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Low-field flux-flow resistivity in $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$

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Current-voltage characteristics of single crystals of the 84-K superconducting phase $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ show no threshold behavior in small magnetic fields at 50–80 K, despite large zero-field critical currents which are only weakly field-dependent at low temperatures (< 20 K). We attribute this to a low-field flux-flow resistivity which shows an empirical scaling behavior near T_c and which we can use to infer some basic properties of the superconductor. This behavior is intrinsic to $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ and has crucial implications for its technological potential of the compound.

Study of the properties of high-temperature superconductors is important both because of the potential technological impact of these materials, and because of the scientific challenges involved in understanding their behavior. The critical current of these materials is of a particular significance, both because the ability to carry a high supercurrent density is crucial to most applications and because it is an extrinsic property of a material and the understanding of this property represents a formidable challenge in materials physics.

In the vortex state ($H > H_{c1}$) of type-II materials, pinning of vortices is necessary to prevent them from moving in the presence of an applied transport current, causing dissipation, i.e., a flux-flow resistivity. When sufficient current is applied, the vortex lattice will either depin or undergo plastic shear; thus defining a critical current. A perfect single crystal, free from defects and inhomogeneities, should have very weak flux pinning, although in practice crystals of both $Ba_2YCu_3O_7$ and $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ have been shown to have quite high critical currents.[1,2] In the former case this has been attributed to pinning at twin boundaries while in the latter case where it is clear that there are no twins,[3] some other feature must be operative. (Of course, if strongly superconducting regions are weakly coupled together, as is the case in ceramic samples of both materials, the overall critical current will be correspondingly low.) We have studied the critical current of single crystals of $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ as a function of temperature and external field H and report a significant deviation from the usual behavior of bulk superconductors: While the critical current is quite high at low temperatures (indicating the presence of strong pinning centers), at high temperatures there is apparently no threshold current for $H > H_{c1}$. We interpret this as reflecting an abrupt decrease in the modulus for plastic shear to essentially zero (i.e., melting of the vortex lattice). In the low-field regime $H \sim H_{c1}$, the flux-flow resistivity scales simply with the flux density B, resulting in a temperature-independent $\rho(H)$ curve. By close analysis of the behavior of the flux-flow resistivity, it is possible to infer some basic properties of $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$.

Single-crystal samples of $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ used for this study were grown from alkali-chloride fluxes as described previously.[4] The crystals grow as rectangular prisms with the c axis normal to the plane of the platelet, and with small crystal thickness (1–4 μm). High-quality in-line contacts were reproducibly made by our depositing a thin film (250 nm) of Ag onto a crystal face through a metal mask, using low-pressure (2.5-mTorr) Ar sputtering. Fine (25-μm-diam) Ag wires were attached to $\sim$1-mm^2 sputtered pads with an Ag cement which was fired at 400 °C. Contacts made by this procedure were nonrectifying with specific contact resistances less than 10^{-5} $\Omega\,cm^2$, and the contacts had considerable mechanical strength. The temperature dependence of the sample resistance was monitored by our applying a low-frequency (21-Hz) ac current across two contacts to the sample and monitoring the voltage on the other contacts with a phase-sensitive detector. High-current transport measurements were made at current densities up to 2×10^5 $A\,cm^{-2}$ both with a slow current ramp and by application of low duty cycle current pulses (1 Hz, 5-ms rise, 1-ms fall). Hysteresis in the I-V curves was observed in the case of the slow current ramp above 1×10^5 $A\,cm^{-2}$ and was attributed to heating; the pulsed measurements did not show indications of heating.

For these experiments, a single-crystal sample was chosen which had a single sharp resistive transition as seen in Fig. 1. The construct used for the definition of R_N as the intersection between the extrapolation of the essentially linear high-temperature region of the curve with the steep drop in the vicinity of the superconducting transition is illustrated. The inset shows the region of the transition on an expanded scale and reveals that $R=0$ is reached at 80 K.

A typical I-V characteristic for a superconductor has a zero-voltage region below a sharp threshold, the critical current. Normally, critical currents are operationally measured by definition of a voltage, electric field, or resistance criterion; the appropriate criterion depends on the application (e.g., a persistent-current magnet might be required[5] to have $\rho < 10^{-13}$ $\Omega\,cm$, while a low-resistance interconnect might only need to have $\rho < 10^{-8}$ $\Omega\,cm$). As shown in the upper portion of Fig. 2 for $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ at 76.6 K with zero applied field, the I-V curve shows fairly classical behavior, albeit with some rounding rather than a sharp threshold. This rounding is

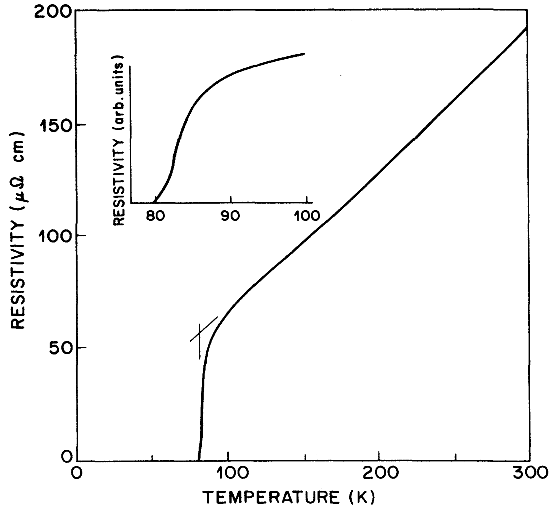

FIG. 1. Temperature dependence of the resistivity of a $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ single crystal.

in distinction to that observed previously by Dubson *et al.*[6] in $Ba_2YCu_3O_7$ ceramics (where it was attributed to weak links) since in the present case we see an extended zero-voltage region. However, the bottom of Fig. 2 illustrates the highly linear *I-V* curve obtained at 51.0 K in a 5-kOe field applied parallel to the *c* axis. More sensitive measurements with a lock-in amplifier verify the linearity of this curve down to 5 $A\,cm^{-2}$, while at current levels higher than shown in the figure, a small degree of curvature is seen, possibly because of the self-field of the current. This vanishing of the critical current is consistent with a reversible magnetization, as has been observed[7] in $(La,Ba)CuO_4$ and $Ba_2YCu_3O_7$ within a few K of T_c. We emphasize that in $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ the resistive behavior in a field extends to temperatures less than 35 K.

We might define a field criterion to extract a formal critical-current-density value from each such *I-V* curve, and data thus obtained are comparable to those reported previously.[2] The values for J_c obtained in this fashion have significance for some applications such as interconnects where a very low-resistivity material is sufficient. However, even in relatively small fields there is no zero-resistance segment in the *I-V* curve: For infinitesimal currents, a finite resistance is obtained due to the motion of vortices. The flux-flow resistivity $\rho_f(B,T)$ reflects the field- and temperature-dependent viscosity for vortex motion.

Figure 3 shows the magnetic field dependence of the normalized flux-flow resistance R_f/R_n for a fixed current density of 520 $A\,cm^{-2}$ and for various temperatures near T_c. Only data for $R_f/R_n \ll 1$ are shown. The low-field regime is particularly interesting since here the vortices interact the least, so that theories for flux-flow dissipation of isolated vortices are most likely to be valid. The curvature seen for $R_f/R_n > 0.05$ is probably related to that seen in the data of Juang *et al.*[8] in higher fields at lower temperatures, and reflects a complex behavior not completely understood at present.

The curvature seen for $R_f/R_n < 0.02$ is much simpler and shows an empirical scaling behavior, as demonstrated in Fig. 4, where data for four temperatures are scaled on the horizontal axis and overlaid. The inset shows the temperature dependence of the scaling field obtained by this procedure. It is expected that the flux-flow resistivity should be proportional to the flux density[9] B, at least at low fields, so the shape of the R_f/R_n vs H/H_{scale} curve should reflect the shape of the $B(H)$ curve for this sample. Indeed, the curve of Fig. 4 is qualitatively similar to the *B-H* curve that we expect for the plate-shaped sample of a type-II superconductor in a magnetic field perpendicular to the plate:

(1) The rounding at low field is attributed to demagnetizing effects (H is perpendicular to the sample plane), that is, the internal field reaches $H_{c1\parallel}$ (where we define $H_{c1\parallel}$ as the case for $\mathbf{H}\parallel\mathbf{c}$) when the applied field is much smaller

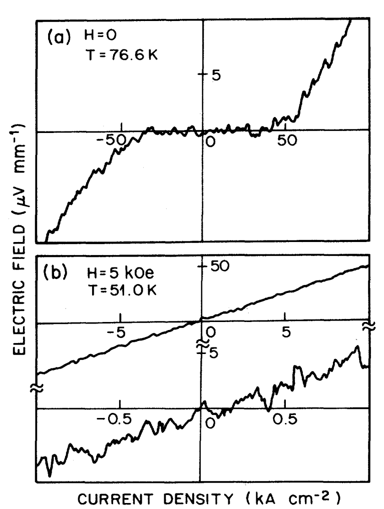

FIG. 2. Current-voltage curves for $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ crystal. Upper: $T=76.6$ K and $H=0$. Lower: $T=51.0$ K and $H=5$ kOe.

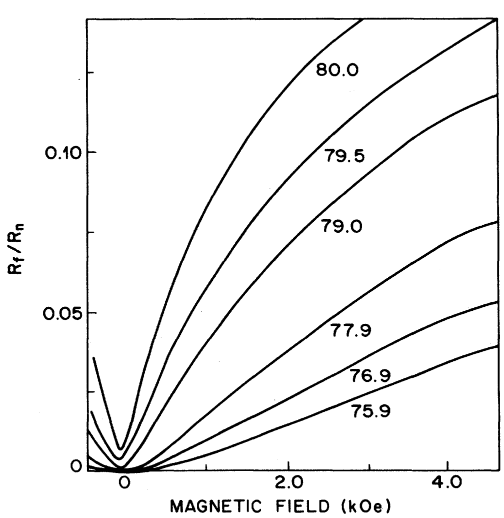

FIG. 3. Field dependence of the flux-flow resistivity as a function of sample temperature.

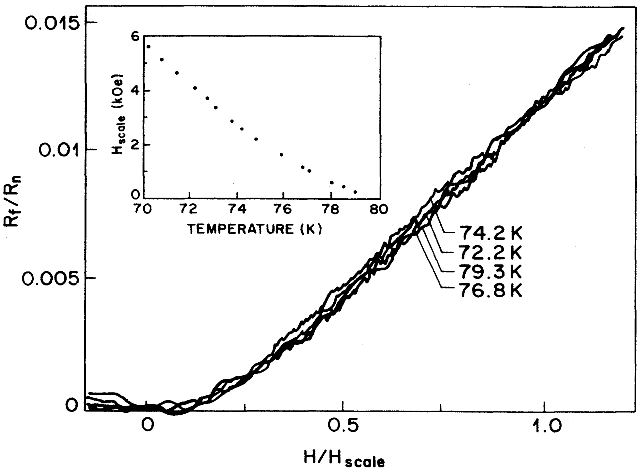

FIG. 4. Scaling behavior of the flux-flow resistivity. The horizontal axis is scaled to make the curves lie upon one another. Inset: temperature dependence of the scaling field.

TABLE I. Parameters for $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ inferred from analysis of the flux-flow resistivity (this work) compared to those inferred by Palstra *et al.* (Ref. 10) from conventional interpretation of $R(T)$ curves. The parameters are listed as critical-field slopes for simplicity: for example, $H_c' \equiv dH_c(T)/dT|_{T_c}$.

	This work	Palstra *et al.*[a]
$H_{c1\parallel}'$	100 Oe/K	b
$H_{c2\parallel}'$	14 kOe/K	7.5 kOe/K
$\kappa_\parallel$	13.5	b
H_c'	740 Oe/K	180 Oe/K
$H_{c1\perp}'$	2.1 Oe/K[c]	2.1 Oe/K
$H_{c2\perp}'$	2000 kOe/K	450 kOe/K
$\kappa_\perp$	1900	1000

[a] Reference 10.
[b] Not measured.
[c] The datum for $H_{c1\perp}'$ is taken from Palstra *et al.* (Ref. 10) and used to infer $H_{c2\perp}'$ and $\kappa_\perp$.

than this.

(2) When the external field approaches $H_{c1\parallel}$, the flux density increases more rapidly and this is reflected in a rapid increase in the flux-flow resistance.

(3) The flux density continues to increase almost linearly as the field increases further, approaching $H_{c2\parallel}$.

Since both $H_{c1\parallel}$ and $H_{c2\parallel}$ are expected to have the same temperature dependence, we expect that the shape of the (demagnetized) B-H curve should be independent of T near T_c, resulting in the observed behavior. The temperature dependence of the scaling field should be that of H_{c1} and H_{c2} as is shown in the inset to the figure. A forced linear fit yields a value of $H_{scale} \sim 750(T_c - T)$ Oe, although the data can be fitted much more accurately to a power law $H_{scale} \propto (T_c - T)^{2\nu}$, with a best fit for $2\nu = 1.93$ and $T_c = 81$ K.

We can use this qualitative interpretation of the R_f/R_n vs H/H_{scale} curve to estimate $H_{c1\parallel}$ and $H_{c2\parallel}$ in the spirit of the Ginzburg-Landau formalism, i.e., using the forced fit to a linear temperature dependence. A similar forced fit is typically used to infer H_{c2} from resistive transitions.[10] We identify the position of the region of highest curvature as being a lower bound on $H_{c1\parallel}$, since demagnetization would always shift this region to lower fields. We then have $H_{c1\parallel} \sim 0.2 H_{scale}$ or $H_{c1\parallel} = 150(T_c - T)$ Oe. We use the Hu-Thompson formula[9] $R_f/R_n = 0.38 B/H_{c2\parallel}$ to infer $H_{c2\parallel}$, using a self-consistent guess for B at the measured field H_{scale}, i.e., taking into account the $B(H)$ constituitive relation as well as the effects of demagnetization. We find $H_{c2\parallel} = 14(T_c - T)$ kOe by this technique, which is used to infer the thermodynamic field $H_c(T)$ and the Ginzburg-Landau parameter κ. Using $H_{c1\perp}(T)$ as measured by Palstra *et al.*,[10] we can infer $H_{c2\perp}(T)$. The results are summarized in Table I. The values for $H_{c2\perp}(T)$ and $H_{c2\parallel}(T)$ thus obtained compare favorably with those reported by Palstra *et al.*, noting that the Palstra estimates for $H_{c2\perp}$ and $H_{c2\parallel}$ (obtained from the field dependence of the resistive transition) are lower bounds. The exact numbers are sensitive to the details of the analysis and should be viewed as rough estimates. Indeed the value of $H_{c1\perp}$ is unexpectedly high, and implies a conduction electron density roughly fivefold larger than that expected for $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$. The upper-critical-field slope $H_{c2\perp}'$ is also extraordinarily high and leads to an unphysically small value for the coherence length, as given by $\xi_c^2(T) = (\Phi_0/2\pi)(H_{c2\parallel}/H_{c2\perp}^2)$. This may signify a fundamental problem in our understanding the effect of magnetic fields on superconductivity in $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$, or it may mean that the present interpretation of flux-flow results, as well as the conventional interpretation of the resistive transition data, are incorrect.

The nonlinearity seen in the temperature dependence of the scaling field of Fig. 4 evidently reflects a nonlinearity in the temperature dependence of $H_{c2\parallel}(T)$, qualitatively similar to that observed in $H_{c2}(T)$ of $Ba_2YCu_3O_7$ by Oh *et al.*,[11] who attribute the nonlinearity to critical fluctuations. A more quantitative interpretation of the power-law exponent which we find governs $H_{scale}(T)$ must await a definitive theory for the temperature dependence of the flux-flow viscosity, as present theories refer to materials which are either gapless[9] or in the dirty limit.[12]

It is clear from this work that the effective flux pinning force is extremely small in $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ at high temperatures. We have shown previously[2] that J_c (inferred from magnetization data at 9 kOe) was quite high at 4 K but decreased abruptly above ~35 K, and now interpret the decrease as due to the onset of flux flow with essentially no threshold current. Two possibilities may explain this behavior: The pinning force itself may be very small,[13] leading to a high creep rate above 35 K, or, alternatively, the flux lattice may melt[14,15] at this temperature, i.e., the shear modulus may vanish, so that the few vortices that are pinned do not prevent motion by the rest. The pinning energies observed by Palstra, Batlogg, Schneemeyer, and Waszczak[16] are sufficiently low to explain a transition from the (low-temperature) flux creep regime to the viscosity-limited regime we have explored in this paper.

The vanishing of the critical current of $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ at low temperatures in moderate fields is observed in all of the single crystals we have measured, as well as in thin films, and is consistent with our measurements of ceramic samples. The significance of this behavior for the technological applications of this material is profound, as even small magnetic fields result in prohibitive levels of dissipation. It may be possible to alter this behavior by modification of the compound, e.g., by doping on the Bi site to affect the carrier density or interplanar coupling. $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ is of significant interest for fundamental studies of possible vortex liquid states as well as flux-flow viscosity.

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