Peculiar Evolution of the c-Axis Charge Transport in $La_{2-x}Sr_xCuO_4$ Single Crystals from Antiferromagnetic Insulator to Superconducting Regime

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Abstract

The in-plane and the out-of-plane resistivities (ρ_{ab} and ρ_c) are measured in high-quality $La_{2-x}Sr_xCuO_4$ single crystals in the lightly- to moderately-doped region ($x = 0.01 - 0.10$). It is found that the resistivity ratio ρ_c/ρ_{ab} at moderate temperatures ($100-300$ K) is almost completely independent of doping for $0.01 \leq x \leq 0.05$. It is discussed that this striking doping-independence of ρ_c/ρ_{ab} is consistent with the idea that charges form a self-organized network of hole-rich paths, which also explains the unusually metallic in-plane transport in the lightly-doped region.

Key words: $La_{2-x}Sr_xCuO_4$; transport properties; charge stripes; c-axis transport

1. Introduction

Recent studies have shown [1,2] that a combination of the pseudogap and the **k**-dependence of the *c*-axis matrix element is largely responsible for the steeply insulating behavior of $\rho_c(T)$. The angle-resolved photoemission spectroscopy (ARPES) measurements of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) have demonstrated [3] that the pseudogap causes destruction of the Fermi surface starting from the $(0, \pm\pi)$ and $(\pm\pi, 0)$ points, and the *c*-axis matrix-element effect [1] tends to amplify the contribution of the electrons on these gapped portions of the Fermi surface to the *c*-axis transport.

On the other hand, the Fermi surface of underdoped $La_{2-x}Sr_xCuO_4$ (LSCO) is observed only near the $(\pm\pi, 0)$, $(0, \pm\pi)$ points (1D-like Fermi surface)[4], which is quite different from that of Bi-2212, and thus it is not likely that the pseudogap shows a similar development on the Fermi surface of the LSCO; therefore it would be illuminating to examine the *c*-axis transport of LSCO, particularly in the underdoped region, and compare it with that of other cuprate systems.

2. Results and Discussions

The series of $La_{2-x}Sr_xCuO_{4-\delta}$ single crystals ($0.01 \leq x \leq 0.10$) are grown by the TSFZ technique[5] and the in-plane and out-of-plane resistivities (ρ_{ab} and ρ_c) are measured using a standard ac four-probe method.

Figure 1(a) shows the temperature dependences of ρ_{ab} of our crystals with the vertical axis in the logarithmic scale. As was emphasized in Ref. [6], the temperature dependence of ρ_{ab} is metallic ($d\rho_{ab}/dT > 0$) at moderate temperatures even in the sample ($x = 0.01$) where ρ_{ab} is as large as 20 mΩcm, which corresponds to $k_F l$ value of only 0.1, and thus the Mott-Ioffe-Regel limit for metallic transport is strongly violated; we have argued that this behavior, in combination with the mobility that is only weakly doping-dependent, is best understood to result from a self-organized network of hole-rich regions that constitute the path for the charge

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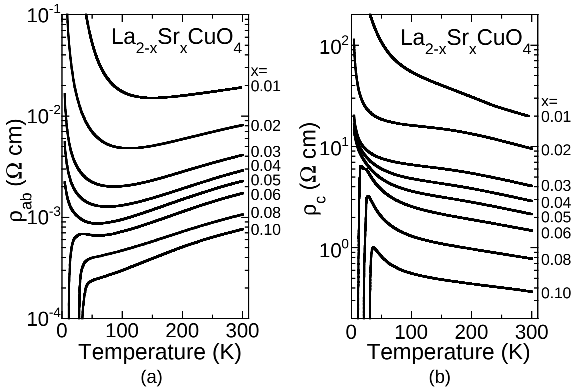

Fig. 1. Temperature dependences of (a) the in-plane and (b) the out-of-plane resistivities of $La_{2-x}Sr_xCuO_{4-\delta}$ single crystals for $0.01 \le x \le 0.10$.

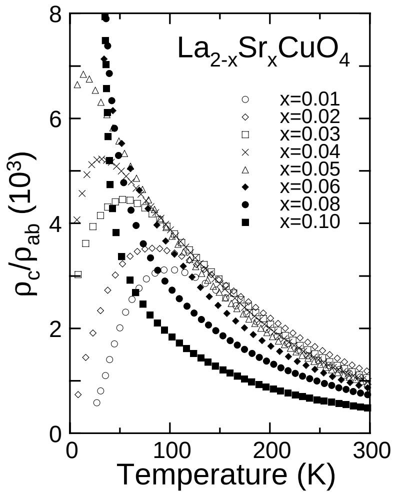

Fig. 2. Temperature dependences of the resistivitie anisotropy ratio ρ_c/ρ_{ab}.

transport.

Figure 1(b) shows the temperature dependences of ρ_c for the same doping range. Although ρ_c increases with decreasing temperature in all the samples, the temperature dependence of ρ_c at moderate temperatures ($100-300$ K) is weak for $x \ge 0.02$ (the change is less than a factor of two), which is in contrast to the $\rho_c(T)$ behaviors of Bi-2212 or Bi-2201 where $\rho_c(T)$ shows a steep divergence below the pseudogap temperature[7]. Since the c-axis transport in any cuprate should necessarily reflect the c-axis matrix element that tends to amplify the development of the pseudogap with a $d_{x^2-y^2}$ symmetry, the $\rho_c(T)$ behavior of underdoped LSCO means either that the pseudogap is already fully developed at 300 K, or that the pseudogap has a symmetry different from $d_{x^2-y^2}$.

The most surprising feature we find in this work is that ρ_c/ρ_{ab} at moderate temperatures is almost completely independent of doping in the non-superconducting regime ($0.01 \le x \le 0.05$), as illustrated in Fig. 2. In this x-independent regime, the magnitude of ρ_c/ρ_{ab} is ∼1000 at 300 K and increases with decreasing temperature, which indicates that the same charge confinement mechanism is at work down to x=0.01. As already mentioned, the metallic in-plane transport that violates the Mott-Ioffe-Regel limit suggests [6] that the transport is occurring through a self-organized network of hole-rich paths[8]. The striking x-independence of ρ_c/ρ_{ab} is naturally understood in this picture of transport through a self-organized network, because in such a case antiferromagnetically correlated magnetic domains, which are separated by charged stripes, tend to align hole-rich domain boundaries along c-axis, then the transport anisotropy is determined by the local electronic nature of the hole-rich segment that is presumably unchanged with x (only the average distance between the hole-rich paths changes with x)[5]. Therefore, the behavior of ρ_c/ρ_{ab} in the lightly-doped region is consistent with the self-organized-network picture and gives strong support to it. For $x \ge 0.06$, ρ_c/ρ_{ab} shows a rapid decrease, which suggests that the c-axis charge confinement becomes less effective as x is increased in the superconducting regime.

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