Nonlinear conductivity of $Bi_2Sr_2CaCu_2O_x$ whiskers near the superconducting transition

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(Submitted 14 April 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **61**, No. 10, 819–824 (25 May 1995)

The resistance R has been measured as a function of the electric field E near the superconducting transition of $Bi_2Sr_2CaCu_2O_x$ whiskers, in a region with $R \neq 0$. It is observed that R increases with increasing E. The shape of the $R(E)$ curves changes in a qualitative way as the temperature is varied. Near the transition temperature T_{c0}, the curvature of the $R(E)$ plot changes sign, and the nonlinear resistance $R(E)-R(0)$ for a given current reaches a maximum. Above T_{c0}, the results are linked with a suppression of a fluctuation conductivity by the electric field; below T_{c0}, they are linked with an excitation of nonequilibrium 2D vortices by the current. © *1995 American Institute of Physics.* Physics.

A dependence of the resistance R on the electric field above the superconducting transition temperature was predicted in Refs. 1 and 2 and has been observed experimentally in superconducting aluminum films.[3] The mechanism for this effect can be summarized by saying that the applied field E accelerates the formation of Cooper pairs in a process involving fluctuations. At a sufficiently strong field E, comparable to the so-called characteristic field $E_c(T)$, the velocity of these pairs can reach the critical level sufficient for the destruction of the pairs. As a result, superconducting fluctuations are suppressed, with the further result that the resistance of the sample is increased.

The high-T_c superconductors have a layered structure, and fluctuation phenomena strongly influence their properties. However, a nonlinear fluctuation conductivity has not been studied experimentally. The expected value of E_c for these compounds is very high [$E_c \sim 10^2$ V/cm at $(T-T_{c0})/T_{c0}=0.01$ (Ref. 4), increasing with increasing T], so the effect would be extremely difficult to observe. The nonlinear conductivity of $Bi_2Sr_2CaCu_2O_x$ (BSCCO) single crystals has attracted particular interest because a (Berezinskiĭ–) Kosterlitz–Thouless transition is observed in this quasi-2D compound.[5] Below T_{c0}, the resistance does not vanish down to the temperature of the Kosterlitz–Thouless transition, $T_c \approx T_{c0}-3$ K: At $T_c<T<T_{c0}$, the motion of thermally activated 2D vortices leads to an energy dissipation and to a finite resistance of the sample.[6] So far, there has been no study of a deviation of the current–voltage characteristics from Ohm's law at $T_c<T<T_{c0}$.

Our purposes in this study were to learn about the dependence $R(E)$ both above and below T_{c0}, using perfect BSCCO single crystals, and to identify the mechanisms for the nonlinear conductivity.

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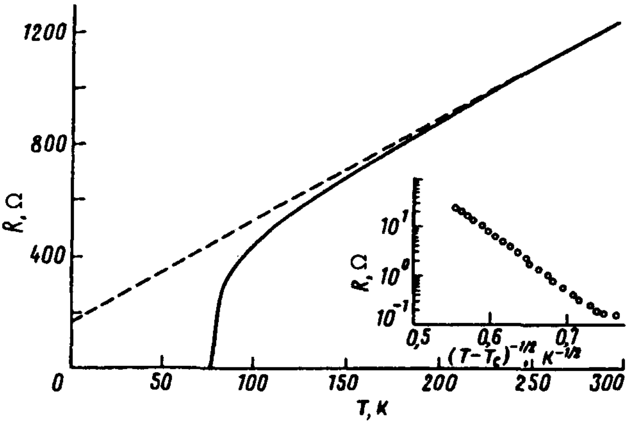

FIG. 1. Resistance of a BSCCO whisker versus the temperature. The inset shows R versus $(T-T_c)^{-1/2}$ at $75.7 < T < 77.2$ K.

As the test samples we selected BSCCO whiskers grown from quenched stock material by the crystals method proposed in Ref. 7. According to transmission electron microscopy, the crystal grow along the a axis. They differ in structural quality and are essentially free of dislocations.[7] Working from the shape of the superconducting transition, we selected for the $R(E)$ measurements two single-phase whiskers with $T_{c0} \approx 80$ K. Figure 1 shows the temperature dependence of the longitudinal resistance of the whisker used for the most-detailed measurements. At T above 200 K, the plot of $R(T)$ is approximately linear; below 200 K, there is a substantial deviation from linearity, apparently because of superconducting fluctuations. Near 80 K the resistance drops sharply and then vanishes smoothly (see the inset in Fig. 1). The resistivity of the whiskers at 300 K is $\sim 3\times 10^{-4}\ \Omega\cdot$cm, and their dimensions are $\sim 1000\times 2\times 0.1\ \mu$m. Because of the small thickness of the samples, there is a good thermal contact with the sapphire substrate; measurements can thus be carried out at currents $\sim 10^5$ A/cm^2 in the normal state. In the measurements at $T < 81.5$ K the samples were in liquid nitrogen at a pressure up to 2 atm. The resulting curves agreed with those measured in a heat-exchange gas, indicating that there was no heating. Electrical contacts with dimensions of $10\times 2\ \mu$m were deposited by laser deposition of gold.[7] The distance between neighboring contacts was 120 μm.

The measurements were carried out in the four-contact arrangement in the given-current regime. Both the dc and ac components of the current were given. The alternating voltage across the potential contacts was measured with a lock-in detector. The readings of this detector were proportional to the differential resistance of the sample, dV/dI. These readings and also the static voltage across the potential contacts were stored by a computer. In this manner we obtained a plot of dV/dI versus the bias voltage V at a fixed temperature. From these results we also calculated the current I and the total (chord) resistance R. This method makes it possible to measure the nonlinearity of the current–voltage characteristics within $\Delta R/R \lesssim 10^{-4}$.

Figure 2 shows a family of curves of dV/dI versus V for various temperatures. Over the entire temperature range, dV/dI increases with increasing V. We see that the curves

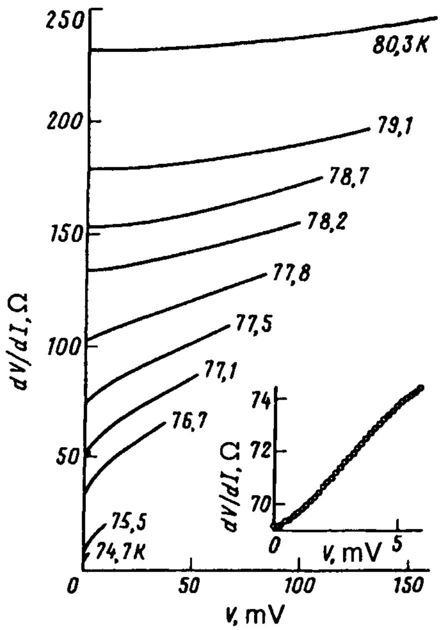

FIG. 2. Differential resistance versus the voltage at various temperatures. The inset shows the initial part of the plot of dV/dI versus V at $T=77.5$ K.

can be divided into two subfamilies: Above 78 K the curves are convex downward, while below this temperature they are convex upward. The curves of the total resistance $R(V)$ have a similar shape. At low values of V and at $77<T<78$ K, there is an inflection point on the plot of dV/dI versus V (see the inset in Fig. 2). Below this point, we again see a convexity downward. Below 76.7 K, the inflection point is not observed at currents $I>10^{-5}$ A.

Figure 3 shows curves of the nonlinear voltage $V_{nl}\equiv I[R-R(0)]$ versus I in full logarithmic scale. We see that these curves can be described by a power law $V \propto I^{\alpha_{nl}}$. The exponent α_{nl} is shown as a function of T in Fig. 4a, along with the exponent $\alpha(T)$ found by the standard method,[8] through a power-law approximation of $V(I)$ ($V \propto I^{\alpha}$). Both exponents were determined at[2)] $I>10^{-4}$ A. At $T\leqslant 74.7$ K the value of $R(0)$ is close to zero, so $V_{nl}(I)$ is essentially the same as $V(I)$, and we have $\alpha_{nl}\approx\alpha$. As T is raised, however, the plots of α_{nl} and α diverge: α approaches one, while $\alpha_{nl}(T)$ decreases only to ≈ 1.6 and then rises, approaching 3 at $T>79$ K.

Figure 4b shows the temperature dependence of the nonlinear voltage V_{nl} measured at two fixed currents. On each plot we see a clearly defined maximum at $T\approx 77$ K. The position of the $V_{nl}(T)$ maximum is near the minimum of $\alpha_{nl}(T)$.

Let us discuss the results. The features observed at $T=77-78$ K—the change in the sign of the curvature of $V_{nl}(I)$, the change in the exponent α_{nl}, and the maximum of V_{nl}—indicate a qualitative change in the nature of the conductivity at this temperature. It is natural to look at the experimental results in two temperature regions.

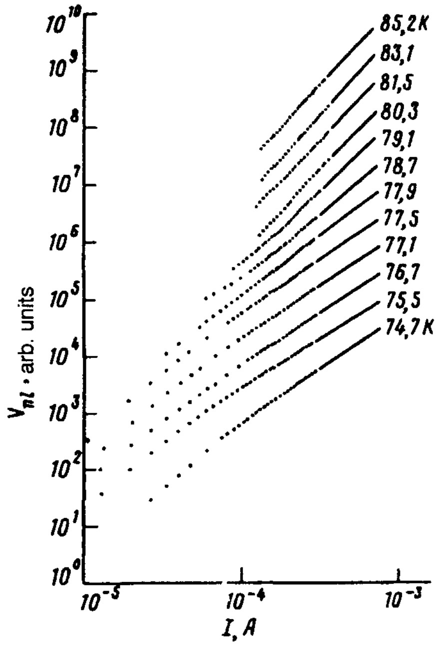

FIG. 3. The nonlinear voltage versus the current at various temperatures (the curves have been shifted along the vertical scale).

We begin with the high-temperature region, where we would expect the electric field to suppress superconducting fluctuations.[1,2] Measurements of the deviation of $R(T)$ from linearity (Fig. 1) show that the temperature dependence of the fluctuation correction to the conductivity in weak fields, $\sigma_{fl}(T,0)$ corresponds at $78<T\lesssim 100$ K to the Aslamazov–Larkin formula for the 2D case,[9] as has been seen previously.[7] The value found for T_{c0} through a linear extrapolation of σ_{fl}^{-1} is 77.1 K. In the 2D case, according to Ref. 2, the fluctuation conductivity σ_{fl} is described as a function of the electric field E by

$$\sigma_{fl}(T,E)=\sigma_{fl}(T,0)\int_0^{\infty}dx\ \exp\{-x-[E/E_c(T)]^2x^3\}, \tag{1}$$

where

$$E_c(T)=[16\sqrt{3}k_BT_{c0}/\pi e\xi(0)][(T-T_{c0})/T_{c0}]^{3/2}\equiv E_{c0}[(T-T_{c0})/T_{c0}]^{3/2}, \tag{2}$$

k_B is the Boltzmann constant, e is the charge of electron, and $\xi(0)$ is the coherence length at $T=0$ K. For BSCCO we have the theoretical estimate[4] $E_{c0}\approx 10^5$ V/cm.[4] The large value of E_{c0} is associated with the high T_{c0} and the small $\xi(0)\sim 50$ Å .

Let us compare Eqs. (1) and (2) with experimental data. From the $R(T)$ dependence we know $\sigma_{fl}(T,0)$. Knowing $\sigma(E)$ at a fixed T, we find $\sigma_{fl}(E)=\sigma_{fl}(0)+\sigma(E)-\sigma(0)$. From the best correspondence between $\sigma_{fl}(E)$ and theoretical relation (1) we find E_c. At $T<78$ K, $\sigma_{fl}(E)$ does not correspond to Eq. (1). The apparent reasons are a transition

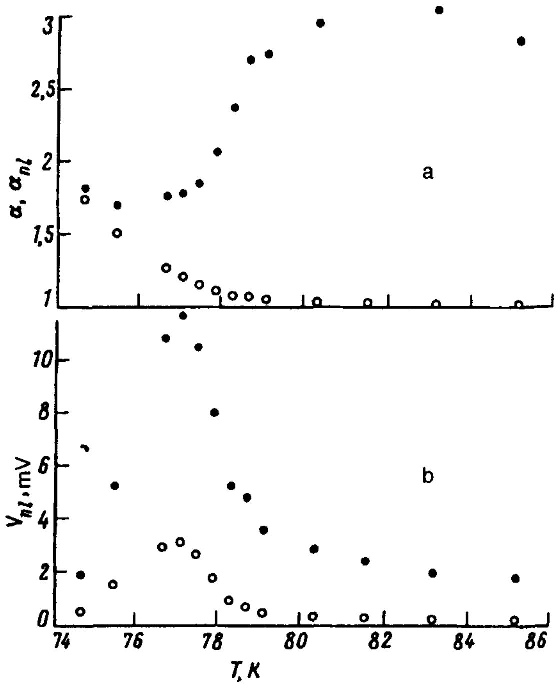

FIG. 4. a: Temperature dependence of two exponents. ●—α_{nl}; ○—α. These exponents were found from the plots of $V_{nl}(I)$ and $V(I)$ at $I \geqslant 10^{-4}$. b: Temperature dependence of the nonlinear voltage at two current values. ●—$I=6.3\times10^{-4}$ A; ○—$I=3\times10^{-4}$ A.

into a region of 3D fluctuations and the large value of $\sigma_{fl} \gtrsim 1/R$. To estimate E_c at $T<78$ K we note that, according to (1), the field corresponding to the inflection point E^* on the plot of $\sigma_{fl}(E)$ is $0.15E_c$. We can thus redetermine E_c as $E^*/0.15$.

Figure 5 shows $E_c^{2/3}$ versus T. The dashed straight line corresponds to Eq. (2) with

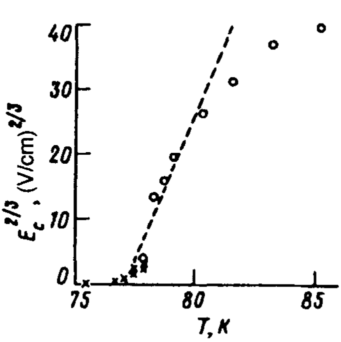

FIG. 5. Characteristic field $E_c^{2/3}$ of the BSCCO whiskers versus the temperature. ○—E_c found from the correspondence between $\sigma(E)$ and Eq. (1); ×—E_c found from the inflection point on the plot of $\sigma(E)$.

the parameter values $T_{c0}=77.1$ K and $E_{c0}=3\times10^4$ V/cm. Corresponding to this value of E_{c0} is $\xi(0)=100$ Å , in agreement with estimates[4] for this compound. We see that at $77.5 < T < 82$ K the experimental results can be described qualitatively by Eq. (2). At $T>82$ K the $E_c(T)$ dependence is quite different from the straight line described by (2). A similar deviation was observed in Ref. 3 on aluminum films. It may be due to an additional mechanism for the suppression of fluctuations.

At $T>78.5$ K the field E is below E_c at all values of the current, and we can simplify Eq. (1): $\sigma_{fl}(T,E)\approx\sigma_{fl}(T,0)[1-6(E/E_c)^2]$. Using $\sigma_{fl}(T,0)\propto(T-T_{c0})^{-1}$ and $E_c\propto(T-T_{c0})^{3/2}$, we find

$$V_{nl}\propto I^3[R(T)]^4(T-T_{c0})^{-4}. \tag{3}$$

Since $R(T_{c0})$ is a finite quantity, we conclude from (3) that there is a sharp increase in the nonlinear voltage at a fixed current as T_{c0} is approached from above (Fig. 4b). Equation (3) also yields the argument of the nonlinear current–voltage characteristics: $V_{nl}\propto I^3$. We thus have $\alpha_{nl}=3$ at $E\ll E_c$, i.e., at $T\gtrsim78$ K. At lower temperatures, the 3D nature of the fluctuations must be taken into account. Since E reaches a value on the order of E_c, the argument α_{nl} should decrease. Near T_{c0}, the field E_c approaches zero, and we have $E\gg E_c$. The theoretical value of the argument for the current dependence of the voltage associated with the suppression of fluctuations is 1.5 in the 3D case. [1,4] Interestingly, α_{nl} drops to 1.6 at $T\approx77$ K (Fig. 4b). This agreement is apparently not purely fortuitous.[3)] The transition from $\alpha_{nl}>2$ to $\alpha_{nl}<2$ as the temperature is lowered reflects a change in the sign of the curvature of the plot of $R(E)$ at $T\approx78$ K (Fig. 2).

The theory of a nonlinear fluctuation conductivity thus makes it possible to explain the $R(E)$, $V_{nl}(T)$, and $\alpha_{nl}(T)$ behavior at $T>T_{c0}$.

We turn now to the $R(E)$ dependence at $T<T_{c0}$. We associate the nonlinearity in this region with a Kosterlitz–Thouless transition, which has been observed in bulk BSCCO single crystals.[6] The resistance of a whisker (see the inset in Fig. 1) falls off in proportion to $\exp[-C/(T-T_c)^{1/2}]$, with decreasing temperature, where $T_c=74$ K. This behavior is characteristic of a Kosterlitz–Thouless transition. It is associated with the thermal excitation of pairs of free 2D vortices above T_c. We believe that in this temperature region there may be additional creation of free vortices by the current. This effect should lead to an increase in R with increasing I and thus to the onset of a V_{nl}. A numerical estimate for our test samples shows that at $I\geq10^{-4}$ A and $T<77$ K the average distance between the thermally activated vortices is greater than the critical pair size r_0, and we can ignore the effect of free vortices on the breakup of pairs by the current. To describe the dependence $V_{nl}(I)$ above T_c, we can thus use the same equations as for $V(I)$ below T_c (Ref. 8). It follows that $V_{nl}(I)$ is of a power-law nature (Fig. 3) with an exponent $1<\alpha_{nl}\leq3$, which increases with decreasing temperature. Figure 4a shows the tendency for α_{nl} to increase from 1.6 as T is lowered from 76 to 74.7 K. At lower temperatures we have $\alpha_{nl}\equiv\alpha$, since we have $R(0)=0$, and the argument increases rapidly, to 3 and above, according to measurements of $V(I)$ on single crystals,[6] including whiskers.[10] The $\alpha_{nl}(T)$ dependence at $T<T_{c0}$ (Fig. 4a) can thus be described at a qualitative level by means of the proposed mechanism.

Let us examine the temperature dependence of V_{nl} below T_{c0}. At a fixed current, the critical pair size r_0 decreases with increasing temperature, in proportion to[8] $(T_{c0}-T)$.

The concentration of vortices excited by the current satisfies $n_f \propto 1/r_0^{\alpha_{nl}}$, so the voltage $V_{nl} \propto n_f$ increases sharply with increasing temperature at $T<T_{c0}$. This conclusion agrees with experiment (Fig. 4b).

In summary, we have observed an increase in the resistance due to an electric field near T_{c0}, in a region with $R \neq 0$, in BSCCO whiskers. The results found above T_{c0} agree with the theory of a nonlinear fluctuation conductivity; demonstrating that this theory can be applied to high-T_c superconductors. We have found the values $E_{c0}=3\times10^4$ V/cm and $\xi(0)=100$ Å. Below T_{c0}, the results indicate a possible excitation of nonequilibrium 2D vortices by the current. Features observed near T_{c0} reflect a qualitative change in the conductivity mechanism at the temperature of the superconducting transition.

We wish to thank A. M. Nikitina and V. U. Antokhina for synthesizing the test samples; S. N. Artemenko, Yu. I. Latyshev, and K. É. Nagaev for a useful discussion; and S. V. Zaĭtsev-Zotov for valuable comments and for assistance in the measurements.

This study was carried out within the framework of the State Program on High Temperature Superconductivity (Project 93046) and was supported by INTAS (Grant A92-056).

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[2)]Since we have $R(0) \neq 0$, the argument α should be equal to one in the limit $I\rightarrow 0$. Strictly speaking, the current–voltage characteristics are not power-law characteristics; the values given here for α were found by fitting a power law to $V(I)$ over the specified current range.

[3)]As $T\rightarrow T_{c0}$, we have a dependence $\sigma_{fl}(0)\approx 1/[R(T)-R(T_{c0})]$, where the finite value $R(T_{c0})$ is due to an additional dissipation associated with the Kosterlitz–Thouless transition. Since we have $1/\sigma_{fl}(0)\rightarrow 0$, we can assume that we have $1/\sigma_{fl}(E)\approx R_{nl}$ at $E\gg E_c$.

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Translated by D. Parsons