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Anisotropic resistivity of the antiferromagnetic insulator $Bi_2Sr_2ErCu_2O_8$

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Abstract. The anisotropic resistivities of $Bi_2Sr_2Ca_{1-x}Er_xCu_2O_8$ single crystals were measured and analysed from 4.2 to 500 K with special interest taken in the parent antiferromagnetic insulator with $x = 1.0$. Although the resistivity is semiconducting along both the in-plane and out-of-plane directions, the temperature dependences are found to be significantly different. As a result, the resistivity ratio for $x = 1.0$ exhibits a broad maximum near room temperature. The electric conduction in the parent antiferromagnetic insulators is different from that in other semiconductors, and is as unconventional as that in high-temperature superconductors.

1. Introduction

Anisotropic transport properties in the normal state are one of the most striking features of high-temperature superconductors (HTSCs) [1]. The metallic in-plane resistivity (ρ_{ab}) accompanied by the non-metallic out-of-plane resistivity (ρ_c) enhances ρ_c/ρ_{ab} at low temperature (T) [2,3], whereas ρ_c/ρ_{ab} is independent of T for conventional metals. The enhancement of ρ_c/ρ_{ab} is often called 'confinement' [4], and can be a key to the elucidation of the mechanism of high-temperature superconductivity. We have studied the anisotropic transport properties of slightly overdoped $YBa_2Cu_3O_y$ crystals [5,6]. Although their resistivities ρ_c and ρ_{ab} are both metallic, the anisotropy is difficult to understand within the Fermi liquid theory.

The next question is that of whether ρ_c/ρ_{ab} is anomalous for a parent antiferromagnetic (AF) insulator, whose resistivities ρ_c and ρ_{ab} are semiconducting. To our knowledge, very little investigation has been done on ρ_c/ρ_{ab}. Thio *et al* [7] have found that ρ_c/ρ_{ab} for La_2CuO_4 *decreases* with decreasing T below 200 K, which is significantly incompatible with ρ_c/ρ_{ab} for HTSCs. Since it does not saturate near 200 K, a higher-temperature measurement is needed.

For studying ρ_c/ρ_{ab} over a wide temperature range, $Bi_2Sr_2Ca_{1-x}R_xCu_2O_8$ (R: rare earth) is most suitable for the following reasons:

(a) Oxygens for $x = 0$ are chemically stable up to 600 K in air, where ρ_{ab} remains 'T-linear' [8].
(b) When x reduces from 1 to 0, the doping level varies from that of a parent AF insulator to that of a (slightly) overdoped superconductor [9].
(c) All of the Cu sites are equivalent, and only the CuO_2 plane is responsible for the electric conduction.

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Here we report on measurements and analyses of $Bi_2Sr_2Ca_{1-x}Er_xCu_2O_8$ single crystals with $x = 0$, 0.1, 0.5, and 1.0. We have found that ρ_c/ρ_{ab} for a parent AF insulator ($x = 1.0$) is quite unique; it increases with T below 100 K, takes a broad maximum near 300 K, and decreases above room temperature. This obviously indicates that a parent AF insulator exhibits a quite different conduction mechanism from conventional semiconductors.

2. Experimental procedure

Single crystals of $Bi_2Sr_2Ca_{1-x}Er_xCu_2O_8$ were grown by a self-flux method [10]. Powders of Bi_2O_3, $SrCO_3$, CuO, $CaCO_3$, and Er_2O_3 of 99.9% purity were mixed, well ground in an Al_2O_3 crucible, heated at 900 °C (1020 °C) for 10 h, and slowly cooled down to 760 °C (820 °C) at 2 °C h^{-1} for $x = 0$ ($x \neq 0$). Since the single crystals were very thin along the c-axis, the thickness was measured with a scanning electron microscope (SEM). The actual compositions were measured through inductively coupled plasma emission spectroscopy. The x-ray diffraction pattern showed no trace of impurities, and the c-axis lattice parameter for $x = 0$ was evaluated to be 30.85 Å, which agrees with the value in the literature [10, 11]. The measured compositions, sizes, and c-axis lattice parameters are listed in table 1. We should note that crystals grown by a flux method are produced with little stress, owing to the slow cooling rate near thermal equilibrium. In fact, we did not observe any serious cracks in the SEM images of our samples. In order to examine the influence of inhomogeneity and disorder on the resistivity, we made measurements for more than 30 samples including ones grown from different batches. The measured resistivities were reproducible enough to warrant their discussion in this paper.

Table 1. Characterization of $Bi_2Sr_2Ca_{1-x}Er_xCu_2O_8$ single crystals. Note that the real composition ratio is represented by setting Cu = 2.

Nominal x	Actual composition Bi:Sr:Ca:Er:Cu	Size (mm^3)	c-axis (Å)
0	1.9:1.9:1.2:0:2	$0.6 \times 1 \times 0.02$	30.85
0.1	1.6:1.8:1.2:0.1:2	$1 \times 1.2 \times 0.02$	30.90
0.5	1.6:1.9:1.0:0.5:2	$1 \times 1 \times 0.004$	30.32
1.0	2.0:2.1:0:0.6:2	$1 \times 1.2 \times 0.004$	30.33

The resistivity was measured with a dc current I in a four-probe configuration along the in-plane direction ($\boldsymbol{I} \perp \boldsymbol{c}$), and in a ring configuration along the out-of-plane direction ($\boldsymbol{I} \parallel \boldsymbol{c}$). We used two measurement systems below and above room temperature. From 4.2 to 300 K, the samples were slowly (100 K h^{-1}) cooled in a liquid-He cryostat, where T was monitored by a Cernox resistance thermometer. Above 300 K, the samples are slowly (50–100 K h^{-1}) heated in air in a cylinder furnace with a Pt resistance thermometer.

3. Results and discussion

Figures 1(a) and 1(b) show ρ_{ab} and ρ_c for $Bi_2Sr_2Ca_{1-x}Er_xCu_2O_8$ single crystals, respectively. The magnitudes of ρ_{ab} and ρ_c increase with x, showing that the hole concentration is reduced by the Er substitution. As is seen in the literature, ρ_c is four or five orders of magnitude larger than ρ_{ab} for all of the samples. For superconducting samples ($x = 0$ and 0.1), metallic ρ_{ab} and semiconducting ρ_c are observed above T_c. Reflecting the slightly overdoped nature of the $x = 0$ sample, T_c (∼84 K) for $x = 0$ is lower than T_c (∼87 K) for $x = 0.1$. These results

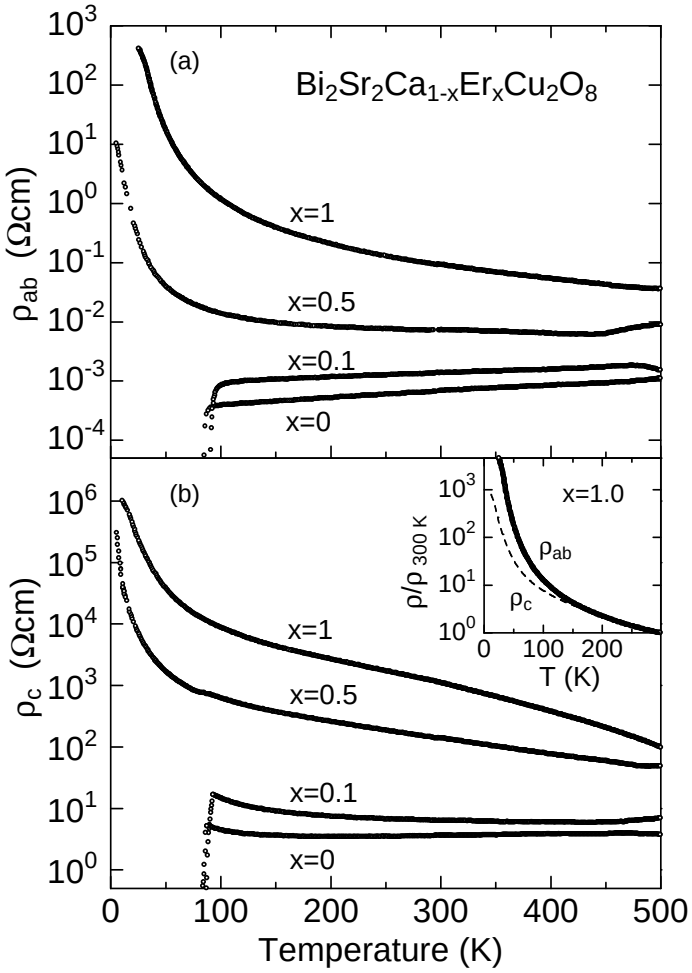

Figure 1. (a) The in-plane resistivity ρ_{ab} and (b) out-of-plane resistivity ρ_c of single crystals of $Bi_2Sr_2Ca_{1-x}Er_xCu_2O_8$. ρ_{ab} and ρ_c for $x = 1.0$ normalized at 300 K are plotted as functions of temperature in the inset.

attest to the quality of our crystals.

Both ρ_{ab} and ρ_c for $x = 1.0$ are semiconducting, but they exhibit different T-dependences. Above room temperature, where ρ_{ab} decreases gradually in comparison with ρ_c, ρ_c/ρ_{ab} decreases with increasing T. On the other hand, ρ_{ab} becomes insulating more rapidly than ρ_c, as shown in the inset of figure 1 where the resistivities are normalized at 300 K. Thus ρ_c/ρ_{ab} decreases with decreasing T below 300 K. These results are not understandable on the basis of conventional theories. In the framework of a band picture, anisotropy is mainly determined by effective masses, implying that the T-dependence of ρ is independent of the direction. In the case of a hole doped in the AF background, the situations are nearly the same. In fact, a nearly T-independent ρ_c/ρ_{ab} has been observed for La_2NiO_4 [12] and $Bi_2M_3Co_2O_9$ (M = Ca, Sr and Ba) [13].

The magnitude of ρ_c/ρ_{ab} for a parent AF insulator is much more difficult to evaluate than that for a superconductor, in that it is an exponentially varying quantity divided by another

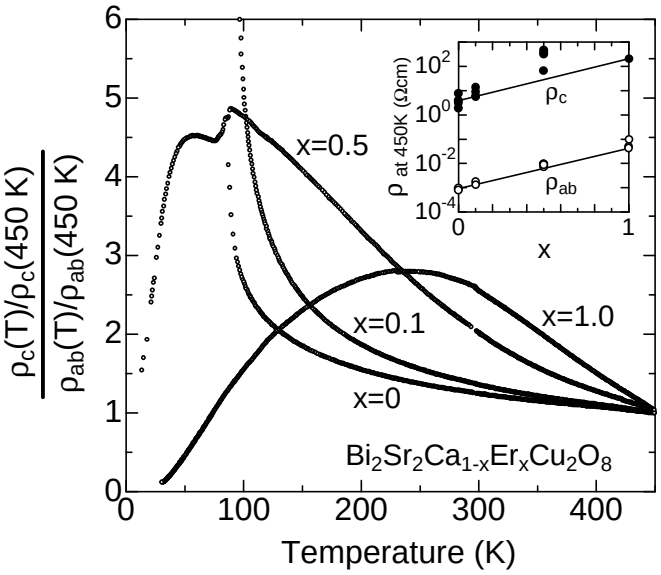

Figure 2. The anisotropic resistivity ratios ρ_c/ρ_{ab} of $Bi_2Sr_2Ca_{1-x}Er_xCu_2O_8$ single crystals normalized at 450 K. Inset: the magnitudes of ρ_{ab} and ρ_c at 450 K are plotted as functions of x. Note that each symbol represents the resistivity of a different sample, measured to check the reproducibility (see the text).

exponentially varying quantity. Since we are interested in the T-dependence of ρ_c/ρ_{ab}, we normalize ρ_c/ρ_{ab} at 450 K in figure 2. As for the magnitude, we show ρ_{ab} and ρ_c in the inset of figure 2, in which each symbol corresponds to a different sample. From the inset, one can see that the magnitude of ρ_c/ρ_{ab} at 450 K is nearly independent of x. Accordingly, the normalization at 450 K will not adversely affect the discussion below.

We would like to point out three features in figure 2. First, ρ_c/ρ_{ab} changes smoothly with x above room temperature; it increases with decreasing T, and the T-dependence is steeper for larger x (smaller hole concentration). If one looked at ρ_c/ρ_{ab} only above room temperature, one could not distinguish a parent AF insulator from a superconductor. Thus we may say that the holes are confined in a parent AF insulator as well as in HTSCs. In this context the former is as unconventional as the latter. Secondly, ρ_c/ρ_{ab} for $x = 1.0$ and 0.5 decreases with decreasing T below 100 K, which is consistent with ρ_c/ρ_{ab} for La_2CuO_4 [7]. The decrease of ρ_c/ρ_{ab} as $T \to 0$ could be understood from the three-dimensional (3D) nature of the localization [14]. Thirdly, ρ_c/ρ_{ab} for $x = 1.0$ and 0.5 takes a maximum at a certain temperature $T_{\max}$, which is very close to the Néel temperature T_N. (For $x = 0.5$, a tiny fraction of a superconducting phase causes a small drop of resistivity near 90 K, which obscures the position of $T_{\max}$.)

The localized f spins of Er^{3+} make it difficult to measure T_N for Cu^{2+} for $x = 1.0$ and 0.5. Instead, we will compare T_N for $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_8$ [15], and we plot T_c, T_N, and $T_{\max}$ in the electronic phase diagram of $Bi_2Sr_2Ca_{1-x}R_xCu_2O_8$ in figure 3. We estimated the hole concentration using an empirical relation to the thermopower [16], which we measured with the same samples for R = Er (not shown here), and used reference [17] for R = Y. $T_{\max}$ is found to lie around the AF boundary. Since no structural transitions and no phase separations are reported for $Bi_2Sr_2Ca_{1-x}R_xCu_2O_8$ [9], it would be natural to relate $T_{\max}$ to the AF transition.

The confinement behaviour above T_N favours some theories based on the two-dimensional

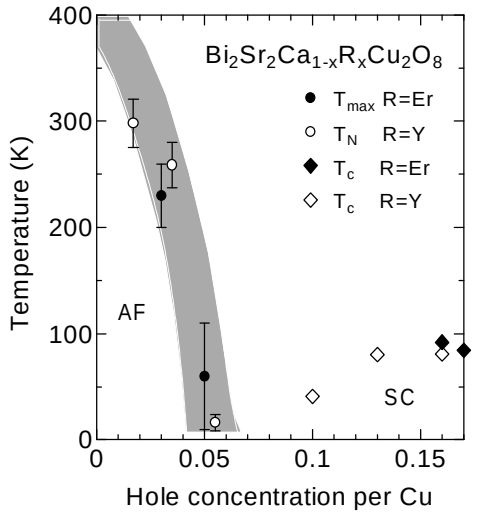

Figure 3. The phase diagram of $Bi_2Sr_2Ca_{1-x}R_xCu_2O_8$ (R = Er and Y). AF and SC represent the antiferromagnetic order and the superconducting phase, respectively. T_{max} (the temperature at which ρ_c/ρ_{ab} takes a maximum), T_N (the Néel temperature), and T_c (the superconducting transition temperature) are plotted as a function of the hole concentration. T_N and T_c for R = Y are taken from references [15] and [17]. The hole concentration is estimated from the room temperature thermopower, as is proposed in reference [16]. The error bars for T_{max} represent the variation from sample to sample.

(2D) spin fluctuation, which exists in parent AF insulators above T_N [18] and in HTSCs above T_c as well [19]. We therefore propose that holes are confined in a CuO_2 plane in the presence of the 2D spin fluctuation, *which occurs irrespective of doping levels*. As the 3D AF order grows below T_N, the confinement becomes less effective. A recent numerical analysis of the bilayer t–J model has also led to the assertion that ρ_c is substantially modified in the presence of the 2D spin fluctuation [20]. We further note that a similar case is seen for the layered ferromagnet $La_{2-x}Sr_{1+x}Mn_2O_7$ [21]. For 100 K $< T <$ 250 K, this compound is in a 2D ferromagnetic state, and exhibits a non-metallic ρ_c together with a metallic ρ_{ab}. Once the 3D ferromagnetic order appears below 100 K, ρ_c becomes metallic and behaves in a 3D-like manner. We believe that the out-of-plane conduction in parent AF insulators involves essentially the same physics as for $La_{2-x}Sr_{1+x}Mn_2O_7$; the only difference is as regards whether the material is an antiferromagnetic insulator or a ferromagnetic metal.

4. Summary

We prepared $Bi_2Sr_2Ca_{1-x}Er_xCu_2O_8$ single crystals for $x = 0$, 0.1, 0.5, and 1.0 and measured the in-plane and out-of-plane resistivities (ρ_{ab} and ρ_c) from 4.2 to 500 K. The present study has revealed that ρ_c/ρ_{ab} for a parent antiferromagnetic insulator ($x = 1.0$) strongly depends on temperature, and that the enhancement of ρ_c/ρ_{ab} with decreasing T is observed above room temperature. In this sense, parent antiferromagnetic insulators are as unconventional as high-temperature superconductors. Their ratios ρ_c/ρ_{ab} take maxima at a certain temperature near the Néel temperature, and we propose that the confinement in the CuO_2 plane is operative in the two-dimensional spin-fluctuation regime regardless of the doping level.

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