International Journal of Modern Physics B
Vol. 21, Nos. 18 & 19 (2007) 3258–3261

TRANSPORT PROPERTIES OF ELECTRON-DOPED $La_{2-x}Ce_xCuO_4$ THIN FILM IN THE UNDER-DOPED REGION

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Received 9 January 2007

Underdoped electron-doped $La_{2-x}Ce_xCuO_4$ (x=0.06-0.09) thin films were successfully grown and investigated for the transport properties in ab-plane. It was found that the in-plane resistivity ρ_{ab} shows a semiconductor behavior when x=0.06, with increasing the Ce concentration to the optimal doping level, it changes to the two dimensional Fermi-liquid behavior. In the films with $x \geq 0.08$, a Kondo effect like scattering is observed in the low temperature range.

Keywords: Underdoped; electron-doped.

1. Introduction

Due to the progress of the general understanding of the high temperature superconductivity, the study of electron-doped superconductors becomes wide in recent years[1,2,3,4,5,6,7]. Comparing with the hole-doped counter part, it is more difficult to synthesize the high quality single crystals and thin films for the electron-doped superconductors. Until now, most experimental studies on the electron-doped superconductor have been performed on the $Ln_{2-x}Ce_xCuO_4$ (Ln=Pr, Nd, etc.) system, especially on $Nd_{2-x}Ce_xCuO_4$ (NCCO)[2,3], since it is relatively easy to fabricate into the high-quality single crystal. Among the T'-phase electron-doped superconductors, the $La_{2-x}Ce_xCuO_4$ (LCCO) has the highest transition temperature. On the other hand, structurally, for all well-known electron-doped superconductors, the dopant Ce^{4+} is larger than the Ln^{3+}, but for LCCO, the La^{3+} is larger than Ce^{4+}. Therefore, some special features are expected[4] for LCCO, especially, for the transport property. In the previous work, the transport properties of LCCO was studied mostly on the optimally doping level of Ce, as well as the over doping level[8,9,10]. in the case of under doping, x<0.09, the samples show large resistivity and semiconductor-like behavior, but the mechanism of transport is an open question. In the present work, we focus our efforts on the transport in the under Ce

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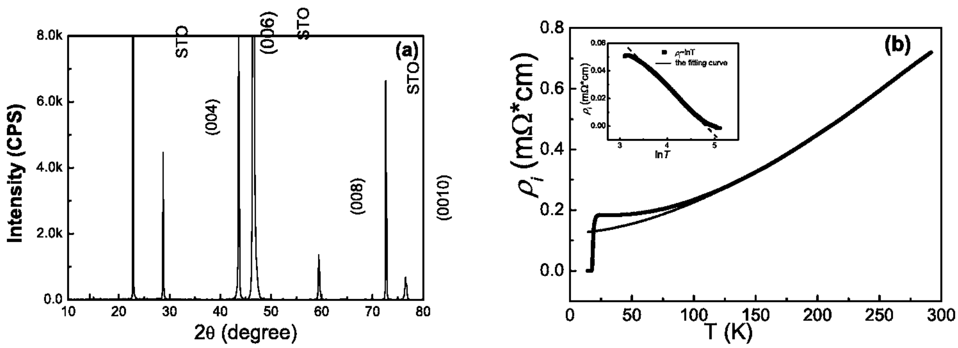

Fig. 1. (a) X-ray diffraction spectra of the LCCO thin film, c-axis oriented on the (001) STO substrate. b) Temperature dependence of resistivity in the thin film with x=0.09, the dash line is the background, $\rho_0+\rho_s$.Inset gives $\rho_i \sim lnT$ which is obtained by subtracting $\rho_0+\rho_s$ from the experimental data, the dash line is from the fit to the Kondo effect (formula (2)) in zero field.

doping region. To compare the transport property of the under doped LCCO and the optimally-doped superconducting T' phase LCCO, for which the structure is characterized by CuO_4 rather than by CuO_6 octahedron, so the T' phase under doped LCCO should be prepared. In addition, the T' phase just can be stabilized in the relatively low temperature, the single crystal can not be grown, so the under-doped LCCO thin films must be grown for this purpose.

In this work, LCCO ($0.06 \leq x \leq 0.09$) thin films were prepared by the dc magnetron sputtering method, the films on (001) $SrTiO_3$ are c-axis oriented. The transport properties in ab-plane change from two-dimensional Fermi liquid behavior with Kondo effect in the low temperature region to the complete semi-conducting type with x decreasing from 0.09 to 0.06.

2. Experiments

Through a conventional solid-state reaction, the stoichiometric targets were prepared. The detailed process in the deposition of the thin films can be found in previous work[8,9,10]. The thickness of the thin films is restricted to be 150 nm. X-ray diffraction measurement shows that the films are highly c-axis oriented (Fig.1(a)) and the surface morphology of all films is examined by atomic force microscope. For transport measurement, the films are patterned into a microbridge with width of 100 μm and length of 1000 μm, by photolithography and chemical etching techniques. Four sliver electrodes were deposited on the surface of LCCO film to carry out the standard four-probe measurements, which are performed by a MPMS-5 SQUID magnetometer.

3. Discussion

The zero-resistance temperature(T_{C0}) of the light under doped thin film with x=0.09 is 17 K. the temperature dependence of the resistivity(ρ-T) curve was plotted in

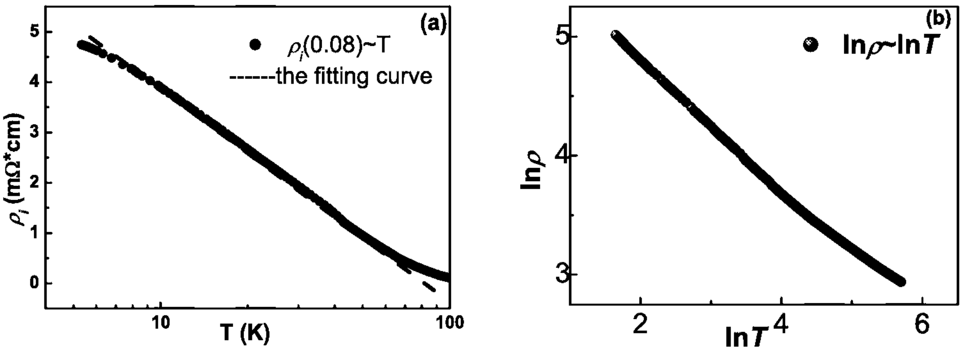

Fig. 2. a)ρ_i T curve of LCCO with x=0.08 is plotted as single logarithmic relation. In the temperature range of 10-70 K, the experimental data and the fitting curve by formula (2) overlap very well. b) $\ln \rho_{ab} \sim \ln T$ curve, the slope of the linear curve is about 0.5. The physical meaning will be studied further.

Fig.1(b), the ρ_{ab} shows metallic behavior in the normal state and an upturn occurs at temperature near and above T_c. The resistivity in the normal state can be presented as, $\rho=\rho_0+\rho_i+\rho_s$, ρ_s comes from electron-electron inelastic scattering[11] , which obeys to the T^2 law in the whole temperature range in the 3D case, ρ_0 is the residual resistivity. For the thin films the relation between ($\rho_0+\rho_s$) and T is modified to follow the 2D Fermi-liquid model, i.e., obeys $\rho(T) = \rho_0 + A(T/T_F)^2 \ln(T/T_F)$[12,13,14](1), with T_F the Fermi temperature, the fitting curve was plotted in inset of fig.1(b). ρ_i can be obtained by subtracting $\rho_0+\rho_s$ from the experimental data, and it gives the temperature dependence of ρ_i, it is found that shows a Kondo effect behavior, which can be present as the form $\rho_K(T) = \frac{\rho_\mu}{2}\{1-\frac{\ln[(T^2+\theta^2)/T_K^2]^{1/2}}{\pi(S(S+1))^{1/2}}\}$[15,16](2), Such behavior is more typically observed in the sample with x=0.08, from the ρ-T curve of the sample with x=0.08, the $\frac{d\rho_{ab}}{dT}$ is positive when T>120K and a more apparent upturn is present at low temperature, T<100K. Fig. 2(a) shows the temperature dependence of ρ_i , in which, ρ_i is linear to in the temperature range of 10K<T<70K. Commonly, Kondo effect comes from the magnetic impurities in the materials, the scattering between electrons and magnetic impurities induces the saturate resistivity at low temperature. Cu^{2+} spins in the CuO_2 planes may be considered as the scattering center in LCCO[15,16]. For the heavily underdoped sample with x=0.06, in the whole measured temperature range, $\frac{d\rho_{ab}}{dT}$ is negative and shows a semiconductor behavior. Different from the samples with x=0.09, 0.08, the anomalous transport properties of LCCO with x=0.06, can not be explained by Kondo effect. It also can not be fitted to the variable range hopping (VRH) model of $\rho \propto exp[(T_0/T)^{1/(n+1)n}]$ (3), where n is the dimension of the conduction path. It obeys the relation, $\rho_{ab} \sim T^{-a}$, a is about 0.5 according to our experimental data. This may be dominated by a combination of several factors, which should be understood further.

4. Conclusion

The in-plane transport properties are investigated in the underdoped LCCO c-axis oriented thin films. With decreasing the concentration of Ce, the conduction behavior changes from the T^2 dependence behavior to a semi-conducting one. When x=0.09,0.08, the upturn in temperature dependence of ρ_i in the low temperature range can be explained as a Kondo effect. The $\rho_{ab} \sim T^{-a}$ for LCCO with x¡0.08 may come from the combination of several factors which must be understood further.

Acknowledgments

This work is supported by grants from the State Key Program for Basic Research of China and the National Natural Science Foundation.

References

1. C.-T. Chen, *et al.*, Phys. Rev. Lett. **88**, 227002 (2002).
2. Beom-hoan O and J. T. Markert, Phys. Rev. B **47**, 8373 (1993).
3. M. A. Crusellas, J. Fontcuberta, and S. *Piñol*, Physica C **235-240**, 1401 (1994).
4. M. Naito and M. Hepp, Jpn. J. Appl. Phys., Part 2 **39**, L485 (2000).
5. Manthiram A and Goodenough J B J. Solid State Chem. **92**, 231 (1991).
6. A. Sawa, M. Kawasaki, H. Takagi, and Y. Tokura, Phys. Rev. B **66**, 014531 (2002).
7. Naito M, Karimoto S and Tsukada A, Supercond. Sci.Technol. **15**, 1663 (2003).
8. L. Zhao, *et al.*, Supercond. Sci. Technol. **17**, 1361 (2004).
9. H. Wu, *et al.*, Phys. Rev. B **73**, 104512 (2006).
10. K. Jin, *et al.*, Phys. Rev. B **74**, 094518 (2006).
11. Dinesh Varshney, K K. Choudhary and R. K. Singh, Supercond. Sci. Technol. **12**, 1119 (2002).
12. G. F. Giuliani and J. J. Quinn, Phys. Rev. B **26**, 4421, (1982).
13. C. C. Tsuei, A. Gupta and G. Koren, Physica C **161** 415 (1989).
14. P. Fournier, *et al.*, Phys. Rev. B **62**, R11993 (2000).
15. T. Sekitani, M. Naito, and N. Miura, Phys. Rev. B **67**, 174503 (2003).
16. E. W. Fenton, Phys. Rev. B **7**, 3144 (1973).