Metallic In-Plane and Divergent Out-of-Plane Resistivity of a High-T_c Cuprate in the Zero-Temperature Limit

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(Received 13 May 1996)

The normal-state in-plane resistivity ρ_{ab} and out-of-plane resistivity ρ_c are measured in La-doped $Bi_2Sr_2CuO_y$ ($T_c \simeq 13$ K) by suppressing superconductivity with 61 T pulsed magnetic fields. In the sample with the smallest ρ_{ab} (130 $\mu\Omega$ cm at 100 K), metallic ρ_{ab} coexists with "semiconducting" ρ_c down to the lowest experimental temperature, 0.66 K ($T/T_c = 0.05$), evidencing the non-Fermi-liquid nature of $Bi_2Sr_2CuO_y$. [S0031-9007(96)00954-4]

PACS numbers: 74.25.Fy, 71.10.Hf, 74.20.Mn, 74.72.Hs

It is widely believed that high-T_c superconductivity is linked to the peculiar normal-state properties of the high-T_c cuprates. One of the normal-state properties which points to an unusual electronic structure is the temperature dependence of the resistivity: The in-plane resistivity ρ_{ab} decreases linearly with decreasing temperature over a wide temperature range, while the out-of-plane resistivity ρ_c increases rapidly at low temperatures ("semiconducting" behavior) [1]. This contrasting behavior of ρ_{ab} and ρ_c has been the subject of intense study, both theoretically and experimentally [2], and is often counted as evidence for the non-Fermi-liquid nature of the cuprates [3]. However, it is not yet known whether this contrasting behavior extends far below T_c and, thus, is a "ground-state" property of the normal state in the absence of superconductivity. It has been predicted that non-Fermi-liquids will localize as $T \to 0$ in the presence of any disorder, because the effective disorder is enhanced in non-Fermi-liquids [4]. It has also been proposed that the contrasting behavior might be a finite-temperature effect in a Fermi liquid, where, for example, c-axis transport is due to phonon-assisted tunneling [5]. Clearly, these questions must be settled by measurements of the normal-state resistivity at low temperatures.

The most straightforward way to measure the normal-state resistivity below T_c is to suppress superconductivity with an intense magnetic field. In the case of the high-T_c cuprates, however, such measurements are made difficult by the extreme magnitude of the upper critical magnetic field H_{c2}. Therefore, the low-temperature measurement of the anisotropic resistivity has been reported only in limited cases: for example, in very overdoped $Tl_2Ba_2CuO_y$ [6] and $Tl_2Ba_2CaCu_2O_y$ [7], where both ρ_{ab} and ρ_c are metallic; in nonsuperconducting $Bi_2Sr_2CuO_y$, where both ρ_{ab} and ρ_c show insulating behavior at low temperatures [8]; in $Nd_{2-x}Ce_xCuO_y$, where ρ_{ab} and ρ_c are either both metallic or both insulating [9]; and in underdoped $La_{2-x}Sr_xCuO_4$, where both ρ_{ab} and ρ_c become insulating even for nearly optimally doped samples which show linear-T ρ_{ab} above T_c [10,11]. To the best of our knowledge, there is no reported measurement of the low-temperature anisotropic resistivity which finds contrasting behavior in ρ_{ab} and ρ_c which extends to low temperatures well below T_c.

In this work, we suppress superconductivity in La-doped $Bi_2Sr_2CuO_y$ (Bi-2201) single crystals with $T_c \simeq 13$ K using a 61 T pulsed magnetic field and measure both ρ_{ab} and ρ_c in the normal state down to 0.66 K. Bi-2201 is a particularly suitable compound for studying the contrasting behavior: T_c is relatively low among the high-T_c cuprates; ρ_c shows a strong divergence [8]; and the linear-T behavior in ρ_{ab} is quite robust (almost independent of doping [12] and extends up to 700 K [8]). Without La doping, Bi-2201 is in the overdoped regime and T_c is less than 10 K. La doping onto the Sr site ($Bi_2Sr_{2-x}La_xCuO_y$) reduces the hole carrier concentration and generally raises T_c [12]. Here we report on $Bi_2Sr_{2-x}La_xCuO_y$ single crystals with nominal $x = 0.05$ and T_c (midpoint) $\simeq 13$ K, which are slightly overdoped [13,14] and show low in-plane resistivities (ρ_{ab} as low as 130 $\mu\Omega$ cm at 100 K).

The single crystals are grown from a copper-oxide-rich melt in Al_2O_3 crucibles [14] and are annealed in flowing oxygen for 1 h at 400 °C after the silver contact pads are painted. Typical size of the samples used for the pulsed-field experiment is $2 \times 0.6 \times 0.01$ mm^3. These sample dimensions are sufficiently small so that the sample is not adversely affected by eddy-current heating during the relatively long 100 msec magnetic-field pulse [15], which is confirmed by checking the agreement among the data from several different maximum-field pulses at a fixed temperature [10]. The thickness of the samples are measured with a scanning electron microscope.

To measure the anisotropic resistivity, we employ a six-terminal method: Two current contacts are located on the top ab face of the crystal with a pair of voltage contacts placed in between; an additional pair of voltage contacts is placed on the bottom face directly beneath the top-face voltage pair. Analyzing the top- and bottom-face voltages using the linear anisotropic resistivity model of Busch *et al.* [16] gives ρ_{ab} and ρ_c. During the first several thermal cycles, microcracks can cause sudden jumps (typically less than 10%) in the measured top and bottom voltages. These jumps introduce a small error in the magnitude but not in the behavior of the calculated ρ_{ab} and ρ_c, provided no additional cracking occurs during a temperature sweep. Even the linearity of ρ_{ab} is insensitive to the microcracks, and no cracking occurred during the pulsed field measurements reported here.

Figures 1(a) and 1(b) show the zero-field ρ_{ab} and ρ_c (solid lines), respectively, for three different samples, denoted A, B, and C in the order of decreasing ρ_{ab}. Because of the presence of microcracking and the small size of the samples, substantial uncertainties (as much as 50%) do exist in determining the absolute value of ρ_{ab}. Nevertheless, because the magnitude of ρ_{ab} among the three crystals is found to vary by a factor of 20, the relative order of the three samples should be correct. Because these crystals are grown in the same crucible and show nearly the same T_c, we conclude that the carrier concentration is nearly identical in the three crystals and that the differences result from disorder. Such variations in ρ_{ab} are common in Bi-2201 and are attributed to a small oxygen deficiency in the CuO_2 plane [14,17].

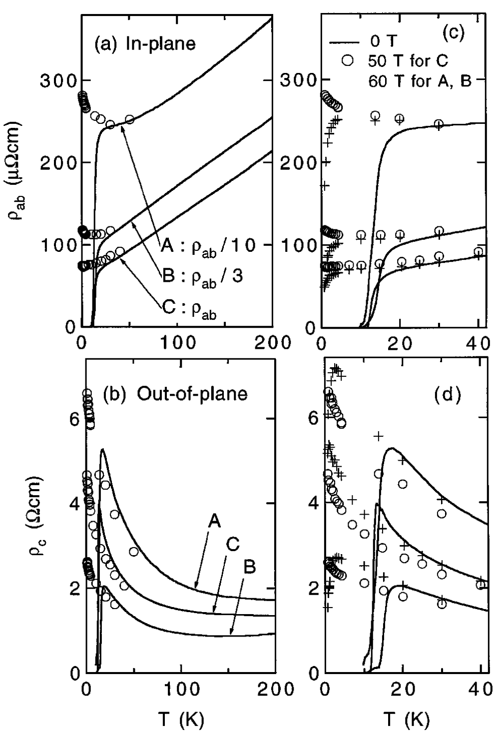

FIG. 1. On the left hand side, (a) ρ_{ab} and (b) ρ_c of three La-doped Bi-2201 single crystals, where ρ_{ab} data of samples A and B are scaled as indicated. On the right hand side, an expansion of the low-temperature (c) ρ_{ab} and (d) ρ_c. Solid lines are zero-field data; crosses are 20 T data; circles are 50 T (sample C) and 60 T (samples A and B) data.

The ρ_{ab} of sample A shows substantial deviation from linear T, which is usually taken as a sign of carrier localization and is consistent with the expectation for a highly disordered sample. In zero field, ρ_{ab} of both samples B and C are linear in T and show no upward deviation from linear T. Since ρ_c is clearly semiconducting in samples B and C, they both exhibit the "ideal" contrasting behavior of ρ_{ab} and ρ_c and differ, we believe, only in in-plane disorder. We note that the magnitude and slope of ρ_{ab} in sample C are essentially identical to the well-known linear-T ρ_{ab} data of Martin *et al.* [8] which extends from T_c to 700 K.

In the pulsed-field experiments, the sample temperature is fixed and the top and bottom voltages are simultaneously measured versus magnetic field using two short-time-constant (10 μsec) lock-in amplifiers driven at ~100 kHz. The typical current density is 10 A/cm^2, which is within the Ohmic range of the normal-state resistivities. The magnetic field is applied parallel to the c axis. Figure 2 shows the magnetic field dependence of ρ_{ab} and ρ_c for sample B at selected temperatures. The resistive transition to the normal state is completed by $B \simeq 40$ T, even at the lowest experimental temperature. The tail in ρ_{ab} at the low-field onset of the resistive transition is an artifact arising from vortex-motion dissipation due to the rather high current density required by the pulsed magnet experiment. We also point out that the linear anisotropic resistivity model, on which the six-terminal analysis is based, is not applicable if vortices in the mixed state cause nonlocal effects [18]. This may affect the calculated anisotropic resistivity in the transition region, but not in the normal state on which we concentrate.

It is apparent in Fig. 2 that a large negative magnetoresistance (MR) is present in the normal-state ρ_c. Such a negative MR in ρ_c has been reported for $Bi_2Sr_2CaCuO_{8+\delta}$ [19,20], $YBa_2Cu_3O_{7-x}$ [19], and $La_{2-x}Sr_xCuO_4$ [10]. Here we do not enter a detailed discussion of the negative MR, but note that the magnetic-

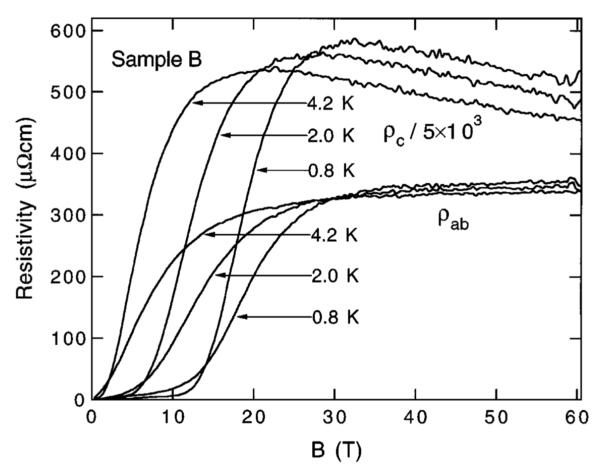

FIG. 2. Magnetic-field dependence of ρ_{ab} and ρ_c of sample B at several temperatures. ρ_c data are divided by 5000.

field dependence of the negative MR is approximately linear and there is no sign of saturation up to 60 T.

When the temperature dependence of the resistivity in high magnetic fields is plotted in Fig. 1, several features become evident. First, as expected, the high-field data provide an extension of the zero-field normal-state data to lower temperatures. This is particularly evident in the 20 T data [(+) in Fig. 1]. The ρ_c data at the highest fields lie below the zero-field data above T_c, due to the large negative MR previously mentioned. Turning attention to the low-temperature behavior of the 60 T data, ρ_{ab} for both samples A and B show distinct upturns at low temperatures, which, coupled with the diverging ρ_c, suggests that the normal state is insulating in all directions in these samples. Note that the upturn is larger and begins at a higher temperature in the more disordered sample. Note also that the observation of an upturn in sample B indicates that a linear-T behavior above T_c does not guarantee metallic in-plane transport below T_c, even when there is no sign of carrier localization above T_c.

The most striking result of the high magnetic-field measurements is seen in sample C. In this sample, ρ_{ab} stays metallic down to the lowest experimental temperature, 0.66 K, and ρ_c continues to diverge. In sample C, therefore, the contrasting behavior in ρ_{ab} and ρ_c persists down to $T/T_c = 0.05$. This strongly suggests that the metallic in-plane conduction and semiconducting out-of-plane conduction can indeed coexist in the zero-temperature limit when in-plane disorder is sufficiently small. Note that ρ_{ab} in sample C becomes as small as 74 $\mu\Omega$ cm, which corresponds to $k_F l \simeq 42$ in the 2D model ($k_F l = hc_0/\rho_{ab} e^2$, where $c_0 = 12$ Å is the interlayer distance). Recalling the uncertainties in the absolute magnitude of ρ_{ab}, we estimate $k_F l \simeq 40 \pm 20$ for sample C. The data suggest that ρ_{ab} is saturating to a residual resistivity, although we cannot exclude the possibility that ρ_{ab} will cross over to insulating behavior below our experimental temperature range. Ordinarily, such a large value of $k_F l$ would assure metallic behavior to extremely low temperatures.

Figure 3 shows a $\log T$ plot of ρ_{ab} and ρ_c from sample C for various fixed magnetic fields in order to emphasize the low-temperature behavior. The large negative MR in ρ_c is evident, and ρ_c diverges roughly logarithmically (or sublogarithmically) at low temperatures, comparable to the behavior reported in $La_{2-x}Sr_xCuO_4$ [10]. On the other hand, ρ_{ab} below T_c shows almost no temperature dependence and little magnetoresistance in this cleanest sample. This suggests that the c-axis transport is uncorrelated with the in-plane transport. This behavior of Bi-2201 contrasts strongly with that of $La_{2-x}Sr_xCuO_4$, where ρ_{ab} becomes insulating whenever ρ_c is diverging at low temperatures [10,11]. Figure 4 shows the temperature dependence of the anisotropy ratio ρ_c/ρ_{ab} for the three samples. The ρ_c/ρ_{ab} value for sample C is comparable to that previously reported for $Bi_2Sr_2CuO_y$ [8]. The lower values for samples A and B are due to the larger

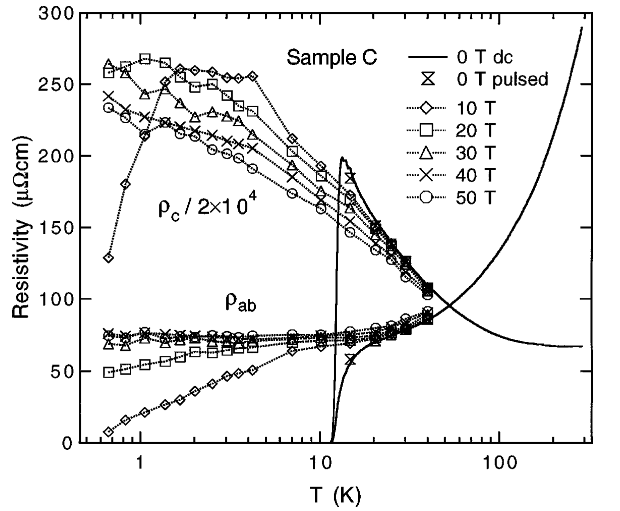

FIG. 3. $\log T$ plot of ρ_{ab} and ρ_c of sample C for fixed values of magnetic field, emphasizing the metallic ρ_{ab} and diverging ρ_c in the zero-temperature limit. ρ_c data are divided by 2×10^4.

ρ_{ab} in the more disordered samples. It is clear that, for all three samples, ρ_c/ρ_{ab} continues to increase below T_c, another indication that the unusual two-dimensional nature of the anisotropic resistivity exists well below T_c. This behavior is also in distinct contrast to underdoped $La_{2-x}Sr_xCuO_4$, for which ρ_c/ρ_{ab} becomes constant at low T [10]. The differences between the two systems may be due to the much higher anisotropy of Bi-2201.

Now let us discuss the implication of these results. Experimental evidence in the literature points toward incoherent c-axis transport, except in very overdoped cuprates [2], mostly because ρ_c exceeds the Mott limit [3]. Within the framework of Fermi-liquid theory, several models have been proposed to explain this incoherence, including

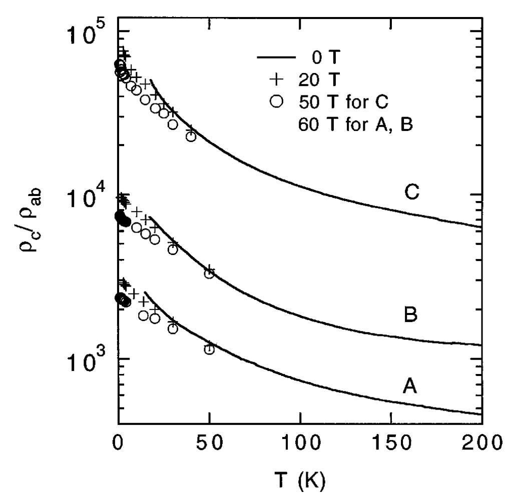

FIG. 4. Temperature dependence of the normal-state anisotropy ratio. Solid lines are zero-field data; crosses are 20 T data; circles are 50 T (sample C) and 60 T (samples A and B) data.

renormalization of the interlayer hopping rate [21], dynamical dephasing [22], and interlayer scattering [5,23]. Accounting for a semiconducting ρ_c in these Fermi-liquid models is more difficult, and two possibilities have been discussed: phonon-assisted hopping [5,21] and temperature-dependent suppression of the density of states at the Fermi energy, $N(0)$ [24]. Rojo and Levin have found that phonon-assisted hopping can give a semiconducting ρ_c over a broad temperature range, which must eventually cross over to metallic behavior as phonons disappear at low temperatures, roughly $T \leq 20$ K (an energy scale which is approximately $1/40$ of the highest energy c-axis phonons) [5]. However, ρ_c continues to diverge at our lowest experimental temperature, 0.66 K, and it is difficult to believe that phonon-assisted hopping plays a role at such low temperatures.

The data pose an additional difficulty for Fermi-liquid models: the fact that ρ_{ab} shows almost no temperature dependence and little magnetoresistance at low temperatures in our cleanest sample, while ρ_c continues to show strong temperature and magnetic-field dependences. In the interlayer scattering models [5,23], the temperature dependence of ρ_c comes from the interlayer scattering time $\tau_\perp$ and, in Ref. [5], also from the in-plane scattering time $\tau_\parallel$. Since the same scattering times enter into the expression of ρ_{ab} in these interlayer scattering models, it is difficult to account for the temperature-independent ρ_{ab}. Alternatively, Zha, Cooper, and Pines have proposed that the low-temperature upturn in ρ_c is due to a reduction in $N(0)$ [24]. Although there is no microscopic calculation of ρ_{ab} in this model [and $N(0)$ might affect the in-plane resistivity nontrivially], one might expect $\tau_\parallel$ and, thus, ρ_{ab} to be temperature dependent when $N(0)$ changes with temperature.

On the other hand, in non-Fermi-liquid theories of the high-T_c cuprates, the incoherence of the c-axis conduction results from in-plane quasiparticle confinement [3,25]. Both the resonating valence bond theory [26,27] and the Luttinger liquid theory [28] give metallic ρ_{ab} accompanied by semiconducting ρ_c in the zero-temperature limit.

To summarize, we observe the coexistence of metallic ρ_{ab} and semiconducting ρ_c down to the lowest experimental temperature, 0.66 K, in a Bi-2201 sample with an estimated $k_F l \simeq 40 \pm 20$. This observation points toward a non-Fermi-liquid ground state in this high-T_c cuprate.

We acknowledge helpful discussions with Y. B. Kim, P. B. Littlewood, A. J. Millis, N. Nagaosa, D. Pines, B. P. Stojković, I. Terasaki, S. Uchida, C. M. Varma, and Y. Zha.

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