Anisotropy of the resistivity of $YBa_2Cu_3O_{7-x}$ single crystals

L. I. Buravov,[1)] L. Ya. Vinnikov, G. A. Emel'chenko, P. A. Kononovich, V. N. Laukhin,[1)] Yu. A. Osip'yan, and I. F. Shchegolev
Institute of Solid State Physics, Academy of Sciences of the USSR

(Submitted 25 October 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 1, 50–52 (10 January 1988)

The resistivity of several $YBa_2Cu_3O_{7-x}$ crystals in the *ab* plane and along the direction of the *c* axis has been measured. The large anisotropy and the small transverse critical current are probably evidence of a significant inhomogeneity of the crystals along the direction of the *c* axis. This inhomogeneity gives rise to multiple Josephson junctions.

Progress in research on the nature of the high-temperature superconducting state of complex copper oxides[1,2] will be impossible without a detailed study of single-crystal samples. Because of the difficulties in synthesizing single crystals of these compounds, only a few papers have been published, and many questions remain unexplained. In the present letter we report measurements of the temperature dependence of the resistivities $\rho_\parallel$ and $\rho_\perp$ of $YBa_2Cu_3O_{7-x}$ single crystals in the *ab* plane and along the *c* axis, respectively. We also report measurements of the critical current I along the *c* axis.

The single crystals are grown from a molten solution by the technique of Ref. 3. The measurements of $\rho_\parallel$ (T) and $\rho_\perp$ (T) are carried out by Montgomery's dc method,[4] as modified in Ref. 5. The modification consists of the use of nonpoint (extended) contacts and allowing for the finite distance between the contacts and the edges of the crystal. The platinum contacts which are used are 10 μm in diameter and are attached with a graphite paste. The typical resistances are $\sim 10^2$ Ω.

Figure 1 shows results on $\rho_\parallel$ (T) for four single crystals; the inset shows the arrangement of the contacts.[2)] There is a significant scatter in the properties of the crystals. As we go from crystal 1 to crystal 4, $\rho_\parallel$ (293) decreases from 520 $\mu\Omega\cdot$cm to 260 $\mu\Omega\cdot$cm, while T_c increases from 80 K to 92 K. The ratio $\rho_\parallel$ $(293)/\rho_\parallel$ (95) increases from 2.6 to 4.3. For crystal 4, the dependence $\rho_\parallel$ (T) is linear over the interval from 300 to 120 K. In crystals 1–3, of lower quality, the deviation from linearity as the temperature is lowered sets in earlier.

Figure 2 shows the results of $\rho_\perp$ (T) for the same crystals (the values of $\rho_\perp$ are essentially identical for crystals 2 and 3). At a measurement current of 0.5 mA the superconducting transition, identified on the $\rho_\perp$ (T) curve, shifts to a slightly lower temperature than that of the transition identified on the basis of the $\rho_\parallel$ (T) curve. We calculated $\rho_\perp$ in the temperature interval in which there is no longitudinal resistance, and Montgomery's equations do not apply, under the assumption that $\rho_\perp$ is proportional to the voltage V_{12} (when the current flows through contacts 34), since the pairs of contacts 13 and 24 (Fig. 1) are in equipotential planes in this case. The value of $\rho_\perp$

 0021-3640/88/010060-04$01.00

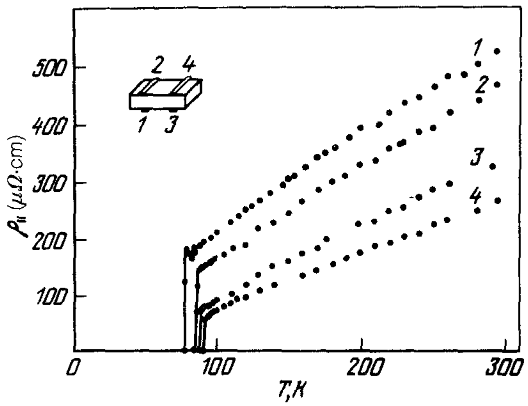

FIG. 1. Temperature dependence of the resistivity in the ab plane of four $YBa_2Cu_3O_{7-x}$ single crystals. The inset shows the positions of the contacts.

of crystal 4 decreases during cooling from 293 K to 170 K.

The ratio $\rho_\perp/\rho_\parallel$ at 293 K varies from 120 for crystal 1 to 48 for crystal 4. As the temperature is lowered, $\rho_\perp$ increases, while $\rho_\parallel$ decreases, and at 95 K the ratio $\rho_\perp/\rho_\parallel$ reaches values of 600–700 for crystals 1–3 and 230 for crystal 4. Even this latter value is nearly an order of magnitude greater than the value ~ 25 which would be expected on the basis of the ratio $\rho_\perp/\rho_\parallel \approx (H_{c2_\parallel}/H_{c2_\perp})^2$, if we use the values for H_{c2} measured in Ref. 6.

This discrepancy is probably caused by an inhomogeneity along the c axis of the crystals used by us and thus by an extrinsic nature of the increase in $\rho_\perp$ with decreasing temperature. However, a careful study of the local crystal structure of the samples in a scanning electron microscope, based on electron channeling patterns, revealed no dielectric interlayers with dimensions $\gtrsim 2$–3 μm in these samples. The orientations of the various parts of the crystals, both in the ac and bc end planes and in the ab plane, remain constant, as do the crystal lattice parameters, within the measurement errors.

It was found that the lowering of the transition temperature inferred from the disappearance of $\rho_\perp$ was a consequence of the finite magnitude of the measurement

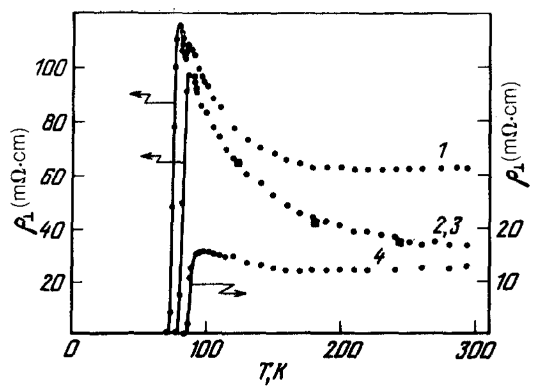

FIG. 2. Temperature dependence of the resistivity along the direction of the c axis. The filled squares show several points corresponding to crystal 3.

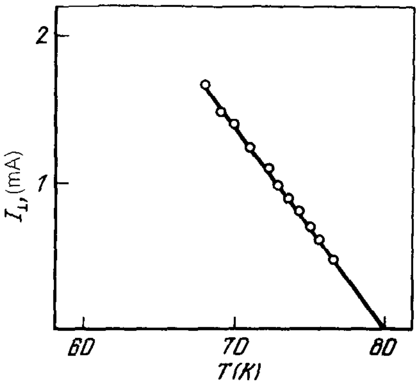

FIG. 3. Temperature dependence of the critical current along the direction of the c axis for crystal 1.

current. If, at 80 K, the current $I_\perp$ through contacts 34 increased, the voltage across contacts 12 appeared in crystal 2 at $I_\perp \approx 1$ mA, while that in crystal 4 appeared at $I_\perp \approx 2$ mA. At these (and much higher) currents the crystals remained superconducting in the longitudinal direction. The temperature dependence of the transverse critical current of crystal 1 is shown in Fig. 3. We see that in the limit $I_\perp \to 0$ the transition temperature tends toward the same value (80 K) which is found from the measurements of $\rho_\parallel$.

The magnitude of the critical current density along the c axis corresponding to these results is $\lesssim 1$ A/cm^2, again much smaller than the values which were found in Ref. 7 from measurements of the maximum diamagnetic moment. We believe that this discrepancy again indicates a significant inhomogeneity of the crystals along the c axis, which leads to the formation of multiple Josephson junctions.

Identifying the nature of this inhomogeneity will require further research. A factor that tends to promote the appearance of an inhomogeneity may be a large anisotropy in the crystal growth rate in different crystallographic directions. This circumstance might lead to, for example, an alternation of layers with different local concentrations of oxygen.

While this paper was being prepared for publication, Tozer *et al.*,[8] published a report of a measurement of the anisotropy of the resistivity of a $YBa_2Cu_3O_{7-x}$ single crystal with $\rho_\parallel$ (293) $= 460\,\mu\Omega\cdot$cm. The value of $\rho_\perp$ of this crystal at 293 K is close to the value of $\rho_\perp$ of our crystal 4, and it increases by $\sim 35\%$ toward the transition point. Tozer *et al.*,[8] suggest that this is intrinsic growth, and they assume that the ratio $\rho_\perp/\rho_\parallel$ at temperatures near T_c is 90, in reasonable agreement with the estimate found for this quantity on the basis of the anisotropy in H_{c2}, measured in Ref. 6. Our data on the small value of critical current in the transverse direction make that conclusion doubtful.

[1)]Division of the Institute of Chemical Physics, Academy of Sciences of the USSR.

[2)]In Montgomery's method, the resistivities $\rho_\parallel$ and $\rho_\perp$ are calculated from the geometric dimensions of the crystal and the voltages $V_\perp$ and $V_\parallel$ which appear across contacts 12 and 13 when currents are passed through contacts 34 and 24, respectively.

[1]J. G. Bednorz and K. A. Müller, Z. Phys. **B64**, 189 (1980).
[2]M. K. Wu, J. R. Ashburn, C. T. Torng *et al.*, Phys. Rev. Lett. **58**, 908 (1987).
[3]G. A. Emel'chenko, M. V. Kartsovnik, P. A. Kononovich *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **46**, 162 (1987) [JETP Lett. **46**, 204 (1987)].
[4]H. C. Montgomery, J. Appl. Phys. **42**, 2971 (1971).
[5]L. I. Buravov, Zh. Tekh. Fiz., 1987, in press.
[6]T. K. Worthington, W. J. Gallagher, and T. R. Dinger, Phys. Rev. Lett. **59**, 1160 (1987).
[7]T. R. Dinger, T. K. Worthington, W. J. Gallagher, and R. L. Sandstrom, Phys. Rev. Lett. **58**, 2687 (1987).
[8]S. W. Tozer, A. W. Kleinsasser, T. Penney *et al.*, Phys. Rev. Lett. **59**, 1768 (1987).

Translated by Dave Parsons