# The Hall effect in $YBa_2Cu_3O_{7-x}$ single crystals in the plane perpendicular to the *c* axis

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The magnitude, the sign, and the temperature dependence ($95\ K < T < 400\ K$) of the Hall voltage of the single crystals of the high-temperature superconductor $YBa_2Cu_3O_{7-x}$ have been measured for the first time in the plane of the Cu-O layers (perpendicular to the *c* axis).

Interest in the study of high-temperature superconductors has increased markedly after the single crystals of these compounds have been obtained. The kinetic and superconducting characteristics of these compounds were found to be strongly anisotropic along ($\|$) the Cu-O layers and perpendicular ($\perp$) to them. At 300 K the ratio $\rho_\perp/\rho_\| \approx 30$ for $YBa_2Cu_3O_{7-x}$ single crystals[1] and at $T \lesssim 300$ K the temperature evolution of $\rho_\|$ was different from that of $\rho_\perp$: $\rho_\|$ decreased while $\rho_\perp$ increased with decreasing temperature. The first Hall measurements of $YBa_2Cu_3O_{7-x}$ single crystals were carried out in the plane parallel to the *c* axis and perpendicular to the Cu-O layers[1] ($H \| b$). The Hall voltage $V_x$ was found to be negative and the Hall constant $R_x$ turned out to be independent of the temperature in the temperature region 300–200 K, increasing by 20% near $T_c$. Our experimental measurements of the Hall voltage and of its temperature dependence were carried out in the plane perpendicular to the *c* axis. The Hall voltage was found to be positive and the shape of the $V_x(T)$ curve was different from that obtained in Ref. 1.

The $YBa_2Cu_3O_{7-x}$ single crystals were synthesized at the Institute of Crystallography of the Academy of Sciences of the USSR.[2] The samples were faceted, parallel-plane, $0.8 \times 0.2$-mm wafers measuring 10–40 $\mu$m along the *c* axis. The contacts, prepared using a silver paste, were annealed to 400–500 °C. The contact resistance, normalized to the surface area of the contact, was $\sim 10^{-4}\ \Omega/\text{cm}^2$ at temperatures in the range 90–400 K. The $V_x(T)$ and $\rho_\|(T)$ curves were measured using the five-probe method. At 400–250 K the $\rho_\|(T)$ curve was nearly linear and at $T < 250$ K the $\rho_\|(T)$ curve decayed more rapidly, as in Ref. 2. The critical temperature $T_c$ was 93 K, the width of the superconducting transition was $< 0.5$ K, $\rho_{\|300}/\rho_{\|95} \approx 4$, and $\rho_{\|300} \approx 300$ $\mu\Omega \cdot$cm.

The Hall voltage, measured in the *ab* plane in fields $H$ of up to 8 kOe ($H \| c$), depended linearly on $H$ and on the magnitude of the measuring current (0.3–60 mA) over the entire temperature interval studied. To determine the sign of $V_x$, we used *n*-type Ge samples for calibration measurements at 300 K. The two single crystals we have studied had a positive Hall voltage and a typical temperature dependence shown in Fig. 1. At 400–280 K the Hall voltage $V_x$ did not depend on the temperature; below

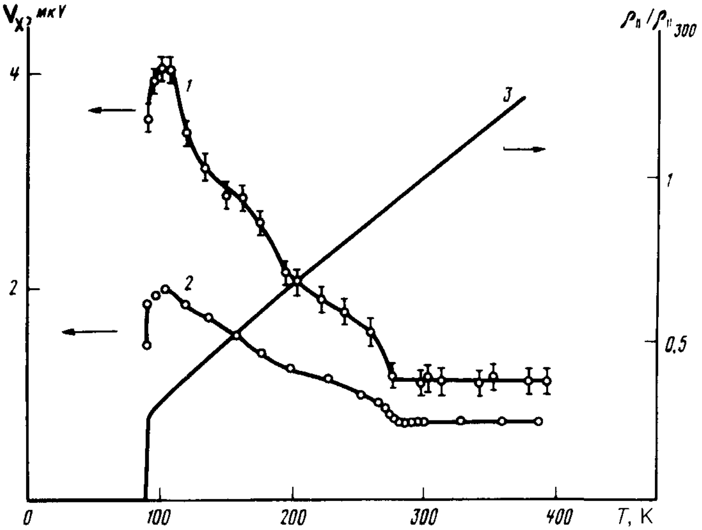

FIG. 1. Temperature dependence of the Hall voltage (curves 1 and 2) and of the electrical resistivity (curve 3) for $YBa_2Cu_3O_{7-x}$ single crystals. Curves 2 and 3 correspond to a sample with $d = 10\ \mu m$ and curve 1 corresponds to a sample with $d = 40\ \mu m$. $H = 8$ kOe, $I = 58$ mA (for curve 1) and 12 mA (for curve 2). The error in the measurement of $V_x$ corresponding to curve 2 is within the size of the circles.

280 K it increased, reached the saturation point at $T = 100$–$110$ K ($V_{x100} / V_{x300} \approx 3$), and then decreased sharply near $T_c$.

At $<300$ K the general behavior and the sign of $V_x(T)$ were in agreement with the measurements we have carried out previously using laser-deposited polycrystalline Y-Ba-Cu-O films[3] (Fig. 2). The Hall measurements with Y-Ba-Cu-O ceramics also

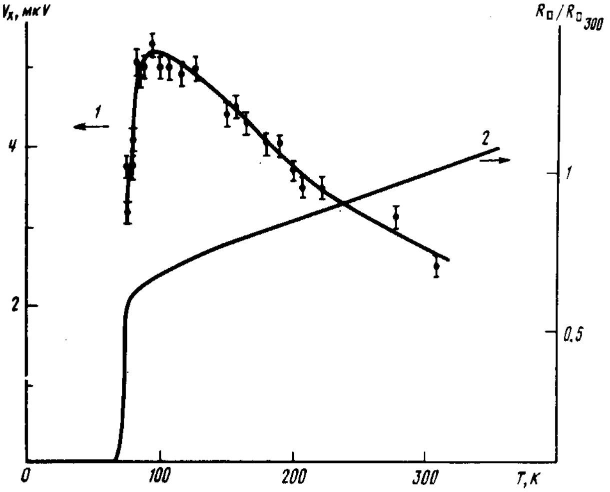

FIG. 2. Temperature dependences of the Hall voltage and of the resistance $R_\square$ for a polycrystalline Y-Ba-Cu-O film deposited on an MgO substrate. $H = 8$ kOe, $I = 0.7$ mA.

showed that the Hall constant has a positive sign.[4] The values of $R_{x300}$ obtained for two single crystals of different thicknesses ($R_{x300} = 8.2 \times 10^{-4}$ cm$^3$/C for $d = 10\ \mu$m and $R_{x300} = 1.1 \times 10^{-3}$ cm$^3$/C for $d = 40\ \mu$m) and for the films ($R_{x300} = 9.3 \times 10^{-4}$ cm$^3$/C for $d = 0.2\ \mu$m) were approximately the same and corresponded to a concentration $p \approx 6 \times 10^{21}$ cm$^{-3}$.

At $T \gtrsim 280$ K the behavior of the $V_x(T)$ curve is of the usual metallic nature. In Ref. 5 the temperature dependence of the thermoelectromotive force $s(T)$ of a single-phase Y-Ba-Cu-O ceramic also exhibited a metallic nature at these temperatures. The rise of the $R_x(T)$ curve observed at temperatures 100–280 K correlates with the increase of $\rho_\perp(T)$ (Ref. 1) and with the anomalous increase of $s(T)$ (Ref. 5) in this temperature region.

A decrease in the carrier density with decreasing temperature, which precedes the superconducting state and which is not observed in ordinary superconductors (such as tin, indium, etc.) at temperatures above the critical temperature, may be attributed to the development of the Peierls instability. The behavior of $\rho_\parallel$, $\rho_\perp$, and $V_x(T)$, which was very similar to that of $YBa_2Cu_3O_{7-x}$, was observed in $TaSe_3$ single crystals at $150\ K < T < 250$ K, where it was attributed to the uncompleted Peierls transition.[6] Indirect evidence of this assumption was seen in the fact that the $YBa_2Cu_3O_{7-x}$ single crystals have a layered structure and that the temperature interval 100–280 K corresponds to the scale of the Peierls transition temperature. The difference in the behavior of $\rho_\perp(T)$ and $\rho_\parallel(T)$ curves stems from the fact that a softening of the phonon spectrum resulting from the Peierls instability generally causes the scattering to increase considerably in the direction perpendicular to the direction of the conducting strings (or layers).[6] In other words, the Peierls structural phase transition is usually preceded by an appreciable increase in the anisotropy of the conductivity. In this case $\rho_\perp(T)$ may increase with decreasing temperature, while $\rho_\parallel(T)$ has the usual metallic nature.

Another explanation of the state observed below 280 K is based on the assumption of the existence of antiferromagnetism, although the antiferromagnetic state observed in the $La_2CuO_{4-x}$ system at temperatures below 240 K (Ref. 7) so far has not been observed in the Y-Ba-Cu-O system.

The saturation and sharp decay of the $V_x(T)$ curve near $T_c$ as the temperature is lowered (Figs. 1 and 2) were observed previously in $(La_{1-x}Sr_{2x})_2CuO_4$ single-crystalline films.[8] This behavior is most likely attributable to the transition of the system to the superconducting state.

The reason for the opposite sign of the Hall voltage in the planes parallel to and perpendicular to the $c$ axis has so far not been fully explained. The fact that $R_x$ may have an opposite sign was nonetheless discussed in Ref. 1, where it was attributed, on the basis of the yet unpublished calculations, to the strong anisotropy of the electronic spectrum and to a deviation of the band structure of $YBa_2Cu_3O_{7-x}$ from the parabolic shape.

We note in conclusion that the development of the Peierls instability may be accompanied by the appearance of diffuse-scattering lines which result from the fluctuation of the superlattice at $T > T_p$ (Ref. 9) and which can be identified by means of structural studies. A question which naturally arises is that of the role of the state in the realization of high-temperature superconductivity at $T < 280$ K: Does it stimulate the superconductivity or does it prevent the superconductivity from occurring even at higher temperatures?

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