Anisotropic Transport Properties of $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ Single Crystals

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Abstract

In-plane and out-of-plane resistivities (ρ_{ab} and ρ_c) are measured in a series of $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ single crystals with various La concentration x ($x = 0.23$ – 1.02), and the anisotropy ratio ρ_c/ρ_{ab} is determined. It is found that for all concentrations $\rho_c(T)$ shows a steeply diverging behavior with lowering T, and as a result the magnitude of the anisotropy ratio ρ_c/ρ_{ab} is observed to be enhanced to as large as 8×10^5, demonstrating that Bi-2201 is the most anisotropic material among cuprates. Detailed analysis of the temperature and doping dependences of ρ_c/ρ_{ab} reveals that not only the charge confinement but also the pseudogap are responsible for the large electrical anisotropy in $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$.

Key words: c-axis transport; transport properties; pseudogap

1. INTRODUCTION

Measurements of the anisotropic transport properties of high-T_c cuprates have been demonstrated to be quite illuminating. For example, it has been shown that: (i) The magnitude of the c-axis resistivity ρ_c is orders of magnitude larger than that expected from band calculations, leading to a huge resistivity anisotropy where ρ_c is up to 10^5 times larger [1] than the in-plane resistivity ρ_{ab}. (ii) The temperature dependence of ρ_c is in most cases semiconducting or insulating ($d\rho_c/dT < 0$), while that of ρ_{ab} is metallic ($d\rho_{ab}/dT > 0$); such a contrasting behavior [2–4] is not expected in ordinary anisotropic metal.

There seem to be two additive mechanisms that are both responsible for the "insulating" $\rho_c(T)$. The first is the charge-confinement mechanism which appears to become increasingly more effective with lowering temperature; this effect causes the c-axis tunneling matrix element to be reduced and keeps ρ_c to be increasing. The other is the effect of pseudogap which causes destruction of the Fermi surface starting from the $(\pm\pi, 0)$, $(0, \pm\pi)$ points; this causes the available density of states for tunneling to be reduced, and ρ_c gets steeply increased as the pseudogap develops. It is expected that these two independent mechanisms, confinement and pseudogap, together cause the rather complicated, "insulating" $\rho_c(T)$ behavior in the cuprates, though their relative roles in determining the actual temperature dependence is not clarified yet.

Given the recent understanding of the *c*-axis transport, it is important to establish a comprehensive picture for the roles of the two mechanisms (confinement and pseudogap) in determining the temperature dependence of $\rho_c(T)$, as well as the anisotropy ratio ρ_c/ρ_{ab}, over a wide range of hole doping. $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (BSLCO) is a very attractive system for such studies, because one can rather easily change the carrier concentration in a wide range, covering both the overdoped and the underdoped regions [5]. In this work we measure in-plane and out-of-plane resistivities (ρ_{ab} and ρ_c) in high-quality BSLCO single crystals and determine the anisotropy ratio ρ_c/ρ_{ab}.

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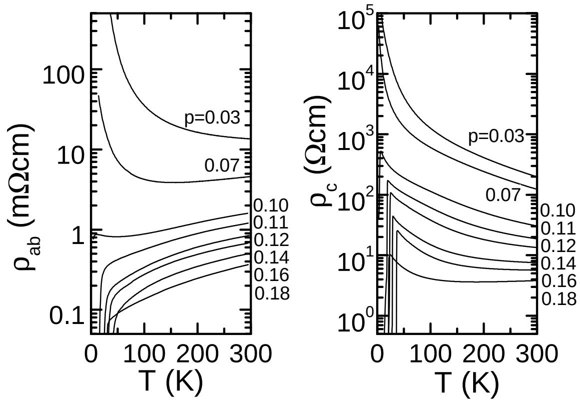

Fig. 1. Temperature dependences of (a) ρ_{ab} and (b) ρ_c of the BSLCO crystals for various p.

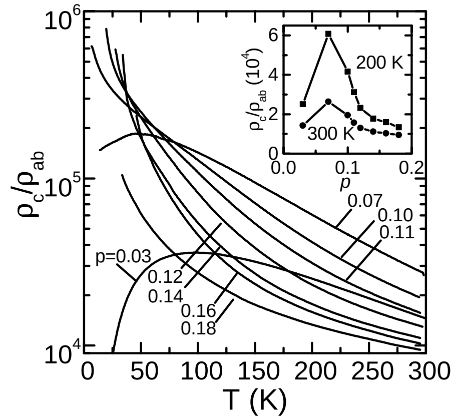

Fig. 2. Temperature dependences of ρ_c/ρ_{ab} of the BSLCO crystals from Fig. 1. Inset: p dependence of ρ_c/ρ_{ab} at 200 and 300 K.

2. RESULTS AND DISCUSSIONS

The single crystals of $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ are grown using a floating-zone technique for a wide range of La concentration ($0.23 \le x \le 1.02$) [5]. Note that a larger x value indicates a more underdoped sample. The optimum doping for BSLCO corresponds to x=0.39 and the maximum T_c is 38 K. The actual concentration of La in the crystals is determined with the inductively-coupled plasma (ICP) analysis. All the samples are annealed in oxygen to sharpen the superconducting transition, whose width (measured with SQUID magnetometer) is typically 2 K after annealing. We have previously determined the actual hole concentration per Cu, p, for various La concentrations x, and have obtained an empirical relation [6]. Hereafter we use the p value in referring to the samples.

Figure 1 shows the T dependence of ρ_{ab} and ρ_c for all the p values studied here (p = 0.03, 0.07, 0.10, 0.11, 0.12, 0.14, 0.16, and 0.18, which correspond to x = 1.02, 0.92, 0.84, 0.73, 0.66, 0.49, 0.39, and 0.23, respectively) in semi-logarithmic scale. The magnitude of $\rho_{ab}(T)$ shows systematic increase with decreasing carrier concentration from $p = 0.18$ to 0.03. In the most underdoped non-superconducting sample ($p = 0.03$), $\rho_{ab}(T)$ shows an insulating behavior ($d\rho_{ab}/dT < 0$) from room temperature, which is quite different from the $\rho_{ab}(T)$ behavior of lightly hole-doped $La_{2-x}Sr_xCuO_4$ that shows a metallic behavior ($d\rho_{ab}/dT > 0$) even at $x = 0.01$ [7].

As is the case with $\rho_{ab}(T)$, the magnitude of $\rho_c(T)$ shows a systematic increase with decreasing carrier concentration. It is found that for all concentrations $\rho_c(T)$ shows a steeply diverging behavior with lowering T. Note that the onset of the insulating behavior in ρ_c moves to higher temperature with decreasing p, which is consistent with the expected behavior of the pseudogap-opening temperature T^*; therefore, the $\rho_c(T)$ behavior appears to reflect the opening of the pseudogap.

Figure 2 shows the temperature dependences of the anisotropy ratio ρ_c/ρ_{ab} for all the concentrations studied. At moderate temperatures (100 - 300 K), the magnitude of ρ_c/ρ_{ab} increases with decreasing p, except for the most underdoped concentration ($p = 0.03$) at which ρ_c/ρ_{ab} suddenly drops; it is probably the case that this drop is caused by the heightened ρ_{ab} value of the $p = 0.03$ sample due to localization. Note that the ρ_c/ρ_{ab} value generally increases with lowering temperature, and exceeds 5×10^5 just above T_c for p = 0.10 - 0.14, demonstrating that BSLCO is the most anisotropic material among cuprates.

The inset of Fig. 2 shows the p dependence of ρ_c/ρ_{ab} at 200 and 300 K. It can be seen that the p dependence of ρ_c/ρ_{ab} for high doping ($p > 0.13$) is weak, while the ρ_c/ρ_{ab} values steeply increases with decreasing p for lower doping ($p < 0.13$), both at 200 and 300 K. It is most likely that the weak p dependence at high doping reflects a change in the strength of the charge confinement, while the steep increase in the underdoped samples reflects an enhancement of the anisotropy due to the pseudogap. Therefore, the large anisotropy in BSLCO is due to the combined result of the confinement and the pseudogap.

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