# Peak effect and flux creep in single crystals in the case of the current flow across the layers

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The resistive transition and the critical current of $Bi_2Sr_2CaCu_2O_x$ single crystals have been studied experimentally when the current was flowing across the CuO layers in magnetic fields up to 14 T. The results are in qualitative agreement with the results obtained when the current was flowing parallel to the CuO layers. The discrepancy is attributed to the formation and motion of core-free magnetic vortices when $I \parallel c$ and $H \parallel ab$.

The existence of Abrikosov vortices ($A$ vortices) in $H \perp ab$ in single crystals of layered high-$T_c$ superconductors has now been established fairly reliably by the decoration methods. The thermal activation of the magnetic resistance[1] and the restriction put on the critical current in the $ab(I_{c\parallel})$ plane are also explained in terms of the motion of these vortices with $I \parallel ab$. The superconductivity in layered high-temperature superconductors in the direction of the $c$ axis is, in all likelihood, governed by the Josephson tunnel coupling between the layers.[2] This coupling may give rise to the appearance in $H \parallel ab$ of Josephson-type magnetic vortices ($J$ vortices).[3] The motion and pinning of such vortices determine the nature of the dissipation and $I_{c\perp}$ for $I \perp ab$. In the present letter we report the results of an experimental study of the thermal activation of the magnetic resistance ($H \parallel ab$) and the $I_{c\perp}(H)$ dependence of BSCCO (2-2-1-2) single crystals when the current flows across the layers.

The method of growing the single crystals, their properties, and their structural characteristics, were described elsewhere.[4,5] The samples were $\approx 0.3 \times 0.3 \times 0.005$ mm in size. We used coaxial end-face indium contacts with a gold sublayer which covered a large part of the surface area of the opposite (001) faces of the single crystal. The contact resistance was $\sim 10^{-6}\ \Omega \cdot \mathrm{cm}^2$, three orders of magnitude lower than the resistance of the crystal along the $c$ axis, $R_\perp$, allowing us to use the two-probe measurement method.

Figure 1 shows plots of $R_\perp(T)$ in various fixed magnetic fields for two orientations of $H$, $H \perp ab$ and $H \parallel ab$. For small values of $R$: $R < 0.1$–$0.2R(T > T_c)$ they have a thermally activated nature, $R_\perp \propto \exp[-U(H)/T]$, similar to that found previously for the resistance in the $ab$ plane.[1] The activation energies $U$ determined from our data ($I \perp ab$) and those determined from the data of Ref. 1 ($I \parallel ab$) are compared in the inset in Fig. 1. Two characteristic features can be pointed out: 1) in the configuration under study, $H_\perp$ and $I_\perp$, the value of $U$ and its dependence on $H(U \propto H^{-1/6})$ coincide with the data of Ref. 1, which were measured in the $H_\perp$, $I_\parallel$ configuration.[1)] In other words, it turns out that $U$ is determined solely by the $H_\perp$ component and does not depend on the orientation of $I$. 2) The largest value of $U$ was obtained for the $H_\parallel$, $I_\perp$ (which was

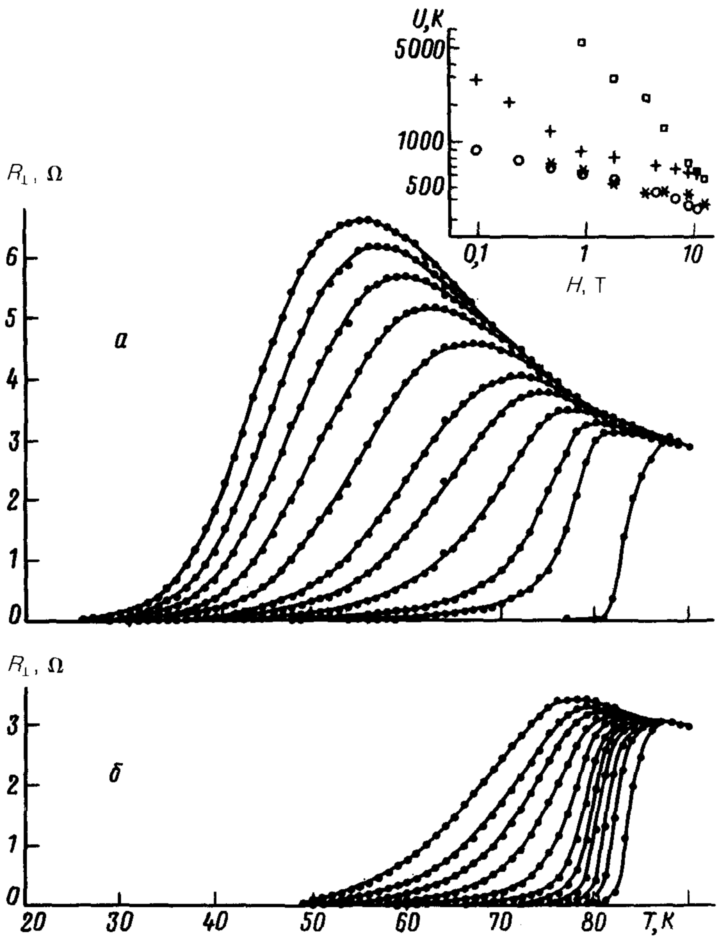

FIG. 1. Resistive transition in a $Bi_2Sr_2CaCu_2O_x$ single crystal along the $c$ axis in magnetic fields (a) $H \perp ab$; (b) $H \| ab$. The curves (from left to right) correspond to the following values of $H(T)$: 14, 12, 10, 8, 6, 4, 3, 2, 1, 0.5, and 0. $I = 100\ \mu A$. The inset shows the plot of the activation energy of the resistance $U$ versus $H$ for various orientation of $I$ and $H$: □—$I_\perp, H_\|$; *—$I_\perp, H_\perp$; + —$I_\|, H_\|$; O—$I_\|, H_\perp$. The data labeled + and O were taken from Ref. 1.

not investigated previously), reaching $5 \times 10^3$ K at $H = 1$ T. It depends most critically on $H$: $U \propto H^{-1}$. The thermally activated motion of $J$ vortices in the $ab$ plane should manifest itself in such a configuration. The large value of $U$ clearly is attributable to the one-dimensional nature of their motion. Further studies, however, must be carried out.

The critical current $I_{c\perp}$ was determined from the sharp deviation (or abrupt change) (at the level of $10^{-5}$ V) on the $I$–$V$ characteristic from the initial region of the $I$–$V$ characteristic close to the resistive region, which is determined by the contact resistance of $\approx 0.01\ \Omega$. With a decrease in the temperature, $I_{c\perp}$ increases and gradually becomes saturated at $T < 20$ K, reaching values of 100–150 mA, which correspond to the current density of $\sim 10^2$ A/cm$^2$. At these temperatures strong fluctuations have been observed in the resistive part of the $I$–$V$ characteristic. The $I$–$V$ characteristic is comprised of sections of nearly constant differential resistance which increases abruptly with increasing $I$ (Fig. 2).

The effect of $H_{\parallel}$ on the $I$–$V$ characteristics is shown in Fig. 2. An increase in $H$ causes the fluctuation of the $I$–$V$ characteristic and the $I_c$ to decrease. At $H \approx 7$ mT, $I_c$ reaches the minimum value, which is about one-third as large as $I_c(0)$, and then begins to increase with a further increase in $H$. A lowering of the magnetic field, beginning at $H \approx 0.1$ T, will cause a hysteresis of $I_c(H)$ (the inset in Fig. 3), which suggests that the flux is captured. The $I_c(H)$ curve goes through the minimum at lower values of $H$. With an increase in $H$ ($H > 0.1$ $T$), the $I_c(H)$ curve continues to increase, goes through the maximum at $H \approx 1$ T, and then decreases. The most surprising point is that at the maximum $I_c(H)$ exceeds the value of $I_c(0)$. The plot of $I_c(H)$

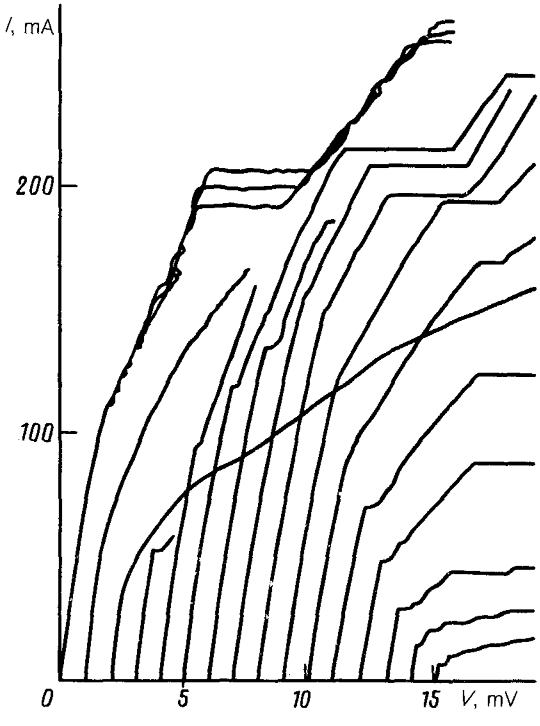

FIG. 2. The $I$–$V$ characteristics of a $Bi_2Sr_2CaCu_2O_x$ single-crystal sample, measured along the $c$ axis for various values of $H \| ab$. The curves (from left to right) correspond to the following values of $H(T)$: 0, 0.003, 0.07, 0.09, 0.27, 0.35, 0.5, 1.0, 1.5, 2.2, 3.4, 5, 8, and 12. The curves for $H > 0$ are sequentially displaced by 1 mV along the $V$ axis. $T = 30$ K. The $I$–$V$ characteristics at $H = 0$ were measured three times under the same conditions.

is qualitatively similar for the orientation $H \perp ab$ (Fig. 3). The $I_c(H)$ plot in this case is displaced by 1.5 to two orders of magnitude down the $H$ scale, and there is virtually no minimum on the plot. It is important to note that in the preceding experiments, in which the $I_c$ was measured in single crystals in the $ab$ plane, the $I_c(H)$ curve always decreased monotonically,[6] although it exhibited nonmonotonic behavior in certain samples.[11,12] The observed nonmonotonic behavior was much weaker and at $H=0$ the current $I_c$ peaked at a lower value than $I_c(0)$. Such a behavior of the curve was attributed in Ref. 12 to the distortion of the Fraunhofer curve in the narrow Josephson junctions between the grains caused by the Abrikosov vortices that move parallel to the transition plane.

In our case, we attribute the nonmonotonic behavior of the $I_c(H)$ curve to the depinning of $J$ vortices and to the effect of $A$ vortices on this process. We note that the lower critical field for penetration of $J$ vortices, $H_{c1}^J$, is small $[H_{c1}^J \approx H_{c1}^A(\lambda/\lambda_c) \approx 10^{-2} H_{c1}^A$, where $H_{c1}^A$ is the lower critical field for penetration of the $A$ vortices]. The $J$ vortices can therefore exist in the sample even in a weak field $H$ in any orientation. If $H_\parallel > H_{c1}^J$ and $H_\perp < H_{c1}^A$, the sample has primarily $J$ vortices, while the concentration of $A$ vortices is low: $N_A \approx N_J H_\perp (\lambda/\lambda_c)[(H_{c1}^A)^2 - H_\perp^2]^{-1/2}$. If $H_\perp > H_{c1}^A$, the induction vector $B$ rotates from the position of being nearly parallel to the layers to

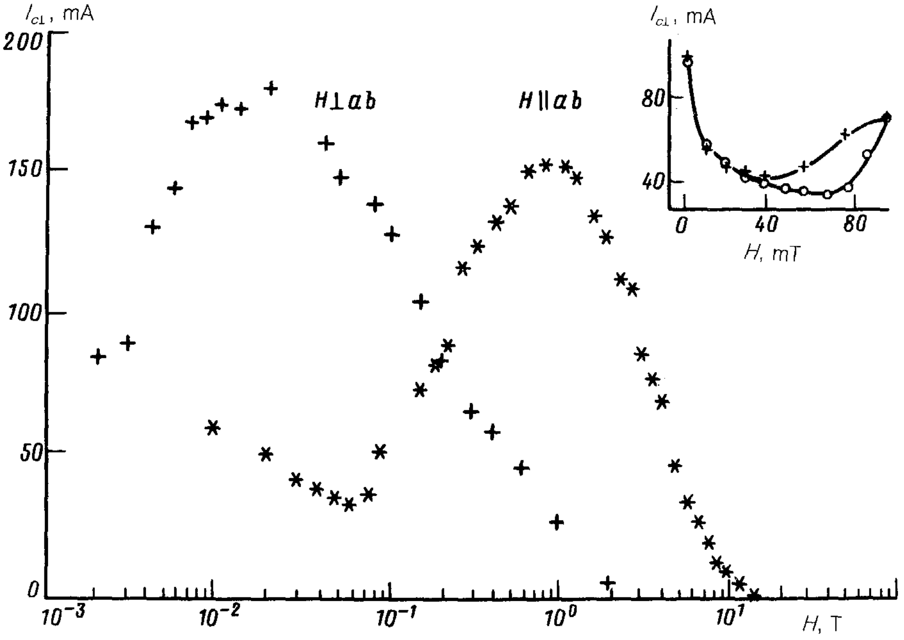

FIG. 3. The critical current of a BSCCO single crystal along the $c$ axis versus the magnetic field in two orientations, measured when $H$ was increased gradually. The inset shows the hysteresis of the $I_{c\perp}(H_\parallel)$ curve. $T = 30$ K.

being perpendicular to them, and the concentration $N_A$ increases rapidly with increasing $H_\perp$: $N_A \approx N_J H_\perp / N_\parallel$ for $H \gg H^A_{c1}$.

The $J$ and $A$ vortex lattices in this case exist independently of each other (in the thermodynamic sense), and interaction between them occurs if a transport current $I$ which causes the vortices to slip, flows through the sample. The $I_\parallel$ component of the current affects the $A$ vortices, and the $I_\perp$ component affects the $J$ vortices in the direction of the layers. The absence of a core in the $J$ vortices allows us to conclude that pinning of $A$ vortices at inhomogeneities is stronger than that of $J$ vortices. The critical current $I_{c\perp}$ is therefore determined by the pinning of $J$ vortices on defects when $N_A$ is small and by the pinning on the $A$ vortices as their concentration increases. To quantitatively describe the $I_{c\perp}(H)$ dependence, Volkov[7] considered a simple model in which a small shear modulus of the $J$ lattice was used. The depinning of $J$ vortices can then be approximately represented as a slipping of the $J$-vortex chain in a Josephson junction, with allowance for the irregularities and $A$ vortices that penetrate the junction. In low fields $H$ the current $I_{c\perp}$ decreases and approaches, with increasing $H$, a constant value which is determined by the pinning of the $J$ vortices on the defects.[8] With an increase in $H_\perp$, the concentration of $A$ vortices increases and the pinning of $J$ vortices can be attributed to the $A$ vortices. In the case of a random distribution of $A$ vortices ($H$ is not too large), we have $I_c \sim I_{c0}\xi^2 N_A(H_\perp)$; i.e., the critical current increases with increasing $H$. With a further increase in $H$, the $A$ vortices form a lattice, whose period in the same direction as the layers is smaller (by a factor of $\sqrt{\lambda_c/\lambda}$) than that of the $J$-vortex lattice. The forces which affect the $J$ vortices and which are attributable to the $A$ vortices average out and $I_c$ will again decrease with increasing $H$ in strong fields. The thermal fluctuations will also lead to a suppression of $I_c$ in strong fields.[9]

The motion of the $J$-vortex lines across the transport current flow, with $I > I_{c\perp}$, may account for the constant differential resistance steps on the $I$–$V$ characteristics which are similar, for example, to those on the $I$–$V$ characteristics for films of ordinary superconductors in the case of the motion of $A$-vortex lines.[10]

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[1)] The data which we have obtained earlier[5] using the same single crystals in the $H_\perp$, $I_\parallel$ configuration in fields $H = 0.3$–$1$ T are also in agreement with Ref. 1.

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