In-plane stress effect on the electron-doped superconductor La$_{1.89}$Ce$_{0.11}$CuO$_4$ thin films

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**Abstract**

(00l)-oriented La$_{1.89}$Ce$_{0.11}$CuO$_4$ (LCCO) thin films are deposited on (00l) different substrates by pulsed laser deposition. A buffer layer BaTiO$_3$ (BTO) is deposited with different thickness to produce various strains on LCCO. The electrical transport properties of LCCO are affected by the in-plane stress. Under the compressive stress, the superconducting transition temperature of LCCO is lower than that under tensile stress. It is attributed to the easier removal of the interstitial apical-oxygen in the film with tensile stress.

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1. Introduction

Potential device applications in superconducting electronics and the further understanding of the micromechanism both require the better understanding of factors affecting the performance of high temperature superconductors. A key issue is the relation between the stress and the superconducting transition temperature [1–3]. Practically, the heteroepitaxial oxide thin films, which are grown on a crystal substrate, are strained due to the inevitable lattice mismatch to some degree. The strain between the epitaxial thin film and the substrate affects the properties of the thin film in different ways. For example, the superconducting transition temperatures of the La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) thin films are doubled by the selected crystal substrates [2]. Up to now, most of the works were focused on the hole-doped high transition temperature superconductors (HTSCs). As an important portion in the HTSCs family, the electron-doped HTSCs have different nature from the hole-doped ones [4,5]. The corresponding study is important for the potential applications and promoting the understanding of the mechanism of superconductivity. In the previous work, the hole-doped HTSC La-214 thin films of La$_2$Sr$_x$CuO$_4$ and La$_2-x$Ba$_x$CuO$_4$ (LBCO), which are grown on the LaSrAlO$_4$ (LSAO) substrate, were investigated. The films are under compressive strain since the lattice constant of LSAO is smaller than that of LSCO and LBCO. The compressed thin films have a higher \( T_c \) than the bulk samples do. The origin of \( T_c \) enhancement is proposed to ascribe to the reduced anti-ferromagnetic spin fluctuation, which is due to the expansion in the bond length between Cu and the apical-oxygen (O$_{apex}$) [6]. Recent experiments of angle-resolved photoemission spectroscopy (ARPES) [7], muon spectroscopy [8] and polarized X-ray absorption spectroscopy (XAS) [9] implies that shift of \( T_c \) is mainly due to the lattice effect. The experiments on the La-214 electron-doped superconductor will bring some information to help further understanding.

In this paper, we describe our recent work for c-axis oriented electron-doped La$_{2-x}$Ce$_x$CuO$_4$ (LCCO) thin films under epitaxial strain. The films are grown on three types of (00l) crystal substrate: LaAlO$_3$ (LAO), SrTiO$_3$ (STO) and MgO, with \( a \)-axis lattice constants \( a = 3.821, 3.900, \) or 4.216 Å, respectively. As the strain will be released to some degree with the thick films [10,11], the films are all prepared in the thickness of 40 nm. To study the strain effect systematically, a buffer layer of BaTiO$_3$ (BTO) with different thickness is introduced to tune the lattice constant [12]. The strain which the films suffer is also varied from a compressive one to a tensile one.

2. Experiments

All the thin films are prepared by a pulse laser deposition method (PLD). The substrates are (00l) oriented. We use a single source of ceramic target, which is synthesized by the conventional solid state reaction. The atomic ratio is controlled as La:Ce:
Cu = 1.89:0.11:1. The background atmosphere before deposition is better than 1.0 \times 10^{-5} \text{ Pa}. The LCCO films are deposited at the temperature about 700 °C with the atmosphere of 15 Pa pure oxygen. After the deposition, the temperature falls down to 600 °C and the chamber is switched into a vacuum state. The films are annealed under this condition for 5–10 min to remove the excess apical-oxygen atoms, which are harmful to the superconductivity of electron-doped superconductor [13,14]. The energy density of laser pulse is 2.0 J/cm². We measure the thickness of the films by the atomic force microscope (AFM) and calculate the ratio of the deposition.

In this way, we can grow the film with the needed thickness.

X-ray diffraction is employed on the LCCO films with different thickness to examine their structure. The film surface morphology is checked by atomic force microscope. Before the measurement of the transport properties, the films were patterned into a microbridge structure by conventional photolithography and ion beam etching. Four-wire method was taken on the transport measurement. The MPMS-5 Superconductivity Quantum Interference Device (SQUID) was used to take the measurement of the transport properties.

3. Conclusions

The X-ray diffraction patterns show that all the films of LCCO are single phase and c-axis oriented. It is indicated that the films are strained by the lattice mismatch. On the LAO substrate, the LCCO films are under a compressive strain, the lattice constant $c = 12.48 \AA$, which is larger than the value 12.44 Å for the bulk. When BTO buffer layer is added, the mismatch is reduced and the c-axis lattice constant of the film decreases. On the MgO substrate, with a tensile strained applied on the LCCO films, the lattice constant $c = 12.40 \AA$, smaller that the value for the bulk. Similarly, the added BTO layer can reduce this tensile.

Fig. 2 shows the surface morphology of the thin film on SrTiO$_3$ substrate. The scanned area is $10 \times 10 \mu m^2$, and the average roughness is about 0.5 Å.

The temperature dependences of resistivity of the films with different substrate conditions are shown in Fig. 3. The film grown on the STO substrate has the zero resistance temperature $T_{co}$ 18 K; while $T_{co}$ of the film directly grown on the LAO substrate is only 7.5 K. With the 20 nm-thick BTO buffer layer deposited on the LAO before the deposition of the LCCO film, the $T_{co}$ rises up to 15 K.

$T_{co}$ of the LCCO deposited directly on the MgO substrate is about 16.0 K, lower than the value for the film on STO. To reduce the mismatch between the film and LCCO, BTO buffer layer with different thickness was added, when BTO layer is 20 nm thick, $T_{co}$ of the film is 18.5 K. On the BTO layer 40 nm thick, $T_{co}$ of the film reaches 25.0 K.

All the films are in the same thickness, so the difference in $T_{co}$ cannot come from the film thickness effect. From the results of the electrical transport measurements, it was found that the LCCO films were sensitive to the epitaxial strain. The compressive strain reduces the in-plane lattice constant, and then via the Poisson effect an expansion in the c-axis direction occurs. This is evidenced by the X-ray diffraction results. On the other hand, under a tensile strain the in-plane lattice parameter is expanded and the lattice parameter in c-axis direction is reduced. From the previous papers [1–3], we know that the compressive epitaxial strain increases the superconducting transition temperature of the La-214 cuprate superconductor. Compared with the present experimental results, in which the tensile strain makes the film get an enhancement in $T_{c}$, the electron-doped La-214 superconductor, the compressive strain suppresses the superconducting transition, in accordance with previous reports [15,16]. When the LCCO was deposited on MgO directly, $T_{c}$ of the film is even lower than the value for the film on STO. Too large misfit between the film and the substrate ($\Delta a = 0.2 \AA, \epsilon = \frac{\Delta a}{a_{film}} = 5.16\%)$ brings a lot of dislocations and defects into the films. These cause the decrease of $T_{c}$. It is the same in the film grown directly on the LAO that compressive strain, dislocations and defects suppress the superconductivity of the films together. As to La$_{2-x}$Sr$_x$CuO$_4$, the CuO$_6$ octahedra are tetragonally deformed and the variation of $T_{c}$ under strain is related to the charge inhomogeneity [17]. In the T-phase electron-doped superconductor, the apical-oxygen atoms in the CuO$_6$ octahedra are absent, so the change in structure is not the same as that in La$_{2-x}$Sr$_x$CuO$_4$. The increase of the c-axis lattice parameter does not lead to the change in the length of Cu–O$_{apex}$ bond; so the reduction of the anti-ferromagnetic fluctuation can not explain the shift of $T_{c}$. In fact, although $T_{c}$ of the films under appropriate tensile strain is higher than that under compressive strain, the highest $T_{c}$ in our experiments has not exceeded the highest record ever obtained in LCCO [16]. So the enhancement is possibly due to the easier removal of the interstitial apical-oxygen, in accordance with the results on the infinite layer electron-doped superconductor Sr$_{1-x}$La$_x$CuO$_3$ [18].

Highly qualified electron-doped La$_{2-x}$Ce$_x$CuO$_4$ ultra-thin superconducting films are grown on single crystal substrates with
different in-plane lattice parameter. It shows that appropriate tensile strain helps films get better superconductivity, while compressive strain suppresses the superconductivity of the films. These results are different from the hole-doped La-214 superconductors. Easier removal of the interstitial apical-oxygen is possibly the cause for the enhancement of $T_c$. The intrinsic mechanism still needs further study (Fig. 1).

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