# Change in the sign of the Hall effect in a superconducting transition in $Bi_2CaSr_2Cu_2O_x$ single crystals

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It is shown that the Hall voltage $V_H$ in superconducting single crystals of $Bi_2CaSr_2Cu_2O_x$ in the resistive state in a magnetic field is characterized by a thermally activated dependence and that its sign is opposite to that in the normal state. The results are explained in terms of the vortex motion.

An important feature of high-$T_c$ superconductors is the fact that at $T < T_c$ they undergo a transition, in a magnetic field $H > H_{c1}$, to the resistive state in which the resistance $R(T)$ decreases to zero in the temperature interval of $T_c - T$ of $\gtrsim 10$ K. In a Bi–Ca–Sr–Cu–O superconductor, in which the anisotropy of the critical magnetic fields and the conductivity are higher than those in YBCO, the "tail" of the $R(T)$ curve extends to lower temperatures. In several studies[1,2] the resistive state is explained in terms of the creep: a thermally stimulated motion of the Abrikosov vortices. Our results of the measurement of the Hall effect confirm that at $T < T_c$ the properties of the resistive state differ markedly from the properties of the normal phase and that they can be explained in terms of the vortex motion.

The single crystals were obtained by a spontaneous crystallization as a result of slow cooling of the melt $Bi_2O_3$, CaO, $SrCO_3$, and CuO with an excess of CuO (Ref. 3). The single crystals were plates with dimensions $\approx 1$ mm in the *ab* plane and $\lesssim 10$ $\mu$m along the *c* axis. According to the data on x-ray diffraction in the *ab* plane and electron diffraction due to the incidence of an electron beam along the [001] direction, the single crystals have an orthorhombic structure with the lattice constants $a = 5.42$, $b = 5.38$, and $c = 30.72$ Å. The composition of the single crystals, determined by means of a microprobe analysis, was approximately equal to that of $Bi_2CaSr_2Cu_2O_x$. The electrical contacts, established by brazing Ag paste in oxygen medium at 600 °C, had a resistance of $\sim 10^{-4}$ $\Omega \cdot cm^2$. The resistivity of the single crystals was $\rho \approx 0.2$ m$\Omega \cdot$cm at 300 K and the residual resistance, determined by extrapolating $R(T)$ to $T = 0$, was 5% of $R$ (300). At 300 K the anisotropy of the conductivity $\sigma_{ab}/\sigma_c$, reaches a value of $2 \times 10^4$ and increases twofold as $T$ is lowered to $T_c$, while the ratio of the fields $H \| c$ and $H \perp c$, which cause the midpoint of the transition to shift by 1 K, is $\approx 20$–30. The Hall voltage was measured in the *ab* plane on the basis of a standard five-band scheme,[3] with a measuring current of $< 20$ mA in fields $H$ up to 9 kOe. For the measurements we chose single-phase samples with $T_c \approx 80$ K.

The temperature dependences of the resistance of single crystals in the *ab* plane for several values of $H \| c$ are shown in Fig. 1. At temperatures in the range 300–100 K the dependence $R(T)$ is linear, below 100 K it begins to diverge from the linear law, near 82 K the resistance decreases rapidly, and, finally, it goes down to zero slightly more smoothly in the last section. In a field $H$ the resistive transition shifts toward low temperatures near the small values of $R$, and $\rho(T) \sim \rho_0 \exp(-U/T)$. At $H = 5$ kOe we have $U \approx 850$ K and $\rho_0 \approx 0.12$ Ω·cm, consistent with the data of Ref. 2. In the resistive state the I–V characteristics are linear to currents of 50 mA.

Figure 1 also shows plots of the Hall voltage, $V_H(T)$. At $T_c \lesssim T < 300$ K we see that $V_H$ corresponds to a positive charge of the current carriers, and $V_H(100)/V_H(300) \approx 1.5$ (see also Ref. 4). Using a simple formula $R_H = 1/nec$, we estimate the carrier density to be $n \approx 4 \times 10^{21}$ cm$^{-3}$. A change in the sign of $V_H$ near $T_c$ was reproducibly observed in five samples.[1)] In all the cases the sign changes at temperatures 3–5 K higher than $T_c$ [$R(T_c) = 0$ at $H = 0$]. The $V_H(T)$ dependence, which was analyzed in greatest detail in the same sample as the $R(T)$ dependence, at $T < 75$

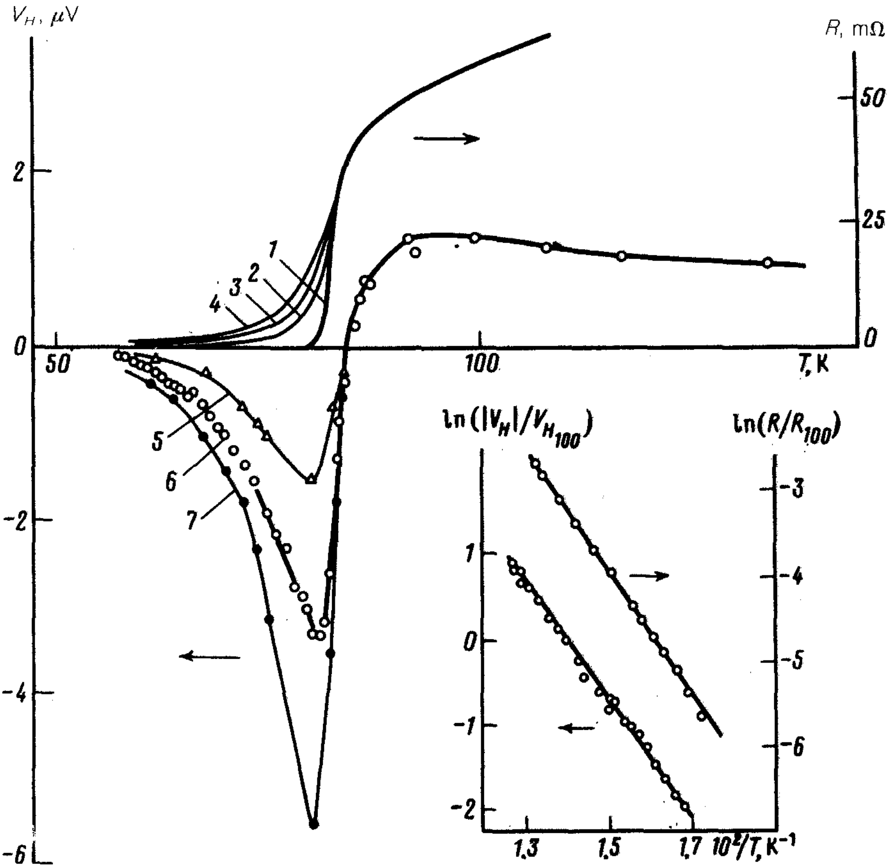


FIG. 1. Temperature dependence of the electrical resistance and Hall voltage in single crystals of $Bi_2CaSr_2Cu_2O$. Curve 1 corresponds to $H = 0$; curves 2 and 5 correspond to $H = 2$ kOe; curves 3 and 6, $H = 5$ kOe; curves 4 and 7, 9 kOe. Curves 5 and 7 are plotted for $T < 84$ K. The inset shows the thermally activated nature of $R(T)$ and $V_H(T)$ at $T < 75$ K and $H = 5$ kOe.

K has the form $V_H(T) \propto \exp(-U/T)$, with the same activation energy $U$ (see the inset in Fig. 1). The Hall angle is $\theta \approx 0.03$. The Hall voltage is linear with respect to the current to 50 mA over the entire temperature interval studied and at $T > 90$ K it is linear even with respect to $H$.

Let us discuss the results. An increase in $V_H$ with decreasing temperature near $T > T_c$, which has also been observed in YBCO single crystals[7] and Tl ceramics,[8] is apparently a common property of high-$T_c$ superconductors. The problem of the nature of such a dependence remains unresolved. The results of the measurements of $V_H$ at $T \lesssim T_c$, as well as the data on $R(T, H)$, are evidence, in our view, in favor of the vortex creep in the resistive state. In the case of creep induced by thermal excitation, the vortices overcome the pinning-center potential and creep between the pinning centers. The transport current $\mathbf{j} = eN_S\mathbf{v}_S$ causes the Magnus force (see, e.g., Ref. 9) $\mathbf{F}_m = K_S\,[\mathbf{v}_S - \mathbf{u}, \mathbf{H}/H]$ (the factor $K_S$ vanishes at $T > T_c$, along with the condensate density $N_S$) to act on the vortices moving between the pinning centers with a velocity $\mathbf{u}$. This force causes the vortices to move not only in the $y$ direction but also to be

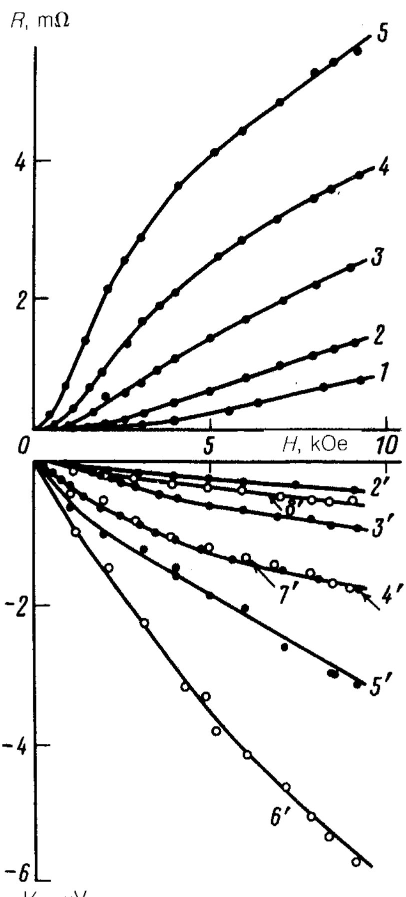


FIG. 2. $R(H)$ and $V_H(H)$ curves for single crystals of $Bi_2CaSr_2Cu_2O_x$ measured at various temperatures: 1—57.8 K; 2,2′—61.5 K; 3,3′—67.5 K; 4,4′—72.0 K; 5,5′—74.5 K; 6′—80.0 K; 7′—83.0 K; 8′—84.0 K.

entrained by the current **j** along the $x$ axis. In a crude approximation it can be assumed that a vortex in motion is also affected by a frictional force $\mathbf{F}_f = -\eta\mathbf{u}$. Equating the forces $\mathbf{F}_m$ and $\mathbf{F}_f$, we find $u_x = (K_S/\eta)u_y$. This relation is also valid for the components of the average velocity $\bar{\mathbf{u}}$. The motion of vortices with an average velocity $\bar{\mathbf{u}}$ leads to the appearance of an average electric field $\mathbf{E} = 1/c\ [\mathbf{H}\bar{\mathbf{u}}]$ in the superconductor, which contributes the component $E_y = -(1/c)Hu_x$ to the Hall voltage, in addition to the component $E_x \| j$.

Since the quasiparticle current is $j_n \neq 0$ in the resistive state, there should also be an ordinary contribution to the Hall voltage which determines the Hall effect in the normal state and which is due to the action of the Lorentz force $\mathbf{F} = e/c\ [\mathbf{vH}]$, where **v** is the drift velocity of the normal carriers. The sign of the Lorentz force is opposite to that of the force acting on the electrons due to the field $E_y$ which is induced by the vortex motion. The resultant field which produces the Hall voltage is $E_H = (1/c)H(v - \bar{u}_x)$. Since $u_y = E_x c/H = j\rho c/H$, and since $j_n = evn = E/\rho_N$ ($\rho_N$ describes the response of the normal excitations to a field $E$; $\rho_N$ near $T_c$ is equal to the normal-state resistivity), we find $E_H = j\ (\rho/\rho_N)[(H/nec)-(K_S/\eta)\rho_N]$. In the superconducting state ($K_S \neq 0$) the second term, which is associated with the entrainment of vortices by the transport current, may dominate in the case of high mobility of the vortices in $E_H$. At the values of $H$ and $T$ at which $N_S$ and $\eta$ change only slightly, the dependence $E_H(H,T)$ is determined by the behavior of $\rho(H,T)$. This situation may account for the fact that the nature of the curves of $V_H$ and $\rho$ vs $T$ and vs $H$ is the same in Figs. 1 and 2.

The fact that $V_H$ changes sign slightly above $T_c$ may be regarded as an indication

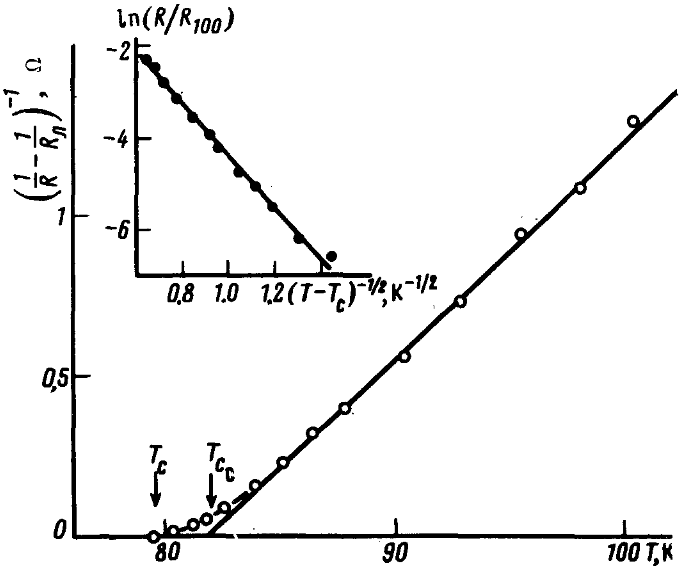


FIG. 3. Deviation of $R(T)$ from a linear curve near $T_c$ (the straight line corresponds to the Aslamazov-Larkin formula for a 2D superconductor of thickness $d = 13$ Å). The inset shows $R(T)$ curve for $T \gtrsim T_c$.

that vortices exist at $T \gtrsim T_c$. Such an approach is valid if it is assumed that $T_c$ is the Kosterlitz-Thouless transition temperature, above which a heat-induced generation of vortices occurs inside the CuO layers. Standard conditions for the occurrence of the Kosterlitz-Thouless transition are (see the review by Mooij[10]) the dependence $R(T) \propto \exp(-C/\sqrt{T_c - T})$ near $T_c$ at $T \gtrsim T_c$, which becomes the dependence for the fluctuational correction to the Aslamazov-Larkin conductivity for the 2D case as the temperature is raised, and the nonlinear I-V characteristics of the type $V \sim I^n$, whose index increase rapidly, $n \geqslant 3$, at $T \leqslant T_c$ as the temperature is lowered. The $R(T)$ dependence indicated above was in fact observed (Fig. 3). The preliminary measurements of the I-V characteristics at $T \lesssim T_c$ also suggest that a Kosterlitz-Thouless transition can occur. A rigorous proof of the existence of such a transition requires, however, further study. We note that dependences characteristic of the Kosterlitz-Thouless transition were observed previously in YBCO single crystals.[11]

The behavior of the Hall voltage in the resistive state can thus be explained in terms of the vortex motion.

[1)]A change in the sign of $V_H$ in BSCCO and YBCO films at $T < T_c$ was observed in Refs. 5 and 6.

[1]M. Tinkham, Phys. Rev. Lett. **61**, 1658 (1988).
[2]T. T. M. Palstra, B. Batlogg, L. F. Schneemeyer *et al.*, Phys. Rev. Lett. **61**, 1662 (1988).
[3]Yu. I. Latyshev, I. G. Gorlova, S. G. Zybtsev *et al.*, Proceedings of the All-Union Conference on High-$T_c$ Superconductivity, Khar'kov, Vol. 1, 1988, p. 149.
[4]H. Takagi, H. Eisaki, A. Maeda *et al.*, Nature **332**, 236 (1988).
[5]C. E. Rice, A. F. G. Levi, K. W. Balolwin *et al.*, Appl. Phys. Lett. **52**, 1828 (1988).
[6]H. L. Stormer, A. F. G. Levi, R. M. Fleming *et al.*, Phys. Rev. **B38**, 2472 (1988).
[7]I. G. Gorlova, S. G. Zybtsev, and Yu. I. Latyshev, Pis'ma Zh. Eksp. Teor. Fiz. **47**, 100 (1988) [JETP Lett. **47**, 121 (1988)].
[8]J. Clayhold, N. P. Ong, P. H. Hor *et al.*, Phys. Rev. **B38**, 7016 (1988).
[9]N. B. Kopnin and V. E. Kvartsov, Zh. Eksp. Teor. Fiz. **71**, 1644 (1976).
[10]J. E. Mooij, in: NATO Advanced Study Institute on Percolation, Localization and Superconductivity, Ed. by A. M. Goldman and S. A. Wolf, Plenum, New York, 1984, p. 325.
[11]P. C. E. Stamp, L. Forro, and C. Ayache, Phys. Rev. **B38**, 2847 (1988).

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