Anisotropic resistivity of the antiferromagnetic insulator Bi$_2$Sr$_2$ErCu$_2$O$_8$

T Kitajima, T Takayanagi, T Takemura and I Terasaki †
Department of Applied Physics, Waseda University, Tokyo 169-8555, Japan

Abstract. The anisotropic resistivities of Bi$_2$Sr$_2$Ca$_{1-x}$Er$_x$Cu$_2$O$_8$ single crystals were measured and analyzed 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 (HTSC’s) [1]. The metallic in-plane resistivity ($\rho_{ab}$) accompanied by the non-metallic out-of-plane resistivity ($\rho_c$) enhances $\rho_c/\rho_{ab}$ at low temperature ($T$) [2,3], whereas $\rho_c/\rho_{ab}$ is independent of $T$ for conventional metals. The enhancement of $\rho_c/\rho_{ab}$ 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$_2$Cu$_3$O$_y$ crystals [5,6]. Although their resistivities $\rho_c$ and $\rho_{ab}$ are both metallic, the anisotropy is difficult to understand within the Fermi liquid theory.

The next question is that of whether $\rho_c/\rho_{ab}$ is anomalous for a parent antiferromagnetic (AF) insulator, whose resistivities $\rho_c$ and $\rho_{ab}$ are semiconducting. To our knowledge, very little investigation has been done on $\rho_c/\rho_{ab}$. Thio et al. [7] have found that $\rho_c/\rho_{ab}$ for La$_2$CuO$_4$ decreases with decreasing $T$ below 200 K, which is significantly incompatible with $\rho_c/\rho_{ab}$ for HTSC’s. Since it does not saturate near 200 K, a higher-temperature measurement is needed.

† To whom correspondence should be addressed. E-mail address: terra@mn.waseda.ac.jp
Table 1. Characterization of Bi$_2$Sr$_2$Ca$_{1-x}$Er$_x$Cu$_2$O$_8$ single crystals. Note that the actual composition ratio is represented by setting Cu = 2.

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

For studying $\rho_c/\rho_{ab}$ over a wide temperature range, Bi$_2$Sr$_2$Ca$_{1-x}$Er$_x$Cu$_2$O$_8$ ($R$: rare-earth) is most suitable for the following reasons: (i) Oxygens for $x=0$ are chemically stable up to 600 K in air where $\rho_{ab}$ remains “$T$-linear” [8]. (ii) 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]. (iii) All of the Cu sites are equivalent, and only the CuO$_2$ plane is responsible for the electric conduction. Here we report on measurements and analyses of Bi$_2$Sr$_2$Ca$_{1-x}$Er$_x$Cu$_2$O$_8$ single crystals with $x=0$, 0.1, 0.5, and 1.0. We have found that $\rho_c/\rho_{ab}$ 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

Single crystals of Bi$_2$Sr$_2$Ca$_{1-x}$Er$_x$Cu$_2$O$_8$ were grown by a self-flux method [10]. Powders of Bi$_2$O$_3$, SrCO$_3$, CuO, CaCO$_3$, and Er$_2$O$_3$ of 99.9 % purity were mixed, well ground in an Al$_2$O$_3$ crucible, heated at 900°C [1020°C] for 10 h, and slowly cooled down to 760°C [820°C] by 2°C/h for $x=0$ [$x\neq0$]. 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 the discussion in this paper.

The resistivity was measured with a dc current $I$ in a four-probe configuration along
3. Results and discussion

Figures 1(a) and 1(b) show \( \rho_{ab} \) and \( \rho_c \) of Bi\(_2\)Sr\(_2\)Ca\(_{1-x}\)Er\(_x\)Cu\(_2\)O\(_8\) single crystals, respectively. The magnitudes of \( \rho_{ab} \) and \( \rho_c \) increase with \( x \), showing that the hole concentration is reduced by the Er substitution. As is seen in the literature, \( \rho_c \) is four or five orders of magnitude larger than \( \rho_{ab} \) for all the samples. For superconducting samples \( (x=0 \text{ and } 0.1) \), metallic \( \rho_{ab} \) and semiconducting \( \rho_c \) are observed above \( T_c \). Reflecting the slightly overdoped nature of \( x=0 \), \( T_c (\sim 84 \text{ K}) \) for the \( x=0 \) sample is lower than \( T_c (\sim 87 \text{ K}) \) for \( x=0.1 \). These results attest to the quality of our crystals.

Both \( \rho_{ab} \) and \( \rho_c \) for \( x=1.0 \) are semiconducting, but they exhibit different \( T \) dependences. Above room temperature, where \( \rho_{ab} \) decreases gradually in comparison
Figure 2. The anisotropic resistivity ratios $\rho_c/\rho_{ab}$ of Bi$_2$Sr$_2$Ca$_{1-x}$Er$_x$Cu$_2$O$_8$ single crystals normalized at 450 K. Inset: The magnitudes of $\rho_{ab}$ and $\rho_c$ 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 text).

with $\rho_c$, $\rho_c/\rho_{ab}$ decreases with increasing $T$. On the other hand, $\rho_{ab}$ becomes insulating more rapidly than $\rho_c$, as shown in the inset of figure 1 where the resistivities are normalized at 300 K. Thus $\rho_c/\rho_{ab}$ 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 $\rho$ 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 $\rho_c/\rho_{ab}$ has been observed for La$_2$NiO$_4$ [12] and Bi$_2$M$_3$Co$_2$O$_9$ ($M$=Ca, Sr and Ba) [13].

The magnitude of $\rho_c/\rho_{ab}$ 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 exponentially varying quantity. Since we are interested in the $T$ dependence of $\rho_c/\rho_{ab}$, we normalize $\rho_c/\rho_{ab}$ at 450 K in figure 2. As for the magnitude, we show $\rho_{ab}$ and $\rho_c$ 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 $\rho_c/\rho_{ab}$ 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, $\rho_c/\rho_{ab}$ 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 $\rho_c/\rho_{ab}$ 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 HTSC. In this context the former is as unconventional as the latter. Secondly, $\rho_c/\rho_{ab}$
for $x=1.0$ and 0.5 decreases with decreasing $T$ below 100 K, which is consistent with $\rho_c/\rho_{ab}$ of La$_2$CuO$_4$ [7]. The decrease of $\rho_c/\rho_{ab}$ as $T \to 0$ could be understood from the three-dimensional (3D) nature of the localization [14]. Thirdly, $\rho_c/\rho_{ab}$ for $x=1.0$ and 0.5 takes a maximum at a certain temperature $T_{\text{max}}$, 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 $T_{\text{max}}$.)

The localized $f$ spins of Er$^{3+}$ make it difficult to measure $T_N$ of Cu$^{2+}$ for $x=1.0$ and 0.5. Instead, we will compare $T_N$ of Bi$_2$Sr$_2$Ca$_{1-x}$Y$_x$Cu$_2$O$_8$ [15], and we plot $T_c$, $T_N$ and $T_{\text{max}}$ in the electronic phase diagram of Bi$_2$Sr$_2$Ca$_{1-x}$R$_x$Cu$_2$O$_8$ 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 Ref. [17] for $R=Y$. $T_{\text{max}}$ is found to lie around the AF boundary. Since no structural transitions and no phase separations are reported for Bi$_2$Sr$_2$Ca$_{1-x}$R$_x$Cu$_2$O$_8$ [3], it would be natural to relate $T_{\text{max}}$ to the AF transition.

The confinement behavior above $T_N$ favors some theories based on the two-dimensional (2D) spin fluctuation, which exists in parent AF insulators above $T_N$ [18] and in HTSC’s 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 $\rho_c$ is substantially modified in the presence of the 2D spin fluctuation [20]. We further note that a similar case is seen for a layered ferromagnet La$_{2-x}$Sr$_{1+2x}$Mn$_2$O$_7$ [21]. For $100\, K < T < 250\, K$, this compound is in a 2D ferromagnetic state, and exhibits a non-metallic $\rho_c$ together with a metallic $\rho_{ab}$. Once the 3D ferromagnetic order appears below 100 K, $\rho_c$ becomes metallic to behave in a 3D-like manner. We believe that the out-of-plane conduction in parent AF insulators includes essentially the same physics as for La$_{2-x}$Sr$_{1+2x}$Mn$_2$O$_7$; the only difference is as regards whether the material is an antiferromagnetic insulator or a ferromagnetic metal.

4. Summary

We prepared Bi$_2$Sr$_2$Ca$_{1-x}$Er$_x$Cu$_2$O$_8$, single crystals for $x=0$, 0.1, 0.5 and 1.0 and measured the in-plane and out-of-plane resistivities ($\rho_{ab}$ and $\rho_c$) from 4.2 to 500 K. The present study has revealed that $\rho_c/\rho_{ab}$ for a parent antiferromagnetic insulator ($x = 1.0$) strongly depends on temperature, and that the enhancement of $\rho_c/\rho_{ab}$ with decreasing $T$ is observed above room temperature. In this sense, parent antiferromagnetic insulators are as unconventional as high-temperature superconductors. Their ratios $\rho_c/\rho_{ab}$ 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.

Acknowledgments

The authors would like to thank T Itoh, T Kawata, K Takahata and Y Iguchi for collaboration. They also wish to express their appreciation to S Kurihara and S Saito for fruitful discussions and valuable comments. One of the authors (I T) is indebted to S Tajima for the collaboration at a preliminary stage of this work. This work was partially supported by Waseda University Grant for Special Research Projects (97A-565, 98A-618).

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