Giant Out-of-Plane Magnetoresistance in Bi-Sr-Ca-Cu-O: A New Dissipation Mechanism in Copper-Oxide Superconductors?

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We have measured the anisotropic magnetoresistivity tensor of single-crystal $Bi_2Sr_2CaCu_2O_8$ in the normal and mixed states. For magnetic fields applied perpendicular to the Cu-O (a-b) planes, the out-of-plane (c-axis) resistivity displays a huge magnetic enhancement, and a large apparent depression in the resistively measured transition temperature T_c(c axis). No such depression is observed in T_c(a-b plane). Although these results suggest a field-induced anisotropy in T_c, we propose an alternate model of novel Lorentz-force-independent fluctuation-induced dissipation in the mixed state. The model may also account for the anomalous anisotropic magnetoresistance seen in layered low-T_c superconductors.

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In addition to their high transition temperatures and peculiar normal-state properties,[1] the high-T_c superconducting oxides are host to an array of exotic magnetic effects, interpreted variously as manifestations of glass-like behavior, flux creep,[2,3] flux flow,[4] vortex-lattice melting, and thermodynamic fluctuations.[5,6] Of particular interest is the anomalously large broadening seen almost universally in the a-b-plane resistive transition for applied magnetic fields $H > H_{c1}$.[3,5,7] Aside from its basic physics interest, this phenomenon has implications for possible technological applications of the high-T_c oxides.

We report here the first measurement of the out-of-plane (c-axis) longitudinal magnetoresistance of single-crystal $Bi_2Sr_2CaCu_2O_8$. We find that under magnetic fields of up to 7 T oriented along **c**, the c-axis resistivity $\rho_c(T,H)$ of $Bi_2Sr_2CaCu_2O_8$ exhibits a huge Lorentz-force-independent magnetoresistance at temperatures below $T_c(H=0)$. $\rho_c(T,H)$ exhibits what *appears* to be a severely depressed magnetic-field-dependent superconducting onset temperature, as well as a broadened transition region. This is in contrast to the a-b-plane magnetoresistance of $Bi_2Sr_2CaCu_2O_8$ where T_c remains essentially constant and only the width of the transition is affected by application of the magnetic field. Although the $\rho(T,H)$ data are suggestive of a novel form of magnetically induced anisotropic superconductivity where the critical temperature is no longer a scalar quantity, we argue in favor of an alternate explanation, based on a model with an isotropic T_c and a novel fluctuation-induced dissipation mechanism for out-of-plane transport.

Single-crystal samples of $Bi_2Sr_2CaCu_2O_8$ with average dimensions of 1 mm×1 mm×0.012 mm were prepared by standard methods.[8] Low-resistance contact (~1 Ω) was made to the samples using fired-on silver pads. The a-b-plane resistivity ρ_{ab} was measured using a linear four-probe contact configuration. The c-axis resistivity ρ_c was measured simultaneously with ρ_{ab} using a modified Montgomery contact configuration.[9] ρ_c was also measured independently using a concentric-ring contact configuration. The average current density used in the experiment was 0.15 A/cm^2, and for $H=7$ T the resistance was linear in this current regime.

Figure 1(a) shows the a-b-plane resistivity of a $Bi_2Sr_2CaCu_2O_8$ crystal for magnetic fields 0, 0.5, and 7

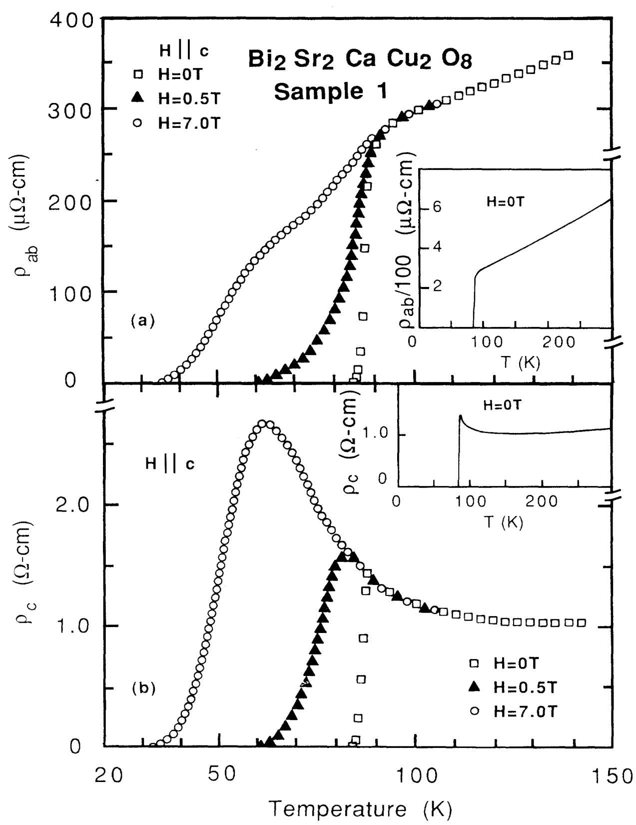

FIG. 1. (a) ρ_{ab} and (b) ρ_c vs T for **H** parallel to **c**. The insets show zero-field behavior.

T oriented parallel to the c axis. The temperature dependence of the magnetoresistance shown here is very similar to that observed previously in $Bi_2Sr_2CaCu_2O_8$ crystals,[3] $Tl_2Ba_2CaCu_2O_y$ crystals and films,[10] and $YBa_2Cu_3O_7$ crystals,[7] and has been interpreted by some as evidence for dissipative vortex motion.[3,11] Others, however, noting the lack of a Lorentz-force dependence in some measurements of the a-b-plane magnetoresistance of $Bi_2Sr_2CaCu_2O_8$ and $Tl_2Ba_2CaCu_2O_y$ films,[5,10] have proposed that the widened a-b-plane transition is due to thermally activated phase-slip events. The a-b-plane data shown in Fig. 1(a) were taken in a configuration with $\mathbf{J}_t \perp \mathbf{H}$ ($\mathbf{J}_t$ is the transport current density), resulting in a nonzero Lorentz force on internal vortices. We note that although the a-b-plane resistivity for the sample of Fig. 1(a) is on the high side of the range found in the literature, other samples having lower resistivity were measured with nearly identical results.

Figure 1(b) shows the out-of-plane magnetoresistivity ρ_c of the same $Bi_2Sr_2CaCu_2O_8$ crystal (measured simultaneously with ρ_{ab} and determined by a Montgomery-method analysis[9]). Rather than displaying a broadened transition starting at $T_c(H=0)$ as seen in $\rho_{ab}(T,H)$, $\rho_c(T,H)$ continues its normal-state behavior *well below* the zero-field T_c, until it eventually turns over at a new, largely depressed, "transition" temperature T^*. For $T < T^*$, $\rho_c(T,H)$ displays a broadened transition to zero resistivity. Comparison of $T^*(H)$ with the relatively unchanged T_c(a-b plane) extracted from the $\rho_{ab}(T,H)$ data suggests the interesting possibility that, under the influence of a magnetic field, superconductivity appears along the copper sheets before it appears along the c direction (i.e., T_c becomes anisotropic). However, as we discuss below, the apparent T_c anisotropy is more likely an artifact of a new out-of-plane dissipation mechanism involving an isotropic T_c. We note that the huge c-axis magnetoresistance observed below $T_c(H=0)$ is sensitive to the direction of the applied H field. For $\mathbf{H} \perp \mathbf{c}$, no dramatic magnetoresistance is observed in ρ_c.

For a precise determination of $\rho_c(T,H)$ it is desirable to find an alternative to the Montgomery method. One reason for this is that the validity of the Montgomery-method analysis in a magnetic field is questionable, especially for a type-II superconductor in the mixed state. As a result, we have measured $\rho_c(T,H)$ employing a new, symmetrical four-point contact configuration [shown schematically in Fig. 2(a)] to insure a uniform current distribution with $\mathbf{J}_t$ parallel to $\mathbf{H}$. The results of such a ρ_c measurement (on a different $Bi_2Sr_2CaCu_2O_8$ crystal) are shown in Fig. 2(a), again for $\mathbf{H}$ parallel to the c axis. The huge magnetoresistance and persistence of normal-state behavior below $T_c(H=0)$ are observed, congruent with the data of Fig. 1(b). At low temperatures, the $\rho_c(T,H)$ data are qualitatively similar to $\rho_{ab}(T,H)$ which has been demonstrated to display activated behavior.[3] The inset of Fig. 2(a) shows

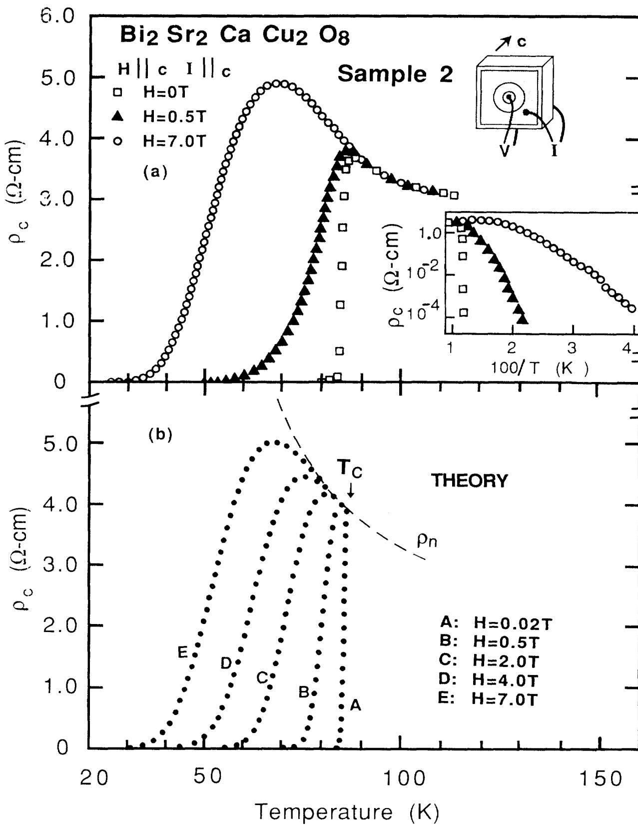

FIG. 2. (a) ρ_c for $\mathbf{H}$ parallel to $\mathbf{c}$ using the symmetric contact configuration shown schematically. Inset: Arrhenius plot of the same data. (b) Equation (4) (solid symbols) fitted to $\rho_c(T<T_c)$ data in (a) with $J_c(0)=5.4\times10^{-6}$ A/cm^2 (see text). ρ_n fit by Eq. (2) is also shown.

$\log[\rho_c(T,H)]$ plotted versus inverse temperature. This Arrhenius plot suggests that, if a thermal-activation mechanism applies, the activation energy is temperature dependent in this temperature range.

We argue that the huge c-axis magnetoresistance effects observed for $Bi_2Sr_2CaCu_2O_8$ cannot be accounted for by previously considered mechanisms. First, we note the lack of a macroscopic Lorentz force in our experimental configuration for ρ_c, as $\mathbf{H}$ is parallel to $\mathbf{J}_t$. A Lorentz force is needed to drive vortices in any flux-creep or flux-flow scenario. It has been suggested that a nonzero Lorentz force might be generated through some sort of misalignment between $\mathbf{H}$ and $\mathbf{J}_t$. However, misalignment due to random microscopic inhomogeneities in the current distribution will average to zero. Similarly, the Lorentz force on a randomly bent vortex (threading the sample parallel to the c axis) should also average to zero. This leaves mechanical misalignment between $\mathbf{H}$ and the c axis. Kes *et al.*[12] have persuasively argued that only the component of $\mathbf{H}$ parallel to $\mathbf{c}$ gives rise to a vortex lattice in the layered high-T_c superconductors.

They suggest that for $\mathbf{H}\perp\mathbf{c}$ there are no vortices and consequently there is no dissipation related to flux flow. If this is indeed the case, then the small $\mathbf{H}\perp\mathbf{c}$ component due to a possible misalignment in our ρ_c measurements is entirely negligible.

Nevertheless, we consider the case in which the $\mathbf{H}\perp\mathbf{c}$ component is non-negligible and causes dissipation due to flux flow. We briefly concentrate on the "high-temperature" portion of the transition region, $T/T_c > 0.85$, where flux flow would be most likely to occur.[3,4] Here we have attempted to fit the $\rho_c(T,H)$ data by the Bardeen-Stephen expression for flux-flow resistivity:[13]

$$\rho(T,H) \approx \rho_n(T) H/H_{c2}(T) . \quad (1)$$

$\rho_n(T)$ is the normal-state resistivity and is obtained by fitting the normal-state portion of the $\rho_c(H=7\ \mathrm{T})$ data in Fig. 2(a) by the empirical expression[9]

$$\rho_n(T) = \rho_0 T^7 \exp(\Delta/kT) \quad (2)$$

and extrapolating to temperatures below $T_c(H=0)$. $H_{c2}(T)$ is assumed to be proportional to $(1-T/T_c)^\nu$. With $\rho_0 = 0.0225\ \Omega\,\mathrm{cm}$, $\Delta/k = 175.9$ K, $\nu = 1$, and $T_c = 86$ K, Eq. (1) yields a $\rho(T)$ that has a positive slope with respect to temperature for $T \le T_c$. Experimentally, however, $\rho_c(T,H)$ displays a negative slope near T_c for all $H \neq 0$. This discrepancy cannot be accounted for by slight changes in ν, nor by including small corrections due to published values of $T_c(H)$.[4] We also note that just below T_c the measured resistivity does not scale with H as expected from Eq. (1). This reasoning, of course, is not so useful if the behavior of the flux-flow resistivity in $Bi_2Sr_2CaCu_2O_8$ differs considerably from Eq. (1). We find this unlikely, however, considering the qualitative agreement with Eq. (1) seen in the a-b-plane flux-flow resistivity measurements of Ref. 4.

The lack of a flux-flow resistivity in our ρ_c measurements also argues against the existence of a flux-creep component to the dissipation seen at lower temperatures, since flux creep should give over to flux flow as the temperature is increased into the regime where kT is greater than U_0, the vortex pinning potential.[3] Previous results[2-4] indicate that for $T/T_c > 0.85$, $Bi_2Sr_2CaCu_2O_8$ is likely in that (reversible) regime. The fact that flux flow is not seen here thus argues against the importance of any dissipative vortex motion in our experimental configuration.

We turn now to a model which quantitatively accounts for the main features of our $\rho_c(T,H)$ data. For $H > H_{c1}$ and $T < T_c$ we accept that the vortices are aligned parallel to $\mathbf{c}$ with average spacing $d \approx (\Phi_0/H)^{1/2}$. Current moving parallel to the c axis is taken to pass through the narrow superconducting channels of area $A \approx d^2$ between the densely packed vortices. This is possibly through defect-mediated interplanar "weak links" as discussed in Refs. 14 and 15. Dissipation occurs through thermodynamic fluctuations which cause the phase of the superconducting order parameter in the c direction to jump by 2π.[16] The crucial assumption of our model is that the fluctuations occurring in each superconducting channel are uncorrelated and independent of the fluctuations occurring in the surrounding channels. Some justification for this assumption can be found in the work of Ikeda, Ohmi, and Tsuneto[6] who suggest that for $H > H_{c1}$ the correlation radius of order-parameter fluctuations cannot grow beyond a fixed scale determined by the applied field in the plane perpendicular to the field.

As a result, c-axis conduction in an applied field parallel to $\mathbf{c}$ occurs through an array of parallel, independently fluctuating, superconducting channels. The dissipative behavior of narrow, superconducting channels (i.e., weak links) in the presence of thermodynamic fluctuations has been studied extensively.[16,17] The resistance of a weak link at finite temperature is given approximately by[16]

$$R = R_n [I_0(hI_c/4\pi ekT)]^{-2} . \quad (3)$$

R_n is the channel's normal-state resistance, h is Planck's constant, e is the charge on an electron, and I_0 is the modified Bessel function. The critical current of the channel is $I_c = J_c A$, where J_c is the critical current density of the channel, and A is its area. J_c is the intrinsic Ginzburg-Landau depairing critical current density $J_c = J_c(0)(1-T/T_c)^{3/2}$. Approximating R_n in Eq. (3) by the extrapolated empirical normal-state expression Eq. (2), we find for the whole sample, below T_c and for $H > H_{c1}$,

$$\rho_c(T,H) = \rho_0 T^7 \exp(\Delta/kT) [I_0((h/4\pi ekT) J_c(0)(1-T/T_c)^{3/2}\Phi_0/H)]^{-2} . \quad (4)$$

With ρ_0 and Δ fixed by $\rho_c(T > T_c)$ [see discussion of Eq. (2)] and $T_c = 86$ K from the zero-field data, we find [neglecting $T_c(H)$] that $J_c(0)$ is the only free fitting parameter in Eq. (4).

Figure 2(b) shows the predictions of Eq. (4) with $J_c(0) = 5.4 \times 10^6$ A/cm^2 for various values of the magnetic field. Equation (4) fits the experimental data almost perfectly for $H = 7$ T over the entire temperature range. For $H = 0.5$ T the fit is still fairly good, but the data show more dissipation at low temperatures than is predicted by the theory. We note that the apparent T_c depression is well accounted for by Eq. (4), which assumes that the true bulk T_c is isotropic and unchanged by the magnetic field.

The value of $J_c(0)$ obtained from the fitting parameter is roughly the same order of magnitude as the measured in-plane critical current density of $Bi_2Sr_2CaCu_2O_8$, but is higher than the measured out-of-plane critical current density.[18] However, care must be taken in comparing $J_c(0)$ extracted here to J_c measured experimentally, as $J_c(0)$ is the intrinsic pair-breaking critical current density while the experimental J_c is limited by extrinsic quantities such as the flux pinning strength. Using published values of the coherence length (ξ_{ab}) and magnetic penetration depth (λ_{ab}) in $Bi_2Sr_2CaCu_2O_8$,[18,19] we find that the expected intrinsic c-axis critical current ranges from 2×10^5 to 5×10^7 A/cm^2.[20] Although there is great disparity in these values (arising mostly from the uncertainty in λ_{ab}), we can still conclude that the value of $J_c(0)$ derived from our data is well within the limits set by current high-T_c literature.

It is interesting to note similarities between the predictions of the c-axis dissipation model presented here and those of other models proposed to account for a-b-plane dissipation. In the closely related Lorentz-force-independent model of Kim *et al.*,[10] the sample is assumed to be threaded by thermally fluctuating Josephson junctions, for which Eq. (3) also applies. However, in this case I_c is the critical current of a tunnel junction, strongly dependent on the temperature and field dependence of the energy gap. Neglecting ρ_n, this leads to a different functional form for $\rho(T,H)$ than Eq. (4). In the vortex-motion-dissipation model of Tinkham,[11] the expression for $\rho(T,H)$ is, aside from a dependence on a "flux bundle volume," functionally identical to Eq. (4). In Tinkham's model, however, the underlying physics is motivated by Lorentz-force-driven flux creep, while in our model we assume neither the existence of a Lorentz force nor any form of vortex motion.

Finally, we remark that a possibly related anisotropic magnetoresistance behavior has been observed in the layered, low-temperature superconductor TaS_2(pyridine)$_{1/2}$.[21] In the presence of a magnetic field, TaS_2-(pyridine)$_{1/2}$ displays a large out-of-plane longitudinal magnetoresistance and an apparent T_c anisotropy similar to that observed here for $Bi_2Sr_2CaCu_2O_8$.[21] TaS_2(pyridine)$_{1/2}$ is structurally similar to $Bi_2Sr_2CaCu_2O_8$ (the two materials also have a comparable electrical anisotropy), and we suggest that the same out-of-plane dissipation mechanism may be applicable to both materials and possibly other classes of layered superconductors.

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