Superconductivity and In-plane Resistivity in La$_{2-x}$Sr$_x$CuO$_4$

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Abstract

The correlation between the in-plane resistivity($\rho_{ab}$) and the superconducting transition temperature($T_c$) has been investigated in La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) under anisotropic pressure up to 8.0 GPa. Although the pressure suppresses the orthorhombic distortion and stabilizes the tetragonal lattice which enhances the superconductivity, the inter-layer compression suppresses the $T_c$ and brings about a kind of localization of $\rho_{ab}$ at low temperatures. The collapse of two-dimensional(2D) metallic state probed by $\rho_{ab}$ is the end of superconductivity in the underdoped samples. On the other hand, overdoped samples lose superconductivity when the cuprates change the electronic state from 2D metal to strongly anisotropic but three-dimensional(3D) metal.

Key words: La$_{2-x}$Sr$_x$CuO$_4$ ; resistivity measurement ; anisotropic pressure effect ; localization

In the high-$T_c$ cuprates, the CuO$_2$ planes with 2D-electronic state is believed to play an important role in the charge pairing. In the non-doped or slightly-doped insulator region, the in-plane resistivity $\rho_{ab}$ and the out-of-plane resistivity $\rho_c$ both show a semiconductor-like upturn at low temperatures. As carriers are further doped, the temperature dependence of $\rho_{ab}$ becomes metallic when superconductivity appears. It suggests that the relation between the $\rho_{ab}$ and $T_c$ provides a key for understanding the high-$T_c$ superconductivity.

In this work we have investigated the correlation between $\rho_{ab}$ and $T_c$ in LSCO under high pressure.

LSCO is one of the most suitable cuprates to investigate the correlation between $\rho_{ab}$ and $T_c$ because of its simple crystal structure and of a wide range of controllable carrier concentration $x$. However, LSCO undergoes a structural phase transition from a tetragonal phase to an orthorhombic phase. The orthorhombic structure disturbs the superconductivity and obscures the intrinsic correlation between $\rho_{ab}$ and $T_c$. In order to remove such difficulties, we have utilized the pressure which stabilized the tetragonal phase[1]. Moreover, we can control $T_c$ by anisotropic pressure[2,3]. In the case of LSCO, the pressure does not change the carrier concentration appreciably[4].

The single crystals of LSCO with $x = 0.06, 0.07, 0.08, 0.18$ and $0.22$ were grown by a traveling-solvent floating-zone method. The sample shape was a parallelepiped along the [001]$_{\text{HHT}}$ with typical dimensions of $0.80 \times 0.30 \times 0.25$ mm$^3$. The resistivity was measured by a standard four probes method. A cubic anvil device was used to generate pressure up to 8.0 GPa. The pressure transmitting medium was a mixture of Fluorinert FC70 and FC77 with an equal volume.

Figure 1 representatively shows $\rho_{ab}(T)$ of LSCO at (a) 0.1 MPa and (b) 8.0 GPa for each sample. The absolute value of $\rho_{ab}$ at 300K decreases by 22, 19, 30, 17 and 14% for $x = 0.06, 0.07, 0.08, 0.18$ and 0.22 respectively, when 8.0 GPa is reached. The most remarkable feature is that samples show a semiconductor-like upturn of $\rho_{ab}$ under pressure at low temperatures. The upturn of $\rho_{ab}$ becomes predominant in the underdoped region. With increasing $x$, the temperature range of upturn becomes narrow.

In the underdoped samples, the resistance $R_G = \rho_{ab}/d$ and conductance $G_G = 1/R_G$ per CuO$_2$ plane.
Thus it is difficult to ascribe the upturn of $\rho$ for overdoped samples. The stronger stress perpendicular to the CuO planes suppressed $T_c$ and enhanced the $\rho_{ab}$ at low temperatures. The localization of $\rho_{ab}$ is prominent in the underdoped region.

have critical values corresponding to Ioffe-Regel’s limit of $kFln_{ab} \sim 1$, where $d = 6.6$ Å is the inter-layer distance, $k_F$ is the Fermi wave number and $l_{ab}$ is the in-plane mean free path. $R_\alpha$ and $G_\|2$ show logarithmic temperature dependence at low temperatures in the underdoped samples. This behavior is frequently observed in the case of the weak localization. The theoretical models of the weak localization in the 2D systems suggests $G_\|2 = G_\|0 + (\alpha e^2/2\pi\hbar) \ln T$ for fermion systems[5] and $R_\alpha = R_\alpha0 + (Ah/4e^2) \ln(1/T)$ for boson systems[6], where $G_\|0$ and $R_\alpha0$ are constant values, $\alpha$ and $A$ are constant parameters of the order $\sim 1$, $h$ is the Plank constant and $e$ is the electron charge. The superconducting-insulating phase transition occurs around $\alpha = 1 \sim 3$ or $A \sim 1$ in the underdoped region as shown in Fig.2(a) and (b). These results support that the enhancement of $\rho_{ab}$ is ascribable to some kind of localization. The localization of $\rho_{ab}$ probably arises from the random potential introduced by Sr distribution or apical oxygen in the block layers, which disturbs the 2D-electronic state in the CuO$_2$ planes.

On the other hand, the upturn in the overdoped samples with $kFln_{ab} \gg 1$ is observed only at high pressures, above 5.0 GPa for $x = 0.18$ and 6.5 GPa for $x = 0.22$. As seen in Fig.2(a) and (b), $\alpha$ and $A$ for overdoped samples deviate far from those for underdoped samples. Thus it is difficult to ascribe the upturn of $\rho_{ab}$ to the weak localization in the overdoped samples. $\rho_{ab}$ in the overdoped region is well fitted by $\rho_{ab} = \rho_0 + \beta T^n$ except for the low-temperature upturn, where $\rho_0$, $\beta$ and $n$ are constant parameters. With increasing pressure, $\rho_0$ and $n$ increase while $T_c$ decreases monotonously as $x = 0.06, 0.07, 0.08, 0.18$ and 0.22 at (a) 0.1 MPa and (b) 8.0 GPa. The stronger stress perpendicular to the CuO planes deviates far from those for underdoped samples. As seen in Fig.2(a) and (b), $disturbs$ the 2D-electronic state in the CuO $\Omega$ systems[6], where $G_{\|}$ over-doped region is well fitted by $\rho_{ab}$ at low temperatures. The localization of $\rho_{ab}$ is prominent in the underdoped region.

References