Peculiar Evolution of the c-Axis Charge Transport in La$_{2-x}$Sr$_x$CuO$_4$
Single Crystals from Antiferromagnetic Insulator to
Superconducting Regime
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Abstract
The in-plane and the out-of-plane resistivities ($\rho_{ab}$ and $\rho_c$) are measured in high-quality La$_{2-x}$Sr$_x$CuO$_4$ single crystals in the lightly- to moderately-doped region ($x = 0.01 - 0.10$). It is found that the resistivity ratio $\rho_c/\rho_{ab}$ 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 $\rho_c/\rho_{ab}$ 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$_x$CuO$_4$; 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$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (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$_x$CuO$_4$ (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$_x$CuO$_{4-\delta}$ 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 ($\rho_{ab}$ and $\rho_c$) are measured using a standard ac four-probe method.

Figure 1(a) shows the temperature dependences of $\rho_{ab}$ of our crystals with the vertical axis in the logarithmic scale. As was emphasized in Ref. [6], the temperature dependence of $\rho_{ab}$ is metallic ($d\rho_{ab}/dT > 0$) at moderate temperatures even in the sample ($x = 0.01$) where $\rho_{ab}$ is as large as 20 m$\Omega$cm, 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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transport.

Figure 1(b) shows the temperature dependences of $\rho_c$ for the same doping range. Although $\rho_c$ increases with decreasing temperature in all the samples, the temperature dependence of $\rho_c$ at moderate temperatures ($100 - 300$ K) is weak for $x \geq 0.02$ (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 $\rho_c/\rho_{ab}$ at moderate temperatures is almost completely independent of doping in the non-superconducting regime ($0.01 \leq x \leq 0.05$), as illustrated in Fig. 2. In this $x$-independent regime, the magnitude of $\rho_c/\rho_{ab}$ is $\sim 1000$ 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 $\rho_c/\rho_{ab}$ 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 $\rho_c/\rho_{ab}$

in the lightly-doped region is consistent with the self-organized-network picture and gives strong support to it. For $x \geq 0.06$, $\rho_c/\rho_{ab}$ 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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References