical current in rare-earth-substituted superconductors $RBa_2Cu_3O_{7-\delta}$ (R = Gd, Dy, Sm, Ho, Y)

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We have measured the transport critical current densities (J_c) of various bulk polycrystalline $RBa_2Cu_3O_{7-\delta}$-type high-temperature superconductors (R = Gd, Dy, Sm, Ho, Y) at 77 K as a function of magnetic field. The substitution of yttrium with magnetic rare-earth elements resulted in no appreciable improvement or deterioration in the transport J_c values (typically in the range 200–600 A/cm^2 at $H = 0$). The similar J_c values of all five barium cuprate compounds and their rapid deterioration in weak magnetic fields in a similar manner ($J_c < 10$ A/cm^2 at $H = 1000$ G) suggest the possibility of generic "weak link" problems in these compounds.

The recent discovery of high-temperature superconductivity in copper-oxide based compounds[1,2] and their potential for significant technological applications led to unprecedented excitement and explosion of research in this field.[3–19] The 90 K superconductor, oxygen-deficient perovskite $YBa_2Cu_3O_{7-\delta}$, has been the most active subject of investigations. High T_c's near 90 K have subsequently been reported for several rare-earth-substituted compounds with a similar stoichiometry and crystal structure.[7,8]

For the new superconductors to be useful, they have to be fabricated into desirable shapes, and should carry sufficiently high electrical currents. The difficulty in fabrication of the brittle $YBa_2Cu_3O_{7-\delta}$ ceramic material has been overcome by several different approaches;[9–12] however, the low critical current densities in polycrystalline materials remain as a main roadblock to significant technical advancement. Indirect measurement of J_c by calculations from the magnetization loops for single crystals and crystalline grains[4,15–18] imply high intrinsic J_c of individual grains, which is not reproduced in actual transport J_c measurements[3,9,13,14,19] in bulk, yttrium-containing superconductors.

In this paper we report the results of our recent measurement of the transport J_c values and their field dependence of $RBa_2Cu_3O_{7-\delta}$ (R = Gd, Dy, Sm, Ho) as compared to those of $YBa_2Cu_3O_{7-\delta}$

Compound samples with a $RBa_2Cu_3O_{7-\delta}$ formula were prepared by mixing $BaCO_3$, R_2O_3, and CuO in stoichiometric proportions, then repeated (4 times) grinding, pressing, and sintering (900–970 °C for 20 h followed by a furnance cooling in an oxygen atmosphere). The samples were typically of rectangular bar shape, $2.5\times2.5\times30$ mm, having a necked region with an approximately 1.5×1.5 mm cross-sectional area for J_c measurement. The lead wire contacts to the superconductors were made either by using four partly embedded silver wires (sintered in place) or by soldering with indium metal.

Shown in Fig. 1 are the typical superconducting transition curves (ac magnetic susceptibility versus temperature) for the five compounds. The sample geometry and weight were kept essentially the same for all the compounds studied. The transition temperatures range between 90–95 K for the Gd, Dy, Sm, and Ho, as well as Y compound, with the change in susceptibility almost identical for each sample. The transition temperatures T_c were also determined by resistivity measurement as given in Table I. While the T_c's are comparable to each other in the five compounds, the normal state resistivity varied considerably by as much as an order of magnitude. The results given in Fig. 1 and Table I are in reasonably good agreement with previously reported transition temperatures.[7,8] It is generally accepted that in the layered structure of the orthorhombic oxygen-deficient perovskite superconductors, the superconductivity is basically confined to the CuO_2-BaO layers with rare-earth atoms (magnetic or nonmagnetic) showing a weak influence on superconducting transition.

Shown in Fig. 2 are the exemplary transport J_c values plotted as a function of applied transverse magnetic field at 77 K. J_c was obtained from the voltage-current (V-I)

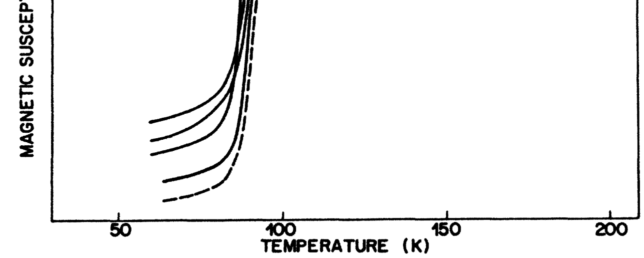

FIG. 1. Magnetic susceptibility vs temperature curves for $RBa_2Cu_3O_{7-\delta}$ (R = Gd, Dy, Sm, Ho, Y).

TABLE I. Superconducting transition temperatures and resistivities of $R\mathrm{Ba_2Cu_3O_{7-\delta}}$ (R = Gd, Dy, Sm, Ho, Y).

	T_c(onset)[a] (K)	T_c(R=O) (K)	ρ(at 100 K) ($\mu\Omega$ cm)	ρ(at 300 K) ($\mu\Omega$ cm)
Gd	96	90	5400	7920
Dy	96	92	840	1950
Sm	94	90	1800	4440
Ho	95	92	1440	3070
Y	96	91	380	810

[a]Defined here as the temperature with a 10% decrease in resistivity from the linear portion.

curves such as shown in Fig. 3 for the case of the dysprosium compound, using a 0.2 μV/mm criterion. As is apparent from Fig. 2, J_c's (in zero field) of the rare-earth-substituted compounds and the yttrium compound are low and typically in the range of 200–600 A/cm^2. If we consider the typical scattering of experimental data encountered in the measurement of J_c for the high-T_c superconductor, the J_c values for Gd, Dy, Sm, Ho, as well as Y, may be viewed as essentially the same. The figure also shows rapid deterioration of the critical current density in the presence of weak magnetic fields for all five compounds in a more-or-less similar fashion.

The critical current density in a polycrystalline cuprate superconductor is likely to be determined by both the intrinsic superconducting properties of the material inside each grain and the grain boundary resistance effects possibly caused by (i) the presence of inhomogeneity or impurities (e.g., $\mathrm{BaCO_3}$), (ii) mechanical defects (e.g., stress concentration or microcracks), (iii) altered stoichiometry (e.g., oxygen content), (iv) structural deviation (e.g., crystal structure), or (v) crystal orientation change (e.g., anisotropic conductivity) at grain boundaries.

The intrinsic J_c properties (magnetization J_c obtained from a single crystal[4,15,17] or from aggregates of grain-sized single crystals[16,18] of $\mathrm{YBa_2Cu_3O_{7-\delta}}$ and rare-earth-substituted cuprates[15,18] appear to be quite high; $\approx 10^{15}$–10^6 A/cm^2 (H=0–40 kG) near 5 K and $\approx 10^4$ A/cm^2 (H=0–15 kG) near 77 K with a much smaller field dependence than that shown in Fig. 2. High values of magnetization J_c as well as transport J_c at 77 K were also reported for epitaxially grown thin films of $\mathrm{YBa_2Cu_3O_{7-\delta}}$.[5]

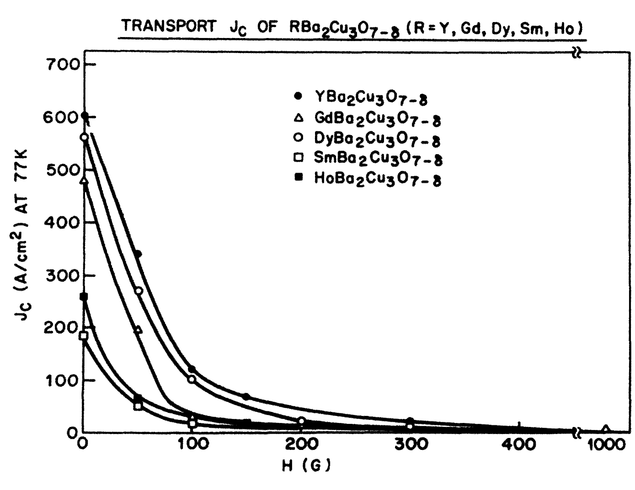

FIG. 2. Transport J_c at 77 K vs magnetic field for $R\mathrm{Ba_2Cu_3O_{7-\delta}}$ (R = Gd, Dy, Sm, Ho, Y).

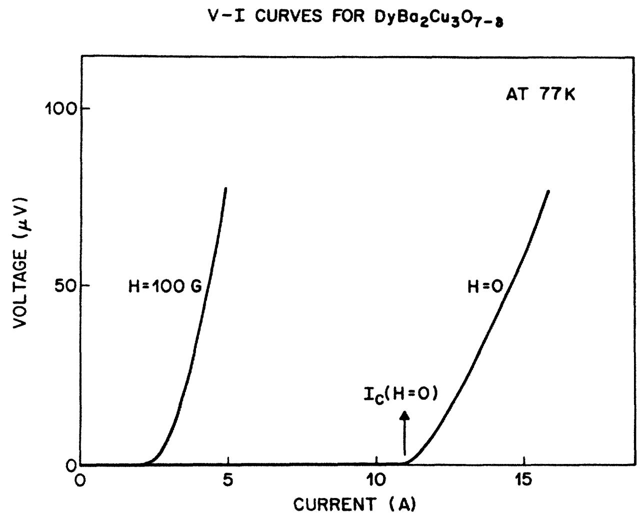

FIG. 3. V-I curves for $\mathrm{DyBa_2Cu_3O_{7-\delta}}$ at 77 K indicating a critical current of 11 A at H=0 and 2.4 A at H=100 G.

The low-transport J_c values of the Gd, Dy, Sm, and Ho compounds and their rapid deterioration in low magnetic fields suggest that the high-J_c grains in these compounds are decoupled by low-J_c regions presumably at grain boundaries. These low-J_c regions could be normal metallic, semiconducting, or insulating layers much thicker than the coherence length, or superconducting layers with suppressed T_c's or H_c's. The strong field dependence of J_c shown in Fig. 2 is indicative of "Josephson weak-link current" behavior. While there are a number of likely sources of grain boundary weak links such as the five possibilities mentioned above, the exact cause of the low-J_c problem has not yet been clearly understood. Further research effort is required to pinpoint the cause and improve the critical currents.

In summary, we have measured the transport critical currents at 77 K of various rare-earth-substituted barium cuprate superconductors containing Gd, Dy, Sm, Ho, or Y. The J_c values are all relatively low with no appreciable differences among the rare-earth elements, and they all exhibit a similarly rapid deterioration in low magnetic fields, indicative of weak links at grain boundaries. We conclude that the low critical current is perhaps a generic problem in bulk rare-earth barium cuprate superconductors caused by similar mechanism(s).

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