

Current-induced highly dissipative domains in high- T_c thin filmsS. Reymond,* L. Antognazza, M. Decroux, E. Koller, P. Reinert, and Ø. Fischer
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We have investigated the resistive response of high- T_c thin films submitted to a high density of current. For this purpose, current pulses were applied into bridges made of $\text{Nd}_{1.15}\text{Ba}_{1.85}\text{Cu}_3\text{O}_{7-\delta}$ and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$. By recording the time-dependent voltage, we observe that at a certain critical current j^* , a highly dissipative domain develops somewhere along the bridge. The successive formation of these domains produces stepped I - V characteristics. We present evidence that these domains are not regions with a temperature above T_c , as for hot spots. In fact this phenomenon appears to be analog to the nucleation of phase-slip centers observed in conventional superconductors near T_c , but here in contrast they appear in a wide temperature range. Under some conditions, these domains will propagate and destroy the superconductivity within the whole sample. We have measured the temperature dependence of j^* and found a similar behavior in the two investigated compounds. This temperature dependence is just the one expected for the depairing current, but the amplitude is about 100 times smaller.

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I. INTRODUCTION

It was observed in the early 1970's that in one-dimensional (1D) classical superconductors quantum effects can dominate the dissipation and give rise to spectacular phenomena such as voltage steps in the I - V curves.^{1,2} The steps are due to the sequential development of phase-slip centers (PSC's),³ which are dissipative regions, where the superconducting order parameter oscillates. Each time it drops to zero the phase of the order parameter "slips" by 2π .⁴ The PSC formation could be observed only in a very narrow interval of temperature below T_c .⁵ At lower temperature, sharp features in the I - V characteristics were also observed, but caused by a different mechanism: thermal instabilities resulting in the development of localized normal regions where the temperature exceeds T_c (hot spots).^{6,7}

Do high- T_c compounds behave similarly? Signatures of phase slippage have been reported near T_c in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ grain boundary junctions,⁸ but also at low temperature in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films⁹ and ceramics,¹⁰ suggesting that the region where the dissipation is dominated by the nucleation of PSC's is not restricted to the vicinity of T_c . In addition, these experiments would imply, if the PSC interpretation is correct, that the PSC picture, developed for a 1D situation, is still valid in a 2D superconductor.

Nevertheless only few publications interpret the steps in the I - V curves at low temperature in terms of PSC. Discontinuities in the I - V characteristics are generally attributed to heating effects (or "bolometric" effects) because thermal instabilities can produce very fast voltage variations in thin films. Indeed the thermal response time, which is equal to the heat capacity of the film divided by the thermal conductance of the film-to-substrate boundary, is typically a few nanoseconds.

Some reports, however, do not interpret the voltage jumps induced by the application of a high current as hot spots, but the proposed explanations are all different from the PSC nucleation scenario.¹¹⁻¹⁵ At low temperature, the steps observed in $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_y$ were explained in terms of a

strongly energy dependent density of states.¹¹ In this picture, unlike the PSC model, these steps do not reflect the nucleation of a spatially limited domain surrounded by low dissipative regions, but are caused by an oscillation of the density of state as a function of energy in the superconducting mixed state. This model is valid only in the clean or superclean limit and therefore cannot be a general model for all superconductors. In contrast, steps attributed to *spatially limited domains* were reported in narrow $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ bridges and interpreted as an effect of edge pinning.¹²

Close to T_c , the application of a high current density has been seen to induce large voltage jumps bringing the sample close to the normal state resistance in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (Refs. 13 and 14) and in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Ref. 15) thin films. These discontinuities in the I - V characteristics were attributed to flux flow instabilities, an effect predicted 25 years ago by Larkin and Ovchinnikov,¹⁶ involving the density of states in the vortex core.

It is likely that a single mechanism is at the origin of most of the abrupt voltage variations observed in high- T_c superconducting (HTS) films at high current density. In an effort to provide an overall picture of this extreme regime, we have performed time resolved transport measurements on two different compounds $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (BSCCO) and $\text{Nd}_{1+x}\text{Ba}_{2-x}\text{Cu}_3\text{O}_{7-\delta}$ (NBCO) thin films, over a wide temperature range.

Based on our measurements, we show that a very systematic and general phenomenon appears in HTS compounds at a certain critical current $j^*(T)$, causing a rapid development of highly dissipative domains. We argue that, unlike what is concluded for conventional superconductors, even at low temperature these domains do not result from a thermal instability. Instead they behave just as the 1D PSC's observed in metallic superconductors near T_c .

We also show that the current induced breakdown of superconductivity seems to result from a large scale propagation starting with an elementary PSC. A full understanding of the way the current induces a switch into the normal state is important in the development of certain applications, in par-

ticular in the use of HTS thin films such as fault current limiters,¹⁷ bolometric detector,¹⁸ or ultrafast superconductive switches.¹⁹

II. EXPERIMENTAL DETAILS

The samples used for the present study are BSCCO and NBCO epitaxial films, 200 nm thick, deposited by rf magnetron sputtering on (100) oriented MgO substrates. The NBCO films are Nd rich (the nominal target composition is $\text{Nd}_{1.15}\text{Ba}_{1.85}\text{Cu}_3\text{O}_{7-\delta}$). This prevents the formation of screw dislocations, resulting in good crystallinity,²⁰ but T_c decreases slightly.²¹ MgO was chosen for its high thermal conductivity (about 25 times larger than SrTiO_3 and LaAlO_3) in order to optimize the heat removal during the measurements. As revealed by x-ray analysis, all films were *c*-axis oriented. 60 μm wide bridges were patterned by standard photolithography into a four-probes configuration, with a distance of 500 μm between the voltage contacts. A gold layer was deposited on all the contact pads to reduce their resistance. The critical temperatures after the patterning, taken at midtransition, are 80 K for the NBCO and 76 K for the BSCCO thin film.

To limit the Joule heating, the current is applied by single pulses. The purpose-built pulsed current source could deliver square or triangular pulses with an amplitude up to 1 Amp and a duration ranging from 10 μs to 1 s. During square pulses, the current varied by less than 1%. Current stability is crucial since any spike above the critical value can result in an abrupt resistance change, leading to wrong interpretations. The voltage is recorded as a function of time by a Tektronics digital oscilloscope. The current is measured simultaneously on the second channel of the oscilloscope by picking the voltage across a 1 Ω resistor in series with the sample.

Resistive measurements were performed from 4 K up to T_c . The sample is glued by a GE heat conducting varnish onto a copper block and surrounded by 100 mbar of helium gas. The sample temperature is controlled by a heater and monitored by a carbon-glass probe placed inside the copper block. Once a pulse is applied, the heat front crosses the substrate and reaches the copper block in about 40 μs . In the dissipative state (normal or mixed state), the heat produced in the film causes a smooth resistance increase, consistent with a simple simulation of heat diffusion through the substrate to the copper block. The thermometer probe is, however, too far to record the real time temperature increase of the film. Therefore we use the evolution of the film resistance to obtain information about its temperature *during a pulse*. A magnetic field generated by a superconducting magnet in a persistent mode can be applied parallel to the *c* axis.

III. RESULTS

A. Critical current

The currents applied in this experiment are well above the critical current which is traditionally defined at the onset of resistance. At high current density (above 10^6 A/cm²), the measured voltage across the bridge exhibits abrupt variations as a function of current or temperature. Two kinds of voltage

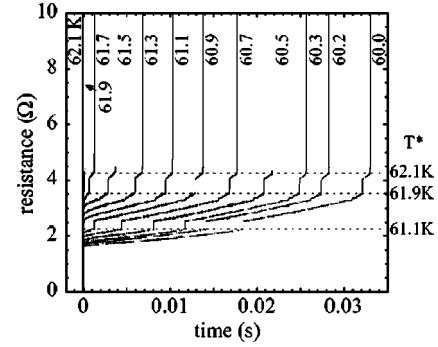


FIG. 1. Resistive response of the NBCO film when a constant current pulse of 1.9×10^6 A/cm² is applied ($B=0.1$ T). For each curve, the initial temperature indicated on the top of the figure is changed; however, each step occurs always at the same temperature T^* (displayed on the right side). The sample temperature at a certain resistance is determined by varying the initial temperature until this resistance appears immediately at the beginning of the pulse.

jumps are observed: small steps where the resistance increase is less than 1% of ρ_n (ρ_n being the normal resistivity just above T_c), and large jumps where the resistance reaches a value close to ρ_n . The voltage increase during a small jump is instantaneous at our time resolution, i.e., the voltage variation is faster than the microsecond rise time of our differential amplifier. With constant current pulses, we show in this section that both kinds of voltage steps are due to a single mechanism, which occurs when the current reaches a critical value that we call $j^*(T)$.

A typical set of results for identical square pulses is shown in Fig. 1 for the NBCO thin film at 0.1 T. The applied current density is 1.9×10^6 A/cm² and each curve corresponds to a different sample temperature, measured just before the pulse application, varying from 60.0 to 62.1 K. Each curve exhibits two clear steps before the total breakdown of superconductivity occurs, with the resistance rising up to ρ_n . Note that each particular jump occurs at a given resistance independent of the initial temperature.

The smooth increase between the steps is due to Joule heating but cannot be recorded in real time by the temperature probe, located in the sample holder. The probe will indicate a temperature corresponding only to the initial resistance appearing at the beginning of the pulse. We use these initial values to obtain the R versus T function at a particular current value. Knowing this calibration function we can relate, at any time during the pulse, the resistance to the sample temperature, and in particular we can determine the temperature at which each jump occurs.

We observe that for a given current, each particular jump (small or large) always occurs at the same temperature, that we call T^* , indicated on the right hand side of Fig. 1. T^* depends on the current [$T^*(j)$ decreases when the current increases], and by varying j , we observe the steps over a wide temperature range, from 4 K up to a temperature close to T_c ($0.7 T_c$), in both NBCO and BSCCO films. Above a certain temperature, which turns out to be near T_c , the uniform resistance presumably caused by vortex motion is so

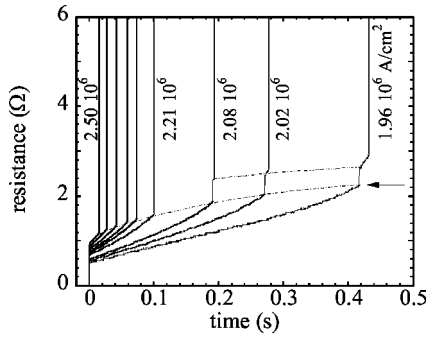


FIG. 2. Resistive response of the NBCO film to square current pulses with different amplitudes ($B=0.1$ T). The initial temperature before the pulse application is 55 K. When decreasing the current amplitude, the small resistance jump indicated by the arrows turns into a large jump where the total sample resistivity reaches the normal state resistance.

high that the sample temperature “runs away” and the abrupt transition is replaced by a smooth upturn of the voltage as a function of time.

The data of Fig. 1 indicate that in one sample for a given current density, there are several temperatures T^* , each one corresponding to a different location along the bridge. The local character of the dissipation was established by adding a third voltage contact in the middle of the bridge: within this configuration, when measuring simultaneously the voltage on both sides of the bridge, the small jumps were detected on only one segment, never on both. As a consequence, while the large jump corresponds to a transition of the whole bridge, each small step is produced by the sudden formation of a localized highly dissipative domain (HDD). Figures 1 and 2 show that these domains can persist over relatively long times without affecting the superconducting state in the rest of the bridge. The extreme reproducibility of the HDD formation (even when the films were warmed up to room temperature and cooled down again) suggests that the T^* spreading for a given current is due to slight spatial inhomogeneities along the bridge.

One of the crucial points, demonstrated in Fig. 2, is that the formation of an HDD is also the origin of the global sample transition characterized by the large voltage jump. In this experiment performed on the NBCO thin film, each curve was measured with a different current (explaining the variation of the jump temperature T^*). Above a certain current, the small step indicated by the arrow is replaced by a global transition.

We now move to the shape of T^* in the j - T plane. To obtain experimentally the reciprocal function $j^*(T)$, we have to detect the formation of a particular HDD over the whole temperature range. The easiest way is to look at the large voltage jump. Figure 3 illustrates the procedure to obtain one point of $j^*(T)$: we fix the current, here 3.1×10^6 A/cm², and then we increase the initial sample temperature, until the global transition occurs immediately at the beginning of the pulse. In this example the sample switches at 47.8 K, i.e., $j^*(47.8\text{K}) = 3.1 \times 10^6$ A/cm². By applying the same procedure for small steps, we have verified that the critical current associated with the small steps has the same temperature

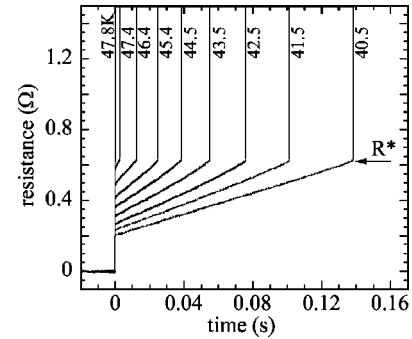


FIG. 3. Resistive response of the NBCO film to pulses of 3.1×10^6 A/cm² at 0.1 T. The sample temperature before the pulse application is indicated on the top of each curve. This temperature is increased from 40.5 to 47.8 K. At the latter temperature the transition occurs immediately at the beginning of the pulse. 47.8 K is therefore interpreted as the temperature T^* corresponding to the applied current.

dependence than the large jumps on some limited intervals (we could not follow a particular small jump from 4 K up to T_c). This confirms the conclusion drawn from Fig. 2, namely, that the small and the large steps have the same origin.

Figure 4 shows the results for NBCO (filled circles) and BSCCO (filled triangles) films. It is remarkable that for both compounds the temperature dependence of j^* is the same. $j^*(0)$, the extrapolated value at $T=0$, which represents the highest current density that can be carried by the film while remaining in the superconducting state, is also found to be similar in the two compounds. $j^*(0)$ in the NBCO film was in fact slightly larger than in BSCCO (5.8×10^6 A/cm² instead of 4.4×10^6 A/cm²), possibly due to the higher T_c of the former.

It should be noted that upon increasing the magnetic field $j^*(T)$ is globally reduced but the shape of the j^* versus T curve remains the same (see Fig. 4 for the 1 T case). The zero-field data are not shown here because they do not exhibit significant differences compared with the 0.1 T case.

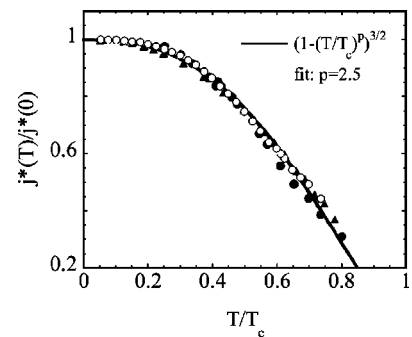


FIG. 4. Temperature dependence of j^* normalized at zero temperature. It represents the nucleation current of a highly dissipative domain. Similar behavior is exhibited by BSCCO (triangles) and NBCO (filled circle) at 0.1 T, as well as NBCO at 1 T (empty circle). The solid line is a fit of the BSCCO data with $[1 - (T/T_c)^p]^{3/2}$, where p is the fitting parameter.

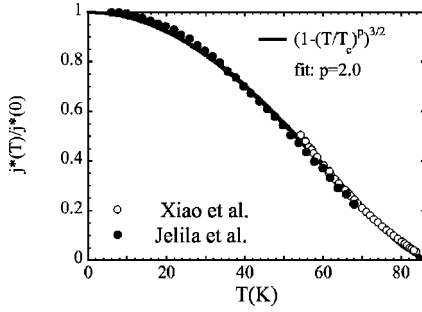


FIG. 5. Normalized critical current producing voltage jumps in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films measured by Jelila *et al.* (Ref. 9) and by Xiao *et al.* (Ref. 13) Both data are fitted by a single curve with two fitting parameters p and T_c . The fit gives $p=2.0$ and $T_c=87.2$ K.

Hence, the temperature dependence of j^* appears to be a general characteristics of HTS compounds. It can be well fitted by

$$\frac{j^*(T)}{j^*(0)} = \left[1 - \left(\frac{T}{T_c} \right)^p \right]^{3/2}, \quad (1)$$

with p ranging from 2 to 2.5. It is worth noting that the temperature dependence described by Eq. (1) also fits other reported measurements of high current-induced phenomena. Figure 5 displays the critical current for PSC formation found by Jelila *et al.*⁹ and the critical current giving rise to a voltage instability near T_c measured by Xiao *et al.*,¹³ both in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films. As for our measurements, the temperature dependence of these data agrees with expression (1).

The picture that emerges so far is that a HDD nucleates somewhere along the bridge when the temperature reaches a critical value $T^*(j)$. In some cases, it rapidly propagates to the whole sample, causing the complete switching into the normal state. The propagation speed of a highly dissipative region at high current densities has been recently measured in large $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films at 77 K:²² it ranges from 20 to 120 m/s. In our experiment, because of the shortness of the bridge, the voltage variation during the propagation seems instantaneous. In conclusion we find that the small steps and the total transition have a common origin. To understand this origin we will focus, in the next section, on small voltage jumps.

B. I - V characteristics

To investigate the nature of the HDD, we present here the I - V characteristics of these domains at low temperature. The aim is to see the HDD signature by sweeping the current, instead of the temperature as in the previous section, across the critical value j^* associated with one particular domain. In this study, we chose to look at the BSCCO film, where numerous small steps could be observed.

In the following experiment the voltage response is recorded during a current ramp. Unlike the experiment using square pulses, we need that the temperature does not increase irreversibly during the application of the current, i.e., that the measured voltage is history independent (except for the possible hysteresis in the HDD formation and disappearance).

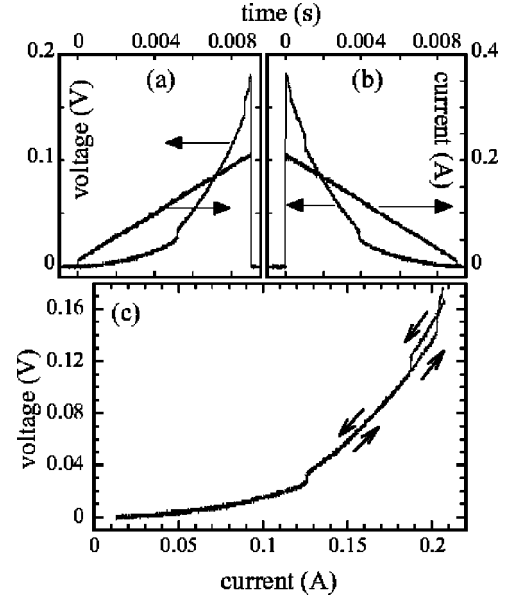


FIG. 6. Voltage response of the BSCCO film at 30 K to an increasing (a) and decreasing (b) current ramp of 20 A/s. The deduced I - V characteristics (c), show the good matching between the two curves and the hysteresis on the HDD formation.

This absence of heating was verified by applying upward and downward current ramps [see Figs. 6(a) and 6(b)]. The ramp duration was reduced so that both curves match together [see Fig. 6(c)]. The only difference is the value of i^* for the second step. Alternatively, we observed that the I - V curves remain the same when the ramping rate is varied. For the example of Fig. 6, the same characteristics are found when the ramping rate is raised from 20 to 500 A/s.

Figure 7 shows that the raw I - V characteristics (curve A) are different below and above i_1^* , the critical current corresponding to the first step. Below i_1^* , the I - V curve can be well fitted by a power law $U \sim i^q$ and represents the homogeneous dissipation in the whole bridge due to vortex motion

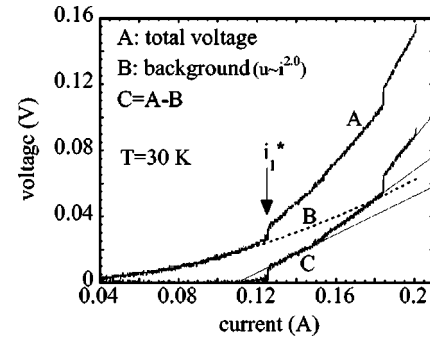


FIG. 7. I - V characteristics of BSCCO at 30 K and 0.1 T showing the first steps obtained by applying a triangular current pulse (curve A). Apart from some hysteresis on HDD's formation, the same voltage is found by increasing or decreasing the current. Before the first step, the dissipation is homogeneous and can be fitted by the curve B, with an exponent $q \approx 2.0$. By subtracting this contribution one obtains the I - V characteristics of HDD's only (curve C).

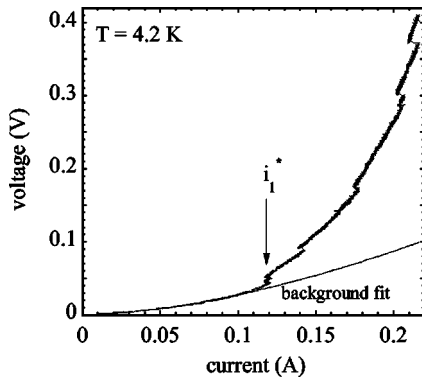


FIG. 8. I - V characteristics of the BSCCO film at 4.2 K and 0.1 T. For each critical current the jump occurs with a slope given by the source impedance (here 1.5 Ω). The differential resistance of the linear portions increases after each jump.

(curve B represents the extrapolation of this voltage to high currents). Above i_1^* , the voltage comes from the uniform dissipation of vortices (curve B) and the contribution of the HDD. Therefore, to obtain the voltage of a *single* HDD, we have to subtract curve B from the raw data.

The resulting I - V characteristics (curve C) are non-Ohmic: the I - V have piecewise linearity but the extrapolated zero-voltage current is nonzero. The differential resistance of the first domain can however be estimated: $dU/di=0.6 \Omega$. Other domains are successively created when the current is raised (see Fig. 8). A very noticeable feature is that after each jump, the slope of the linear portion increases.

It should be noted that the characteristics displayed in Fig. 7, performed at 30 K, are representative of the BSCCO behavior at low temperature, because we do not see a significant change below 30 K. For instance, as one can see in Fig. 4, $j^*(T)$ does not vary significantly at low temperature.

IV. DISCUSSION

Since in metallic superconductors, resistive domains result, at low temperature, from thermal instabilities, we will first examine if the voltage steps can be attributed to hot spots creation. By “hot spot” we mean a localized domain with a temperature above T_c . A hot spot can result from a thermal instability that takes place when the heat generated in the system (which can be the film) cannot be evacuated into the heat sink. Such an instability produces necessarily domains above T_c .²³

In Fig. 9 we plot the resistance of a single HDD as a function of the current, at $T=10$ K. Here, the resistance is defined as the voltage divided by the total current, which is the appropriate quantity for a normal domain. The HDD resistance is obtained after subtracting the background, as in Fig. 7, and therefore it is the resistance we would obtain by placing local voltage probes just across the HDD.

If the HDD is a hot spot, then its length can be deduced directly from the ratio of its resistance over the total bridge resistance just above T_c , i.e., 31 Ω . This yields a length of 1.3 μm . As a consequence, right after the nucleation the HDD would be a thin line (1.3 \times 60 μm) cutting the bridge

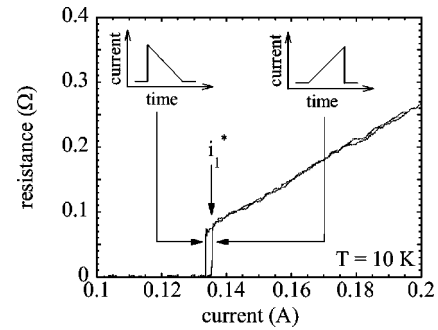


FIG. 9. Resistance of the first HDD defined as the voltage divided by the total current in the BSCCO film at 10 K and 0.1 T. The current is ramped at the rate of 30 A/s, so that the whole curve is taken in 3 ms. Above i_1^* , there is a good agreement between the curves obtained with the upward and the downward ramp. As observed for many HDD's, the current induced nucleation is hysteretic.

perpendicularly to the current direction.

The main point comes directly from the inspection of Fig. 9. Since the HDD, when created, does not have an Ohmic behavior, it cannot be a normal zone above T_c , unless the domain *temperature* or *size* changes as a function of the applied current. However, above i_1^* , the I - V curves are the same with an ascending or a descending current ramp. This indicates that the application of the current does not result into an irreversible heating or expansion of the HDD. Therefore, if these changes occur, they do in a *stationary* manner.

Gurevich and Mints⁶ have shown that in a stationary situation, the hot spot size must *decrease* with an increasing current, in order to evacuate the excess of heat generated in the domain. Hence, a change in the domain size cannot explain the resistance increase of Fig. 9.

Furthermore, the resistance increase is too large to be explained by a temperature increase alone. Indeed, if the value just after the nucleation ($R_{\text{nuc}}=0.07 \Omega$) corresponds to the normal state at 90 K, then when the resistance reaches 0.26 Ω (on the right side of Fig. 9), the HDD would be over room temperature (334 K). Furthermore, in this sample, I - V measurements were performed up to 0.3 Amp, and the resistance continued to increase, corresponding to a hypothetical hot spot of 700 K. At these temperature, the HDD would irreversibly damage the film, in particular causing a loss of oxygen, and the I - V would not be reproducible.

Thus, the hot spot model cannot explain the observed voltage steps. This conclusion is also supported by the following quantitative argument.

Let us estimate the temperature increase ΔT in a hypothetical hot spot of 1.3 μm , just after its creation, when we neglect the heatlink with the helium gas. Since all the power produced in excess must be evacuated toward the substrate, we have $R_{\text{nuc}} i_1^{*2} = S \lambda \Delta T$, where S is the area of the interface with the substrate and λ the thermal conductance between the film and the substrate. Taking $\lambda = 10^7 \text{ W K}^{-1} \text{ m}^{-2}$, a value generally obtained for the boundary conductance between $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and MgO ,²⁴⁻²⁶ the temperature increase in the HDD right after its formation would be around 2 K. This rough estimate yields

that the power generated in the HDD is not sufficient to maintain the temperature above T_c .

Plotted as the voltage versus current, as in Fig. 7, we see that the only deviation from an Ohmic behavior is a nonzero intercept at zero voltage. Therefore the HDD can be understood as a normal region where the current that generates dissipation is just a fraction of the total current. In other words, in addition to the normal current, a supercurrent would be flowing across the HDD.

In fact, with respect to the three features, piecewise linearity, positive zero-voltage intersect and hysteresis, the I - V curves obtained here resemble the measurements performed in tin whiskers² and microbridges.³ In both systems, dissipation was well explained by the standard model of PSC nucleation of Scokpol, Beasley, and Tinkham (SBT).³ According to this model, only part of the total current contributes to the dissipation of a PSC and this current produces a normal state resistance. Therefore, the I - V characteristic of a single PSC is given by

$$V = 2\Lambda\rho(j - j_0), \quad (2)$$

where ρ is the normal resistivity, Λ the diffusion length of the quasiparticle generated in the PSC core, and j_0 the time averaged supercurrent. In the SBT description, the suppression of the order parameter occurs in a small region of size ξ , but the measured voltage drop is governed by the diffusion of quasiparticles over a much larger distance Λ .

Several experiments carried out in Sn films show that the ‘‘PSC kind’’ of I - V , i.e., a series of linear section separated by sharp steps is also visible in wide samples.^{27–29} It suggests that a 2D system exhibits the same behavior as a narrow superconductor, but the 1D core is replaced by a thin line crossing the bridge width (i.e., a phase-slip line) or a channel of rapidly moving vortices.³⁰ This extension to a 2D case is also supported by theory.^{30,31}

Therefore, we can evaluate Λ , the extension of the HDD, using Eq. (2): the differential resistance of a single HDD is $2\Lambda\rho/\sigma$, where σ is the bridge cross section. This determination requires an estimate of the normal carriers resistivity ρ at temperature $T < T_c$. Taking into account the reduction of the scattering rate at low temperature, one can assume a resistivity of the form $\rho(T) = \rho_d + \rho_s(T)$ where ρ_d is due to defects and becomes dominant at low temperature³² and $\rho_s(T)$ is the linear component measured above T_c . Qualitatively such a behavior for the normal state resistivity is observed under high magnetic fields.³³ Since we see little change below 30 K in the I - V characteristics, we estimate ρ_d as $\rho_n T_d / T_{\text{onset}}$, where T_d is the saturation temperature we estimate to be 30 K and T_{onset} is 80 K, the temperature just above the transition. This estimate yields $30 \mu\Omega \text{ cm}$ for the resistivity entering in expression (2). Therefore, the first HDD shown in Fig. 7, with a differential resistance of 0.6Ω , has a characteristic length $2\Lambda = 27 \pm 10 \mu\text{m}$, much larger than in the hot spot case. The error allows for the large uncertainty in ρ . Note that the first HDD could include several PSC and therefore this estimate represents an upper limit of the PSC size.

Coming back to the temperature dependence of j^* , it is interesting to note that such a temperature dependence is what is most likely expected for the depairing current $j_d(T)$ in high- T_c superconductors. Indeed, using Ginzburg-Landau relations for j_d , we have

$$j_d(T) \propto \frac{1}{\lambda^2(T)} \frac{1}{\xi(T)} \propto \left(\frac{1}{\lambda^2(T)} \right)^{3/2}, \quad (3)$$

where the $1/\lambda^2(T)$ factor is the temperature dependence coming from the superfluid density and $1/\xi(T)$ is the contribution of the critical velocity. The last proportionality is obtained by assuming that the Ginzburg-Landau parameter $\kappa = \lambda/\xi$ is only weakly temperature dependent. The temperature dependence of j_d will be the one displayed on the right-hand side of Eq. (1), because the temperature dependence of the superfluid density measured from zero to T_c is well described by $1 - (T/T_c)^p$ with p ranging from 1.7 to 2.9.^{34–36}

However, the amplitude of j^* is well below the depairing current (about two orders of magnitude). In a perfect superconducting filament, in contrast, a PSC would develop when the supercarriers reach the critical velocity. The fact that a HDD appears at a current representing a small fraction of j_d implies that the energy cost to create a phase-slip line or a channel of fast moving vortices is well below the one needed to destroy completely superconductivity in the film. A theoretical prediction of j^* would require an understanding of the exact mechanism causing the development of the PSC. This is presently beyond the scope of this article. Nevertheless, we can deduce from the similarity of j^* in the different compounds that this mechanism is not dependent on the nature of the defects, and therefore not related to vortex pinning.

V. CONCLUSION

In every high- T_c thin film of BSCCO and NBCO we measured, the high current part of the I - V characteristics exhibits some sharp voltage variations. These are robust features and are observed over a wide temperature range, from 4 K up to the vicinity of T_c . This behavior of superconducting films traversed by a high density of current seems very systematic, since it has been reported by other groups in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (Refs. 9,11–14) or $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_y$,¹¹ with various interpretations. We believe that a very general mechanism occurs in the superconducting state at high current density independently of the defects, such as pinning centers, etc. By means of time resolved resistance measurements, we have shown that this mechanism accounts for both small voltage steps and a more dramatic event like the current-induced breakdown of superconductivity. The small voltage steps are associated with the nucleation of local dissipative domains. We have brought new arguments showing that these domains do not result from thermal instabilities, such as hot spots (the situation is quite different in bulk superconductors, where Joule heating may dominate). Another mechanism, directly related to superconductivity must therefore be at the origin of the formation of these domains. Even though the samples cannot be considered as one dimensional, the transport prop-

erties are in good agreement with a dissipative state dominated by phase-slip centers, in which the superconductor is locally driven far from its equilibrium point. If this interpretation is correct, transport measurements at high current density allow us to access intrinsic properties of the superconductor. The fundamental character of this dissipation process is confirmed by the temperature dependence of the critical current which is similar in different high- T_c compounds and

turns out to be close to the one expected for the depairing current.

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