Nelson-Kosterlitz jump in $Bi_2Sr_2CaCu_2O_x$ single crystals

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Current-voltage characteristics of the $V \propto I^a$ type have been observed in the ab plane of BSCCO single crystals at temperatures below T_c, with a characteristic dependence $a(T)$ with a universal jump at $T = T_c$. The results of the measurements are explained in terms of a Kosterlitz–Thouless transition accompanied by the creation of 2D magnetic vortices within the superconducting layers.

The high-temperature superconductors have a layered structure, as is known quite well, so one might expect to see manifestations of effects associated with a 2D superconductivity. Recent papers indicate the occurrence of a Kosterlitz-Thouless (KT) transition, which is characteristic of 2D systems in single crystals[1] and ceramic samples[2] of YBCO. Some evidence in favor of a transition of this sort in BSCCO was also noted in Ref. 3.

A KT transition, in the course of which there is a thermally activated creation of pairs of magnetic vortices, is observed in thin films of ordinary superconductors (see the review by Mooij[4]). A KT transition is characterized by a behavior of the vortex concentration and thus the resistance of the crystal which is described by $R/R_N \propto n\xi^2 \propto \exp(-c/\sqrt{T-T_c})$ at temperatures just above T_c, which is the temperature of the KT transition. One of the primary pieces of evidence in favor of such a transition is a current-voltage characteristic described by $V \propto I^{a(T)}$, with a dependence $a(T)$ which shows an abrupt increase from 1 to 3 at $T = T_c$ (a Nelson-Kosterlitz jump), followed by an increase with decreasing temperature. In experiments on YBCO, nonlinear current-voltage characteristics were observed, but the $a(T)$ dependence was smooth, having no jump,[1,2] and its shape was not that characteristic of a KT transition in a film. Dubson *et al.*[2] suggested that a KT transition occurs in a system of weak links between the grains of the ceramic; Stamp *et al.*[1] suggested that the transition was caused by solitons which exist even in the normal state. The possibility that a KT transition results from the formation of ordinary magnetic vortices was rejected on the basis that the 2D vortices in the ab plane, which would be required for a KT transition, would be linked into 3D lines of magnetic flux.[1)]

In this letter we examine a KT transition in BSCCO crystals, in which the anisotropy of the conductivity is greater by two orders of magnitude. We have observed a Nelson-Kosterlitz jump. We show that the results of these measurements can be explained in terms of the formation of ordinary magnetic vortices within the superconducting layers and that a coupling of vortices due to magnetic and Josephson coupling does not play a major role.

Single crystals were synthesized by spontaneous crystallization during the slow cooling of molten Bi_2O_3, CaO, $SrCO_3$, and CuO with an excess of CuO and also from a solution in molten KCl. The crystals were wafers with dimensions ~ 1 mm in the ab plane and 1–15 μm along the c axis. The quality of the crystals was tested by x-ray and electron diffraction and also by microprobe analysis. Contacts fabricated by brazing an Ag paste in an O_2 atmosphere at 600 °C had a resistance $\sim 10^{-4}\ \Omega\cdot cm^2$. The resistivity of the crystals was $\rho(300) \sim 0.2$ mΩ·cm, and the residual resistivity was 5% of $\rho(300)$. The conductivity anisotropy σ_{ab}/σ_c at $T \approx T_c$ reaches 5×10^4. For the measurements we used single-phase samples with $T_c \approx 80$ K. The resistance measurements were carried out by the four-contact method.

Figure 1 shows current-voltage characteristics, in logarithmic scale, measured at various temperatures. At low currents the characteristics are nonlinear and are described by $V \propto I^{a(T)}$. Figure 2 shows a corresponding $a(T)$ dependence. We see a jump in $a(T)$ near T_c, spread out over $\lesssim 1$ K. As the current is increased, the nature of these characteristic changes: At certain characteristic points $I_x(T)$ the exponent in the $V(I)$ dependence decreases significantly. The inset in Fig. 2 shows the temperature dependence of I_x.

Let us discuss the results. In quasi-2D superconductors, the individual layers can be treated in a first approximation as 2D superconductors which are coupled by the Josephson coupling.[5] Putting aside 3D effects for the moment, we can say that the interaction of a vortex-antivortex pair in one layer, with a distance $r \ll \Lambda$ between the constituents of the pair, where $\Lambda = \lambda_L^2/d_0$, and d_0 is the thickness of the superconducting layer, is determined by the kinetic energy of the superconducting currents:

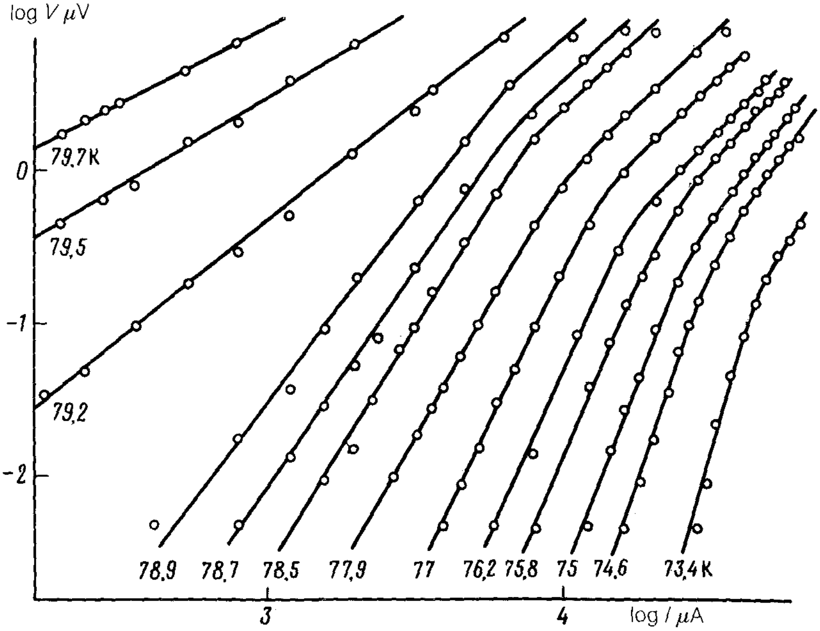

FIG. 1. Nonlinear current-voltage characteristics of a $Bi_2Sr_2CaCu_2O_x$ single crystal with dimensions of $1.1\times0.5\times0.0015$ mm at various temperatures $T \lesssim T_c$.

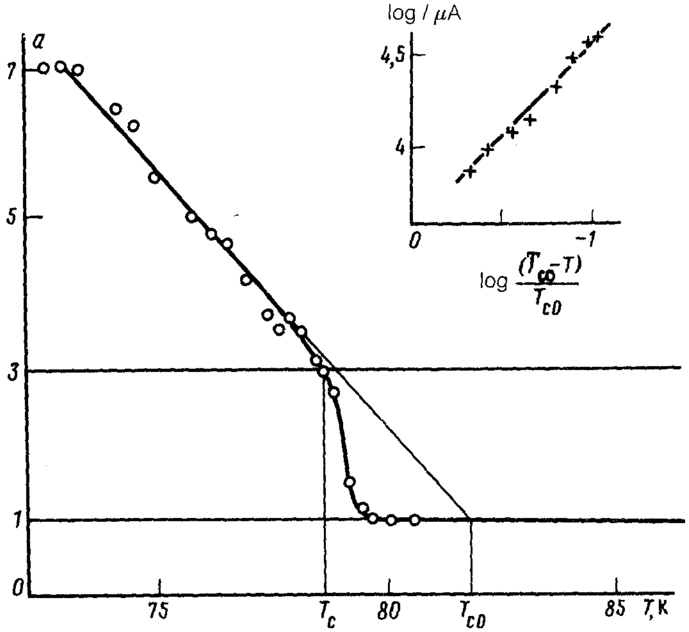

FIG. 2. Temperature dependence of the exponent of the nonlinear current-voltage characteristics. The inset shows the temperature dependence of the current I_x, at which the nature of the $V(I)$ dependence changes.

$$W_k = \frac{\phi_0^2}{(4\pi)^2 \Lambda \epsilon_0} \ln (r/\lambda_c) , \tag{1}$$

where ϕ_0 is the fluxoid, $\varepsilon_0 \sim 1$ incorporates the weakening of the interaction of the coupled vortex pairs, and λ_c is to be understood as the smaller of the two lengths Λ and L, which are the dimensions of the sample in the plane of the layers. The current-voltage characteristics are nonlinear because the flow of a transport current adds to interaction energy (1) a linear term which describes the effect of the current on the vortex and antivortex, in opposite directions. As a result, the binding energy decreases, and a maximum is reached when the vortices are separated by a distance

$$r_0 \approx c\phi_0 / 4(2\pi)^3 \Lambda j, \tag{2}$$

where j is the current in the layer per unit width of the sample. The result is a thermal creation of pairs of vortices separated by a distance r_0. The concentration of these vortices which have overcome the energy barrier is $n \propto j^{a-1}$, where[4]

$$a(T) = \frac{\phi_0^2}{(4\pi)^2 \Lambda \epsilon_0 T} + 1. \tag{3}$$

Comparing this behavior with Fig. 2, we can find Λ. A linear $a(T)$ dependence with decreasing temperature, which has also been observed in films of ordinary superconductors,[4] means that the London depth $\lambda_L \propto \sqrt{(T_{c0} - T)/T_{c0}}$ depends on T, as described by the Bardeen-Cooper-Schrieffer (BCS) model (where T_{c0} is the superconducting transition temperature in the absence of a KT transition). At $T=T_c$ we have $\Lambda \approx 100\,\mu$m. We have previously[3] observed a $R(T)$ dependence which is characteristic of an Aslamasov-Larkin fluctuation correction for 2D superconductors of thickness $d_0 = 13$ Å. Using this value, we find $\lambda_L \approx 0.3\,\mu$m at $T=T_c$.

The change in the nature of the $V(I)$ dependence at currents $I \sim I_x$ can be explained on the basis that—as we see from (2)—at sufficiently large values $j \gtrsim j_x$ vortices are created at $r_0 \sim \xi$ (ξ is the correlation length), with the result that upon a further increase in j, the energy barrier which the vortices overcome decreases more slowly, so the number of vortices and the resistance will correspondingly increase more slowly. Setting $r_0 \approx \xi$ in (2), we find an estimate of the current j_x. There is an important circumstance to be noted here: If the 2D vortices in different layers are moving independently, then at $T \approx T_c$ with $\Delta \neq 0$, a current should flow in the layer λ_L, while at $R \ll R_N$ the current will be dominated by superconducting electrons. In contrast with the normal state and in contrast with a state with 3D vortices, for which R is determined by the entire thickness of the superconductor,[6] the resistance near T_c would then be independent of the crystal thickness. This assertion agrees with our measurements for crystals of various thicknesses. Taking this circumstance into account, we find the following expression for the total characteristic current $I_x \sim (\lambda_L/d)\, j_x$: $I_x \sim c\phi_0 L d_0/32\pi^3 \xi \lambda_L d$ (d is the distance between the nearest superconducting layers). This behavior agrees with the data in Fig. 2 provided that we use $\xi \propto \lambda_L \propto \sqrt{T_{c0} - T}$, as in the BCS model.

We now consider the magnitude of the 3D effects which would prevent a KT transition. The energy of the magnetic interaction of vortices in layers separated by distance $z \gg d_0$, with z, $r \ll \lambda_c$, is small: $W_M = (\phi_0^2 z/2(4\pi)^2\Lambda^2)\ln \times (z+\sqrt{z^2+r^2}/\lambda_c) \ll W_k$. For a Josephson coupling of two vortices in neighboring layers, in the case of a dirty superconductor with a hopping conductivity between layers, we find

$$W_J = -\frac{\phi_0^2}{(4\pi)^2\Lambda}\,\frac{\sigma_c}{\sigma_{ab}}\,\frac{r^2}{2d^2}\ln\frac{r}{\lambda_c}\ . \tag{4}$$

A Josephson coupling also contributes to an attraction between vortices in a common layer; the corresponding energy is $2W_J$. It can be seen from (1) and (4) that in the case of a pronounced conductivity anisotropy we have $W_J < W_k$, even at large distances. Near T_c a characteristic distance is the screening length for the interaction between vortices, $\delta = \sqrt{4\pi\Lambda T\varepsilon_0/\phi_0^2 n}$. The Josephson energy can be ignored if the relation $W_J < W_k$ holds at $r \lesssim \delta$. Using $2\pi(n\xi^2) \sim \rho/\rho_N \propto (R/R_N)(2\lambda_L/h)$, along with the behavior of R/R_N which we have found experimentally,[3] we can find the temperature dependence $n(T)$, in which the only quantity that we have not found experimentally, ξ, appears in such a way that the result of the estimate depends only weakly (logarithmically) on it. Assuming $\xi \sim 80$ Å, we find that the Josephson coupling of vortices in BSCCO can be ignored even at $T - T_c \gtrsim 0.5$ K.

At $T < T_c$ the Josephson coupling will prevent the creation of vortices by a current unless the current j in (2) corresponds to such small values of r_0 that the relation $W_J(r_0) < W_k(r_0)$ holds. The meaning here is that the coupling between layers must lead to the existence of a critical current $j_c \approx (c\phi_0/4(2\pi)^3 \Delta d\epsilon_0)\sqrt{\sigma_c/\sigma_{ab}}$. At $j \gg j_c$, non-linear current-voltage characteristics with $a(T)$ as in (3) should be observed. In BSCCO, j_c is small, beyond the capabilities of our measurements. In YBCO, where the anisotropy of the conductivity is less by two or three orders of magnitude than in BSCCO, j_c should be larger. In the plot of $a(T)$, this larger value might be manifested as a sharp increase in $a(T)$ with decreasing temperature. It is possible that a situation of this type prevailed in Ref. 2.

In summary, a KT transition in quasi-2D BSCCO crystals is very similar to a transition in a 2D system: superconducting thin films. The weakness of the coupling between vortices in different layers of the crystal makes possible a thermal creation of vortices and an independent motion of these vortices in different layers.

[1)]Martin *et al.*[7] presented a case for the possibility of a KT transition in BSCCO single crystals on the basis of the behavior $\rho(T,H)$ in weak magnetic fields near T_c.

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