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Research Report

Normal State Resistivity of $La_{2-x}Sr_xCuO_4$ Thin Films under Epitaxial Strain

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Abstract

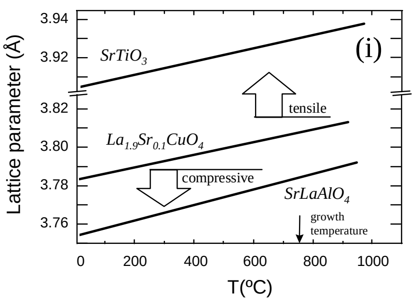
Recently, the normal state resistivity of high-temperature superconductors (in particular in $La_{2-x}Sr_xCuO_4$ single crystals) has been studied extensively in the region below T_c by suppressing the superconducting state in high magnetic fields. In the present work, we focus on the influence of epitaxial strain on the normal state resistance of $La_{2-x}Sr_xCuO_4$ thin films measured below T_c by applying pulsed fields up to 60 T.

1 Introduction

Recently, important progress has been made in the study of the normal state properties below T_c of the $La_{2-x}Sr_xCuO_4$ high-temperature superconductor [1]. By changing the Sr doping concentration x, the superconducting critical temperature T_c can be tuned to values below 37 K, while superconductivity can be suppressed by fields of H_{c2} ~ 60 T. The most commonly used method to achieve these high fields is the pulsed field technique. This work deals with the normal state properties below T_c of ultra thin films whose properties were modified by epitaxial strain [2].

2 Experimental results and discussion

To reveal the mechanism of high-temperature superconductors, it is believed that the knowledge of the normal state transport properties at low temperatures plays a crucial role. Using pulsed magnetic fields up to 60 T, we have suppressed superconductivity in strained $La_{2-x}Sr_xCuO_4$ thin films [2]. The advantage of this preparation technique is that for a fixed stoichiometry, the lattice dimensions can be changed (enlarged or decreased), thus strongly affecting the critical temperatures T_c. In this work, we present data on three samples with $x = 0.1$: Sample A and B are, respectively, 125 and 150 Å thin films, grown on $SrLaAlO_4$, whereas sample C is a 150 Å thin film grown on $SrTiO_3$. Using $SrLaAlO_4$ as a substrate leads to compressive strain, since the lattice parameters of $SrLaAlO_4$ are smaller than those of $La_{1.9}Sr_{0.1}CuO_4$. The inverse happens when growing films on $SrTiO_3$: tensile stress is induced due to the larger in-plane lattice parameters of $SrTiO_3$. Figure 1(i) shows the different values of the *ab*-plane lattice parameters.



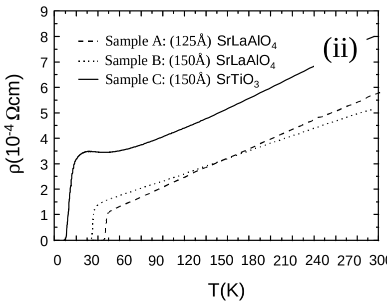


Figure 1. (i) The temperature variation of the lattice parameters of bulk $SrTiO_3$, $La_{1.9}Sr_{0.1}CuO_4$ and $SrLaAlO_4$. **(ii)** Temperature dependence of the resistivity for different $La_{1.9}Sr_{0.1}CuO_4$ samples (A, B and C).

The influence of the stress induced by the substrate on T_c can be seen in Figure 1(ii). By applying tensile stress, and thus increasing the *ab*-lattice parameters while expanding the *c*-axis, the T_c values can be reduced. By applying compressive stress, the opposite structural effects occur, leading to an increase of T_c. The magnitude and sign of these changes is in agreement with the uniaxial pressure and strain coefficients found in the literature [3].

Using pulsed magnetic fields, $\rho(H)$ was measured up to 50 T. A typical set of data obtained on sample A (T_c ~ 45 K) is shown in the inset of Figure 2. From this type of experiments, we have taken the $\mu_0 H = 50$ T data to reveal the normal state $\rho(T)$ below T_c (Figure 2). It should be mentioned that these data also contain the normal state magneto-resistance contribution which is not to be ignored completely, as can be seen from the inset of Figure 2 (especially from the measurements above T_c ($T = 72.7$ K, $T = 61.6$ K)). Considering the temperature-dependent $\rho(T)$, it can be noted that the general trend of $\rho(T)$ above T_c is just extrapolated to the temperatures below T_c. For sample A ($SrTiO_3$ substrate) above T_c one can already see a tendency towards an increasing resistivity at low temperatures. For the samples prepared on $SrLaAlO_4$, a metallic like behavior is observed above T_c which seems to saturate below T_c. In addition, we must point out that these $\rho(T)$ curves are different from those published for bulk $La_{2-x}Sr_xCuO_4$ [1].

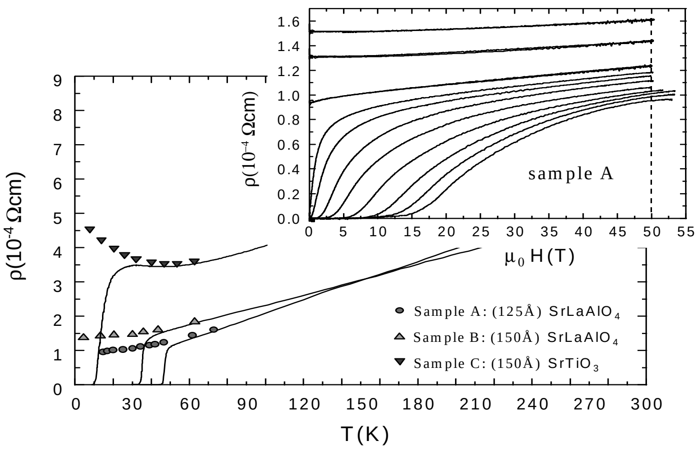


Figure 2. The temperature dependence of the resistivity for the different $La_{1.9}Sr_{0.1}CuO_4$ samples (A, B and C). The datapoints indicated by the symbols are the B = 50 T resistivity values. **Inset:** Magneto-resistivity of sample A at different temperatures (from top to bottom: T = 72.7, 61.6, 46.5, 41.9, 39.0, 34.4, 30.2, 25.1, 19.9, 16.9 and 14.7 K).

These results suggest that besides chemical doping with Sr, a change of the lattice parameters can also produce a metal-to-insulator (MI) transition. Since the Sr doping is the same in the three samples and the lattice deformations essentially keep the volume constant, the carrier density should also be approximately the same. Comparing the behavior of strained films with that of optimally doped single-CuO_2-layer compounds, it was concluded that not the in-plane distances but increasing the charge-reservoir–CuO_2 distance determines the different $\rho(T)$ trends [4]. The consequences of this for the various scattering mechanisms are not yet clear. Moreover, the change of the in-plane lattice parameter also causes a change in overlap between the Cu^{3d} and O^{2p} orbitals and a change of the antiferromagnetic (AF) superexchange coupling J between the Cu^{2+} spins and the holes. In this context, one may interpret the MI transition as a separation of the CuO_2 planes into hole-rich metallic stripes with AF Mott insulator regions [5]. Such stripes were observed in bulk $La_{2-x}Sr_xCuO_4$ [5] and indications exist for their presence in underdoped $YBa_2Cu_3O_x$ and in $YBa_2Cu_4O_8$ [6]. It has been argued that such a local modulation of the density of carriers might in some cases be triggered by a structural asymmetry of the CuO_2 planes: orthorhombicity for $La_{2-x}Sr_xCuO_4$ or 1D features for the spin ladder $Sr_{2.5}Ca_{11.5}Cu_{24}O_{41}$, single or double CuO chains in $YBa_2Cu_3O_x$ or $YBa_2Cu_4O_8$, respectively. Compared to bulk compounds, strained ultra thin films tend to have a higher symmetry imposed by the substrate; high resolution microscopy [7] of strained 150 Å $La_{2-x}Sr_xCuO_4$ thin films shows no evidence of orthorhombic distortions. However, these static distortions are just a trigger for the *dynamic* stripes.

In view of this, we can verify whether stripes can explain the features of the $\rho(T)$ behavior of, for example, the sample with the diverging resistivity. At high temperatures, the CuO_2 plane can be considered as a 2D Heisenberg system, with a linear $\rho(T)$ dependence. On decreasing the temperature, dynamic stripes are formed [5] and 1D quantum transport sets in [6], resulting in a curved $\rho(T)$ behavior. At low T, Josephson coupling between the stripes results in the onset of a

2D superconducting state. The increase of ρ at low T in sample C might then be due to pinning of the metallic stripes to impurities in the film (strain). We can test whether the $\rho(T)$ behavior of our samples can be modeled with the proposed 1D quantum transport dependence $\rho(T) = \rho_0 + C \cdot T \cdot \exp(-\Delta/T)$ in spin stripes [6]. Agreement was found with a spin-gap Δ of 38, 51 and 107 K for samples A, B, and C, respectively. The decreasing value of Δ with increasing strain is in agreement with earlier observations on copper-oxides under hydrostatic pressure [6] although care should be taken using this 1D picture on the sample with the highest pressure, which is in the overdoped regime. These values for Δ are very small compared to the value of the pseudogap T^* reported for this compound, suggesting that the magnetic correlation length may not be the only one determining electrical transport. To conclude, we have demonstrated a striking difference in the normal state resistance between compressive and tensile strained $La_{1.9}Sr_{0.1}CuO_4$ ultra thin films. At constant doping, expanding the in-plane lattice parameters slightly while decreasing the out-of-plane lattice parameters leads to a diverging insulating behavior $\rho(T \rightarrow 0)$ and a lower T_c; the opposite lattice deformation leads to a metallic behavior with an increase of T_c.

3 Acknowledgments

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