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

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Abstract

The correlation between the in-plane resistivity(ρ_{ab}) and the superconducting transition temperature(T_c) has been investigated in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$(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 interlayer compression suppresses the T_c and brings about a kind of localization of ρ_{ab} at low temperatures. The collapse of two-dimensional(2D) metallic state probed by ρ_{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: $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$;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 ρ_{ab} and the out-of-plane resistivity ρ_c both show a semiconductor-like upturn at low temperatures. As carriers are further doped, the temperature dependence of ρ_{ab} becomes metallic when superconductivity appears. It suggests that the relation between the ρ_{ab} and T_c provides a key for understanding the high-T_c superconductivity. In this work we have investigated the correlation between ρ_{ab} and T_c in LSCO under high pressure.

LSCO is one of the most suitable cuprates to investigate the correlation between ρ_{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 ρ_{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 $[001]_{\text{THT}}$ 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 ρ_{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 ρ_{ab} under pressure at low temperatures. The upturn of ρ_{ab} becomes predominant in the underdoped region. With increasing x, the temperature range of upturn becomes narrow.

In the underdoped samples, the resistance $R_\square = \rho_{ab}/d$ and conductance $G_\square = 1/R_\square$ per CuO_2 plane

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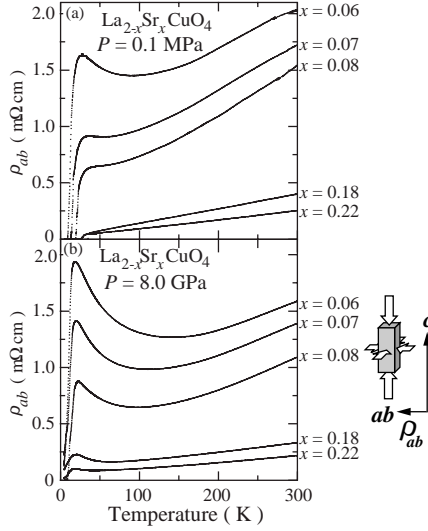
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Fig. 1. The temperature dependence of ρ_{ab} in LSCO with $x =$ 0.06, 0.07, 0.08, 0.18 and 0.22 at (a) 0.1 MPa and (b) 8.0 GPa. The stronger stress perpendicular to the CuO$_2$ planes suppressed T_c and enhanced the ρ_{ab} at low temperatures. The localization of ρ_{ab} is prominent in the underdoped region.

Fig. 2. (a) T_c-A plots, (b) T_c-α plots, (c) T_c-ρ_0 plots and (d) T_c-n plots for LSCO under pressure. The inset of Fig.2(d) is T_c-β plots. The broken lines are guides to the eyes.

have critical values corresponding to Ioffe-Regel's limit of $k_F l_{ab} \sim 1$, 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. $R_\square$ and $G_\square$ 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 $G_\square = G_0 + (\alpha e^2/2\pi\hbar)\ln T$ for fermion systems[5] and $R_\square = R_0 + (Ah/4e^2)\ln(1/T)$ for boson systems[6], where G_0 and R_0 are constant values, α and A are constant parameters of the order ~ 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 ρ_{ab} is ascribable to some kind of localization. The localization of ρ_{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 $k_F l_{ab} \gg 1$ 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), α and A for overdoped samples deviate far from those for underdoped samples. Thus it is difficult to ascribe the upturn of ρ_{ab} to the weak localization in the overdoped samples. ρ_{ab} in the overdoped region is well fitted by $\rho_{ab} = \rho_0 + \beta T^n$ except for the low-temperature upturn, where ρ_0, β and n are constant parameters. With increasing pressure, ρ_0 and n increase while T_c decreases monotonously as
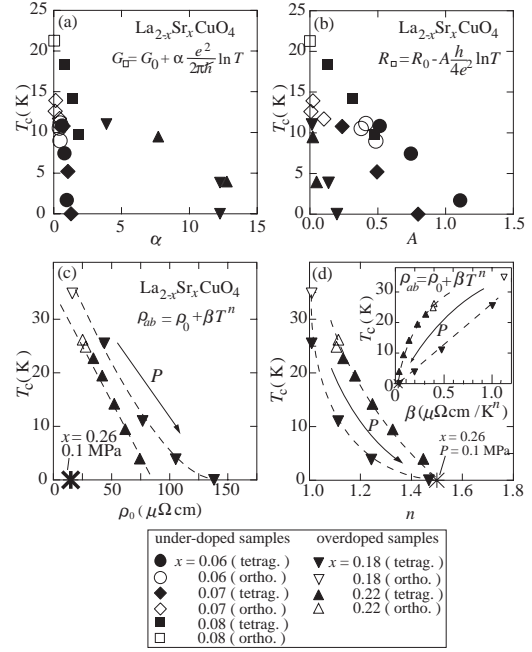
seen in Fig.2(c) and (d). T_c is usually correlated with ρ_0 due to the impurities and the similar correlation is observed in Fig.2(c). However, the present data suggest that the variation of T_c is described as a function of β and n. As n approaches $n \sim 1.5$ which is the value for non-superconducting and tetragonal LSCO with $x = 0.26$ at 0.1 MPa, where T_c tends to vanish. It suggests that the dimensional crossover of the electronic state from 2D to anisotropic 3D metallic state suppress the superconductivity in the overdoped region.

In conclusion, all these experimental results seem to indicate that the 2D metallic state of CuO$_2$ planes at low temperatures is essentially important to the high-T_c superconductivity, but 3D metallic state kills the superconductivity in the metallic layered cuprates.

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