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Resistance noise in high-T_c and low-T_c granular superconducting films

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Measurements of the resistance noise in thick films of Y-Ba-Cu-O, in thick films of Bi-Sr-Ca-Cu-O, and in thin films of NbN, at the superconducting transition are reported. The transition to the $R=0$ state was obtained by either changing the temperature at fixed currents or by lowering the current through the sample at fixed temperatures. In both kinds of experiments, we have observed the divergence of the power spectral density S_v/V^2 as the $R=0$ state is approached. Our results are consistent with a percolative interpretation of the resistive transition of granular superconductors.

INTRODUCTION

The resistive transition of granular superconductors has been the subject of research, both theoretical and experimental, for many years. Systems such as thin films of the traditional superconductors Pb, Sn, and NbN, artificially made composites, and the large family of high-T_c superconducting ceramics are included in this category of granular superconductors. The percolative nature of the resistive transition of these granular systems, which can be viewed as a network of Josephson-coupled superconducting grains, has been demonstrated experimentally in measurements of the temperature dependence of the critical current in both traditional superconductors, such as NbN (Ref. 1) and in the high-T_c ceramics[2,3] as well as in the temperature dependence of the resistance of composites such as Tsuei wires[4] and in measurements of the temperature dependence of the magnetic penetration length.[5] At a given fixed temperature, the fraction of coupled superconducting grains p can be varied by changing the current I through the sample, reaching the threshold value p_c when $I=I_c(T)$. By changing the temperature at fixed current, the $R=0$ state is attained at the percolation critical temperature $T_c(R=0)$.

Measurements of the resistance noise in high-T_c (Refs. 6–12) superconductors in the normal state show that the power spectral density S_v/V^2 of the resistance noise, exhibiting a frequency dependence of the $1/f$ type, is several orders of magnitude larger than in metals and that it rises further at the resistive transition. Those effects have tremendous implications for the practical applications of the high-T_c superconductors as detectors, since this intrinsic noise would set a limit to the resolution of the devices. The rise of the noise at the transition has also been observed in low-T_c (Ref. 13) superconductors. In all those measurements, the transition is reached by changing the temperature and the sharp rise of the resistance noise is associated to temperature fluctuations whose effect should be important where dR/dT is largest. In fact, several authors[6,8–10] have measured maxima in the spectral density S_v/V^2 of the resistance noise at temperatures at which dR/dT has peaks, although there is not quantitative agreement between the measured noise in the high-T_c samples and the prediction of the thermal fluctuation model of Voss and Clarke.[14] An alternative explanation for the high levels of the noise at the transition of high-T_c ceramics is based on the motion of current-driven magnetic vortices.[15–17] Celasco *et al.*[17] have interpreted the hysteretic dependence of the noise on the magnetic field H in terms of the nonuniformity of the demagnetizing field due to the inhomogeneous structure of the ceramic material. According to this interpretation, noise measurements could be used as a sensitive tool to determine the irreversibility line by finding the boundary between the hysteretic and nonhysteretic regimes of the S_v/V^2 vs H dependence, a major advance in understanding the flux line formation and pinning in these granular superconductors.

Very close to the $R=0$ state, when the fraction of coupled grains approaches its threshold value, a percolation description of the macroscopic transport properties should be the most adequate to describe the sharp rise of the magnitude of the resistance noise.

The role of the granularity in the enhancement of the noise at the transition has been made evident by the suppression of this enhancement in highly c-axis oriented films of Y-Ba-Cu-O,[12] in single crystal of Y-Ba-Cu-O,[18] and in epitaxially grown films of Bi-Sr-Cu-Cu-O.[19] On the other hand, measurements of the noise in individual grain boundaries[20] have made evident that the origin of the resistance noise in high-T_c ceramics are the conductance fluctuations of each one of the intergrain junctions, although the microscopic origin of these fluctuations has not been definitively established. Here a grain is defined as each one of the island of superconducting material surrounded by regions where the order parameter is considerably depressed, either by defects such as twinning or by deviations of the stoichiometry, to which superconductivity is very sensitive in the high-T_c cuprates.

In this paper we present an extensive study of the divergence of the power spectra density S_v/V^2 of the resistance noise as the $R=0$ state is approached. We have found that our data can be interpreted in terms of a percolation model of the resistive transition of granular superconductors. The measurements were performed in thick films of the Y-Ba-Cu-O compound, in thin films of NbN and in thick films of the Bi-Sr-Ca-Cu-O compound.

According to the theoretical models[21,22] of percolating systems, the fluctuation of the conductance G of superconductor-nonsuperconductor mixtures diverges as

$$\langle \delta G^2 \rangle / \langle G \rangle^2 \propto (p_c - p)^{-\kappa'} , \tag{1}$$

where p is the fraction of superconducting coupled grains and p_c is the critical value, that is, $R=0$ for $p > p_c$. In terms of the noise power spectrum, Eq. (1) can be written as

$$S_v / V^2 \propto (p_c - p)^{-\kappa'} , \tag{2}$$

where $V=IR=I/G$ is the voltage across the sample. As it has been mentioned above, the fraction p can be decreased by either increasing the current at a fixed temperature T, reaching the critical value p_c when the current reaches its critical value $I_c(T)$, or by increasing the temperature up to $T_c(R=0)$ at fixed current I. We have accomplished both situations experimentally and we have measured the divergence of S_v/V^2 as predicted theoretically.

EXPERIMENTAL

Four types of samples were measured: thick films of Bi-Sr-Ca-Cu-O and thick films of Y-Ba-Cu-O prepared by a paint-on method,[3] thick films of Bi-Sr-Ca-Cu-O prepared by multiple source evaporation,[23] and thin films of NbN fabricated[24] by reactive sputtering on glass substrates. The samples were attached to a copper block inside a brass can which is immersed in a liquid-nitrogen or liquid-helium bath. The temperature can be varied by pumping on the bath and/or applying current to a heater controlled by a temperature controller. In order to measure the resistance noise we used a four-probe configuration. A dc current is applied to the sample and the ac signal between the voltage probes is fed through a transformer PAR190 (that improves the impedance matching and amplifies the signal by a factor of 100) into an amplifier PAR113 ($\times$10 000) in series with a home-made low-pass filter (cutoff frequency of 1 kHz), the output of which is measured by a spectrum analyzer HP3582A. The current-independent background noise is measured by turning the current through the sample off. The two signals are subtracted and the result is normalized accordingly in order to obtain the power spectral density S_v/V^2 (in the frequency range from 0.1 to 100 Hz) of the excess noise. This is done by a microcomputer that also controls the spectrum analyzer.

RESULTS AND DISCUSSION

In the normal state, that is, far from the superconducting transition, we have found that S_v is proportional to V^2, that is, S_v/V^2 is independent of the current over various orders of magnitude of values of V. This result is valid also for temperatures below T_c^{onset} but well above T_c $(R=0)$. If the temperature is lowered below T_c^{onset}, the peaks of S_v/V^2 associated to the peaks in dR/dT are observed,[10] the magnitude of these peaks being independent of the current. As the temperature is lowered further toward $T_c(R=0)$, S_v/V^2 diverges. Below $T_c(R=0)$, S_v falls below our experimental resolution. The divergence of S_v/V^2 is observed independently of how the $R=0$ state is attained: by either lowering the current toward $I_c(T)$ at fixed temperature $T_c(R=0) < T \ll T_c^{\text{onset}}$ or by lowering the temperature toward $T_c(R=0)$ at fixed current.

Figure 1 shows the magnitude of S_v/V^2 at $f=100$ Hz as a function of I-$I_c(T)$ at fixed temperature T for two thick films of Y-Ba-Cu-O. Figure 2 shows the same kind of plot for a thick film of Bi-Sr-Ca-Cu-O at $f=10$ Hz.

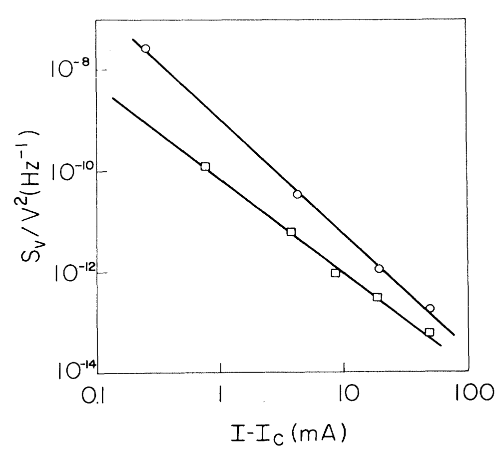

FIG. 1. Current dependence of S_v/V^2 at $f=100$ Hz of the resistance noise in a thick film of Y-Ba-Cu-O prepared by a paint-on method on Zr(Ca)O_2 (○) (sample No. 1) and on sapphire (□) (sample No. 2).

The divergence of the noise as a function of the current, such as those shown in Figs. 1 and 2 was found in all the samples measured within a few degrees of $T_c(R=0)$ (although only within 0.2 K approximately for the NbN sample). These temperature ranges are much wider than the temperature range in which thermodynamic fluctuations are expected to be important and consequently their contribution to the measured noise should be negligible. Our results can be interpreted if a relation between p and I exists such that

$$(I-I_c)\propto(p_c-p)^x \tag{3}$$

which combined with Eq. (2) gives

$$S_v/V^2\propto(I-I_c)^{-\kappa'/x} . \tag{4}$$

This is the type of dependence measured in all our samples, both of high- and low-T_c superconductors. In Table I we present the average values of the exponent κ'/x. Other physical parameters of these samples are given elsewhere.[25]

The values for x were obtained by taking the theoretical results of Hui and Stroud[22] for the values of κ' for a uniform network. These values are $\kappa'=0.660$ for a 3D system like the thick films and $\kappa'=1.339$ for a 2D system like the thin films. With the exception of sample No. 4, the values for the exponent x are very similar. This result is quite striking if we consider that a relation between the fraction of coupled superconducting grains and the current through the sample should depend on the distribution of the magnitude of the critical currents of the intergrain weak links, e.g., small values of x would be expected in samples with a narrow distribution of intergrain critical currents. The relative wide uncertainty in the value of κ'/x for the NbN sample is a consequence of the fact that the shape of the power spectrum is not of the $1/f$ type and that it changes with the current. The sharp transition of these films made it difficult to take data at various points of the transition and to study the origin of this deviation; nonetheless, the divergence was evident.

TABLE I. Average values of the exponents κ'/x and x for each one of our samples and exponents κ'/y and y for sample No. 5. Samples No. 1, 2, and 5 were prepared by a paint-on method and sample No. 4 by multiple source evaporation.

No.	Sample	κ'/x	x	κ'/y	y
1	Y-Ba-Cu-O	2.26±0.02	0.29		
2	Y-Ba-Cu-O	1.9 ±0.1	0.35		
3	NbN	5.7 ±1.4	0.23		
4	Bi-Sr-Ca-Cu-O	0.60±0.03	1.1		
5	Bi-Sr-Ca-Cu-O	2.6 ±0.1	0.25	4.6±0.1	0.14

In some of our samples we were able to measure the divergence of S_v/V^2 as a function of the temperature. This effect was observed previously,[10] although the precise temperature dependence was not measured at that time. Figure 3 shows the result for sample No. 5. It can be seen that the relation between S_v/V^2 and T is similar to the relation between S_v/V^2 and I and consequently we propose that

$$(T-T_c)\propto(p_c-p)^y \tag{5}$$

which combined with Eq. (2) gives

$$S_v/V^2\propto(T-T_c)^{-\kappa'/y} , \tag{6}$$

where T_c is the percolation critical temperature $T_c(R=0)$. From the data shown in Fig. 3 we obtain $\kappa'/y=4.6$ and $y=0.14$. All we are saying is that the number of coupled grains in the percolating network can be varied by changing either the current or the temperature and that very close to the threshold value p_c, the relations between p and I and between p and T can be written as Eqs. (3) and (5), respectively.

We have also studied the dependence of the resistance of our samples with the temperature and with the current. We found that, in the same temperature range and current range in which the noise exhibits the behavior discussed above, the resistance follows power laws

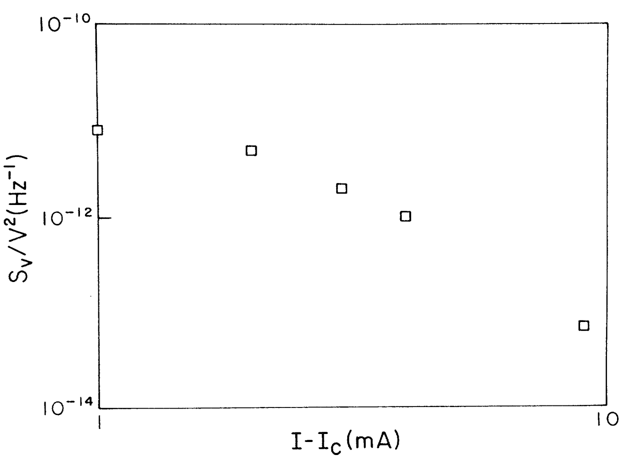

FIG. 2. Current dependence of S_v/V^2 at $f=10$ Hz of the resistance noise in a thick film of Bi-Sr-Ca-Cu-O prepared by a paint-on method on a $Zr(Ca)O_2$ (sample No. 5).

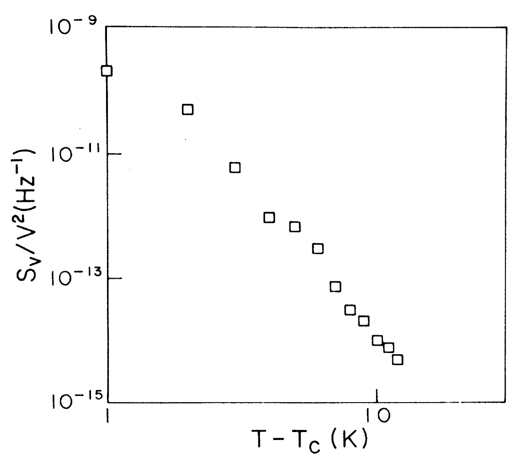

FIG. 3. Temperature dependence of S_v/V^2 of the resistance noise in a thick film of Bi-Sr-Ca-Cu-O prepared by a paint-on method on a $Zr(Ca)O_2$ substrate (sample No. 5). $T_c=64$ K.

with $(T-T_c)$ and $(I-I_c)$. This result can be interpreted in terms of the percolation models. By combining the expression for the resistance versus (p_c-p) from Ref. 21 with Eqs. (3) and (5) from this paper we obtain

$$R \propto (I-I_c)^{s/x} \tag{7}$$

and

$$R \propto (T-T_c)^{s/y} , \tag{8}$$

where s is a critical exponent with theoretical values[21] of 1.30 for 2D systems and 0.76 for 3D systems. By using the values for x (and for y) from Table I and the experimental values for s/x (and for s/y), we obtain the following values for s: 0.19, 0.30, 0.73, 1.2, and 0.18 for samples No. 1, 2, 3, 4, and 5, respectively. The disagreement between these values and the theoretical values listed above is not surprising given that those theoretical values for s, as well as the values for κ' used in this paper to estimate the magnitude of x and y, are for uniform networks.[21,22] Furthermore, the magnitude of s is expected to be greatly affected by the type of coupling between grains.[26,27] Consequently, we believe that an interpretation of the resistance transition of these granular superconductors in terms of percolation models is still valid.

Finally, we would like to point out that the $R=0$ state can also be approached by keeping the temperature and the current fixed and by changing the magnetic field. In fact, very recently, Çelik-Butler, Yang, and Butler[28] have reported measurements of the resistance noise in Y-Ba-Cu-O thin films as a function of the magnetic field and they have found that the noise increases with decreasing field and that this effect becomes more important closer to $T_c(R=0)$. These results are consistent with the results presented in this paper, the effect of the externally applied magnetic field in breaking the coupling between grains being combined to the effect of the transport current (a finite voltage develops between each pair of grains each time a magnetic flux line, driven by the transport current, moves across the intergrain junction). Further measurements are needed in order to test the existence of a relation between p and the magnetic field H similar to expressions (3) and (5).

CONCLUSIONS

We have measured the power spectral density S_v/V^2 of the resistance noise in granular superconductors in the proximity of the superconducting transition as a function of the current for fixed temperature and as a function of the temperature at fixed current. We have found that the magnitude of S_v/V^2 diverges as the $R=0$ state is approached and that it is zero below the transition. These results are explained in terms of the percolative description of the resistive transition of normal-superconducting networks such as the superconductors studied here. We have also found that very close to the threshold, the relations between the fraction of superconducting coupled grains p and the current I and between p and the temperature T can be written as $(I-I_c)\propto(p_c-p)^x$ and $(T-T_c)\propto(p_c-p)^y$.

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