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Anisotropy of Normal Resistivity in Oxygen-Deficient $YBa_2Cu_3O_{7-x}$ Single Crystals

V. N. Zverev* and D. V. Shovkun

Institute of Solid-State Physics, Russian Academy of Sciences, Chernogolovka, Moscow region, 142432 Russia
**e-mail: zverev@issp.ac.ru*

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Temperature dependences of the resistivity tensor components ρ_{ab} and ρ_c were measured for $YBa_2Cu_3O_{7-x}$ single crystals with different oxygen contents. The resistivity anisotropy ρ_c/ρ_{ab} was found to grow exponentially with decreasing temperature. The results are compared with the predictions of different models describing transverse transport in the normal state of cuprate high-T_c superconductors. © *2000 MAIK "Nauka/Interperiodica".*

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Cuprate high-T_c superconductors are strongly anisotropic materials with a clearly defined laminated structure. The presence of cuprate CuO_2 planes, which are responsible, as is customarily believed, for superconductivity, is the common feature of these compounds. Although the normal conductivity of cuprate high-T_c superconductors has been intensively studied both experimentally and theoretically since the very discovery of high-T_c superconductivity (HTSC), there is still much debate over the mechanism of normal conductivity of these materials.

Within the CuO_2 layers, the conductivity of the cuprate HTSC compounds is metallic, with the resistivity ρ_{ab} linearly decreasing with a decrease in temperature over a wide temperature range. To explain such a dependence, new particles—holons and spinons—were introduced into the RVB model [1] and the theory of marginal Fermi liquid was suggested in [2]. This dependence can also be successfully explained by the usual electron–phonon scattering [3].

In the direction perpendicular to the CuO_2 layers, the resistivity of $YBa_2Cu_3O_{7-x}$ may increase with decreasing temperature even in the optimally doped ($x \approx 0$) samples [4]. As the oxygen concentration decreases, the $\rho_c(T)$ dependence becomes progressively steeper with a negative slope over the whole range from room temperature to T_c. Such behavior was originally explained by the crystal imperfections, namely, by the effect of semiconducting interlayers or by the disorder and localization effects in the transverse motion [5]. More recently, several theoretical models were suggested that explained such behavior for perfect crystals. In the theory of Anderson and Zou [1], the linear term in the temperature dependence is supplemented by a contribution proportional to $1/T$. The theory of Alexandrov and Mott predicts a considerably steeper exponential growth [6, 7]. In their theory, the transverse conductivity is mediated by polarons, whose concentration exponentially decreases with decreasing temperature because of polaron binding into bipolarons.

Recently, Abrikosov [8] proposed a new mechanism for carrier transport along the *c* axis in the HTSC materials, namely, resonance electron tunneling between the CuO_2 planes through the localized states in the CuO chains. It should be stressed that the Abrikosov theory assumes that the centers mediating the resonance tunneling are positioned exactly halfway in between the neighboring CuO_2 planes. This situation is automatically realized in $YBa_2Cu_3O_{7-x}$ single crystals with reduced oxygen content, where the role of such resonance levels may be played by the fragments of broken CuO chains. The applicability of the Abrikosov model to other cuprate HTSC compounds is unclear. It follows from the calculations in [8] that the temperature dependence of the resistivity anisotropy in the tunneling mechanism should have the form

$$\rho_c/\rho_{ab} = AT\cosh^2(T_0/T), \qquad (1)$$

where A is a constant dependent on the parameters of the electron spectrum and the doping level, and T_0 is the characteristic activation energy specified by the energy levels mediating resonance tunneling. Equation (1) is expected to hold for the samples with oxygen concentration lower than optimal, where the CuO chains are broken, while the lower bound for the oxygen concentration is near the metal–insulator transition because of the competition with direct carrier tunneling between the CuO_2 planes. To our knowledge, no works devoted to the experimental verification of this model were published after appearance of the theory [8].

The purpose of this work is to experimentally study the temperature dependence of resistivity anisotropy for perfect $YBa_2Cu_3O_{7-x}$ single crystals with different carrier concentrations and to compare the results with

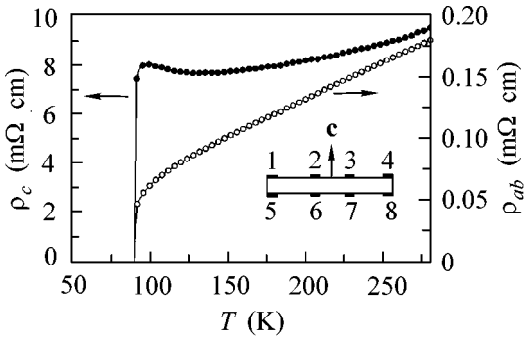

Fig. 1. Temperature dependence of the resistivity components ρ_{ab} and ρ_c for an initial single crystal of $YBa_2Cu_3O_{7-x}$. The geometry of contacts is shown in the inset.

the theory. In these studies, it is necessary to measure the resistivity tensor components ρ_{ab} and ρ_c for the same sample with different doping levels. To this end, we used the dc flux transformer method [9], allowing these components to be calculated from the measured potential differences arising at the opposite surfaces in the central part of the sample upon passing a current though the contacts at the edges of one of the surfaces. These measurements require at least six contacts (two current and four potential). We made measurements for samples with eight contacts, four at each of the surfaces (Fig. 1). This made it possible to pass current both through the upper pair of current contacts (1, 4) and through the lower pair (contacts 5, 8) and each time measure voltages $V_{2,3}$ and $V_{6,7}$ followed by averaging the measurement results. This minimized the error caused by the inaccurate positioning of the contacts.

The results of this work were obtained for a $YBa_2Cu_3O_{7-x}$ single crystal shaped like a rectangular plate $1.5 \times 0.2 \times 0.05$ mm in size, with the crystallographic *c* axis coinciding with the normal to the plate plane. The contacts were made from 30-μm-diameter gold wires glued by silver paste to the surfaces perpendicular to the *c* axis. The sizes of the contact areas were no greater than 0.15 mm, and the resistance of the fired contacts was on the order of 1 Ω. The initial $YBa_2Cu_3O_{7-x}$ single crystals were grown in a ZrO_2 crucible by the method described in [10]. After annealing at 500°C in oxygen, the samples showed a narrow (of width less than 0.5 K) superconducting transition and critical temperature $T_c \approx 91$ K (Fig. 1). The desired decrease in the oxygen concentration was achieved by choosing an appropriate temperature of annealing in air at atmospheric pressure followed by quenching in liquid argon, according to the data reported in [11–13].

When annealing, the samples were dusted with a powder of $YBa_2Cu_3O_{7-x}$ to preserve the high quality of the surfaces.

For measuring the temperature dependences of resistivity, the sample and nearby thermometer and heater were placed inside a glass Dewar vessel, which was immersed upside down in liquid helium. To enhance temperature homogeneity, the sample was placed in a sapphire container.

The temperature dependences $\rho_{ab}(T)$ and $\rho_c(T)$ of the initial optimally doped single crystal are presented in Fig. 1. One can see that the $\rho_{ab}(T)$ dependence is linear over almost the whole temperature range except for a region near T_c, where the deviations from linearity are caused by fluctuative superconductivity. By contrast, the $\rho_c(T)$ curve is nonlinear and has a portion with a negative slope near T_c. The characteristic values of the resistivity tensor components and their temperature behavior correspond to the ones typically observed for high-quality single crystals [4].

It is seen from Fig. 2 that the $\rho_c(T)$ curve is linearized when the product $\rho_c T$ is plotted as a function of T^2. This fact suggests that the temperature dependence $\rho_c(T)$ has the form

$$\rho_c = A_c/T + B_c T. \qquad (2)$$

Expression (2) was used in a series of works as an argument in support of the RVB model, which predicts such a temperature behavior for both resistivity tensor components [1]. We would like to call attention to the fact that, for a doping level lower than optimal, the temperature dependences $\rho_{ab}(T)$ and $\rho_c(T)$ are no longer described by the function of type (2), as is demonstrated by the curves corresponding to the samples with $T_c < 91$ K (Fig. 2).

Let now turn to the results obtained for the resistance anisotropy. The temperature dependence ρ_c/ρ_{ab} for a sample with reduced oxygen content ($T_c = 77$ K, $x \approx 6.77$) is shown in Fig. 3. The approximation of the experimental results by Eq. (1) is shown by the dashed line with optimal parameters $A = 0.178$ K^{-1} and $T_0 = 223$ K. For comparison, the exponential approximation

$$\rho_c/\rho_{ab} = A_1 \exp(\Delta/T) \qquad (3)$$

is also shown in Fig. 3 by the solid line. It is seen that Eq. (1), although satisfactorily describing the experimental data, makes it noticeably worse that does the activation exponent in Eq. (3). The log–1/*T* plots of resistivity anisotropy are shown in Fig. 4 for several levels of doping with oxygen. In these coordinates, the experimental curves are seemingly linearized, whereas the dependence corresponding to Eq. (1) (dashed lines) is at variance with the experiment. Note that the optimization by Eqs. (1) and (3) was carried out in the same temperature range for each of the sample states. The temperature dependence is saturated at high values of resistivity anisotropy $\rho_c/\rho_{ab} > 10^3$; the saturation is most pronounced for the upper curve. This is likely caused by shunting of the conduction along the *c* axis, e.g., by virtue of direct carrier tunneling between the CuO_2 layers or through conduction along the dislocations or any other imperfections in the sample. The saturation of temperature dependence $\rho_c(T)$ narrows the interval where the temperature dependence can be

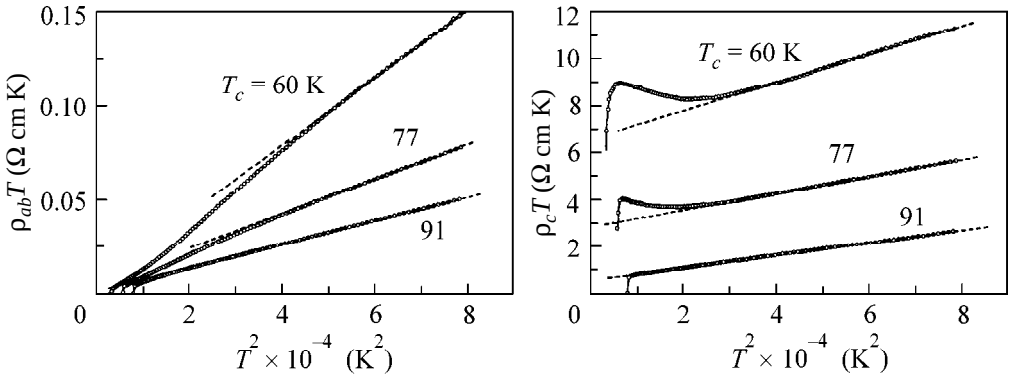

Fig. 2. Plots of $\rho_{ab}T$ and ρ_cT as functions of T^2 for the samples with different oxygen content. Dashed lines are drawn through the rectilinear portions of the experimental curves.

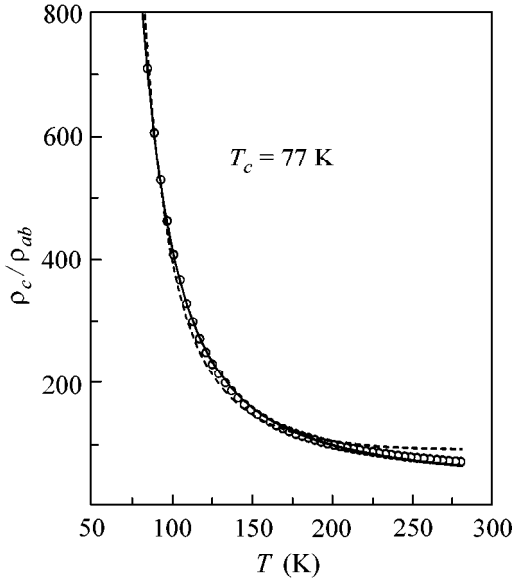

Fig. 3. Temperature dependence of the resistivity anisotropy for the sample with T_c = 77 K. The dashed and the solid curves are the interpolations by Eqs. (1) and (3), respectively.

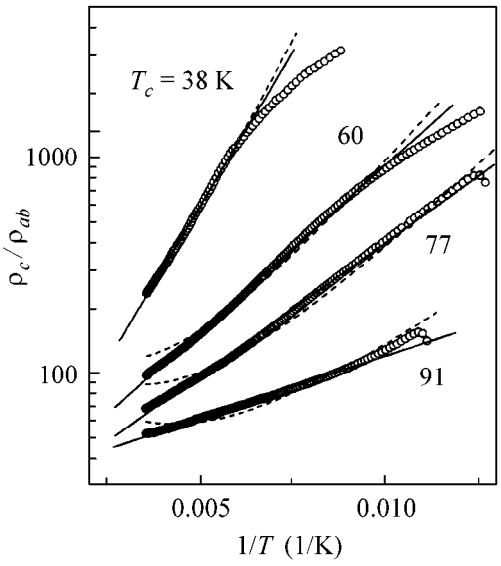

Fig. 4. Temperature dependences of the resistivity anisotropy for the samples with different doping level. Dashed lines are the interpolations by Eq. (1).

rationalized by one of the discussed theoretical models. In the upper curve, this interval is narrowed to 150 < T < 280 K, within which the distinction between Eqs. (1) and (3) becomes insignificant.

The rectilinear portions in the curves shown in Fig. 4 correspond to the activation energies Δ increasing with a decrease in T_c; they are equal to 146, 295, 356, and 665 K for the four curves shown in the figure. The preexponential factor A_1 virtually does not change and lies in the range 20–30. The exponential dependence of the anisotropy may be due to the fact that either the carriers are forced to overcome an energy barrier in moving across the CuO_2 planes or the concentration of carriers involved in transverse transport depends exponentially on temperature at $T > T_c$. The latter is possible, e.g., if the normal transport is preceded by the thermal decay of somehow "preprepared" electron pairs. Among the models providing the temperature exponent for the concentration of normal excitations, the bipolaron model of Alexandrov and Mott [6, 7], in which conduction along the *c* axis is accomplished by thermally excited polarons, is noteworthy. This should result in the temperature dependence of type (3) with an activation energy of half the bipolaron binding energy. The latter is independent of temperature but increases with decreasing carrier concentration. Note that exponential temperature behavior was previously observed for the resistivity anisotropy in $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals with different oxygen content [14] and interpreted within the framework of this model.

To summarize, it is established that the temperature dependence of the resistivity anisotropy in oxygen-

deficient $YBa_2Cu_3O_{7-x}$ single crystals with $0 < x < 0.5$ is best described by an exponential function. The Abrikosov theory qualitatively fits the experiment but yields steeper temperature dependences. The RVB theory does not describe the experimental results for samples with oxygen concentrations below the optimal.

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