Physical properties in layered transition-metal oxide crystals and anisotropic transport measurement

K. Q. Ruan, Y. Yu, S. L. Huang, H. L. Li, S. Qian and L. Z. Cao

Structure Research Laboratory, Department of Physics, University of Science and Technology of China, Hefei, Anhui 230026, P. R. China

Two kinds of measurement methods are applied to study the systematic transport property of both $Bi_{2-x}Pb_xSr_2Co_2O_y$ single crystals with various Pb content and $Bi_2Sr_2CaCu_2O_y$ single crystals with various oxygen content. The completely different anisotropic transport properties are observed in both $Bi_{2-x}Pb_xSr_2Co_2O_y$ and $Bi_2Sr_2CaCu_2O_y$ crystals. The result is discussed.

INTRODUCTION

Since the discovery of high-T_c cuprate oxides layered structure quasi-two dimensional transition-metal oxides have attracted extensive attention due to the strong electrical anisotropy manifested in their transport properties. The strongly contrasting anisotropic transport behaviors have been observed in different layered structure systems. For high-T_c cuprates, in-plane resistivity ρ_{ab} keeps metallic in underdoped region, whereas out-of–plane resistivity ρ_c remains non-metallic down to T_c. However, Sr_2RuO_4 has different transport properties from high-T_c cuprates [1]: ρ_{ab} is always metallic, ρ_c is non-metallic ($d\rho_c/dT < 0$) above $T_M \approx 130$ K, and becomes metallic ($d\rho_c/dT > 0$) below T_M. This should indicate that the layers appear as "isolated" at high temperatures, but connected at low temperature to give a 3D system. Many experimental and theoretical studies have investigated the peculiar transport properties. However, anisotropic transport property measurement in strongly layered structure material is a challenge task. A key point is to overcome problems involving non-uniform current flow in the measuring process. In this paper, we employed two kinds of measurement methods to study the systematic transport property of both $Bi_{2-x}Pb_xSr_2Co_2O_y$ single crystals with various Pb content and $Bi_2Sr_2CaCu_2O_y$ single crystals with various oxygen content. $Bi_{2-x}Pb_xSr_2Co_2O_y$ is a misfit-layered compound [2], and Co ions in the conducting CoO_2 layer form a triangular lattice instead of a rectangular one in the conducting CuO_2 layer of high-T_c cuprate oxides. The completely different anisotropic transport properties are observed in both $Bi_{2-x}Pb_xSr_2Co_2O_y$ and $Bi_2Sr_2CaCu_2O_y$ crystals. The result is discussed.

EXPERIMENTAL

Pb-doped $Bi_{2-x}Pb_xSr_2Co_2O_y$ and $Bi_2Sr_2CaCu_2O_y$ single crystals were grown by a self-flux method. Bi_2O_3 was included in excess to act as a flux for crystal growth. The as-grown $Bi_2Sr_2CaCu_2O_y$ crystals were annealed at 450^oC and various oxygen partial pressures in the range $10^{-8} – 10$ MPa so as to obtain crystals covering from underdoped to overdoped levels. Analyses of the cation stoichiometry of the single crystals were performed by energy-dispersive X-ray analysis (EDX) using a scanning electron microscopy, with uncertainty ±0.01. All crystals for use in the measurements were verified to be single phase by means of X-ray diffraction (XRD). Two kinds of methods are employed to accomplish anisotropic transport measurement. In-plane and out-of-plane resistivity measurements of Pb-doped $Bi_{2-x}Pb_xSr_2Co_2O_y$ single crystals were carried out by a DC four probe method with current electrodes configurations shown in Fig. 1. A generalization of the Montgomery method shown in Fig. 2 was applied to measure anisotropic resistivities of $Bi_2Sr_2CaCu_2O_y$ single crystals. Good electric contacts were achieved by soldering copper wire onto the surface of the samples on which the pure silver evaporated with the electrical contact of no
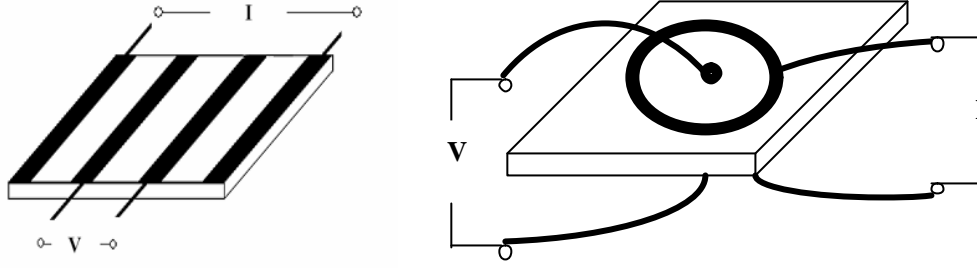
more than 2Ω.

Figure 1   The electrode configurations for ρ_{ab} and ρ_c measurements by a DC four probe method.
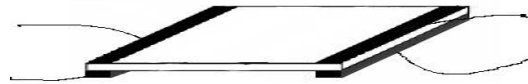

Figure 2   A generalization of the Montgomery method for anisotropic resistivity measurement.

RESULTS AND DISCUSSION

Figure 3 and Figure 4 show the temperature dependence behaviors of the in-plane and out-of-plane resistivity of crystals with x = 0.32, 0.41, 0.48 and 0.52, respectively. As Pb content increases, $\rho_{ab}(T)$ become more metallic. $\rho_c(T)$ show rather complex behavior, and the sign change of $d\rho_c/dT$ occurs with the increase of Pb content. For x = 0.32, 0.41 and 0.48 samples, $\rho_c(T)$ changes from non-metallic to metallic at $T_{max} \approx 160$ K, 180 K and 210 K respectively. For x = 0.52 sample, ρ_c shows metallic behavior up to room temperature.
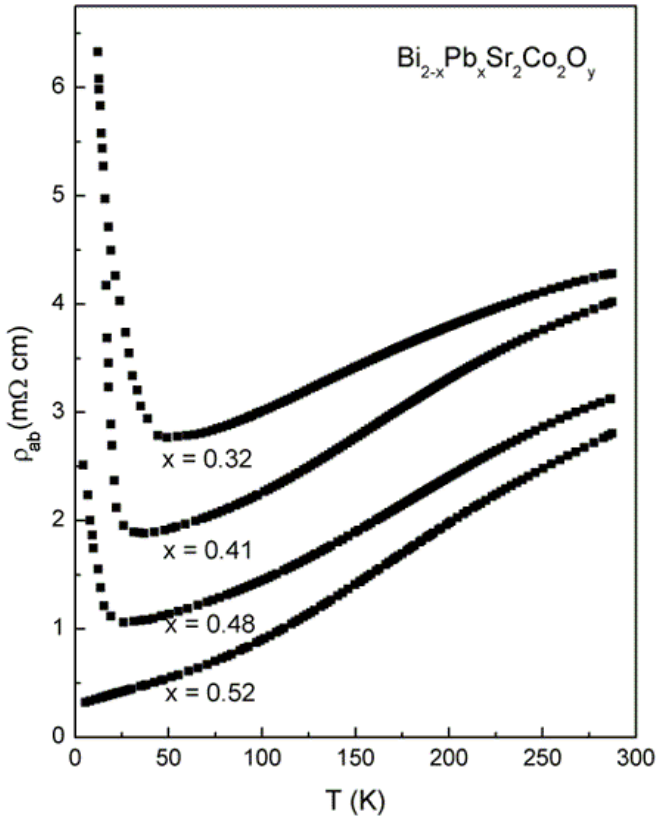

Figure 3   Temperature dependence of in-plane resistivity of $Bi_{2-x}Pb_xSr_2Co_2O_y$ crystals.
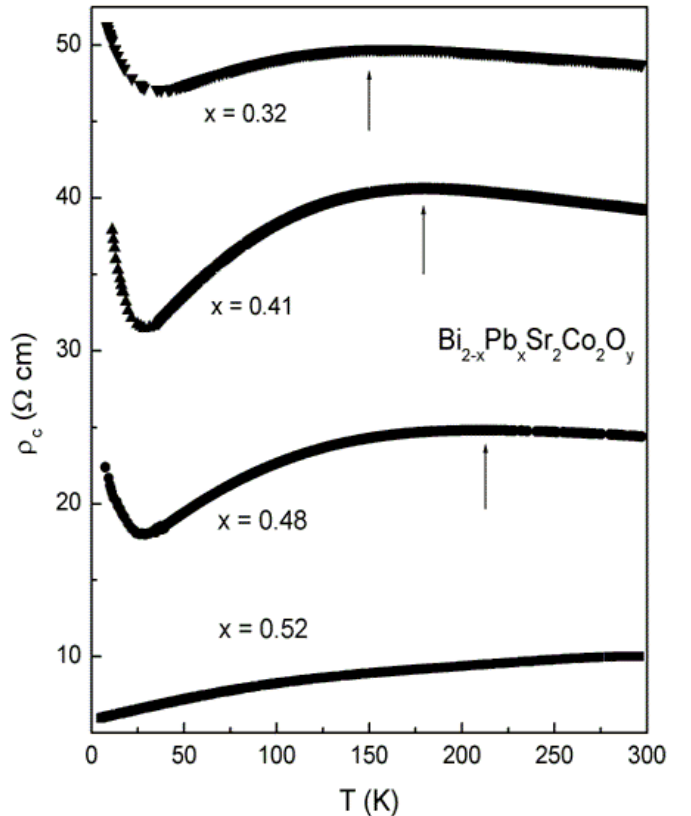
Figure 4   Temperature dependence of out-of-plane resistivity of $Bi_{2-x}Pb_xSr_2Co_2O_y$ crystals.

What induces the complex behavior of ρ_c with the increase of Pb content? The magnetic measurements show that there is no magnetic transition in $Bi_{2-x}Pb_xSr_2Co_2O_y$ compounds down to very low temperature about 4 K. This indicates that the crossover behavior of ρ_c is not due to the magnetic origin. The valence-band photoemission as well as the O_{1s} and Co_{2p} X-ray absorption spectra indicate that Co^{3+} and Co^{4+} have the low-spin t_{2g}^6 and t_{2g}^5 configurations in $Bi_{2-x}Pb_xSr_2Co_2O_y$ compounds [3]. Angle-resolved photoemission spectra further shows that the dispersion of the t_{2g} feature is very small compared to its width at each angle, and suggest that the electron-lattice coupling energy is much larger than the kinetic energy of the t_{2g} electrons and the carriers in the Co-O triangular lattice are essentially polarons formed by Co^{4+} in the non-magnetic Co^{3+} background. In fact, with the doping of Pb in $Bi_{2-x}Pb_xSr_2Co_2O_y$, there is strong interaction between the carrier and crystal lattice when the carrier concentration reaches some critical value, which forms the small polaron. At low temperature small polaron states overlap sufficiently to allow the formation of a polaron band, in which ordinary band conduction can take place. In the vicinity of T_{max} the bandwidth becomes less than the uncertainty in energy due to the finite lifetime of polaron states. Above this temperature the small polaron can be thought of as localized, and the only way in which the polaron can contribute to conduction is by "hopping" from one lattice to another. For x = 0.32, 0.41 and 0.48 samples, the crossover behavior of ρ_c is observed around T_{max} located below the room temperature. For ρ_{ab}, there are two kinds of possibilities. One possibility is that there is no small polaron in the ab plane due to $t_{ab} \gg T_{phonon}$, the small polaron only can be formed in the c-direction. The transport behavior of in-plane resistivity can be interpreted using Boltzmann transport theory. The other is that small polaron can be formed both in ab- and c-direction, but $T_{max}^{ab} \gg T_{max}^c$, i. e., T_{max}^{ab} is located far above the room temperature. Both possibilities indicate that ρ_{ab} behaves metallic.

Figure 5 and Figure 6 show the temperature dependences of the in-plane resistivities ρ_{ab} and out-of-plane resistivities ρ_c for $Bi_2Sr_2CaCu_2O_y$ single crystals, respectively. Crystals A, B, C, D, E and F were respectively annealed under oxygen pressures of 10^{-8}, 10^{-6}, 10^{-4}, 10^{-1}, 1 and 10 MPa. T_c and the resistivities for six crystals alter systematically. A typical T-linear behavior of ρ_{ab} and the highest T_c (90K) are observed for the optimally doped C crystal. Although the oxygen contents of the crystals have not been directly determined, it can certainly be deduced that crystals A and B are both in the underdoped regime, while crystals D, E, and F are in the overdoped regime. For the overdoped D, E and F crystals, a slightly upward curve of ρ_{ab} is observed and $\rho_{ab} = \rho_0 + \alpha T^n$ (n = 1.5-1.8) is satisfactorily obeyed for the above crystals [4].
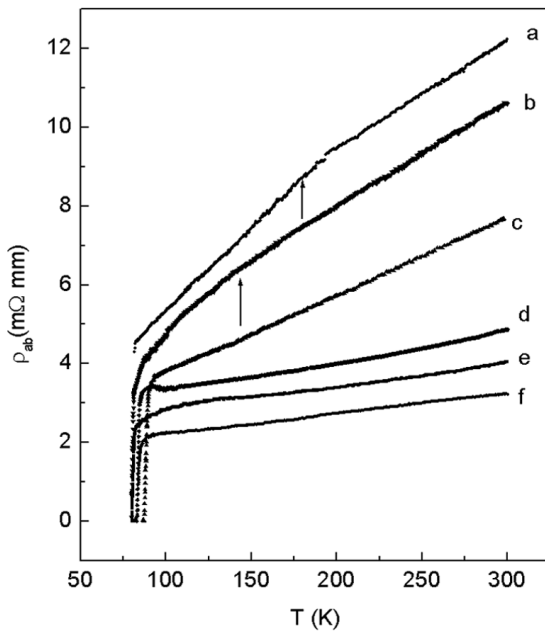

Figure 5   Temperature dependence of in-plane resistivity of $Bi_2Sr_2CaCu_2O_y$ crystals.
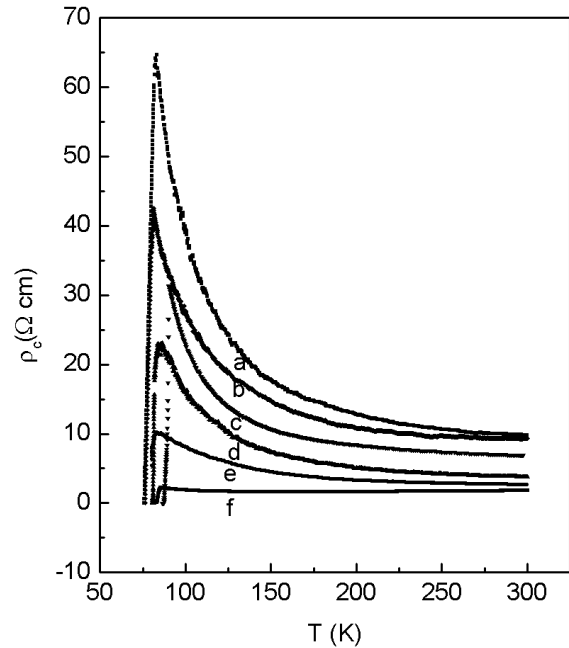
Figure 6   Temperature dependence of out-of-plane resistivity of $Bi_2Sr_2CaCu_2O_y$ crystals.

For the underdoped crystals A and B, ρ_{ab} deviates from the high temperature T-linear behavior at a

characteristic temperature T^* (shown by the arrows), far above T_c. From Fig. 4 it is observed that, with increasing level of underdoping, the overall magnitude of ρ_c as well as its semiconductive temperature dependence increases. It is worth pointing out that there is always an activation-type component included in the semiconductor behavior of ρ_c (T) even for the slightly overdoped Bi-2212 crystal. In order to interpret a semiconductor behavior along c-axis coexisting with a metallic in-plane resistivity over a wide temperature and carrier concentration range, the origin of a pseudogap was suggested [5]. However, the pseudogap is only observed in the underdoped regime, and the semiconductive behavior of the slightly overdoped crystal casts doubt on the origin of the semiconductive behavior being a pseudogap.

CONCLUSION

The transport properties of $Bi_{2-x}Pb_xSr_2Co_2O_y$ single crystals with various Pb content and $Bi_2Sr_2CaCu_2O_y$ single crystals with various oxygen content were measured. For $Bi_{2-x}Pb_xSr_2Co_2O_y$ crystals, the evolution of ρ_c behavior from semiconductive through crossover to metallic behavior is interpreted by a small-polaron model. As for high-T_c cuprate, there is no consensus about the origin of semiconductor behavior of ρ_c (T) so far. Therefore, more systematic investigation on related layered strongly correlated metals will help to clarify this problem.

ACKNOWLEDGEMENT

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