Temperature Dependence of the Resistivity Tensor in Superconducting $Bi_2Sr_{2.2}Ca_{0.8}Cu_2O_8$ Crystals

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A strongly anisotropic resistivity tensor was measured from $T_c = 81$ to 600 K in crystals of the new high-T_c superconductor $Bi_2Sr_{2.2}Ca_{0.8}Cu_2O_8$. The a-b plane anisotropy is $\rho_a/\rho_b \approx 2$, with ρ_a and ρ_b linear in T. The perpendicular component $\rho_c \sim 10\ \Omega$ cm is 10^5 greater than ρ_a or ρ_b. Evidence for nonmetallic temperature dependence is found for the ρ_c/ρ_{ab} resistivity ratio. The data are consistent with the notion of quasiparticle tunneling between planes, but an alternative explanation in terms of weak interplanar coupling by topological defects is also presented.

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Among the fascinating aspects of the known high-T_c superconductors[1-3] are the anisotropic layered structure, the nearly two-dimensional (2D) confinement of the carriers to Cu-O planes, and their implications for the mechanisms of electrical transport and superconductivity. The recently discovered $Bi_2(Sr,Ca)_3Cu_2O_x$ (BSCO) class of superconductors[4-8] is striking by a 12-Å spacing between the Cu-O planes, which is larger than in the $(La,Sr)_2CuO_4$ (LSCO) and $YBa_2Cu_3O_x$ (YBCO) superconductors and in itself suggests enhanced two-dimensional character of electronic properties. Moreover, BSCO is found to be thermally stable with respect to oxygen stoichiometry and can be grown as single crystals in the form of thin sheets oriented with the c axis normal. By comparison, the oxygen intercalation in superconducting YBCO can be inhomogeneous and the larger orthorhombicity leads invariably to microscopic twinning.

In this work we report measurements of the resistivity tensor components ρ_a, ρ_b, and ρ_c in orthorhombic crystals of nominal composition $Bi_2Sr_{2.2}Ca_{0.8}Cu_2O_8$ (estimated from Rutherford backscattering analyses), which show more pronounced anisotropy than the other oxide superconductors[9-13]: $\rho_c/\rho_a = 1.5\times10^5$ at T_c, decreasing to about 5×10^4 at 600 K. The a-b-plane resistivity is also anisotropic with a ratio of $\rho_a/\rho_b \approx 1.7$. These new results can be explained by 2D transport within the Cu-O planes which are nearly insulated from one another, giving a resistivity linear in T.[14] The high value of ρ_c is consistent with the larger separation between Cu-O planes in BSCO. The nonmetallic, approximately T^{-1}, term in ρ_c may be indicative of interplanar quasiparticle tunneling, as proposed by Anderson and co-workers.[15] However, we present an alternative argument that the observed conductivity along the c axis may not be intrinsic, if there are topological defects acting as local short circuits distributed throughout the crystal.

Single crystals used in our study were grown in alkali-chloride fluxes in the form of thin platelets.[16] Results described here were obtained on a crystal of dimensions $L_a = 0.6$ mm, $L_b = 1.1$ mm, and $L_c = 1\ \mu$m. The samples were oriented by x-ray diffraction, which shows the characteristic superlattice splittings only along $[0k0]$ and a peak at (300) but not at (030). As shown schematically as insets in Fig. 1, Au wires (25 μm diam) were attached at six points on the crystal with a Au-paste and Ag-paint mixture which was cured by heating to $\simeq 300\,^\circ$C in dry O_2. Contacts were monitored to verify stable Ohmic (0.5–5 mΩ cm^2) behavior with temper-

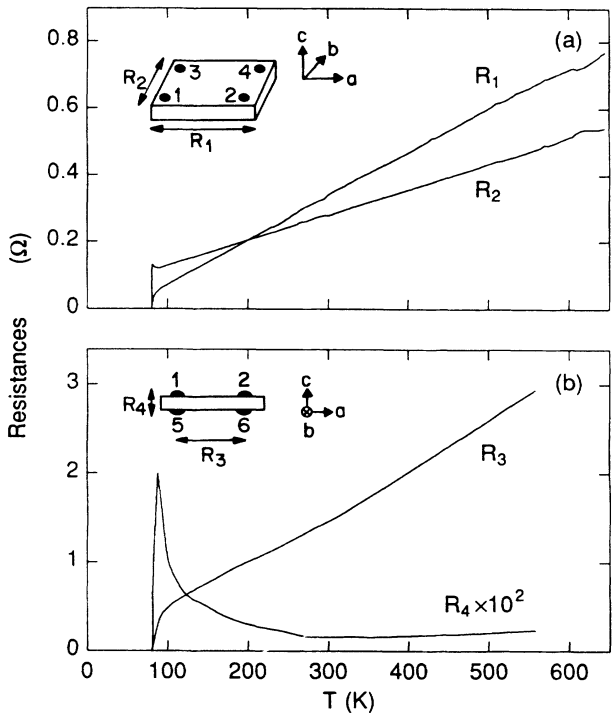

FIG. 1. (a) Temperature dependence of the resistances measured along the a and b axes of a BSCO single crystal. Inset: Schematic of the contact configuration. Onset of superconductivity occurs at $T = 90$ K and zero resistance is reached at $T_c = 81$ K. (b) Temperature dependence of the resistances measured along the a and c axes. The lines are drawn through closely spaced data points.

ature cycling. Measurements were performed in a single oven-cryostat with O_2 above 300 K and He below. Resistances were measured by a standard ac phase-sensitive technique with 350-μA excitation current and $f=11.3$ Hz.

Figure 1(a) shows data obtained from measurements in the a-b plane. Refering to the contact configuration, resistance R_1 was measured by our passing current through contacts 1 and 2 (a axis) and measuring the potential difference between 3 and 4. R_2 was obtained by a 90° rotation of the configuration (b axis). We found zero resistance at $T_c=81$ K, an onset of the superconducting transition at about $T=90$ K, and the absence of higher-T_c phases in selected samples. Both R_1 and R_2 show less than 10% deviation from a linear temperature dependence up to 600 K.

Figure 1(b) shows the results of measurements performed along the a and c directions. The resistance R_3 along the a direction increases monotonically with temperature, but shows a clear deviation from linearity. R_4 rises sharply at T_c and then decreases with increasing temperature. A strong temperature dependence for R_4 is seen only between 100 and 250 K. We emphasize, however, that the measured resistances are influenced by the geometry of the contacts and do not necessarily reflect the true behavior of the resistivities.

To make the transformation from the R_i measurements to the ρ_i components of the resistivity tensor, we followed the basic method of Montgomery[17] and Logan, Rice, and Wick,[18] which maps the anisotropic crystal of physical dimensions L_i into an equivalent isotropic block of scaled dimensions l_i. Because of the small L_c dimension of the crystals and the placement of inevitably finite-size contacts, the Montgomery analysis should not be used in its original form, as it assumes that contacts are located at the corners of a crystal face. We therefore generalized the method-of-images solution presented by Logan, Rice, and Wick, upon which Montgomery's analysis is based, to simulate the actual points of electrical contact. The lattice sums[18] were evaluated by Ewald's method.[19] We determined calibration curves giving the dependence of the resistance ratios R_i/R_j, corresponding to a specific configuration of four contacts in crystal plane k (cyclic order), as functions of effective length ratios l_i/l_j. These functions have properties similar to those of Montgomery and Logan, Rice, and Wick, except that they lack inversion symmetry. Our procedure was also used to test effects of contact misalignment and uncertainty in the contact positions, due to the finite contact size. Since we employed six contacts, the resistance-ratio data were partially redundant and gave us a consistency check. It confirmed the accuracy of our contact coordinates on the crystal. We then derived l_a/l_b and l_c/l_a from the two sets of data, R_1/R_2 and R_4/R_3. The final step was to calculate resistivity ratios according to the scaling formula $\rho_i/\rho_j=(l_i/l_j)^2(L_j/L_i)^2$.

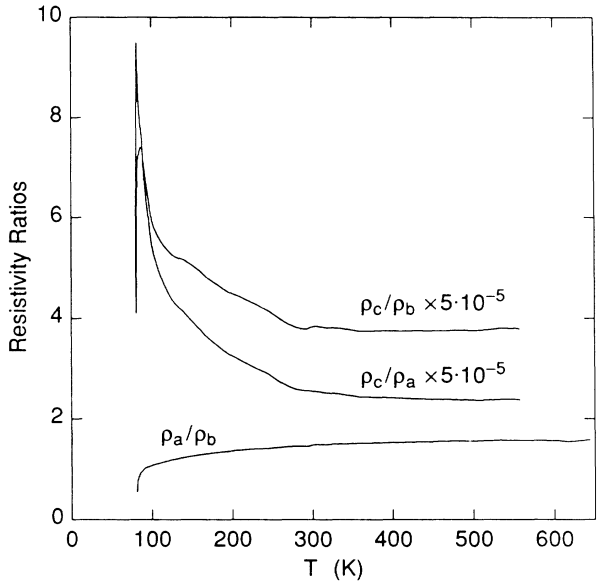

FIG. 2. The in-plane (ρ_a/ρ_b) and out-of-plane (ρ_c/ρ_a and ρ_c/ρ_b) resistivity ratios calculated from the measured data of Fig. 1. The anisotropies are ≈ 1.7 and $\approx 10^5$, respectively.

The results of the deconvolution of the data are shown in Fig. 2 which gives the temperature dependence above T_c for the three independent resistivity ratios ρ_a/ρ_b, ρ_c/ρ_a, and ρ_c/ρ_b. The results indicate the presence of a temperature-dependent ρ_a/ρ_b resistivity anisotropy in the a-b plane, which decreases significantly for $T\lesssim 300$ K. Measurements in several samples yielded values for the a-b anisotropy ranging from 1.5 up to about 2, which is in reasonable agreement with results obtained from epitaxial films of BSCO.[20] The ratios ρ_c/ρ_a and ρ_c/ρ_b are found to decrease monotonically with increasing temperature, as shown in Fig. 2. We note a strong temperature dependence from T_c to about 275 K and saturation behavior above 275 K.

When one of the l_i is smaller than the other two, i.e., $l_k<(l_il_j)^{1/2}$, one can analyze the R_i/R_j ratio corresponding to $l_i<l_j$. In this case one obtains the geometric average $\rho_{ij}=(\rho_i\rho_j)^{1/2}=R_iL_kf(R_i/R_j,l_k)$ which is a generalization of the van der Pauw analysis.[17] For the data of Fig. 1 the electrically thinnest dimension turns out to be L_c. Figure 3(a) gives the temperature dependences of ρ_{ab} and ρ_c/ρ_{ab} derived in this manner. Figure 3(b) shows resistivity tensor components which were calculated from ρ_{ab} and the resistivity ratios (Fig. 2). The uncertainty in the resistivity values scales with that of the crystal thickness (factor $\simeq 2$).

The averaged a-b-plane resistivity ρ_{ab} increases proportionally to the temperature with a slope of $\alpha_{ab}=0.46$ $\mu\Omega$ cm K^{-1}. At ambient temperature we have $\rho_{ab}=140$ $\mu\Omega$ cm, in good agreement with previous reports.[6] We find that ρ_a and ρ_b also increase linearly over the complete temperature range. The extrapolation to $T=0$ K

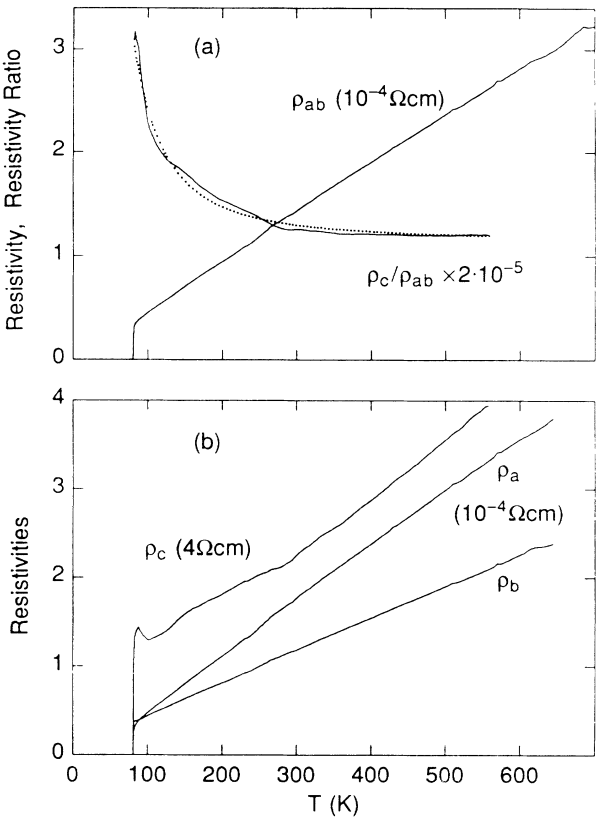

FIG. 3. (a) The averaged a-b-plane resistivity ρ_{ab} and the ratio ρ_c/ρ_{ab} calculated from the measured data as described in the text. The dotted line is the result of a two-parameter fit $\rho_c/\rho_{ab}=a+bT^{-2}$. (b) The three components of the resistivity tensor as functions of temperature.

yields residual resistivities of less than 10 $\mu\Omega$ cm. The resistivity along the c axis is found to be unusually large, with a linear temperature dependence commencing above 275 K. Below 275 K an increase of ρ_c above the linearly extrapolated values can be clearly seen. As in YBCO crystals, the absence of saturation behavior leads to a weak electron-phonon coupling constant $\lambda \lesssim 0.2$; from α_{ab} we estimate a transport plasma energy of $\Omega_{ab} \lesssim 1.3$ eV, and a London penetration depth of $\lambda_{ab} \lesssim 1400$ Å.[21]

In contrast with data from YBCO single crystals, we find that BSCO samples exhibit a resistive anisotropy perpendicular to the Cu-O planes which is 3 orders of magnitude larger. If we consider each Cu-O plane to be an electrically isolated metallic sheet, with four sheets per lattice constant c, then the sheet resistance is $R_{ab}=\rho_{ab}(c/4)^{-1}\approx 300\ \Omega/\square$ just above T_c. This is low enough to allow for metallic behavior and the occurrence of two-dimensional superconductivity, apart from phase fluctuations.[22] The calculation for YBCO yields 4000 $\Omega/\square$, which is too large to agree with our first assumption of a good 2D superconductor.[22] The magnitude of the interplanar coupling can now be estimated by our relating the difference in the spacing between planes for YBCO ($d=8.3$ Å) and BSCO ($d=12$ Å) with the anisotropy ratio being smaller in YBCO by 10^3. If the anisotropy ratio is proportional to the transmission coefficient t, $\rho_c/\rho_{ab} \propto t \propto \exp(-\kappa d)$, where κ is the decay parameter for tunneling through Cu-O planes involving similar potential barriers ($\simeq 2$ eV), then we arrive at $\kappa = 1.6$ Å^{-1}.

Recently, Hagen *et al.*[10] showed that ρ_c in YBCO contains a T^{-1} term, which Anderson and co-workers[15] have interpreted as evidence for a quasiparticle tunneling mechanism of electrical transport between planes. The authors proposed that the measured ρ_c contains a linear-T term from ρ_{ab}, because of contact misalignment. The T^{-1} dependence of the intrinsic ρ_c and the T dependence of ρ_{ab} combine such that the ratio ρ_c/ρ_{ab} has a T^{-2} term. Recognizing the possibility of mixing, we try to reveal this divergence in a transparent manner by plotting in Fig. 3(a) the ratio ρ_c/ρ_{ab}, a quantity which is similar to the resistivity ratios presented in Fig. 2. The dotted curve in Fig. 3(a) shows the result of a linear fit $\rho_c/\rho_{ab}=a+bT^{-2}$, but plotted on the linear-T scale, to give intrinsic $\rho_c=(300\ \Omega\ \text{cm K})T^{-1}$, and a mixing fraction $a^{-1}=2\times10^{-5}$. Assuming a power-law behavior, we obtain a T^{-1} dependence to within 10% systematic error in the -1 exponent.

In this present case our numerical analysis could not eliminate the saturation behavior of the ρ_c/ρ_{ab} curve by repositioning the contact points. This finding, and the difficulty in our explaining large observed resistivities together with metallic temperature dependences, suggest that, in general, an alternative explanation should be considered. We postulate that current transport along the c axis could be dominated by defects acting as links between otherwise electrically insulated a-b planes. These defects could be comprised of missing or extra sublayers, stacking faults, or dislocations, which have been recently observed by transmission-electron-microscopy studies in BSCO[23] and in YBCO,[24] indicating that defect structures may be relatively common.

A simple model starting with unity anisotropy, and attributing the large ρ_c for $T>T_c$ and $\rho_c=0$ for $T<T_c$ to gross exfoliation of the material, cannot correctly account for a temperature dependence in the resistivity ratios. Instead we assume that there is a random network of marginally metallic paths caused by an unspecified defect topology along c, which we represent by a regular array of links spaced ξ apart in the a-b directions and span the mean distance $d_\perp$ between planes. Representing the link resistance by R_d and the a-b-plane resistance between links as R_{ab}, we can see that the apparent resistivity along the c direction becomes $\rho_c=(R_d+R_{ab})\times(\xi/2)^2 d_\perp^{-1}$. We take $R_{ab}=\rho_{ab}d_\perp^{-1}$, and obtain $\rho_c/\rho_{ab}=(1+R_d/R_{ab})(\xi/2d_\perp)^2$. From the data of Fig. 3(a) we can conclude that $R_{ab}\gg R_d$ for $T\gtrsim 275$ K and the saturation yields $\xi\approx 500 d_\perp=0.6$ μm. The apparent diver-

gence at low temperatures could be attributed to a negative temperature coefficient of R_d, arising simply from a distribution of activated conducting paths.

In conclusion, we have measured the resistivity tensor of BSCO single crystals as a function of temperature. We find an a-b-plane anisotropy $\rho_a > \rho_b$, which shows that the highest conductivity is along the superlattice. In the c direction the large anisotropy factor of about 10^5 is interpreted in terms of a highly two-dimensional character of the electronic structure. Although the T^{-1} divergence of ρ_c in our data at low temperatures could be accounted for by quasiparticle tunneling between planes, we caution that the high resistivity also implies high sensitivity to bridging defects which can short circuit the Cu-O planes. Various transport parameters are derived from the data, most importantly an interplanar tunneling constant, a-b-plane transport plasma energy, London penetration depth, and the electron-phonon coupling constant.

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