Equivalence of the effect of weak magnetic field and current on the resistance of $Bi_2Sr_2CaCu_2O_x$ single crystals below the Berezinskiĭ–Kosterlitz–Thouless transition temperature

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The resistance of $Bi_2Sr_2CaCu_2O_x$ single crystals in the ab plane below T_c is found to depend equally on the magnetic field ($H \| c$) and the current ($I \perp c$): $R \propto H^{b(T,I)}$, $R \propto I^{a(T,H)}$. The dependence $b(T,I)_{I\to 0} \equiv a(T,H)_{H\to 0}$ and, in general, changes abruptly at $T = T_c$. The results show that the vortex pairs can be excited by the Meissner currents.

The results of the most recent studies of single crystals of the strongly anisotropic high-T_c superconducting systems—BSCCO (Refs. 1 and 2) and TBCCO (Ref. 3)[1)]—have shown that they have a Kosterlitz–Thouless transition with a transition temperature T_c a few degrees lower than the Ginzburg–Landau superconducting transition temperature T_{c0}. The Kosterlitz–Thouless transition in those experiments was linked with the thermal excitation of 2D magnetic vortex pairs in single Cu layers (or pairs of layers) which were isolated sufficiently well from each other in these compounds. At $T < T_c$ the $R(I)$ curves[2] are similar to those observed in thin (2D) films of ordinary superconductors. The power-law $R(H)$ curves were analyzed by analogy with thin films.[1,3] In those studies the behavior of the $R(H)$ curves was attributed to an increase in the concentration of 2D vortices, with the same orientation of the magnetic moment, as H was increased, and to a decrease in the energy of the interaction of vortex-antivortex pairs as a result of this process. Under this assumption the exponent $b = d(\ln R)/d(\ln H)$ should be twice as large as the exponent $a = d(\ln R)/d(\ln I)$: $a = 2b$. Until now, however, this ratio has not been checked in BSCCO compounds, and in TBCCO single-crystal films it was checked only in a narrow temperature interval, ~ 1 K, near T_c (Ref. 3), where a/b varied between 0.5 and 2. Our studies of BSCCO single crystals showed that $a = b$, suggesting that the behavior of $R(H)$ is determined largely by the screening currents.

The experiment was carried out with single-phase BSCCO single crystals of the 2–2–1–2 composition.[2] The single crystals, with $T_c \approx 87$ K, were grown from a KCl melt by a method used in Ref. 6. At 300 K the electrical resistivity was $\sim 150\,\mu\Omega\cdot$cm in the ab plane and the conductivity anisotropy σ_{ab}/σ_c reached $\sim 10^5$ at $T \approx 100$ K.

At the specified value of the magnetic field we measured the current-voltage characteristics while systematically varying discretely the temperature in steps of < 0.5 K. The measurements were then repeated at the next value of H, and so on. From these data we plotted the $R(I)$ curves for various fixed values of H and T and the $R(H)$ curves for fixed I and T. As can be seen in Fig. 1, the $R(H)$ curves (up to

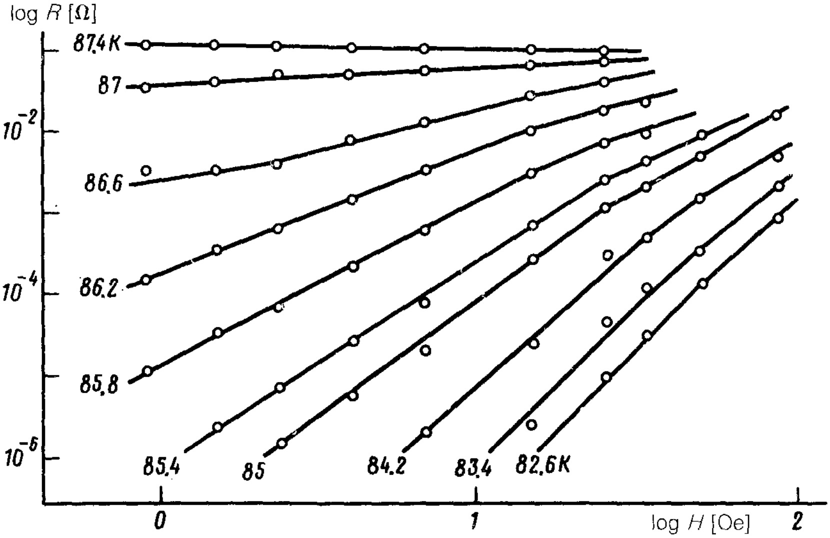

FIG. 1. Nonlinear resistance of a $Bi_2Sr_2CaCu_2O_x$ single crystal in the *ab* plane vs the magnetic field $(H \| c)$ at various temperatures $(I = 4$ mA).

$H = 30$–50 Oe) are power functions. The corresponding temperature dependences of the exponent b for various values of I are shown in Fig. 2b. For small values of I $(I < 1$ mA) the curve of $b(T)$ is exactly the same as the curve of $a(T)$ at $H < 0.5$ Oe (Fig. 2a) with a universal jump at $T = T_c$. The ratio a/b is close to 1 over the entire temperature interval (Fig. 2c). With an increase in I (up to $I \sim 50$ mA) the $R(H)$ curves remain power functions, as do the $R(I)$ curves when H is raised (to ~ 100 Oe). The slopes of $a(T)$ and $b(T)$ in this case decrease and the jump of a and b at $T \approx T_c$ gradually becomes diffuse (Fig. 2). A comparison of the quantities H and I, which lead to the same decrease in the values of a and b, showed that they are related linearly $I = kH$, where $k \approx 2.5$ mA/Oe (Fig. 3).

Let us discuss the results. The weak magnetic field $H < H_{c1}$ (H_{c1} in BSCCO near T_c amounts to several tens of oersteds[7]) should not penetrate into the interior of the sample in the form of 3D magnetic vortices and the state of the system will be determined by the Meissner currents. It can be assumed that like the transport current, these screening currents create vortex pairs, thereby affecting the resistance of the sample. The exponents of the $R(I)$ and $R(H)$ curves in this case should be the same $a = b$, since the screening current $I_s \propto H$. An estimate has shown that $I_s \sim (4\pi/c)\lambda H$, where λ is the penetration depth of the magnetic field $H \| c$. In other words, the magnetic field and the transport current I, which change resistance identically, are related by $I/H \sim (c/4\pi)\lambda$. Substituting for λ the quantity ≈ 0.3 μm, which is determined from the $a(T)$ curve at $T \approx T_c$ (Ref. 2), we find $I/H \sim 2.5$ mA/Oe, in agreement with the value obtained experimentally (Fig. 3).

The experimental data accordingly indicate that the screening current can break the coupled vortex pairs and increase the density of the free vortices and antivortices.

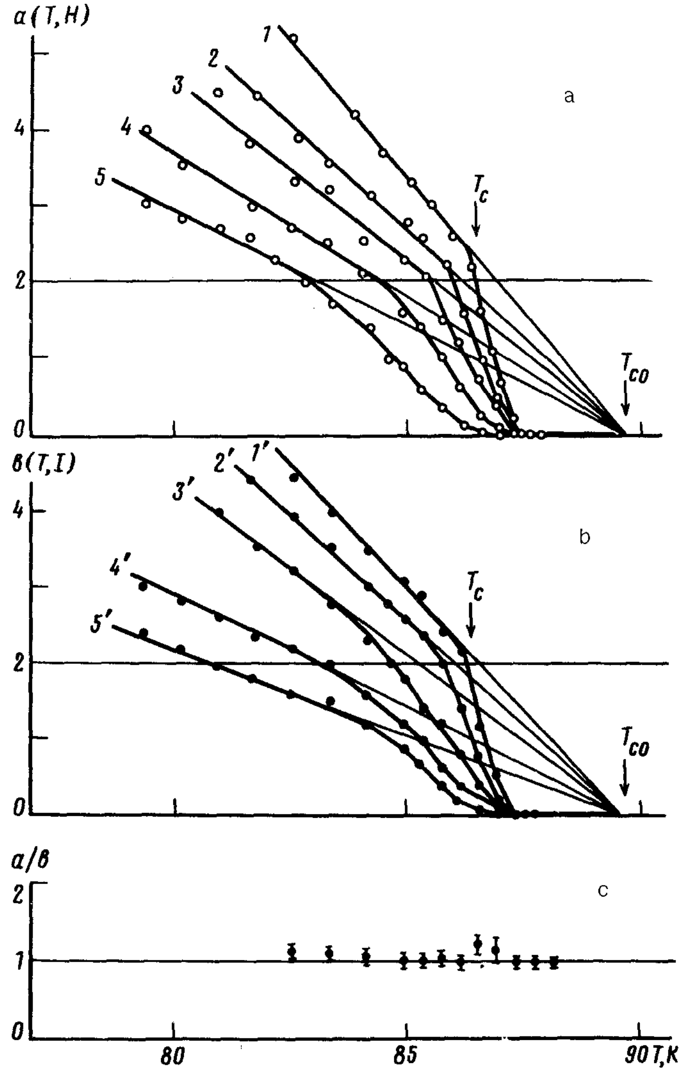

FIG. 2. Temperature dependence of the power indices a and b of the nonlinear charactistics. a) $R(I)$ for various H: 1—<0.5 Oe; 2—0.9; 3—2.4; 4—7.1; 5—15 Oe; b—$R(H)$ for various I: 1'—1.2 mA; 2'—4.0; 3'—12; 4-4'—25; 5'—40 mA; c) the ratio a/b obtained by comparing the limiting curves 1 and 1'.

In contrast with the transport current, the screening current should nonetheless remain dissipationless. Determining the diamagnetic response of the system[8] the screening current cannot in all likelihood set in motion the vortices it creates.

The results we have obtained are inconsistent with the model proposed by Martin *et al.*[1] In this model the action of the magnetic field is linked with the creation of vortices of the same orientation in each layer, just as in the thin films of ordinary

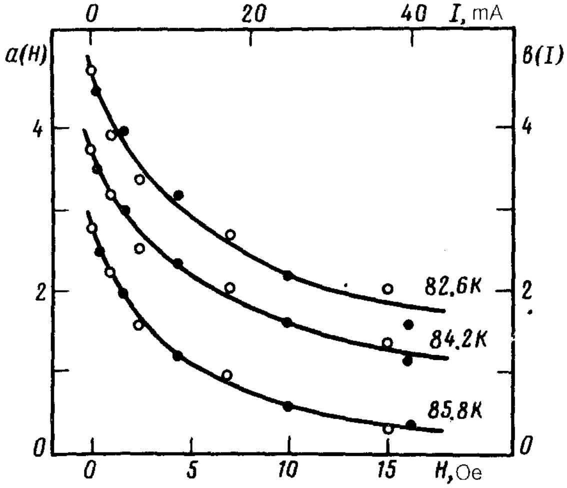

FIG. 3. A comparison of H and I which lead to an equivalent reduction of the power indices $a(H)$—○ and $b(I)$—● at three different temperatures.

superconductors. On the basis of the assumption of Martin *et al.*[1] the exponents of $R(H)$ and $R(I)$ should differ by a factor of two: $a = 2b$. This ratio, however, was not verified experimentally by them, since the nonlinear characteristics of $R(I)$ were not measured. They also did not observe a universal jump on the curve of $R(H)$, which would have allowed them to see how a and b are related at $T \approx T_c$. By itself this model ignores the 3D characteristics of the system and assumes that H_{c1} of a layered crystal is the same as that of a single layer.

We have thus shown that the effect of a weak magnetic field on the resistance of BSCCO single crystals can be explained in terms of the creation of vortex pairs in the superconducting layers. In contrast with the $R(I)$ curve, the behavior of the $R(H)$ curve for a single crystal differs from that of a thin film of an ordinary superconductor and is probably determined by currents which screen the magnetic field.

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[1)] It has been suggested in Refs. 4 and 5 that a Kosterlitz-Thouless transition occurs in YBCO systems.

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