Anisotropy of the electrical resistance of single crystals of the high-temperature superconductor $YBa_2Cu_3O_x$

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The resistivities $\rho_\parallel$ and $\rho_\perp$ of the single crystals of $YBa_2Cu_3O_x$ have been measured in the directions parallel to the basal plane of the unit cell and perpendicular to it. The samples of the two sets of crystals with orthorhombic structure ($T_c \sim 93$ K) and tetragonal structure ($T_c \sim 80$ K) have been studied. The transverse resistivity $\rho_\perp$ and anisotropy $\rho_\perp/\rho_\parallel$ were found to increase as the temperature approached T_c.

In this letter we report the results of an experimental study of the anisotropy of the electrical conductivity of single crystals of the composition $YBa_2Cu_3O_x$. Two sets of samples (*A* and *B*) were studied. The samples were grown in platinum crucibles from a nonstoichiometric melt at temperatures of 900–1000 °C and were annealed in an oxygen stream at a temperature of 700 °C. The original crystals were square wafers with average dimensions $5\times5\times0.03$ mm. Some characteristics of the crystals of these sets of samples are given in Table I.

We wish to emphasize that the crystals of set *B*, in contrast with those of set *A*, retained the tetragonal structure after being annealed in oxygen. This may be attributable to the copper deficit in their composition (see Table I).

As samples for the measurement of the electrical resistance we selected fragments of crystals of regular form with a mirror-smooth surface. Low-resistance electrical contacts ($R<1$ Ω) were established by brazing a silver paste in an oxygen atmo-

TABLE I.

Set	Chemical composition[1]	Symmetry and lattice constants,[2] Å		T_c[4]	
		before annealing	after annealing	before annealing	after annealing
A	$Y_{0.92}(TR)_{0.03}Ba_2Cu_{2.95}O_x$	tetragonal $a = 3.857$ $c = 11.828$	orthorhombic[3] $a = 3.823$ $b = 3.879$ $c = 11.735$	~60	~93
B	$Y_{0.94}(TR)_{0.02}Ba_2Cu_{2.98}O_x$	tetragonal $a = 3.865$ $c = 11.704$	tetragonal $a = 3.868$ $c = 11.604$	–	60–80

sphere. The direct-current measurements were carried out by the four-probe method with the use of a digital voltmeter which allowed us to effectively measure the signals at the 0.2-μV level. The current that was passed through the sample was 0.5-1 mA in magnitude. The temperature was measured with a copper-constantan thermocouple within ~0.01 K.

Figure 1 shows the results of measurements of the electrical resistance of two samples of set *A*, carried out at temperatures near the superconducting transition. Curves I and II were obtained from the same sample with dimensions 515×210×18 μm, using the electrode configuration shown in Fig. 1a. Curve I characterizes the

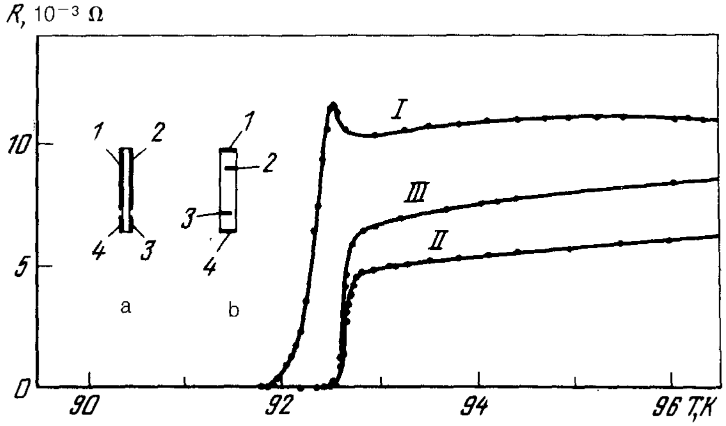

FIG. 1. Change in the electrical resistance of the single crystals of set *A* near the superconducting transition. a—The arrangement of electrodes for measuring the resistance $R_\perp$ (the *c* axis of the crystal is in the plane of the figure); b—the same as in (a), but for measuring $R_\parallel$ in the direction parallel to *ab*; I and II—the results of a measurement of $R_\perp$ and $R_\parallel$ of the same sample based on scheme *a*; III—the $R_\parallel(T)$ curve for a different sample which was measured on the basis of scheme *b* and reduced to curve II at $T \gtrsim 200$ K.

behavior of the transverse (along the c axis of the crystal) electrical resistance $R_\perp$ (1 and 2 are current probes; 3 and 4 are potential probes). Curve II qualitatively describes the temperature dependence of the longitudinal ($\|ab$) electrical resistance $R_\|$ (1 and 4 are current probes; 2 and 3 are potential probes). Curve III is a correct $R_\|$ (T) curve for a sample with dimensions $900\times130\times15$ μm. This curve was measured according to the scheme in Fig. 1b and was reduced to curve II at $T \gtrsim 200$ K. As can be seen in Fig. 1, the parts of curves II and III in which the electrical resistance changes sharply match with respect to temperature, making it possible to use curves I and III to determine the anisotropy of the electrical properties of the crystal.

Looking at curves I, we notice that a sharp peak, which occurs at a temperature corresponding to a nearly total disappearance of resistance $R_\|$, precedes a sharp decrease in the resistance $R_\perp$. Such a behavior of the resistance $R_\perp$ can apparently be explained in terms of a sharp increase in the anisotropy of the conductivity near the superconducting transition. This behavior of the anisotropy of the conductivity could mean that the onset of a superconducting state or partially superconducting state occurs primarily in the parallel direction. It follows from Fig. 1 that something like this does in fact occur. The temperature values corresponding to the fastest change in the resistance $R_\perp$ and $R_\|$ are separated by an interval of ~0.5 K. This interval is appoximately equal to the sum of the values of ΔT, which characterize the width of the superconducting transition determined formally from $R_\|$ and $R_\perp$ (0.1 K and 0.4 K, respectively) at the level (0.1–0.9) R_n, where R_n is the resistance of the normal phase.

The results of measurements of the electrical resistance of the samples of set A are shown in Fig. 2 in units of the resistivity (see also Table II). The error in the values of $\rho_\|$ and $\rho_\perp$, which stems from the error in determining the geometric factor of the samples, is $\pm$ 18% and $\pm$ 12%, respectively.

We call attention to a recently published paper,[1] in which similar measurements were carried out. Despite the marked difference in the experimental procedure and the

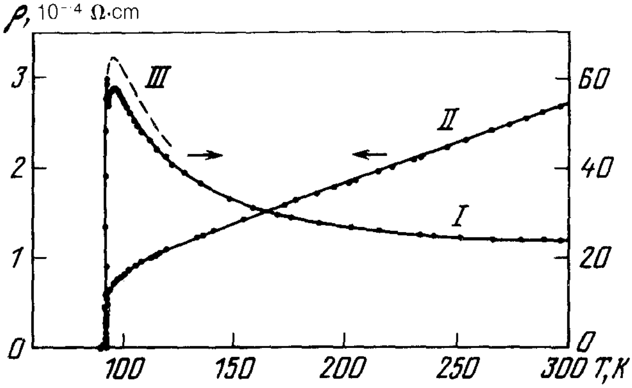

FIG. 2. Resistivity of the single crystals of set A. I—$\perp$ ab; II—$\|$ ab; III—the $\rho_\perp$ (T) curve with a correction for the nonideal measurement conditions.

TABLE II.[5)]

Set		$T=T_c$				$T=295$ K	
	$\rho_\perp$	$\rho_\parallel$	$\rho_\perp/\rho_\parallel$	$\rho_\perp$	$\rho_\parallel$	$\rho_\perp/\rho_\parallel$	$\partial\rho_\parallel/\partial T$
A	5.99×10^3	54	111	2.45×10^3	268	9.14	0.909
B	1.01×10^5	150	673	1.63×10^4	698	23.4	1.293

quality of the single crystals that were studied, the anisotropy of the electrical resistance measured in that experiment at $T\sim T_c$ is very close to the value obtained by us for the samples of set *A*. We must emphasize that the $\rho_\parallel(T)$ curve for the sample of set *A* is in agreement, within the measurement error, with the data which were obtained independently.[2]

Figure 3 shows the results of the measurement of $\rho_\perp$ and $\rho_\parallel$ of the single crystals of set *B*. The measurements were carried out with samples $360\times300\times45$ μm ($\rho_\perp$) and $780\times280\times39$ μm ($\rho_\parallel$) in size. The corresponding errors in the values of ρ are $\pm17\%$ and $\pm24\%$. These data show (see Fig. 3 and Tables I and II) that the quality of the crystals of set *B* is much lower than that of the samples of the preceding set. The larger width ΔT of the resistive transitions in the longitudinal direction (0.9 K) and transverse (7.4 K) direction is also evidence of this fact. The samples of set *B* showed no evidence of the peculiar behavior of $\rho_\perp$ near T_c described above. This behavior most likely is the result of their extremely high anisotropy (see Table II).

A comparison of the data obtained from single crystals *A* and *B* (see Figs. 1 and 2

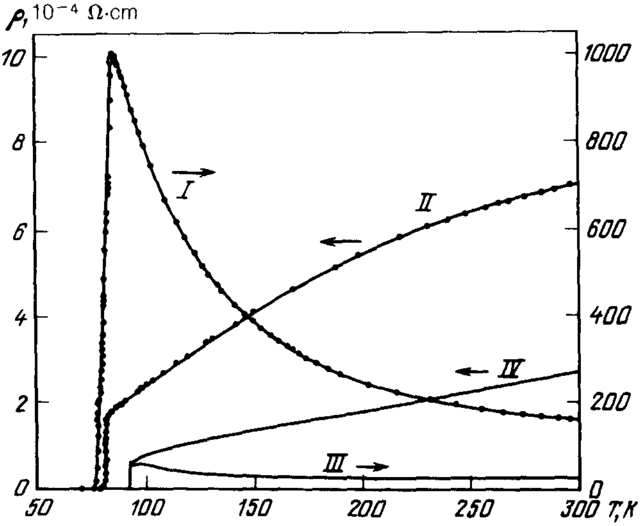

FIG. 3. Resistivity of the single crystals of set *B*. I—⊥ *ab*; II—∥ *ab*; III, IV—the same as in Fig. 2.

and Table II) shows that the anisotropy of the electrical resistance $\rho_\perp/\rho_\parallel$ and its temperature dependence apparently are strongly linked with the high quality of the samples. It is conceivable that the anisotropy of a perfect crystal is of a slightly different nature.

We note in conclusion that the plot of the temperature of the resistive transition versus the direction(6) (see Fig. 1) cannot yet be explained trivially. It is possible that this behavior can be explained in terms of the superconducting fluctuations. In this case it must be assumed, however, that the resistive transition in $YBa_2Cu_3O_x$ compounds is simply a fluctuational precursor of a total disappearance of the electrical resistance.

Although the nature of the temperature dependence of the magnetic moment and the particular way in which the magnetic field affects the resistive transition in $YBa_2Cu_3O_x$ single crystals[2] tend to favor this viewpoint, they do not rule out the effects associated with the inhomogeneity of the samples.

We are deeply indebted to I. V. Aleksandrov for determining the lattice constants and G. I. Shmanenkova for analyzing the chemical composition of the test samples.

(1) The composition was determined within ~1%; TR-La, Yb, Nd.
(2) The lattice constants were determined within 0.001 Å.
(3) The crystals of set *A* exhibit a clearly defined twinning structure.
(4) T_c—Temperature of the transition to the superconducting state.
(5) ρ—$\mu\Omega\cdot$cm; $\partial\rho/\partial T$—$\mu\Omega\cdot$cm/deg.
(6) This of course does not imply that there is a corresponding difference in the temperatures at which the resistance vanishes completely. This conclusion, however, cannot be verified directly because of the limited accuracy of the measurements.

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[1]S. W. Tozer, A. W. Kleinsasser *et al.*, Phys. Rev. Lett. **59**, 1768 (1987).
[2]L. Z. Avdeev, A. B. Bykov *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **46**, 196 (1987) [JETP Lett. **46**, 249 (1987)].

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