Nonlinear I-V characteristics above $T_c(R=0)$ in Bi-Sr-Ca-Cu-O thin films

C. Attanasio, L. Maritato, S. L. Prishepa,* R. Scafuro, and R. Vaglio
Dipartimento di Fisica, Università di Salerno, I-84081, Baronissi (Sa), Italy
(Received 2 March 1992)

We have measured the nonlinear I-V characteristics of some c-axis-oriented Bi-Sr-Ca-Cu-O thin films in a temperature range of few kelvin degrees above $T_c(R=0)$. A power-law behavior characterized by a temperature-dependent exponent, jumping from a value of 1 to a value of 1.5 when approaching $T_c(R=0)$, has been observed. We discuss this effect in terms of the granular-superconductor model and the time-dependent Ginzburg-Landau theory. Both of these models fail to describe our experimental results.

Nonlinear I-V characteristics above the critical transition temperature $T_c(R=0)$ have been observed in several high-temperature superconducting (HTSC) compounds.[1,3] The presence of this nonlinearity has been related to the granularity of the system[1,2] or to superconducting fluctuations above T_c.[3] In particular, on $YBa_2Cu_3O_{7-x}$ (YBCO) thin-film samples,[1,2] the nonlinear I-V curves have been explained in terms of a three-dimensional XY model drawing an analogy with the magnetic case,[4] while the measurements done on c-axis-oriented Tl-Ba-Ca-Cu-O films have been interpreted in the framework of the time-dependent Ginzburg-Landau theory.[5,6] However, the Hurault theory[5] used in this case is only valid in the superconducting dirty limit ($\xi \gg l$), where l is the electronic mean free path and ξ is the superconducting coherence length. For HTSC compounds, the superconducting clean limit ($\xi \ll l$) more properly applies.

We have measured I-V characteristics of $Bi_2Sr_2CaCu_2O_x$ (BSCCO) highly oriented thin films above and below the critical temperature $T_c(R=0)$, and we have observed an Ohmic (linear) behavior for temperatures $T > T_{c1} \simeq 83$ K while a nonlinear behavior has been seen for temperatures in the range $T_c(R=0)=78\ \mathrm{K} \le T \le T_{c1}$.

Recently, Varlamov and Reggiani[7] have formulated an expression for the I-V nonlinearity in the framework of the time-dependent Ginzburg-Landau theory in the superconducting clean limit for a layered system.

We discuss these results in terms of both the XY model and the Varlamov-Reggiani theory.

EXERIMENTAL RESULTS AND DISCUSSION

The thin films have been fabricated by completely electron-beam evaporating weighted amounts of BSCCO pellets on MgO(100) single-crystal substrates.[8] After an annealing in air at 880 °C for several hours, the films have shown a $T_c(R=0)$ of about 80 K, which was only slightly reduced after a wet photolithographic procedure to obtain the desired geometry. The critical current density J_c at 4.2 K, measured using a 5 μV/cm criterion, was 5×10^4 A/cm^2. The θ-2θ x-ray-diffraction analyses have shown a strong preferential orientation of the films with the c axis perpendicular to the plane of the substrate, along with the presence of small amounts of the low-T_c (2:2:0:1) phase.[8] This preferential orientation has been confirmed by the rocking curves typically showing half height widths less than 0.7 degrees. In Fig. 1 the transition curve (R vs T) and the critical current density vs temperature (J_c vs T) curve are shown together in a temperature range close to $T_c(R=0)$. The arrow in the figure points out the temperature T_{c1} below which the I-V characteristics are no longer linear. For the film in the figure we have obtained $T_c(R=0)=78$ K. We have measured the I-V characteristics of the film in Fig. 1, up to 3.6 mV. In the voltage range from 0.4 to 3.6 mV, the I-V curves were well fitted by a power law of the type

$$V \simeq I^{N(T)}, \tag{1}$$

where the exponent N is temperature dependent. Above T_{c1} the I-V curves were linear and $N(T)=1$. For temperatures below T_{c1}, some of the measured I-V curves are plotted in Fig. 2 in a bilogarithmic scale and the solid lines represent the best fit obtained using Eq. (1). The slope of these lines is the exponent $N(T)$ of Eq. (1). $N(T)$ changes in the temperature range $T_c(R=0) \le T \le T_{c1}$ from 1 to 1.5, as shown by the points in Fig. 3. At temperatures below $T_c(R=0)$, the I-V characteristics are well fitted by the formula

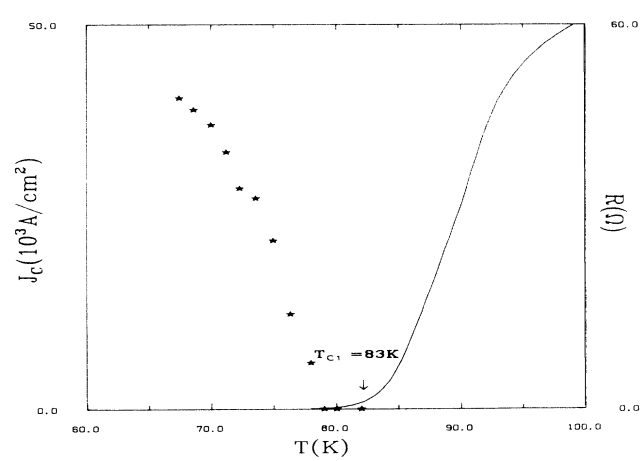

FIG. 1. Critical current density J_c (stars) and electrical resistance R (solid line) vs temperature curves in a range close to the critical temperature $T_c(R=0)$.

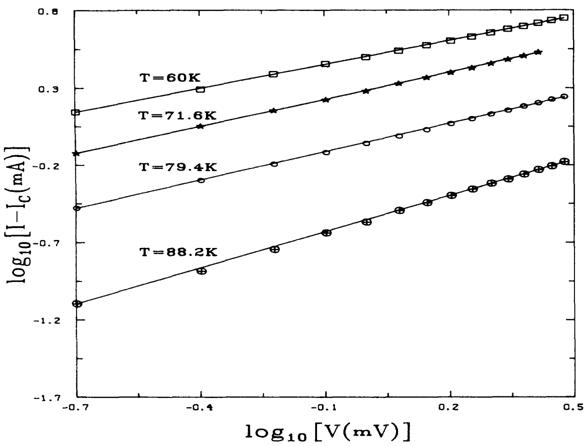

FIG. 2. $\text{Log}_{10}(I-I_c)$ vs $\log_{10}(V)$ curves at different temperatures. The solid lines are the best fits obtained by Eq. (1) above T_c and by Eq. (2) below T_c (see text). The slope of these lines represents the exponent N in Eqs. (1) and (2).

$$V \simeq [I - I_c(T)]^{N(T)} , \tag{2}$$

where $I_c(T)$ is the critical current value. In this range $N(T)$ varied from 1.5 to 2 as shown by stars in Fig. 3. We want to point out that, as it is clear in Fig. 3, the change of the exponent N takes place already at temperatures above T_c and that at $T = T_c$ the value of N is 1.5.

The reduced critical current density value of our BSCCO thin films at 4.2 K, when compared with the values obtained in the case of other BSCCO thin films,[9] can be tentatively explained in terms of the granularity present in the samples.

In the case of a superconducting granular system in which the superconducting properties are more influenced by the strength of coupling between the grains than by the superconductivity of the grains themselves, the model elaborated by Rosenblatt *et al.*,[4] which is developed in analogy with the XY theory for the transition to the magnetism, predicts a nonlinear behavior of the I-V characteristics which follows Eq. (1) with the

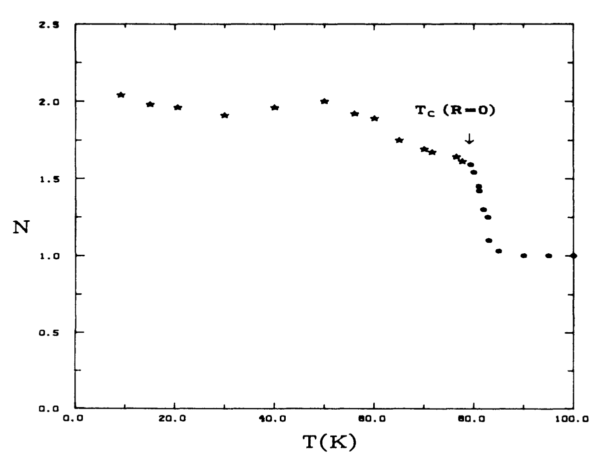

FIG. 3. Exponent N vs temperature. Points are the values measured above $T_c(R=0)$ and stars are the values measured below $T_c(R=0)$.

value of the exponent $N(T)$ at T_c given by

$$N(T_c) = (d+1)/(d-1+\eta) . \tag{3}$$

Here d is the dimensionality of the system and η is the exponent characterizing the order-parameter correlation function.

Generally η is expected to be very small so that for a three-dimensional superconducting system ($d=3$), one has $N(T_c)=2$. This result has been confirmed by measurements done on granular YBCO films which showed a very large (~ 30 K) superconducting transition width.[2] Similar experiments performed on Xe-Hg and NbN thin films[10,11] have also given $N(T_c)=3$, which is in good agreement with the formula (3) if $\eta \sim 0$ and $d=2$. Hence, the model of Rosenblatt *et al.* has been experimentally tested and gives a value of the exponent $N(T)$ at $T=T_c$ that follows Eq. (3) with $\eta \sim 0$ both in the three-dimensional and in the two-dimensional case. As clearly shown in Fig. 3, our experimental data give a value of $N(T_c)=1.5$, which seems difficult to explain in the framework of the Rosenblatt theory for a granular-superconductor system, assuming $\eta \sim 0$.

To check directly the granularity of our BSCCO films, we have measured the magnetic behavior of the R vs T and J_c vs T curves. Both the curves were independent upon the application of weak external magnetic fields up to ~ 30 Oe. Moreover, the scanning electron microscopy analyses showed uniform platelike zones with typical radii of several hundreds micrometers.[8] At this point, it is worth mentioning that the presence of the low-T_c (2:2:0:1) phase, if completely included inside zones of the high-T_c (2:2:1:2) phase, cannot affect the magnetic behavior of our films, even though it can reduce the critical current density value.

Another model that also predicts a nonlinear behavior of the I-V characteristics, which follows Eq. (1), is the time-dependent Ginzburg-Landau theory. This theory has been elaborated in the clean limit by Varlamov and Reggiani[7] for a three-dimensional layered superconductor, in which the coherence length perpendicular to the planes $\xi_\perp$ is much larger than the distance a between the planes ($\xi_\perp \gg a$). The model predicts a value of 1.5, very close to our experimental results, for the exponent $N(T_c)$ when $\xi_\perp \gg a$, while $N(T_c)=3$ in the case of a two-dimensional system in which $\xi_\perp \ll a$.

Previous data obtained on the same films[8] have shown the excess conductivity to be due to superconducting fluctuations above T_c, a typical two-dimensional behavior in the range $88 \le T \le 98$ K. Therefore, according to the Ginzburg-Landau theory, our BSCCO films behave like two-dimensional superconducting systems in the temperature range $88 \le T \le 98$ K far from T_c, while in a temperature range much closer to T_c they act like three-dimensional superconductors. If real, this behavior is the one expected for extremely anisotropic systems[12] such as BSCCO thin films. In fact, the superconducting coherence length $\xi_\perp$ in the direction perpendicular to the ab planes diverges at $T=T_c$ and hence the crossover between two- and three-dimensional behavior takes place, with $\xi_\perp$ going from the $\xi_\perp \ll a$ limit to the $\xi_\perp \gg a$ limit when approaching T_c.

However, another important parameter in the Varlamov-Reggiani theory is the critical electric field E_c, above which the nonlinearity takes places. The value of this electric field E_c is temperature dependent and tends to zero as T goes to T_c. Assuming $T_c=80$ K, $v_F=3\times10^7$ cm/s, and a value for $\epsilon=(T-T_c)/T_c=10^{-2}$, we get for E_c the value

$$E_c=\frac{54k_B^2T_c^2\epsilon^{3/2}}{e\hbar v_F}=10^2\ \text{V/cm}\ , \qquad (4)$$

which is two orders of magnitude greater than the highest electric field $E_{\max}$ we applied to our films. In the range of the applied electric fields, this model predicts a simple Ohmic behavior. Although the value of the electric field actually applied to the samples depends upon its real dimensions, which can be influenced by the presence of zones of the (2:2:0:1) phase, the discrepancy of two orders of magnitude between E_c and $E_{\max}$ seems very difficult to explain.

Hence, from these arguments, it follows that both the models we discussed failed to fully explain the observed nonlinearity in the I-V characteristics of our films.

CONCLUSIONS

Nonlinear I-V characteristics have been observed in BSCCO thin films in a temperature range very close to T_c. The temperature-dependent exponent $N(T)$ associated with the power law in Eq. (1) showed a jump 1 to 1.5 when approaching T_c. As we discussed, this behavior cannot be explained in terms of both the granular-superconductor model and the time-dependent Ginzburg-Landau theory.

The first model fails in predicting the observed exponent in the power-law behavior at $T=T_c$, while the second, even though predicting a value very close to the experimental result, shows nonlinearity only above a critical electric field much greater than the highest we actually applied to the samples.

Probably, both the models are based on overly simplified assumptions and a more general theory is needed to explain the behavior of a system like BSCCO in which granularity and supeconducting fluctuations could simultaneously be present.

---

*Permanent address: Radio Engineering Institute, Minsk, 220600, U.S.S.R.

[1]M. A. Dubson, S. T. Herbert, J. J. Calabrese, D. C. Harris, B. R. Patton, and J. C. Garland, Phys. Rev. Lett. **60**, 1061 (1988).

[2]P. England, T. Venkatesan, X. D. Wu, and A. Inam, Phys. Rev. B **38**, 7125 (1988).

[3]T. Chen, S. Liang, H. Zhang, Y. Sun, S. Yan, and Sho. Yan, Solid State Commun. **76**, 345 (1990).

[4]J. Rosenblatt, C. Lebeau, P. Peyral, and A. Raboutou, in *Josephson Effects: Achievements and Trends, Torino, 1985,* edited by A. Barone (World Scientific, Singapore, 1986), p. 320.

[5]J. P. Hurault, Phys. Rev. **179**, 494 (1968).

[6]L. G. Aslamazov and A. I. Larkin, Phys. Lett. **26A**, 238 (1968).

[7]A. A. Varlamov and L. Reggiani, Phys. Rev. B **45**, 1060 (1992).

[8]C. Attanasio, L. Maritato, A. Nigro, S. Prishepa, and R. Scafuro, Mod. Phys. Lett. B **5**, 1203 (1991).

[9]P. Schmitt, L. Schultz, and G. Saemann-Ischenko, Physica C **168**, 475 (1990).

[10]S. A. Wolf, D. U. Gubser, and Y. Ymry, Phys. Rev. Lett. **42**, 324 (1979).

[11]K. Epstein, A. M. Goldman, and A. M. Kadin, Physica B+C **107B**, 323 (1981).

[12]W. E. Lawrence and S. Doniach, in *Proceedings of the Twelfth International Conference on Low Temperature Physics, Kyoto, 1970,* edited by Eizo Kamada (Keigaku, Tokyo, 1971), p. 361.