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Out-of-plane current transport in $Bi_2Sr_2CaCu_2O_8$ in the mixed state

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We have investigated c-axis dissipation in single crystals of $Bi_2Sr_2CaCu_2O_8$ in the mixed state. We find that the c-axis DC electrical resistivity ρ_c depends strongly on the magnitude and orientation of the magnetic field. Variations in ρ_c are interpreted within the framework of different dissipation mechanisms.

The anomalously large broadening of the ab-plane resistive transition in a magnetic field has been among the most extensively studied aspects of the high-temperature superconductors [1–5]. Because of its direct relevance to the structure of the mixed state in high-T_c superconductors (as well as being fundamental to possible technological applications), the origin of this phenomenon is a pressing scientific concern. A great number of dissipation models have been advanced, including Josephson junction networks [1], thermally activated flux creep [2], curved flux lines [6], flux entanglement [7], and thermodynamic fluctuations [3].

We here report on measurements of c-axis DC electrical resistivity, $\rho_c(T, H)$, of single crystals of $Bi_2Sr_2CaCu_2O_8$ in magnetic fields up to 7 T oriented parallel and perpendicular to the applied current. As in a previous study [8], we find that when the magnetic field is oriented along the current direction ($\boldsymbol{H}\|\boldsymbol{c}$, i.e. absence of a Lorentz force), the c-axis resistivity, $\rho_c(T, \boldsymbol{H}\|\boldsymbol{c})$, of $Bi_2Sr_2CaCu_2O_8$ exhibits a huge magnetoresistance at temperatures below $T_c(H=0)$. This becomes manifest as an apparent severe depression of the superconducting onset temperature (≈ 30 K at 7 T) followed by a broadening of the resistive transition. This is in sharp contrast to the well known ab-plane behavior, $\rho_{ab}(T, \boldsymbol{H}\|\boldsymbol{c})$, for which there is a strong depression of the zero resistivity point but the onset of superconductivity is hardly depressed [2,8]. On the other hand, the c-axis resistivity for magnetic field oriented perpendicular to the current direction, $\rho_c(T, \boldsymbol{H}\perp\boldsymbol{c})$, exhibits only a small depression of the onset T_c. There is a broadening of the resistive transition, and the functional form of $\rho_c(T, \boldsymbol{H}\perp\boldsymbol{c})$ is strongly dependent on the magnitude of the c-axis transport current.

High purity single crystals of $Bi_2Sr_2CaCu_2O_8$ were prepared by standard methods [9]. A low resistance contact was made to the samples using fired on silver pads. $\rho_c(T, H)$ was measured using a concentric ring contact configuration [8], and unless otherwise noted a nominal current density of 0.17 A/cm^2. As an added check, $\rho_c(T, H=0)$ was also measured simultaneously with ρ_{ab} using a modified Montgomery contact configuration [10], with essentially the same results.

Figure 1(a) shows $\rho_c(T, \boldsymbol{H}\|\boldsymbol{c})$ for a $Bi_2Sr_2CaCu_2O_8$ crystal for selected magnetic fields 0 T, 0.5 T, 3.5 T and 7 T oriented parallel to the c-axis. In zero field, the resistive transition is sharp with a midpoint $T_c=85$ K and a width of $\Delta T_c<2$ K. The application of a magnetic field causes $\rho_c(T, H=\text{const.})$ to apparently continue its normal-state "semiconductor-like" behavior with a concomitant depression of the onset transition temperature, followed by a broad resistive transition. The temperature interval over which $\rho_c(T, H=\text{const.})$ continues its semiconduc-

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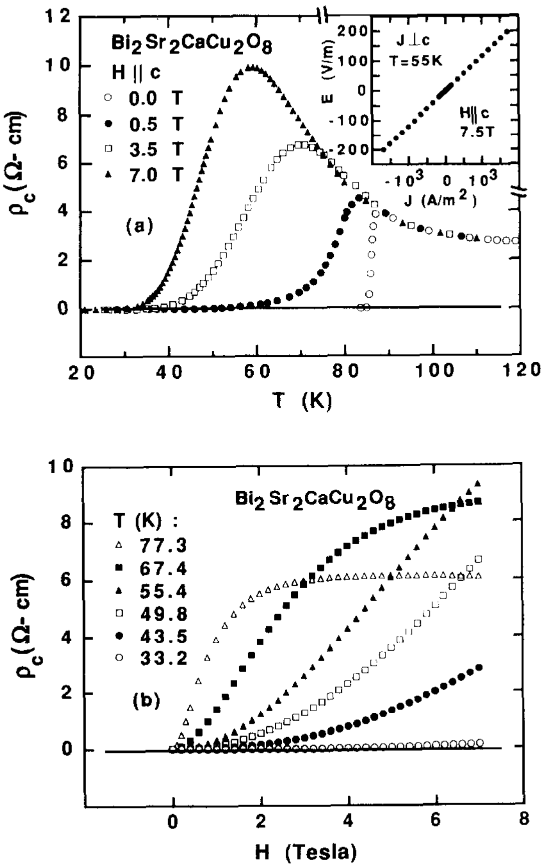

Fig. 1. (a) The resistive transition $\rho(T, \boldsymbol{H}\|\boldsymbol{c})$ of $Bi_2Sr_2CaCu_2O_8$ single crystal for various values of the field, and (b) $\rho_c(H)$ at selected temperatures for $\boldsymbol{H}\|\boldsymbol{c}$ up to 7 T. The current density was 0.17 A/cm^2. The inset shows a typical I–V for this configuration.

tor-like trend increases as the magnetic field increases.

In the inset of fig. 1(a) we show a typical current–voltage (I–V) characteristic for $Bi_2Sr_2CaCu_2O_8$. Experimentally, the I–Vs are found to be linear at low current density and high temperature, though they deviate from linearity at the lowest temperatures and highest currents. At $H=7.5$ T, for example, nonlinear I–Vs are observed at temperatures below 45 K.

Figure 1 (b) shows the magnetic field dependence of the out-of-plane resistivity, $\rho_c(T=\text{const.}, \boldsymbol{H}\|\boldsymbol{c})$, at selected temperatures, for magnetic field up to 7 T. At low temperatures ρ_c exhibits positive curvature as it smoothly increases with magnetic field. At higher temperatures the slope of $\rho_c(T=\text{const.}, \boldsymbol{H}\|\boldsymbol{c})$ becomes steeper at low fields and its curvature is observed to become negative. At temperatures close to the zero field transition temperature, $\rho_c(T=\text{const.}, \boldsymbol{H}\|\boldsymbol{c})$ becomes magnetic field independent at the highest fields tested. We also note that high temperature and low temperature curves are found to cross over at a particular value of magnetic field; larger temperature differences between the curves lead to higher values of this "crossing" magnetic field.

The apparent depression of T_c displayed in fig. 1(a) cannot simply be accounted for by the suppression of superconductivity at $H>H_{c2}(\|\boldsymbol{c})$ since $-\mathrm{d}H_{c2\|}/\mathrm{d}T$ is 0.75 to 1.4 T/K obtained form ab-plane transport measurements [11,12]. The $-\mathrm{d}H_{c2\|}/\mathrm{d}T$ implied by fig. 1(a) is ≈ 0.2 T/K.

Other mechanisms based upon a Lorentz force [8] are considered unlikely due to the geometry of this experiment. In ref. [8] it was argued that the origin of the c-axis dissipation in this configuration is thermally activated phase slip across weak links threading the sample. Figures 2(a) and (b) show the theoretical fits of the data shown in fig. 1 to the expression for the resistivity of a weak link at finite temperature [8,13]:

$$\rho_c=\frac{\rho_n(T)}{\left\{I_0\left(\frac{\hbar}{2ekT}J_c(0)\left[1-\frac{T}{T_c}\right]^{3/2}\frac{\Phi_0}{H}\right)\right\}^2}, \tag{1}$$

where I_0 is the zeroth order modified Bessel function. The normal resistivity has been approximated by the empirical expression [10]

$$\rho_n(T)=\rho_0 T^{0.7}e^{\Delta/k_BT}, \tag{2}$$

with $\rho_0=0.00947$ Ωcm and $\Delta/k_B=268.406$ K, and the critical current of a superconducting weak link of area $A=\Phi_0/H$ has been rewritten as

$$I_c=J_cA=J_c(0)\left(1-\frac{T}{T_c}\right)^{3/2}\frac{\Phi_0}{H}, \tag{3}$$

where J_c is the intrinsic Ginzburg–Landau depairing critical current density. $T_c=85$ K is assumed to be field independent.

With ρ_0 and Δ fixed by data taken at zero field ($H=0$ T, $T_c=85$ K), $J_c(0)$ becomes a free fitting parameter. The data are best fit with $J_c(0)=5.1\times10^6$ A/cm^2. As expected, our deduced value of the intrinsic *depairing* critical current density is significantly larger than the experimentally determined c-

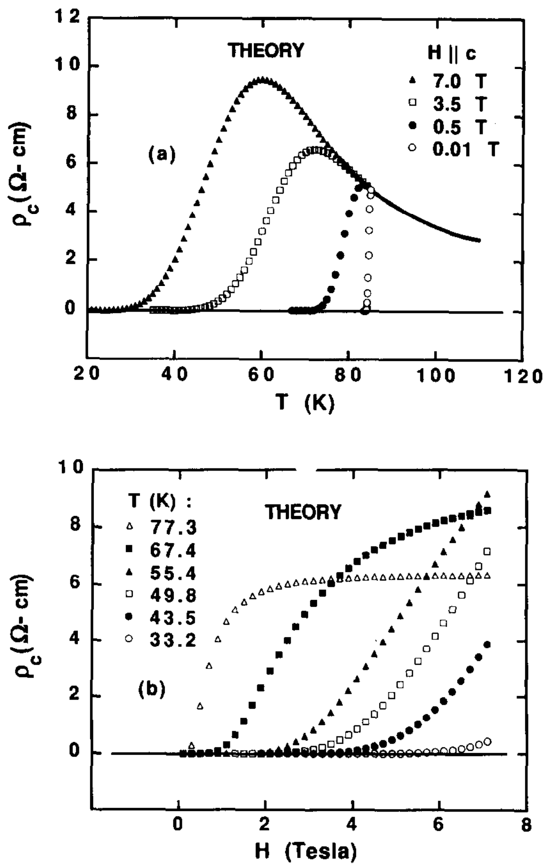

Fig. 2. (a) Equation (1) fitted to $\rho_c(T<T_c, \boldsymbol{H}\|\boldsymbol{c})$ data in fig. 1 (a) with $J_c = 5.08\times10^6$ A/cm^2 (see text). $\rho_n(T>T_c)$ is also shown. (b) Fitted $\rho_c(H)$ curves with the same parameters.

axis critical current density, $J_{c\,\mathrm{exp}}(0) = 4.7\times10^4$ A/cm^2 [14]. From our determined $J_c(0)$, we may extract the London penetration depth [15]

$$\lambda_c = \left(\frac{c\Phi_0}{12\pi^2\sqrt{3}\xi J_c(0)}\right)^{1/2}. \qquad (4)$$

Combining $J_c(0) = 5.1\times10^6$ A/cm^2 with $\xi = 38\times10^{-4}$ μm [14] we find $\lambda_c = 0.72$ μm. This value is intermediate to the two other values of the London penetration depth for $Bi_2Sr_2CaCu_2O_8$ reported in the literature: Malozemoff, et al. [16] find $\lambda = 0.3$–0.6 μm, while Biggs, et al. [14] report $\lambda = 7$ μm.

The theoretical curves in fig. 2 are found to describe the apparent depression of T_c very well, and agree quantitatively with the experimental data at high fields and high temperatures. The extra dissipation observed experimentally at low temperature and low magnetic field may be due to sample inhomogeneities, not taken into account by the theory. We also remark that recently an order-parameter fluctuation theory has been suggested [17] to account for the $\rho_c(T, \boldsymbol{H}\|\boldsymbol{c})$ behavior. The fluctuation model also gives reasonable fits [17] to a subset of our experimental data.

We now turn to the measurement of the out-of-plane magnetoresistivity, $\rho_c(T, \boldsymbol{H}\perp\boldsymbol{c})$, of the same $Bi_2Sr_2CaCu_2O_8$ crystal for magnetic fields oriented parallel to the *ab*-plane. The results of such a measurement are shown in fig. 3 for magnetic fields 0 T, 0.5 T, 3.5 T, and 7.0 T. In the presence of a magnetic field, $\rho_c(T, \boldsymbol{H}\perp\boldsymbol{c})$ behaves similarly to $\rho_c(T, \boldsymbol{H}\|\boldsymbol{c})$, i.e. it continues its semiconductor-like behavior for a few degrees below the $T_c(H=0)$, until it turns over and displays a broadened transition to zero resistivity. In fact, it is tempting to interpret $\rho_c(T, \boldsymbol{H}\perp\boldsymbol{c})$ as resulting from a slight misalignment of the magnetic field since $\rho_c(T, \boldsymbol{H}\perp\boldsymbol{c} = 7.0\ \mathrm{T})$ closely resembles $\rho_c(T, \boldsymbol{H}\|\boldsymbol{c} = 0.5\ \mathrm{T})$. As we demonstrate below, however, this is not the case.

To investigate a possible "scaling" of $\rho_c(T)$ curves for different H-field orientations, I–V characteristics were examined for the configuration ($\boldsymbol{H}\perp\boldsymbol{c}$, $\boldsymbol{J}\|\boldsymbol{c}$, i.e., $\boldsymbol{H}\perp\boldsymbol{J}$). Figure 4 shows the broadening of the resistive transition for various current densities ranging from 1.7×10^{-5} to 0.17 A/cm^2, at a fixed magnetic field ($H = 7.5$ T). $\rho_c(T, \boldsymbol{H}\perp\boldsymbol{c})$ is independent of the

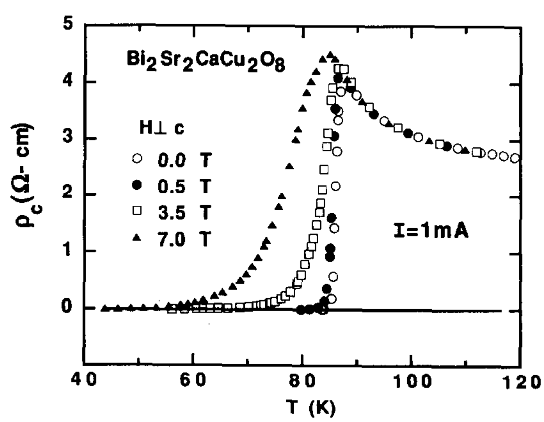

Fig. 3. The resistive transition $\rho(T, \boldsymbol{H}\perp\boldsymbol{c})$ of $Bi_2Sr_2CaCu_2O_8$ for selected values of $\boldsymbol{H}\perp\boldsymbol{c}$, and current density 0.17 A/cm^2.

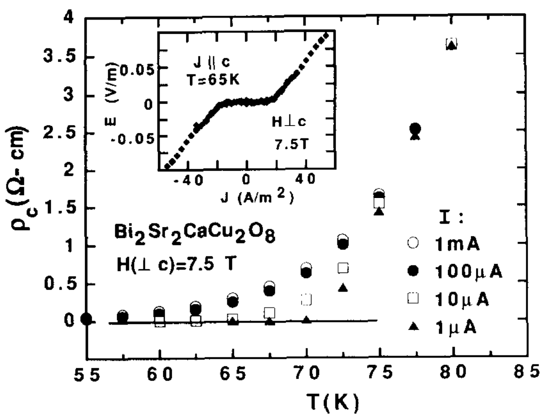

Fig. 4. Dependence of $\rho(T,\ \boldsymbol{H}\perp\boldsymbol{c})$ on measuring current, for $H=7.5$ T; solid lines are a guide to the eye. The area of the sample is 0.588 mm^2, thus the current density is given by $J=170\times I$ A/cm^2. The inset shows a typical I–V for this configuration.

probing current density at temperatures close to T_c. However, as the temperature is lowered, $\rho_c(T,\ \boldsymbol{H}\perp\boldsymbol{c})$ displays an increasing dependence on the measuring current density. Smaller probing currents result in lower resistivity, with a subsequent narrowing of the resistive transition. A typical I–V characteristic is shown in the inset of fig. 4, where *threshold* behavior can be observed, i.e. no dissipation is detected until the current exceeds a critical current. This threshold behavior rules out the scaling i.e. misalignment hypothesis since $\boldsymbol{H}\|\boldsymbol{c}$ yields only linear I–V characteristics (inset to fig. 1 (a)). The threshold current decreases with increasing temperature and increasing magnetic field.

To account for $\rho_c(T,\ \boldsymbol{H}\perp\boldsymbol{c})$ and $J_{\text{threshold}}$ we need to consider the presence of a finite Lorentz force. In such circumstances, an expression similar to eq. (1) has been used to explain the broadening of the *ab*-plane resistive transition [1]. Flux creep models [2] have also been advanced. However, both are unable to account for the existence of a critical depinning current, since they both predict ohmic I–V characteristics in the low current regime. We also attempted to fit the $\rho_c(T,\ H)$ data to the original Bardeen–Stephen expression for flux flow resistivity [18]:

$$\rho(T,H\perp c)\approx\rho_n(T)\,\frac{H}{H_{c2}(T)}\,, \qquad (5)$$

where $\rho_n(T)$ is the normal state resistivity obtained from eq. (2). Equation (5) yields a $\rho(T,\ \boldsymbol{H}\perp\boldsymbol{c})$ that has a positive slope with respect to temperature for $T\leqslant T_c$. Experimentally, however, $\rho_c(T,\ \boldsymbol{H}\perp\boldsymbol{c})$ displays a negative slope near T_c for all $H\neq 0$. We also note that just below T_c the measured resistivity does not scale with H as expected from eq. (5).

It is hard to reconcile the existence of a threshold current in the geometry $\boldsymbol{J}\perp\boldsymbol{H}$ with the lack of one in the orientation $\boldsymbol{J}\|\boldsymbol{H}$. One possibility is to consider Abrikosov vortices to be more strongly pinned when $\boldsymbol{H}\perp\boldsymbol{c}$ than when $\boldsymbol{H}\|\boldsymbol{c}$. However, Feinberg and Villard [19] have investigated theoretically the pinning properties of Abrikosov vortices in a layered superconductor. They find that, for $\boldsymbol{J}\|\boldsymbol{c}$, Abrikosov vortices with $\boldsymbol{H}\perp\boldsymbol{c}$ are very weakly pinned with respect to motion parallel to the superconducting planes. The vortices lie between the planes, in a region where the superconducting order parameter is depressed. For this reason, the core-pinning energy of the vortices is very low when they pin to defects between the planes. On the other hand, a vortex that pierces the planes ($\boldsymbol{H}\|\boldsymbol{c}$) has a much higher core-pinning energy when it pins to a defect in the superconducting plane, where the superconducting order parameter is substantially greater than between the planes. Recent picovoltmetry measurements in $Bi_2Sr_2CaCu_2O_8$ [20] with $\boldsymbol{J}\perp\boldsymbol{c}$ and $\boldsymbol{H}\|\boldsymbol{c}$ (i.e. Abrikosov vortex motion parallel to the CuO planes) yielded only linear I–V characteristics. We interpret these results as evidence that Abrikosov vortex motion is not responsible for the observed threshold behavior.

Another possibility is the existence of Josephson vortices for $\boldsymbol{H}\perp\boldsymbol{c}$, and that the threshold currents observed in the I–V characteristics signal the onset of sliding of Josephson vortices along the *ab*-plane [21]. Kleiner et al. [22] have recently shown that $Bi_2Sr_2CaCu_2O_8$ is a weakly-Josephson-coupled layered superconductor, and it has been shown theoretically that a Josephson vortex lattice (from the $\boldsymbol{H}\perp\boldsymbol{c}$ component) and an Abrikosov vortex lattice (from the $\boldsymbol{H}\|\boldsymbol{c}$ component) coexist in such a superconductor [23]. In this scenario, each coreless Josephson vortex has a width $=\Phi_0/H_{\|}d$, where d is the distance between superconducting layers and $H_{\|}$ is the component of $\boldsymbol{H}$ parallel to the *ab*-plane. A Josephson vortex in a pinning potential remains pinned as the current is increased until the Lorentz force on the vortex overcomes the defects pinning force [24] resulting in an I–V characteristic displaying threshold behavior. This model deserves further testing.

Finally, we note that $\rho_c(T, \boldsymbol{H}\perp\boldsymbol{c})$ measurements similar to those described above for $Bi_2Sr_2CaCu_2O_8$ have been performed on $YBa_2Cu_3O_7$ [25] in a restricted temperature range close to T_c. A melting line is identified. At temperatures above T_m, the dissipation is ohmic, while below T_m the normalized resistivity versus scaled temperature follows a universal curve independent of H. From our $\rho_c(T, \boldsymbol{H}\perp\boldsymbol{c})$ measurements on $Bi_2Sr_2CaCu_2O_8$, such an interpretation could yield a melting temperature $T_m(H=7.5\ \mathrm{T})\approx 80$ K (fig. 4). In fig. 3, the $\rho_c(T, H=7.0\ \mathrm{T})$ data for $Bi_2Sr_2CaCu_2O_8$ show a small but noticeable kink near 80 K, consistent with this identification. Whether an actual $T_m(H)$ phase boundary exists in $Bi_2Sr_2CaCu_2O_8$ is not clear at present, and its confirmation would necessitate a detailed investigation of $\rho_c(T, \boldsymbol{H}\perp\boldsymbol{c})$ near T_c in this material. Such a study is presently underway.

In summary, we have measured mixed state transport along the c-axis of $Bi_2Sr_2CaCu_2O_8$ for magnetic fields oriented both parallel and perpendicular to the c-direction. We see a tremendous variation in the character of the c-axis transport depending upon magnetic field strength and orientation. The dissipative behavior of $Bi_2Sr_2CaCu_2O_8$ is complicated by a rich interplay of fluctuations and the possible coexistence of Abrikosov and Josephson vortices.

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