Magnetotransport Properties of Antiferromagnetic \( YBa_2Cu_3O_{6.25} \) Single Crystals

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Abstract

In-plane \( \Delta \rho_{ab}/\rho_{ab} \) and out-of-plane \( \Delta \rho_c/\rho_c \) magnetoresistivities of antiferromagnetic \( YBa_2Cu_3O_{6.25} \) single crystals were measured in magnetic fields \( H \) applied along the \( ab \) plane. \( \Delta \rho_{ab}/\rho_{ab} \) is a superposition of two components: The first component is strongly in-plane anisotropic, changing sign from negative when \( H \parallel I \) to positive when \( H \perp I \). The second component is positive, quadratic in \( H \), and isotropic in the \( ab \)-plane. \( \Delta \rho_c/\rho_c \) displays a fourfold symmetry upon in-plane rotation of the magnetic field, with maxima along the easy axes of antiferromagnetic spin ordering and minima along unfavorable directions of spin orientation (45° from the \( Cu-O-Cu \) bonds).

Key words: high \( T_c \) cuprates, magnetoresistance, antiferromagnetism

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1 Introduction

The high \( T_c \) cuprates exhibit a large range of behaviors, from antiferromagnetic insulators to superconductors and normal metals. The interplay between charge and spin subsystems present in the \( CuO_2 \) planes is considered to be the tuning factor between all these different phases. Information about this interaction can be obtained by investigating the charge transport of the compositions which display antiferromagnetism, the precursor of superconductivity. Magnetotransport measurements represent an attractive way of investigation since they can detect changes in the scattering mechanisms of charge carriers and trace the onset of magnetic ordering.
Here we present in-plane magnetoresistivity $\Delta \rho_{ab}/\rho_{ab} = [\rho_{ab}(H) - \rho_{ab}(0)]/\rho_{ab}(0)$ measurements of antiferromagnetic $YBa_2Cu_3O_{6.25}$ single crystals, performed in sweeping a magnetic field $H$ applied parallel to the $ab$ plane and parallel or perpendicular to the electrical current $I$. These measurements reveal the presence of two terms contributing to $\Delta \rho_{ab}/\rho_{ab}$. The first term is anisotropic with respect to in-plane magnetic field $H$ orientation, strongly temperature dependent, and saturates at higher fields. The second term is isotropic in the $ab$ plane, positive, and quadratic in $H$. Upon the in-plane rotation of the magnetic field, the out-of-plane magnetoresistivity $\Delta \rho_c/\rho_c$ exhibits a fourfold symmetry with maxima along the in-plane crystallographic axes, which are also easy axes of antiferromagnetic spin-ordering. All these results are consistent with the presence of antiferromagnetic domains and in-plane orthorhombic distortion of the crystal lattice due to its coupling to the antiferromagnetically ordered Cu(2) magnetic moments.

2 Experimental Details

Single crystals of antiferromagnetic $YBa_2Cu_3O_{6.25}$ were grown by a method described elsewhere [1]. Typical dimensions are 0.8x0.5x0.04 mm$^3$ with the c-axis of the single crystals oriented along the smallest dimension. We have used an eight lead terminal configuration for the simultaneous determination of in-plane $\rho_{ab}$ and out-of-plane $\rho_c$ resistivities and their respective magnetoresistivities (MR). Thus, we applied a low electrical current across the top face and measured the top $V_{top}$ and bottom $V_{bot}$ face voltages. The homogeneity of the single crystals was checked by performing multiple sets of multiterminal transport measurements in zero field while sweeping the temperature between 10 $K \leq T \leq 300$ $K$. The MR measurements were performed at constant temperature $T$ either by sweeping the magnetic field $H$ up to 14 $T$ or by rotating a magnetic field of 14 $T$ in the $ab$ plane of the single crystal. During magnetic field sweeps, $H$ was applied parallel to the $ab$ plane of the crystal, with two different orientations with respect to the electrical current $I$: (i) $H \parallel I \parallel ab$, and (ii) $H \perp I \parallel ab$. Special care was taken to account for the magnetoresistance of the temperature sensors (Pt or Cx) and to eliminate the contribution of the Hall effect to the measured voltages [2].

3 Results and Discussion

Figure 1 shows the temperature dependence of the in-plane $\rho_{ab}$ and out-of-plane $\rho_c$ resistivities measured in zero magnetic field on a typical $YBa_2Cu_3O_{6.25}$ single crystal. This sample is antiferromagnetic for all measured temperatures.
Fig. 1. Temperature $T$ dependence of in-plane $\rho_{ab}$ and out-of-plane $\rho_c$ resistivities of $YBa_2Cu_3O_{6.25}$ single crystal measured in zero magnetic field.

$(T \leq 300 \text{ K})$. Note that $\rho_{ab}(T)$ maintains a weak metallic behavior down to $T \approx 175 \text{ K}$, despite the fact that this sample is strongly underdoped. At lower temperatures, $\rho_{ab}(T)$ is nonmetallic, increasing sharply with decreasing $T$. Over the same $T$ range ($10 \text{ K} < T < 300 \text{ K}$), $\rho_c(T)$ is very large and displays a nonmetallic behavior.

The field dependence of the in-plane magnetoresistivity $\Delta \rho_{ab}/\rho_{ab}$ is shown in Fig. 2 for the two different orientations of $H$ with respect to $I$ and for several temperatures. The open circles correspond to data taken with $H \parallel I \parallel ab$, while the squares represent data measured with $H \perp I \parallel ab$. The main feature of these data is that the field dependence of $\Delta \rho_{ab}/\rho_{ab}$ is a result of two contributions, each dominant over a different field range: (i) An anisotropic contribution with respect to field orientation, $\Delta \rho_{ab,anis}/\rho_{ab}$, dominant at low-$H$ values, which is positive for $H \perp I$ and negative for $H \parallel I$. (ii) A contribution $\Delta \rho_{ab,is}/\rho_{ab}$ which is positive and isotropic dominates at high-$H$ values.

To better understand the nature of the mechanisms present at this antiferromagnetic concentration, it is useful to identify the two contributions to $\Delta \rho_{ab}/\rho_{ab}$ measured at constant $T$. Figure 3(a) shows $\Delta \rho_{ab}/\rho_{ab}$ vs H data, measured at $125 \text{ K}$ under both field orientations (filled circles). The small difference between the high-$H$ curves arises from the small asymmetric contributions of the anisotropic term. Therefore, one can determine the isotropic term [square symbols in Fig. 3(a)] by taking the average of $(\Delta \rho_{ab}/\rho_{ab})(H)$ data measured with the two field orientations (filled circles). Then, the anisotropic
contribution $\Delta \rho_{ab,\text{anis}} / \rho_{ab}$ to $\Delta \rho_{ab} / \rho_{ab}$ is obtained by subtracting $\Delta \rho_{ab,\text{is}} / \rho_{ab}$ term from the measured $\Delta \rho_{ab} / \rho_{ab}$. The resulting curves for $H \parallel I$ and $H \perp I$ are shown in Fig. 3(a) as open triangles. These two curves have the same $H$ dependence, namely, $\Delta \rho_{ab,\text{anis}} / \rho_{ab}$ varies quadratically with $H$ in low fields and approaches saturation for $H \geq H_{\text{sat}}$. Also, the two curves are not completely symmetric: the anisotropic contribution when $H \perp I$ is smaller than the anisotropic contribution when $H \parallel I$.

Figure 3(b) is a plot of the $H$ dependence of $\Delta \rho_{ab,\text{anis}} / \rho_{ab}$ scaled with respect to its value at $H = 14$ T, measured at several $T$ with $H \perp I$. These data show that for low-$H$ values, $\Delta \rho_{ab,\text{anis}} / \rho_{ab}$ increases faster with $H$ the higher the temperature. Also, $\Delta \rho_{ab,\text{anis}} / \rho_{ab}$ approaches saturation at $H \geq H_{\text{sat}}$. The inset to Fig. 3(b) illustrates the $T$ dependence of $H_{\text{sat}}$ and of $\Delta \rho_{ab,\text{anis}} / \rho_{ab}$ measured at $H_{\text{sat}}$. Both $H_{\text{sat}}$ and $\Delta \rho_{ab,\text{anis}} / \rho_{ab}(H_{\text{sat}})$ decrease monotonically with increasing $T$. Note that $\Delta \rho_{ab,\text{anis}} / \rho_{ab}$ changes noticeable with temperature in the measured $T$ range, in contrast to the isotropic contribution $\Delta \rho_{ab,\text{is}} / \rho_{ab}$ which is practically $T$ independent (see Fig. 2).

Figure 4 is a plot of the out-of-plane magnetoresistivity $\Delta \rho_c / \rho_c$ measured at 100 K in a magnetic field of 14 T vs the angle $\theta$ the field $H$ makes in the $ab$ plane with the crystallographic axis $a(b)$. Note that $\Delta \rho_c / \rho_c$ is anisotropic with a fourfold symmetry. The maxima are at preferred spin orientations (0 and 90°, hence, along the $CuO$ bond), while the minima are at
Fig. 3. (a) Magnetic field $H$ dependence of total in-plane magnetoresistivity $\Delta \rho_{ab,\text{tot}}/\rho_{ab}$ measured at $T = 125$ K with $H \perp I \parallel ab$ and $H \parallel I \parallel ab$ (filled circles), and of the two terms that contribute to its value: the anisotropic contribution $\Delta \rho_{ab,\text{anis}}/\rho_{ab}$ (open triangles) and the isotropic $H^2$ contribution $\Delta \rho_{ab,\text{is}}/\rho_{ab}$ (open squares). (b) Magnetic field $H$ dependence of the anisotropic term $\Delta \rho_{ab,\text{anis}}/\rho_{ab}$ for $50 \leq T \leq 225$ K. The data are normalized with respect to $\Delta \rho_{ab,\text{anis}}/\rho_{ab}(H = 14T)$. Inset: Temperature $T$ dependence of $H_{\text{sat}}$ and of $\Delta \rho_{ab,\text{anis}}/\rho_{ab}$ measured at $H_{\text{sat}}$.

Favorable spin orientations (45° from the $Cu-O-Cu$ bonds). This behavior reveals the intrinsic relationship between the out-of-plane conduction and the antiferromagnetic spin ordering in the $CuO_2$ planes.

Two different scenarios have been put forward to explain the intriguing behavior of the anisotropic contribution to $\Delta \rho_{ab}/\rho_{ab}$, which changes sign from
positive to negative when $H$ changes from $H \perp I$ to $H \parallel I$, respectively. The first scenario invokes the segregation of charges within an array of stripes that form the boundaries between the antiferromagnetic domains [3]. The stripes order along the direction of the magnetic field as a result of the ferromagnetic coupling between the field and the domain walls. Field ordering of the stripes along $I$ decreases the resistivity from its value in the absence of a magnetic field, while field ordering of the stripes perpendicular to $I$ increases the resistivity. As a result, $\Delta \rho_{ab}/\rho_{ab} < 0$ for $H \parallel I$ and $\Delta \rho_{ab}/\rho_{ab} > 0$ for $H \perp I$. The second scenario invokes the presence of an in-plane orthorhombic distortion of the crystal lattice in the AF state due to its coupling with the ordered Cu(2) magnetic moments [4,5]. This leads to an in-plane anisotropy of the bulk resistivities: resistivity is larger when $I$ is parallel with the sublattice magnetization and smaller when it is perpendicular. An average resistivity is measured in the absence of a magnetic field. Since the sublattice magnetization in high fields is perpendicular to the magnetic field, $\Delta \rho_{ab}/\rho_{ab} < 0$ for $H \parallel I$ and $\Delta \rho_{ab}/\rho_{ab} > 0$ for $H \perp I$.

Thus, both scenarios account for the strong anisotropy of $\Delta \rho_{ab}/\rho_{ab}$ and the sign of $\Delta \rho_{ab, anis}/\rho_{ab}$ for the two $H$ orientations with respect to $I$. However, the anisotropy in $\Delta \rho_c/\rho_c$ upon field rotation within the $CuO_2$ plane, with maxima along the in-plane crystalographic axes, is hard to understand in the stripe scenario unless the stripes also produce a positive $\Delta \rho_c/\rho_c \,(H \parallel ab)$ which increases with increasing $H$. According to Ref. [6] this is not the case,
namely, the effect of the magnetic field on the stripes gives rise to a negative contribution to $\Delta \rho_c/\rho_c$ for all measured $H$ values. On the other hand, this angular anisotropy of $\Delta \rho_c/\rho_c$, with its fourfold symmetry, can be explained in the second scenario which invokes the presence of an in-plane orthorhombic distortion of the crystal lattice in the AF state [7].

None of the two models presented above can explain the positive, isotropic contribution to $\Delta \rho_{ab}/\rho_{ab}$ when $H \parallel I \parallel ab$ or $H \perp I \parallel ab$. A strong, positive, quadratic in $H$ contribution to $\Delta \rho_c/\rho_c$ when $H$ $\parallel c$-axis of samples with similar oxygen concentration was reported to sharply develop upon cooling through $T_N$ and to persist in the antiferromagnetic state as well [8]. This contribution was attributed to field suppression of spin fluctuations which might assist the out-of-plane electron hopping. The change in the ordering state of the spin subsystem at $T < T_N$ could also affect the in-plane transport and produce this positive isotropic contribution to $\Delta \rho_{ab}/\rho_{ab}$.

4 Summary

Magnetoresistivity measurements were performed on antiferromagnetic $YBa_2Cu_3O_{6.25}$ single crystals in magnetic fields $H \parallel ab$ plane. The in-plane magnetoresistivity $\Delta \rho_{ab}/\rho_{ab}$ contains two terms, reflecting two different mechanisms present in this antiferromagnetic composition. The first term is strongly in-plane anisotropic for the two field orientations, $H \parallel I \parallel ab$ and $H \perp I \parallel ab$. This term is quadratic in $H$ for low $H$ values and saturates at higher fields (for example, $H_{sat} = 6 T$ at $T = 100 K$). The second term is positive over the whole measured $T$ range, independent of field orientation, and dominates at $H > H_{sat}$. The out-of-plane resistivity exhibits an in-plane anisotropy, with four-fold symmetry, revealing the correlation between the out-of-plane transport and preferred directions of antiferromagnetic spin ordering in the $ab$ plane. All these results are consistent with the presence of antiferromagnetic domains and an in-plane orthorhombic distortion of the crystal lattice due to its coupling with the ordered Cu(2) magnetic moments.

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