Anisotropic resistivity of $Bi_2Sr_2CuO_x$ crystals

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We report measurements of the anisotropic resistivity of $Bi_2Sr_2CuO_x$ crystals using the Montgomery method. We find that the *ab*-plane resistivity is nearly linear with temperature down to 10 K, but deviates slightly from linearity below 40 K. The out-of-plane resistivity is metallic above 105 K, but nonmetallic below 105 K. The anisotropy ratio ρ_c/ρ_{ab} is temperature dependent and the maximum value is 9×10^4 at low temperature. We estimate the effective mass, the Fermi energy, and Fermi velocity, etc., using Kresin and Wolf's model. The plasma frequency and the transport electron-phonon coupling constant λ_{tr} are also calculated in a self-consistent way in combination with our resistivity and Hall coefficient data. We discuss the resistivity in the context of existing theories.

The unusual normal-state transport properties of high-T_c superconductors have been the focus of many theoretical and experimental studies.[1-3] A central problem is whether or not the normal-state properties can be understood by the conventional Fermi-liquid theory. One of the dramatic features of the high-T_c superconductors is that the in-plane resistivity varies linearly with temperature. The linearity of resistivity can be seen over a wide range of temperature. For $YBa_2Cu_3O_7$ it can extend up to 600 K and for $La_{2-x}Sr_xCuO_4$ it can extend up to 1000 K.[4] An important issue is whether this linearity of in-plane resistivity arises from the electron-phonon interaction or from some other mechanisms which are closely related to the high-T_c superconductivity. A further issue concerns the intrinsic behavior of the out-of-plane resistivity of the cuprates. Up to now, no consensus has been achieved on whether it is metallic ($d\rho/dT>0$) or nonmetallic ($d\rho/dT<0$). Since $Bi_2Sr_2CuO_x$ (Bi2201 hereafter) has very low transition temperatures, it is the best candidate for the study of the normal-state properties of the cuprates at low temperature. Previous studies on Bi2201 showed that the in-plane resistivity ρ_{ab} is linear with temperature between 7 and 700 K.[5] It was argued that the conventional electron-phonon mechanism cannot account for this behavior, because the linearity remains well below Θ_D, where Θ_D is the Debye temperature. Early studies[5] also showed that the out-of-plane resistivity ρ_c varies as a power law $T^{-\alpha}$, $\alpha\approx0.5-1$.

In this paper we present a detailed study of the temperature dependences of both the in-plane and the out-of-plane resistivity of Bi2201 crystals using the Montgomery method.[6,7] We will demonstrate that ρ_{ab} of Bi2201 is nearly linear with temperature between 10 and 300 K, but a slight deviation from linearity occurred below 40 K. In contrast with the earlier report,[5] we find that ρ_c is metallic above 105 K, but nonmetallic below 105 K.

High-purity single crystals of Bi2201 were grown by a self-flux method using CuO as flux. We prereacted the mixture of Bi_2O_3, $SrCO_3$, and CuO to form the Bi2201 phase. The product was melted at 950 °C in a gold crucible for 2 h, followed by a slow cooling to room temperature. The single crystals were thin and platelike, grown in the *ab* plane, with a typical size of $7\times8\times0.05$ mm^3. Both magnetization and resistivity data showed that the as-grown crystals are superconducting with transition temperatures up to 7.5 K. We verified by x-ray diffraction and transmission electron microscopy that the crystals were single phase. Energy-dispersive x-ray analysis (EDX) was used to determine the Bi, Sr, and Cu content. The results indicated that the actual ratio of Bi, Sr, and Cu is 2.0:1.9:2.1.

The crystal used to measure resistivity had a size of 1 mm $\times$ 0.7 mm $\times$ 4 μm with the shortest dimension along the *c* axis. The thickness of the crystal was determined by a scanning electron microscope. The resistivity was measured by the dc method and a schematic of the Montgomery contact configuration is shown in the inset of Fig. 1(a). The current was provided by a Keithley 220 programmable current source and the voltage was measured by a Keithley 181 nanovoltmeter. The current passed through the crystal was between 2 and 4 mA. Good electrical contacts were achieved by soldering thin gold wires (20 μm) onto the crystal with silver paint. After annealing the crystal in air for hours the contact resistance could be reduced to 1–3 Ω. A Rh-Fe resistance thermometer was used to measure the temperature. The temperature ramp rate was kept to 1 K/min. A crystal of Bi2201 from the same batch was used to measure the Hall coefficient. The Hall effect was measured by the dc method and the measurements were conducted in the cryostat of a Quantum Design magnetometer with a magnetic field of 5 T parallel to the *c* axis. The detailed results of Hall-effect measurements will be published elsewhere.

Figure 1(a) shows the temperature dependence of the in-plane resistivity of a superconducting Bi2201 crystal with a T_c about 5.3 K. We find that the temperature dependence of ρ_{ab} is approximately linear with T up to 300 K. By a linear fit we obtain a slope of $\Delta\rho_{ab}/\Delta T=0.58$ $\mu\Omega$ cm/K and an extrapolated residual resistivity of $\rho_0=91$ $\mu\Omega$ cm. Xiao *et al.* reported a T-linear resistivity for Bi2201 on ceramic samples.[8] Martin *et al.* reported a remarkable linearity of in-plane resistivity between 7 and 700 K on Bi2201 crystals.[5] Our results are basically consistent with their results. Within the conventional Fermi-liquid theory the T-linear resistivity can be explained by the electron-phonon interaction, i.e., the Bloch-Grüneisen formula.[9] However, T-linear resistivity only occurs when $T > \Theta_D^*$ and a T^5 behavior will be followed when $T < \Theta_D^*$, where Θ_D^* is the transport Debye temperature, which can be a factor of 2–4 smaller than the thermodynamic Debye temperature Θ_D for the materials with small k_F.[5] The heat-capacity measurements on polycrystalline Bi2201 samples indicated that the Debye temperature is about 220 K.[10] Because we could not find a T^5 temperature dependence in resistivity even with T down to $\Theta_D/20$, the linearity of ρ_{ab} cannot be attributed to the electron-phonon interaction. Martin *et al.*[5] fitted their resistivity data to the Bloch-Grüneisen formula and found an unphysically low transport Debye temperature, $\Theta_D^* \approx 35$ K. These facts strongly suggest that the electron-phonon mechanism is inadequate to account for the electrical transport along the *ab* plane in the cuprates. There are several models proposed to explain the T-linear resistivity in cuprates. These include the resonating-valence-bond model by Anderson and Zou,[11] marginal-Fermi-liquid theory by Varma,[12] and the nested Fermi liquid by Virosztek.[13] However, until recently no consensus was achieved on which model is correct. The T-linear resistivity is still one of the least understood problems in the study of high-T_c superconductivity.

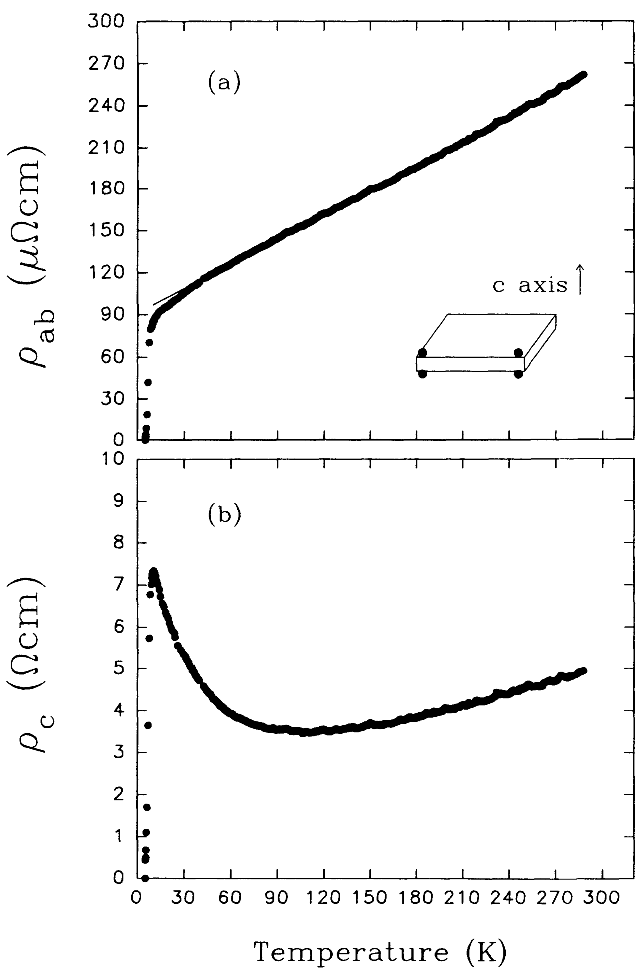

FIG. 1. (a) Temperature dependence of the in-plane resistivity of the $Bi_2Sr_2CuO_x$ crystal. The solid line is the linear fit. Inset: schematic of the electrical contact configuration. (b) Temperature dependence of the out-of-plane resistivity of the $Bi_2Sr_2CuO_x$ crystal.

A careful examination, however, shows a slight deviation from linearity below 40 K. The superconductivity-induced excess conductivity (paraconductivity) has been extensively observed in the high-T_c materials. We consider that the deviation cannot be attributed to the paraconductivity which is related to the fluctuation of superconductivity, because the T_c is so low and the temperature at which the deviation occurs is far away from the T_c. We notice that Mandrus *et al.* also observed a similar phenomenon in Bi2201 below 50 K.[14] They used the nested-Fermi-liquid theory to explain the deviation and argued that in the cuprates the Fermi surface is nested and electron-electron umklapp scattering produces T-linear behavior only for temperatures such that $E(K)-E(K\mp Q)=\varepsilon<T$, where ε is the energy difference from the perfect nesting condition. If $T<\varepsilon$ the nesting condition is no longer satisfied and deviation from linearity will occur. We think that Mandrus *et al.*'s argument is one of the possible explanations for this phenomenon.

Based on Fermi-liquid theory, Kresin and Wolf proposed a model to analyze the normal-state properties of the cuprates, in particular for $La_{2-x}Sr_xCuO_x$.[15,16] They thought that the cuprates have a typical layered structure with the interlayer distance much greater than the in-plane lattice period, $d_c \gg d_a, d_b$. They also assumed that the Fermi surface is cylindrically shaped and the dispersion relation $E(\mathrm{p})$ is highly anisotropic and does not depend on p_z. Based on these assumptions they derived the following formulas:

$$m^* = (3\hbar^2/\pi)k_B^{-2}d_c\gamma \ , \tag{1}$$

$$E_F = (\pi^2 k_B^2/3)n/\gamma \ , \tag{2}$$

$$v_F = (2m^* E_F)^{1/2}/m^* \ , \tag{3}$$

$$k_F = m^* v_F/\hbar \ , \tag{4}$$

where m^* is the effective mass, k_B is the Boltzmann constant, γ is the Sommerfeld constant, E_F is the Fermi energy, v_F is the Fermi velocity, and n is the carrier density in the *ab* plane. There are strong experimental evidences to show that cuprates have a cylindrically shaped Fermi surface.[17–19] The Bi2201 phase also possesses a typical layered structure with strongly two-dimensional characteristics. Its anisotropy ratio in resistivity ρ_c/ρ_{ab} is as large as 9×10^4 (see text below). Hence we use Kresin and Wolf's model to estimate the normal-state properties of the Bi2201 phase. We measured the Hall coefficient of Bi2201 and found that it is less temperature dependent compared with that of $YBa_2Cu_3O_x$. The Hall coefficient at 25 K is 1.27×10^{-9} m^3C^{-1}. The carrier density, which is defined by $1/R_H e$, can be readily calculated to be 4.9×10^{21} cm^{-3}. According to the heat-capacity data by Collocott *et al.*[10] on polycrystalline Bi2201, γ is about 9.19 $mJ\,mol^{-1}\,K^{-2}$. If we take $d_c=12.33$ Å for the Bi2201 phase, the calculated parameters are listed in Table I. We obtain a large effective mass $m^*=6.5m_e$ that indicates the Bi2201 phase possesses the heavier carriers. It is noted that other high-T_c materials have similar results, for example, m^* of $La_{2-x}Sr_xCuO_4$ is estimated to be $5m_e$.[15,16] The Fermi energy is equal to 0.22 eV, which is much smaller than those of metals (E_F of metals normally is 5–10 eV). The small Fermi energy of the cuprates is supported by the thermal conductivity experiments. Such experiments indicate that the thermal conductivity is dominated by the phononic contribution rather than the electronic contribution which is proportional to E_F at low temperature. We think that a small Fermi energy is one of the distinct features of the cuprates.

The Drude plasma frequency ω_p is an important parameter and it is defined by $\omega_p^2=4\pi ne^2/m^*$. Based on the values of n and m^* in Table I, ω_p is obtained: $\omega_p=1.53\times10^{15}$ s^{-1}, i.e., $\hbar\omega_p=1.0$ eV. The relaxation time can be calculated by the formula $\tau=4\pi/\omega_p^2\rho$. At 25 and 300 K, τ is 4.5×10^{-14} and 1.8×10^{-14}s, respectively. It is noted that alkali metals at 77 K have a typical value of 1.8×10^{-13} s.[20] Hence the relaxation times of Bi2201 are considerably smaller than those of alkali metals. The mean free path l ($l=\tau v_F$) is found to be 48 Å at 25 K. This clearly indicates that Bi2201 is a clean superconductor. All transport parameters of Bi2201 calculated are summarized in Table II. If we assume only phonon scattering at high temperature, then the transport electron-phonon coupling constant λ_{tr} can be estimated by the formula[4]

$$\lambda_{tr}=(\hbar\omega_p^2\alpha)/8\pi^2k_B \ , \tag{5}$$

where α represents the slope of the linear resistivity. By substituting the slope of 0.58 $\mu\Omega$ cm into the above formula we obtain a very small $\lambda_{tr}=0.14$. Martin *et al.*[5] obtained $\lambda_{tr}=0.08$ based on the in-plane resistivity data of Bi2201 and London penetration depth of $La_{2-x}Sr_xCuO_4$. For most of the high-T_c materials, λ_{tr} obtained from the dc resistivity varies between 0.08 and 0.3.[21] Infrared optical measurements also give similar results.[21] A simple approximation has been used by some authors to estimate the electron-phonon coupling strength: $\lambda_{tr}\approx\lambda$ where λ is the electron-phonon coupling constant which appears in the Eliashberg equation.[4,22,23] Allen *et al.* showed that for many metals the ratio λ_{tr}/λ is nearly equal to 1.[24] If we think this approximation is appropriate for the high-T_c superconductors, the small value $\lambda_{tr}=0.14$ seems to suggest a very weak electron-phonon interaction. This result seems to be consistent with the isotope effect of the high-T_c materials. The isotope effect showed a weak electron-phonon interaction, $\alpha\approx0.019$ ($T_cM^\alpha=$const) for $YBa_2Cu_3O_7$.[25,26] However, Zeyher showed that $\lambda>\lambda_{tr}$ for $YBa_2Cu_3O_7$ and argued that a small λ_{tr} does not imply a weak electron-phonon coupling.[27] We think that at present there is no generally accepted explanation for the small λ_{tr} nor a consensus about its implication for the high-T_c superconductivity. On the other hand, the possibility that the linear resistivity arises from other unknown scattering processes at high temperature could not be ruled out too.

TABLE I. The normal-state properties of Bi2201 crystals.

n(25 K) (10^{21} cm^{-3})	n(300 K) (10^{21} cm^{-3})	m^*	E_F (eV)	v_F (10^7 $cm\,s^{-1}$)	k_F (10^7 cm^{-1})
4.9	6.2	$6.5m_e$[a]	0.22	1.08	6.12

[a] m_e represents the free-electron mass.

TABLE II. The transport parameters of Bi2201.

	τ (10^{-14} s)	l (Å)	ρ_{ab} ($\mu\Omega$ cm)	k_Fl
25 K	4.5	48	107	29
300 K	1.8	19	267	11

Figure 1(b) shows the temperature dependence of the out-of-plane resistivity ρ_c. The values of ρ_c are by four orders of magnitude larger than those of the in-plane resistivity. In contrast with the previous reports, we find ρ_c is metallic above 105 K and nonmetallic below 105 K. We measured several Bi2201 crystals and found the same trend of ρ_c. Martin *et al.* reported $\rho_c\simeq T^{0.5-1}$ over the entire temperature range.[5] Ito *et al.* also observed an entirely nonmetallic ρ_c in La-doped Bi2201 crystals.[28] However, we notice that our results on ρ_c are quite similar to those reported in $Bi_2Sr_2CaCu_2O_8$ and $La_{2-x}Sr_xCuO_4$ crystals where different temperature dependencies ($d\rho_c/dT>0$ and $d\rho_c/dT<0$) in the same crystal were found. Nakamura and Uchida[29] made a systematic study of the temperature dependence of ρ_c on carrier density for $La_{2-x}Sr_xCuO_4$. They found that ρ_c is strongly carrier dependent. For underdoped crystals, ρ_c showed a nonmetallic behavior at low temperature and metallic behavior at high temperature. With increasing carrier density, the temperature at which $d\rho_c/dT$ becomes positive decreases. For overdoped crystals, ρ_c showed an entirely metallic behavior over a wide temperature range (30–800 K). A similar trend was also found in $Bi_2Sr_2CaCu_2O_8$ crystals.[30] On the other hand, an entirely metallic ρ_c ($d\rho_c/dT>0$) was reported in crystalline $YBa_2Cu_3O_7$,[31] $Tl_2Ba_2CaCu_2O_8$,[32] $Bi_2Sr_2CaCu_2O_8$,[33] and $Nd_{2-x}Ce_xCuO_4$.[34] Therefore we suggest that the temperature dependence of ρ_c of the cuprates is mainly determined by the in-plane carrier density. We attribute the different temperature dependencies of ρ_c to different carrier densities. Their detailed relation remains to be further clarified.

There are only a few models concerning the out-of-plane resistivity of the cuprates. The resonating-valence-bond model[11] by Anderson and Zou predicts $\rho_c\propto1/T$, which contradicts apparently the complicated temperature behavior we observed in Bi2201. Kumar and Jayannavar[35] proposed a model based on coherent interplanar tunneling between neighboring layers. One feature of this model is that ρ_c has the same temperature dependence as

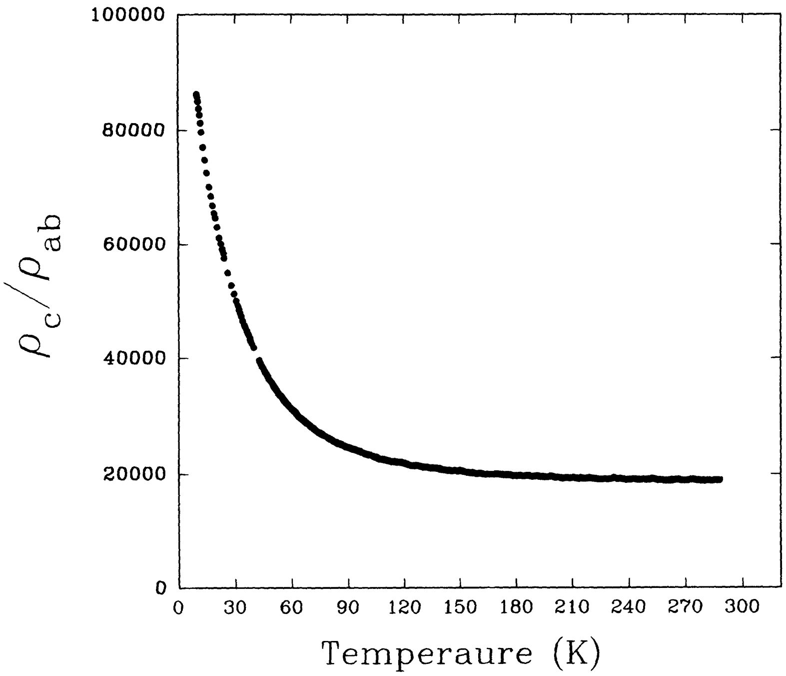

FIG. 2. Temperature dependence of the anisotropy ρ_c/ρ_{ab} for the $Bi_2Sr_2CuO_x$ crystal.

ρ_{ab}. It is clear that our result also disagrees with Kumar and Jayannavar's model. As pointed out by Ito *et al.*[28] the Mott-Ioffe-Regel criterion for metallic conductivity is not satisfied for the electrical conduction along the c axis of the cuprates. We believe that the electrical transport along the c axis is dominated by an unknown scattering process.

Figure 2 shows the temperature dependence of the anisotropy ρ_c/ρ_{ab} for the Bi2201 crystal. The largest anisotropy ratio is 9×10^4 at low temperature. This result basically agrees with an early report that showed a ρ_c/ρ_{ab} of 2×10^5 for Bi2201.[5] Other high-T_c materials, such as $Bi_2Sr_2CaCu_2O_8$,[36] also showed a strong anisotropy in the electrical resistivity, $\rho_c/\rho_{ab}\approx10^5$. The observed large anisotropy in resistivity coincides with the superconducting properties of the cuprates. For example, $Bi_2Sr_2CaCu_2O_8$, which is closely related to Bi2201, showed a large anisotropy in both the critical current density,[37] $J_{c\parallel}/J_{c\perp}\approx10^3$, and the superconducting effective mass,[38,39] $m_c/m_{ab}\approx10^3$. It is evident that strong two-dimensionality is one of the striking features of the cuprates. It is possible that their unusual normal-state and superconducting-state properties partially arise from this striking feature.

In summary, we have measured the resistivity tensor of Bi2201 crystals as a function of temperature. The in-plane resistivity increases approximately linearly with temperature between 10 and 300 K. A slight deviation from linearity is found below 40 K. The out-of-plane resistivity is metallic above 105 K but nonmetallic below 105 K. The largest anisotropy ratio is found to be 9×10^4. Based on Kresin and Wolf's model, the effective mass, Fermi energy, Fermi velocity, and Drude plasma energy $\hbar\omega_p$ are estimated. The transport electron-phonon coupling constant λ_{tr} is found to be 0.14 and its implications for high-T_c superconductivity are discussed.

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