Magnetotransport properties of antiferromagnetic YBa$_2$Cu$_3$O$_{6.25}$ 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$_2$Cu$_3$O$_{6.25}$ 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 $H\|I$ 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). © 2001 Elsevier Science B.V. All rights reserved.

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 (MR) $\Delta\rho_{ab}/\rho_{ab} = [\rho_{ab}(H) - \rho_{ab}(0)]/\rho_{ab}(0)$ measurements of antiferromagnetic YBa$_2$Cu$_3$O$_{6.25}$ 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 MR $\Delta\rho_c/\rho_c$ exhibits a fourfold symmetry with maxima along the in-plane crystallographic axes, which are also easy axes of antiferromagnetic spin ordering. The anisotropic behavior of MRs is consistent with the presence of antiferromagnetic domains and in-plane

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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_3-$O_{6.25}$ were grown by a method described elsewhere [1]. Typical dimensions are $0.8 \times 0.5 \times 0.04$ 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 ρ_{ab} and out-of-plane ρ_c resistivities and their respective MRs. 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 $10 \leqslant T \leqslant$ 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) $H\|I\|ab$, and (ii) $H\perp I \|ab$. 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

Fig. 1 shows the temperature dependence of the in-plane ρ_{ab} and out-of-plane ρ_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 ($T \leqslant 300$ K). Note that $\rho_{ab}(T)$ maintains a weak metallic behavior down to $T \approx 175$ 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 ($10 <$
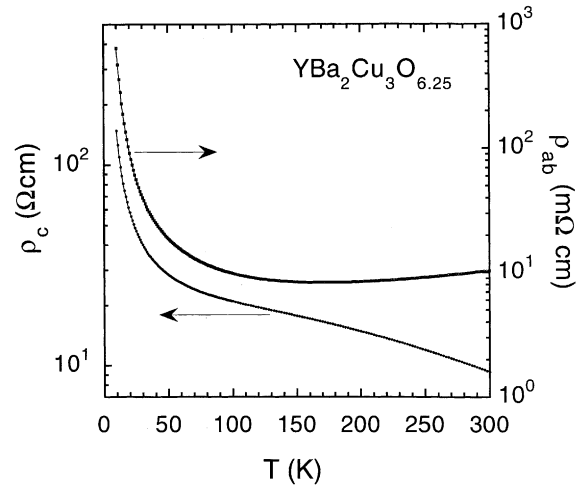

Fig. 1. Temperature T dependence of in-plane ρ_{ab} and out-of-plane ρ_c resistivities of $YBa_2Cu_3O_{6.25}$ single crystal measured in zero magnetic field.

$T < 300$ K), $\rho_c(T)$ is very large and displays a nonmetallic behavior.

The field dependence of the in-plane MR $\Delta\rho_{ab}/\rho_{ab}$ 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 $H\|I\|ab$, while the squares represent
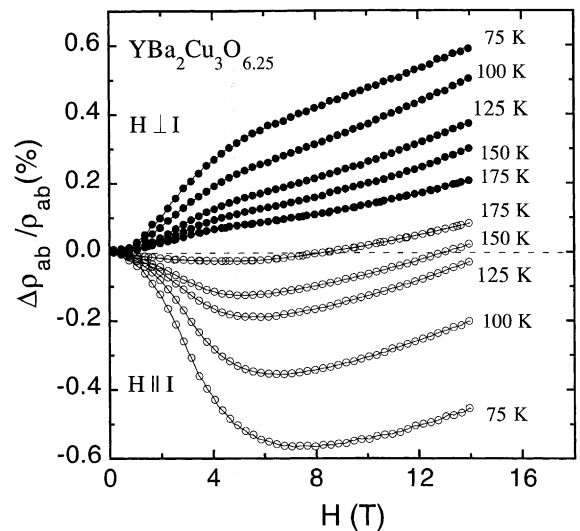

Fig. 2. Field H dependence of in-plane MR $\Delta\rho_{ab}/\rho_{ab}$ measured with two field orientations. The filled circles correspond to $H\perp I\|ab$ while the open circles correspond to $H\|I\|ab$.

data measured with $H\perp I\|ab$. 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, $\Delta\rho_{ab,\text{anis}}/\rho_{ab}$, dominant at low-$H$ values, which is positive for $H\perp I$ and negative for $H\|I$. (ii) A contribution $\Delta\rho_{ab,\text{is}}/\rho_{ab}$ which is positive, isotropic, and 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. Fig. 3(a) shows $\Delta\rho_{ab}/\rho_{ab}$ vs H data, measured at 125 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 $H\|I$ 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 $H\geqslant H_{\text{sat}}$. Also, the two curves are not completely symmetric: the anisotropic contribution when $H\perp I$ is smaller than the anisotropic contribution when $H\|I$.

Fig. 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 $H\geqslant H_{\text{sat}}$. The inset to Fig. 3(b) illustrates the T dependence of H_{sat} and of $\Delta\rho_{ab,\text{anis}}/\rho_{ab}$ measured at H_{sat}. Both H_{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).

Fig. 4 is a plot of the out-of-plane MR $\Delta\rho_c/\rho_c$ measured at 100 K in a magnetic field of 14 T vs
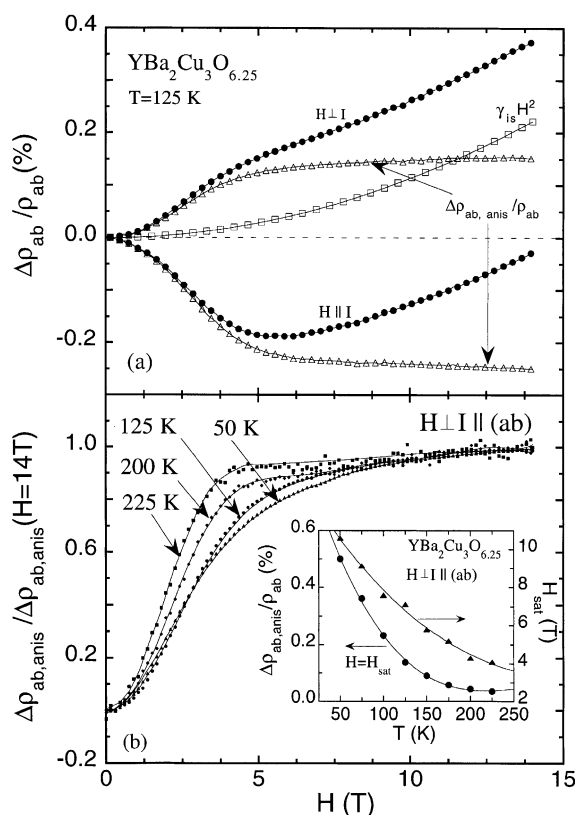

Fig. 3. (a) Magnetic field H dependence of total in-plane MR $\Delta\rho_{ab}/\rho_{ab}$ measured at $T=125$ K with $H\perp I\|ab$ and $H\|I\|ab$ (●), and of the two terms that contribute to its value: the anisotropic contribution $\Delta\rho_{ab,\text{anis}}/\rho_{ab}$ (△) and the isotropic H^2 contribution $\Delta\rho_{ab,\text{is}}/\rho_{ab}$ (□). (b) Magnetic field H dependence of the anisotropic term $\Delta\rho_{ab,\text{anis}}/\rho_{ab}$ for $50\leqslant T\leqslant 225$ K. The data are normalized with respect to $\Delta\rho_{ab,\text{anis}}/\rho_{ab}$ ($H=14$ T). Inset: temperature T dependence of H_{sat} and of $\Delta\rho_{ab,\text{anis}}/\rho_{ab}$ measured at H_{sat} with $H\perp I$.

the angle θ 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 Cu–O–Cu bonds), while the minima are at unfavorable 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 main scenarios have been put forward to explain the intriguing behavior of the anisotropic
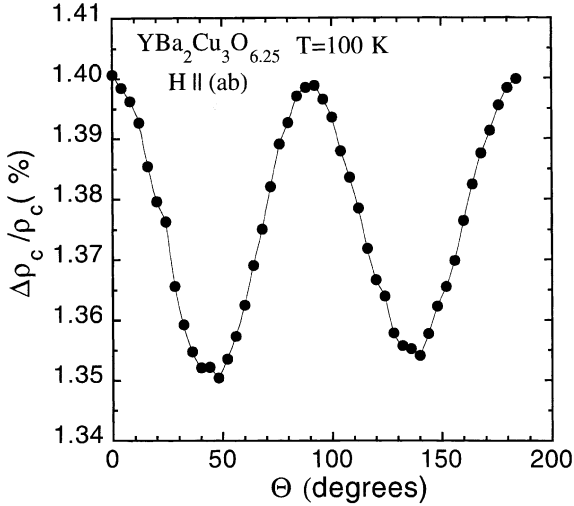
Fig. 4. Plot of the out-of-plane MR $\Delta\rho_c/\rho_c = [\rho_c(\theta) - \rho_c(0)]/\rho_c$ measured at 100 K in a magnetic field of 14 T vs the angle θ the field H makes in the ab-plane with the crystallographic axis $a(b)$.

contribution to $\Delta\rho_{ab}/\rho_{ab}$, which changes sign from positive to negative when H changes from $H\perp I$ to $H\|I$, 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 $H\|I$ 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 $H\|I$ 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 $\Delta\rho_{ab,\text{anis}}/\rho_{ab}$

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 crystallographic axes, is hard to understand in the stripe scenario unless the stripes also produce a positive $\Delta\rho_c/\rho_c$ ($H\|ab$) 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 $H\|I\|ab$ or $H\perp I\|ab$. A strong, positive, quadratic in H contribution to $\Delta\rho_c/\rho_c$ when $H\|$ 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

MR measurements were performed on antiferromagnetic $YBa_2Cu_3O_{6.25}$ single crystals in magnetic fields $H\|ab$ plane. The in-plane MR $\Delta\rho_{ab}/\rho_{ab}$ 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, $H\|I\|ab$ and $H\perp I\|ab$. This term is quadratic in H for low-H values and saturates at higher fields (for example, $H_{\text{sat}} = 6$ T at $T = 100$ K). The second term is positive over the whole measured T range, independent of field orientation, and dominates at $H > H_{\text{sat}}$. 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. The anisotropic behavior of MRs is consistent with the field reorientation of the antiferromagnetic domains and the presence of in-plane orthorhombic distortions of the crystal lattice due to its coupling with the ordered Cu(2) magnetic moments.

Acknowledgements

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