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Extended Domain of Existence for PSCs in Superconductors

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By means of nanosecond pulse techniques, we have studied the current-induced dissipation in one-dimensional superconducting bridges, namely, metallic and high-T_c films. It is well known that narrow strips dissipate through phase-slip centers (PSC) close to T_c, or hot spots (HS) at low T, rather than by flux flow. When driven by step pulses of current, PSC give stable voltages, while HS produce a voltage linearly changing with time. By using two-step pulses of current, we have studied the decay of a HS into another HS, or a PSC, or into a zero-resistance state. It was thus found possible to reach the PSC state at arbitrary low temperatures.

KEY WORDS: nonequilibrium superconductivity; weak links; high-T_c films; high-speed techniques; conventional superconducting films.

1. INTRODUCTION

Current-induced dissipation in one-dimensional superconducting bridges first appears in the form of one, or several, localized (≈1 μm) resistive zones, or quantum phase-slip centers (PSC) [1]. These appear, generally close to T_c, as tiny steps in the resistive transition $R(T)$, and in their current–voltage (I–V) characteristics as well. However, there is a competition between the critical current I_c and the "thermal" threshold current I_h, above which film cooling is not sufficient to prevent the transition into the normal state ($T > T_c$) under the form of hot spots (HS). Because of the special temperature dependences of $I_c(T)$ and $I_h(T)$, the PSC regime is usually considered [2] to be confined to a very restricted temperature range, not more than a fraction of a kelvin below T_c. An experimental difficulty arises in the usual dc voltage-bias configuration, since then both PSCs and HS manifest themselves by discontinuities in the I–V curves.

We depart from the traditional method in two ways: (a) pulse excitation and (b) current bias supply. By monitoring the transient response on the nanosecond scale, one is able to lift the ambiguity between the quantum (PSC), and the normal (HS) dissipation modes and, in particular, to study the transformation into one another.

2. THE RESISTIVE SINGULARITIES AND THEIR OBSERVATION

In the standard model [1,2], a PSC is a localized quantum dissipation unit where the current periodically alternates at the Josephson frequency $\nu = 2\,\mathrm{eV/h}$ between the superfluid and the normal forms. Each cycle is accompanied by one $\pm 2\pi$ phase slip between the two sides of the superconducting wave function, thereby allowing a voltage drop, with no loss of coherence along the bridge, however. The PSC mode is typical of unidimensional structures (transverse dimensions smaller than the coherence length ξ), but was found to apply to more general conditions.

The PSC extends over ξ, but the associated resistance step corresponds to a segment of normal material twice longer than the inelastic diffusion (or Pippard) length Λ_{qp} (typically 1 μm). The quasiparticles emitted at each cycle of the oscillation are responsible for this effect.

The temperature rise at the PSC location due to the dissipation may cause the transition of the PSC zone into a normal HS ($T > T_c$). Let us define the

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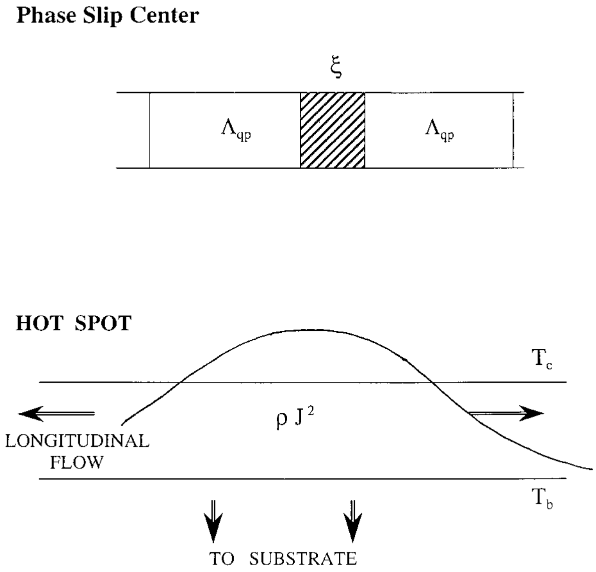

Fig. 1. Top: Phase-slip center. Medium zone of extension ξ. Resistance spreads over 2 Λ_{qp} Bottom: Hot spot. Temperature profile in a hot spot, and thermal transfers in and out: Joule dissipation, heat conduction along the film, and escape to the substrate.

threshold current density J_{h} as the current density sufficient for ϱJ_{h}^2 (see Fig. 1) to compensate for the heat loss to the thermal bath, plus the heat conduction along the bridge (ϱ = normal state resistivity). If the heat transfer to the bath T_{b} (essentially the substrate) is expressed as the volumic quantity $C\tau^{-1}(T - T_{\text{b}})$, with C as the specific heat and τ as the bolometric cooling time of the film, we obtain

$$\varrho J_{\text{h}}^2 = bC\tau^{-1}(T_{\text{c}} - T_{\text{b}}) \tag{1}$$

b being a numerical factor of order 2 in the linear approximation [3,4].

Whether one operates pulse-wise or dc-wise, a PSC manifests itself by a stable discontinuity of voltage as the current I is scanned through I_{c}. However, in the case of a HS, we have to specify the type of excitation we provide to the superconducting bridge: if the electrical supply is voltage-biased (low-impedance source), the HS adapts its size to the voltage prescription [5], so that it appears more or less similar to a PSC on I–V curves or in a pulse experiment. On the other hand, current-biasing (high-impedance source) reveals the unstable character of the HS: the response to a rectangular step of current ($I > I_{\text{h}}$) is a voltage linearly growing with time, at a definite velocity [6]. A dc current results in a total invasion of the bridge [3].

Our present data concern c-axis-oriented YBCO films on crystalline MgO, or niobium films on sapphire wafers, patterned as bridges 5–100 μm wide. The experimental apparatus is described in [4]. While all connections lead to 50-ohm coaxial cables, the requirement of controlled-current bias imposes a higher impedance probe when an appreciable resistance (about 10 ohms) sets in.

To summarize, as a pulse of current is provided to the bridge, a flat voltage response will signal the presence either of a PSC, or of a marginally stable HS (current just equal to I_{h}). A HS generally may be growing or receding, leading to a linearly rising, or linearly decreasing ($I < I_{\text{h}}$), voltage at the probes.

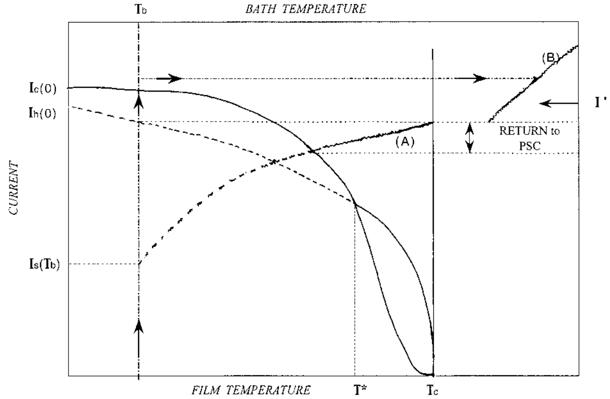

Fig. 2. Theoretical diagram in the I–T plane for the appearance of PSCs and of hot spots (see text). With a single pulse excitation, PSCs are observable only in a limited temperature domain above T^*. With a two-step excitation, a passage through a HS state can lead to a PSC (curve A) while the bath temperature $T_{\text{b}} < T^*$.

3. PSCs AND HOT SPOTS IN THE *I–T* REPRESENTATION

We plot $I_{\text{c}}(T)$ and $I_{\text{h}}(T)$ on the same current–temperature graph, while noting that T is the film temperature on $I_{\text{c}}(T)$, and the bath temperature T_{b} for $I_{\text{h}}(T)$. Close to T_{c}, the critical current I_{c} follows a $(1 - T/T_{\text{c}})^{3/2}$-dependence [1], while, according to Eq. (1), $I_{\text{h}}(T)$ has a $(1 - T/T_{\text{c}})^{1/2}$-dependence. As a result, the two curves usually intersect[4] at a temperature T^* (Fig. 2). Clearly, in the region $T^* < T_{\text{b}} < T_{\text{c}}$, one can apply a current I larger than $I_{\text{c}}(T_{\text{b}})$ and smaller than $I_{\text{h}}(T_{\text{b}})$, the proper condition for PSC formation, in conformity with the general consensus [1,2].

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[4] It may happen that the two curves never cross, for I_{c} < ideal depairing limit. Then, the PSC condition $I_{\text{c}} < I < I_{\text{h}}$ is possible at all T.

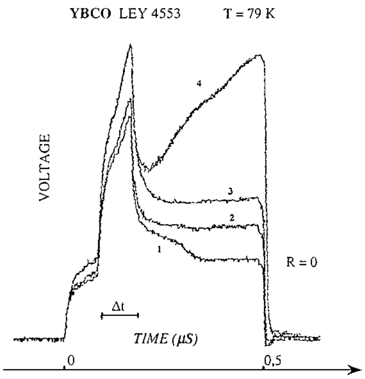

Fig. 3. Time dependence of voltage along YBCO bridge LEY 4553w (120 nm on MgO; width: 10 μm) excited by a two-step pulse at 79 K. According to the value of I', the film is left either in the zero-resistance state (1), or in a PSC state (2–3), or in a hot spot state (4). Baseline $R = 0$ corresponds to the voltage drop in contacting pads and wires.

At $T_b < T^*$, it has been stated in different places that the voltage steps of I–V curves are due to hot spots because $I_h(T_b)$ is reached before $I_c(T_b)$. Our interpretation runs differently. If one applies a step of current whose intensity I is gradually increased, the value I_h is reached first, before I_c, but this brings in no voltage as long as $I < I_c(T_b)$. So, $I_h(T)$ below T^* is a latent branch of the full $I_h(T_b)$ curve. A voltage signal appears only when I is raised up to $I_c(T_b)$. Then, a transient PSC is created, which immediately—within time τ—transforms into the normal state ($T > T_c$).

However, even in this domain $T_b < T^*$, we claim that a PSC can be created thanks to a special contour in the I–T plane involving the superposition of two pulses. The film is first boosted into a HS state by applying $I > I_c(T_b)$, and then left with a smaller I'. If $I' > I_h(T_b)$, one still sustains a growing HS (curve 4 in Fig. 3), although T(film) gets smaller when I' is reduced (arc B in Fig. 2) until, as the speed of expansion is reduced, a flat response is reached. This defines $I_h(T_b)$, which we missed in increasing currents.

Then, for pulse amplitudes $I' < I_h(T_b)$, we could expect receding HS (negative growth). Such is not the outcome of the experiments, as it is developed below.

4. RETURN FROM ABOVE: HOT SPOT BACK TO PSC

Figure 3 shows the voltage response of a 120-nm thick $YBa_2Cu_3O_7$ strip to a two-step pulse of current at temperature $T_b = 79$ K. A relatively large current, supplied during time Δt, excites an HS, which may reach a few micrometers in length in its final phase. Then, the pulse amplitude is reduced to I', which runs from 1 to 4.

For the HS signal (rising voltage, curve 4), a quasi-linear rise was expected, were it not for a spurious bump, which can be traced to a deficiency in the middle of the delay line. For curves 3 and 2, because the response is flat after some decrease of the voltage, and because there is a range of I' (not a single value), we believe I' has passed below the HS threshold $I_h(T_b)$. We interpret these responses as coming from PSC maintained by dissipation at $T > T^*$, although the bath is still at low temperature.

By definition, $T < T_c$ out of the HS, and part of the current is carried as a superfluid, although I' is still larger than the critical value. The conditions are met for the phase-slip process. Inside the PSC, dissipation is sufficient to compensate the heat loss to the thermal bath.

However, at still lower current I', dissipation becomes too weak: the temperature falls to a value T where $I_c(T) > I'$. The resistance after some time suddenly goes to zero (curve 1). Presumably, the strip has resumed the initial superconductive state.

5. CONCLUSION

In this work, we have attempted to explain the frontiers between the PSC and HS regimes, to display the role of PSCs as initiators of the current-driven HS and shown how to bypass the thermal barrier which prevents PSC formation at low T.

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