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Critical currents and thermally activated flux motion in high-temperature superconductors

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We have measured the resistance below T_c of single crystals of the high-temperature superconductors $Ba_2YCu_3O_7$ and $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ in magnetic fields up to 12 T. The resistive transition of both compounds is dominated by intrinsic dissipation which is thermally activated, resulting in an exponential temperature dependence of the resistivity well below T_c. The dissipation is significantly larger and of different character in the Bi-Cu compound than in $Ba_2YCu_3O_7$. The relation between the activated behavior and the depinning critical current is discussed.

In this letter we report high sensitivity measurements of the resistive transition of single-crystal $Ba_2YCu_3O_7$. We will show that the transition is dominated by thermally activated flux motion similar to, but smaller than in single-crystal $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$.[1] Our single-crystal study of dissipation below T_c addresses the limitations of the current-carrying capacity within a (single-crystal) grain of the oxide superconductors.[2] This dissipation, associated with flux motion,[3,4] has consequences for the application of this material in large magnetic fields at an operating temperature of 77 K.

The crystal growth and a detailed characterization of the crystals has been described elsewhere.[5] The $Ba_2YCu_3O_7$ crystal has dimensions of $1.02\times0.46\times0.019$ mm^3 and was oxygenated for four weeks at 400 °C. The electrical resistivity was probed with a dc current density of $J = 57$ A/cm^2 in the a, b basal plane using a bar-shaped geometry. The current-voltage (I-V) curves in a magnetic field are linear from this value down to 0.1 A/cm^2, which is the instrumental resolution. The current direction was always perpendicular to the magnetic field. The experimental details for $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ have been described elsewhere.[1]

In Fig. 1 we show the resistive transition of $Ba_2YCu_3O_7$. The inset shows the zero field data, which are approximately linear from room temperature to 110 K, where the superconducting transition sets in. The linear part of the curve extrapolates to a low value for the resistivity intercept at $T = 0$, which has been correlated in thin films[6] with good sample quality. The resistive transition of $Ba_2YCu_3O_7$ in various magnetic fields is shown for $H \parallel a,b$ in the upper part and for $H \perp a,b$ in the lower part of Fig. 1. These data are in good agreement with data found in literature,[7-9] e.g., resulting in similar values of the upper critical field slopes, if $T_c(H)$ is defined at the midpoint of the transition. This definition, however, is *not* justified for the high T_c materials because of the large dissipation.[10]

The thermally activated behavior becomes evident when replotting these data as $\log \rho$ vs T^{-1} (Fig. 2). This Arrhenius plot shows that the resistivity in a magnetic field approaches zero exponentially. The straight lines for low resistivity indicate that the dissipation mechanism is thermally activated, and their slopes give the activation energy U_0 for flux motion. These energies U_0 range from 10^4 K for the largest magnetic field (12 T) to 2×10^5 K for the lowest fields (0.1 T). In comparison the activation energies for the Bi-Cu compound range from 330 K (12 T) to 3000 K (0.1 T).

The model of flux creep provides a framework to discuss the results.[11] In this model the creep velocity is given by

$$v_\phi = 2\nu_0 L \exp(-U_0/k_B T)\sinh(JBV_c L/k_B T),$$

with ν_0 the attempt frequency of a flux bundle of volume V_c to hop over an energy barrier U_0 and move a distance L. J is the current density and B the magnetic induction. At this point we emphasize the difference between flux creep and flux flow. Flux creep occurs when the Lorentz force $F_L = J\cdot B$ is smaller than the pinning force $F_p = J_c\cdot B$, which is defined by the *depinning* critical current density J_c. The above formula shows that flux creep gives linear I-V

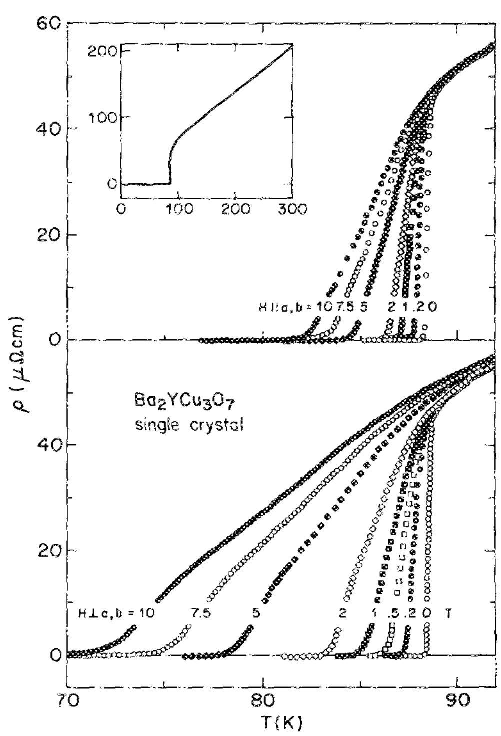

FIG. 1. Temperature dependence of the electrical resistivity of $Ba_2YCu_3O_7$ in various magnetic fields parallel to the a,b basal plane (upper panel) and perpendicular to the basal plane (lower panel) ranging from 0 to 12 T. The inset shows the zero field resistivity up to room temperature.

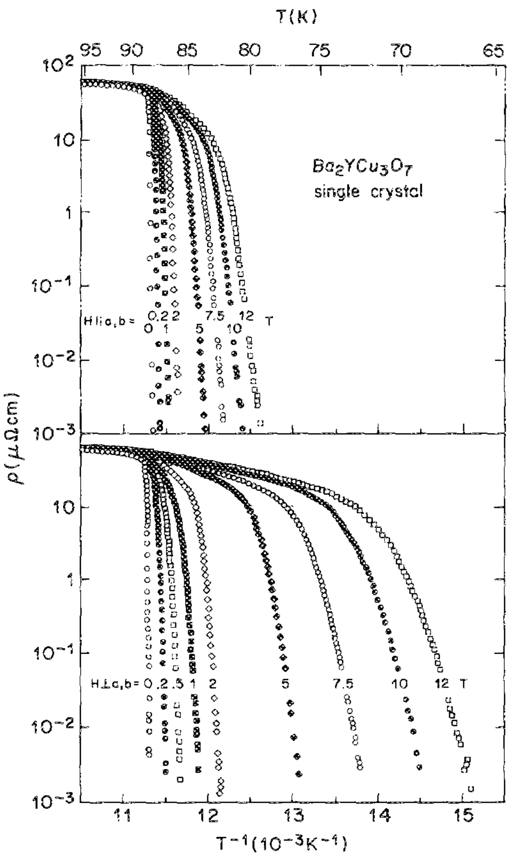

FIG. 2. Arrhenius plot of the electrical resistivity of $Ba_2YCu_3O_7$ for magnetic fields parallel to the basal plane (upper panel) and perpendicular to the basal plane (lower panel) ranging from 0 to 12 T.

curves (J-v_ϕ) for currents for which $JBV_cL \lesssim k_BT$, and an exponential I-V curve for larger currents. The main part of Fig. 3 is a schematic representation of this relationship, and the insert gives our data on a double logarithmic scale to emphasize the large range over which linearity is observed. Flux flow, on the other hand, gives linear I-V curves for $F_L > F_p$ or $J > J_c$. In $Ba_2YCu_3O_7$ the pinning is large because of the large values of the activation energy U_0. Therefore, the experimentally observed linear I-V curves are the result of flux creep, and *not* flux flow. (Our single-crystal data should not be confused with polycrystalline data,[12] for which power law behavior is observed $V \propto I^a$, $a > 1$, due to additional dissipation in, or associated with grain boundaries, etc.). Furthermore, the transition from creep to flow at $F_L = F_p$ or $J = J_c$ gives no sharp anomaly, because of the large dissipation which already occurs in the creep regime. Only at low temperature, where flux creep does not dominate, can the critical depinning current be determined by transport measurements. Thus, the linearity of the measured I-V curves sets an upper limit for the value of V_cL, and we can replace the hyperbolic sine by its argument. We find

$$\rho = v_\phi B/J = 2\nu_0 B^2 V_c L^2 \exp(U_0/k_BT)/k_BT.$$

Consequently, $\rho(T,H)$ is determined by the temperature and field dependence of the microscopic parameters of the pinning process, viz., the attempt frequency ν_0, the flux bundle volume V_c, the hopping distance L, and the activation energy U_0. As we lack detailed knowledge of the pinning process for any of the oxide superconductors, we cannot give *a priori* the functional dependence of $\rho(T,H)$.

Now, we discuss the relation between the activation energy U_0, measured experimentally, and the depinning critical current density J_c. Defined as the current for which $F_p = F_L, J_c$ is related[13] to the activation energy U_0 via $U_0 = J_cBV_cr_p$, with r_p the range of the pinning potential. If we assume $V_c \simeq a_0^2 d$ (amorphous limit of the flux line lattice[14]) and point defects, so that $r_p \simeq \xi_{GL}$, with ζ_{GL} the Ginzburg–Landau coherence length, we find that $J_c = U_0/\phi_0 d\xi_{GL}$, with $\phi_0 = Ba_0^2$ the flux quantum and d the sample thickness. This formula only holds for thin samples for which the correlation length along the flux line L_c is larger than d. For thicker samples, d must be replaced by L_c. Assuming $L_c = d$, we find for $Ba_2YCu_3O_7$ that j_c(77 K) = 7,2, and 0.6×10^5 A/cm^2 for $H_{\perp a,b} = 0.1,1$ and 10 T, respectively.

Here, we would like to clarify the shortcoming of experimental criteria used traditionally to measure "critical currents" in high T_c superconductors. The inset of Fig. 3 clearly shows that a 1 μV/mm criterion, a criterion commonly used to define J_c, does not yield the critical current, because the I-V curve is linear. The depinning critical current is in the exponential part of the I-V curve at much larger current densities, as sketched in Fig. 3. Moreover, the critical current density in these materials does not represent the value below which no dissipation occurs.

The consequence of thermally activated flux motion is a significant resistance even well below T_c in a magnetic field. From our measurements we can evaluate how seriously this affects certain applications. One of the major applications is in generating large magnetic fields. For the construction of superconducting magnets a resistivity criterion of $\sim10^{-6}$ $\mu\Omega$ cm is used.[15] This is only three orders of magnitude lower than our sensitivity limit. From Fig. 2 we can estimate for which field this criterion is fulfilled in $Ba_2YCu_3O_7$ crystals for any given temperature. This result, shown in Fig. 4, indicates that material with characteristics of this single crystal

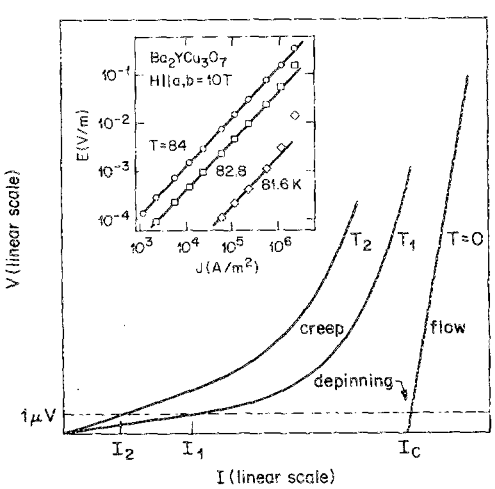

FIG. 3. Schematic representation of I-V curves for the high-temperature superconductors. At $T = 0$ the true depinning critical current is observed, but at higher temperatures flux creep results in dissipation and a 1 μV criterion gives an arbitrary current density. The inset shows three experimental linear I-V curves (low current regime) on a double logarithmic scale.

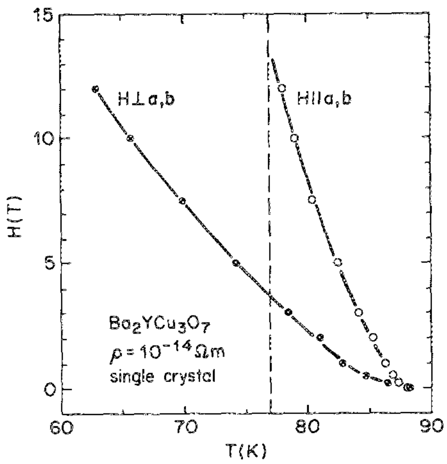

FIG. 4. Temperature dependence of the magnetic fields meeting a resistivity criterion of 10^{-6} $\mu\Omega$ cm as extrapolated from Fig. 2. The broken line indicates 77 K.

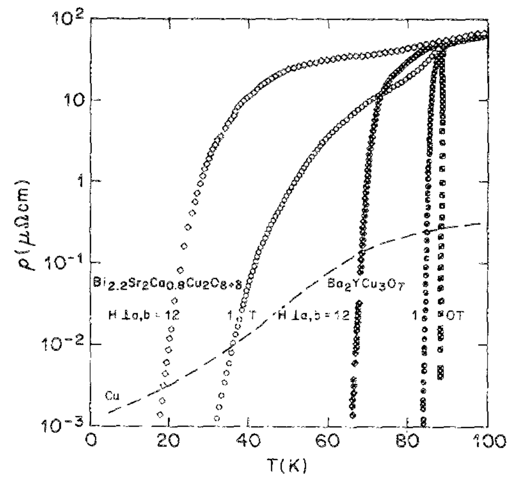

FIG. 5. Temperature dependence of the electrical resistivity of $Ba_2YCu_3O_7$ and $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ on a semilog scale for three magnetic fields.

could withstand a magnetic field of 15 T for alignment of $H \| a,b$ when operating at 77 K. For alignment of $H \perp a,b$ this field is reduced to 4 T. For interconnects the resistance criterion is less stringent; however, self-field effects need to be considered.

Finally, we compare the dissipation of $Ba_2YCu_3O_7$ and $Bi_{2.2}Sr_2Ca_{2.8}Cu_2O_{8+\delta}$ (Fig. 5). The former compound withstands considerable fields at 77 K, opening the possibility for generating magnetic fields with this material if the properties of a wire can equal the performance of this crystal. The 10^{-6} $\mu\Omega$ cm criterion pushes the operating temperatures for superconducting magnets using the latter material back to liquid-helium temperatures. This figure also clearly shows the different behavior of the two materials, and the resistivity of copper as a reference.

The different behavior of the two compounds may be associated with the difference in typical defect structure, or with the difference in interplanar coupling. $Ba_2YCu_3O_7$ crystals are extensively twinned but otherwise relatively free of interior defects. These twin planes extend through the thickness of the crystal, and could act as extended pinning centers for flux passing along them ($H \| c$ axis). The $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ crystals are defective, with extensive cross substitutions (as indicted by the observed stoichiometry) and intergrowths. These defects are not likely to be extended along the c axis, and would give smaller pinning energies. Still, the greater number of weak pinning sites in this material results in comparable "critical current densities" at low temperature for the two compounds,[16,17] However, larger values of J_c for the Bi-Cu compound at 77 K in magnetic fields require larger activation (pinning) energies, and thus extended pins.

On the other hand, if the degree of pinning is related to the interplanar coupling,[18] the Bi- and Tl-based superconductors would have intrinsic disadvantages particularly relative to three-dimensional high-temperature superconductors.

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