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Temporal Evolution of Normal Hot Spots in Current-Driven Superconducting Films

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In addition to the critical current I_c (T), which generates Phase-Slip Centers (PSCs), thin superconducting films possess a well-defined second limiting current I_h, or current intensity able to maintain a preestablished hot spot. By pulsing step functions of the current and monitoring the voltage response on the nanosecond scale, we have determined ($T \leftrightarrow I_c$) and ($T \leftrightarrow I_h$). From a dynamic study of the two main modes of dissipation in YBCO and Nb films, it is concluded that PSCs are stable structures in current-biased bridges. In contrast, hot spots grow at a constant rate of a few tens of meters per second, determined by the thermal diffusivity of the material and by its bolometric response time. On reducing the current from I_h, the so-called healing length, or minimum normal length, was found, of the order of 0.2 μm in YBCO and 2 μm in Nb. In summary, the experiment provides three independent measurements (PSC nucleation time, velocity of growth, and minimum length) for only two parameters (D and τ).

KEY WORDS: critical currents; high-T_c films; nonequilibrium superconductivity; boundary layer heat flow; thermal stability; thermal effects.

1. INTRODUCTION

The current-induced superconducting-to-resistive transition is gradual in type-II materials, but becomes steplike in narrow bridges (thin films or whiskers). That is due to the appearance along the bridge of dissipative zones of two kinds: Phase Slip-Centers (PSCs) [1] and hot spots (HS), which were described in detail by Skocpol *et al.* [2], a paper referred to as SBT-74 in the following. Most of the preceding studies on PSCs and HS have concerned metallic superconductors and have been performed in conditions of voltage-bias with the double objective of protecting the device against damage, and of stabilizing the (possible) instabilities of these dissipative singularities. We adopt here a different point of view, by supplying our bridges with short pulses of *current*, in the manner of Pals and Wolter [3], who discovered the PSC time of nucleation (see [4] for an application to high-T_c materials). Current-bias also results in the enhancement of the HS instabilities, which is the main subject of this Communication. We have measured the velocities of growth of hot spots on both low and high-T_c materials, and compare them to a new quantitative model [5].

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2. HOT SPOTS CURRENT DENSITIES $J_h(T_b)$ AND $J_1(T_b)$

Let a thin film of area A, of thickness d, of normal resistivity ρ, of critical temperature T_c, deposited on a substrate at (bath) temperature T_b, be traversed by a current density J (Fig. 1a). In order to sustain a temperature at least equal to T_c, the joule power $P = A \cdot d \cdot \rho \cdot J^2$ must compensate for the heat transmission P_{bd} through the film-to-substrate boundary, which we write equivalently in the linear approximation:

$$P_{bd} = A\alpha(T - T_c) = A \cdot d \cdot C(T - T_c) \cdot \tau^{-1} \qquad (1)$$

Here T is the film temperature and α is the coefficient of heat transfer through the interface. The parameter τ then appears as a cooling, or bolometric, time constant. That is not a redundant definition, since several

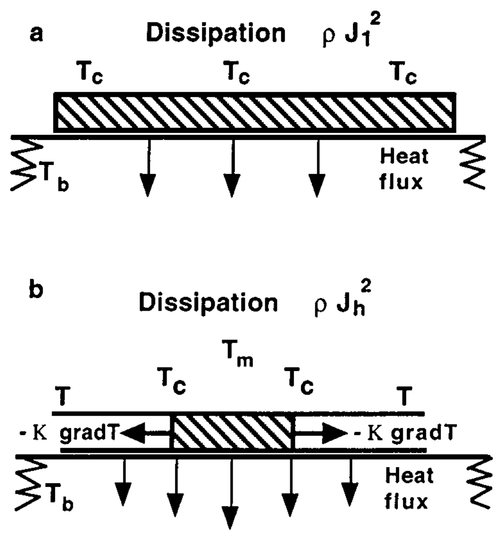

Fig. 1. Representation of heat transfers for a film traversed by a current in a homogeneous heating situation (a) for the definition of I_1 and in hot spot conditions (b) for the definition of I_h.

procedures of evaluating the thermal properties of the interface directly provide this time. It is the case of many measurements of the photoresistance decay. It is also the case of PSC nucleation time experiments [4,6] carried out on $YBa_2Cu_3O_7$ epitaxial films on MgO substrates, which led to the very useful result that the quantity τ/d is only little temperature and thickness dependent and close to 75 ps/nm. Actually, we found that other combinations, such as niobium-on-sapphire, have τ/d of the same order. (This amounts to a phonon transmissivity of about 2%.)

By these definitions, the threshold current for a normal zone to exist is J_1, which is given by

$$\rho J_1^2 = \frac{C(T_c - T_b)}{\tau}. \qquad (2)$$

However, a true hot spot is an isolated structure, bounded by (colder) superconducting regions, so that the heat conduction along the film comes of importance (Fig. 1b). It turns out that, whatever the diffusion coefficient D, the minimum current J_h that sustains a hot spot is related to J_1 by $J_h = 2^{1/2} J_1$, at least in the linear approximation [2]. Current densities convert into intensities by $I = w \cdot d \cdot J$ (w = width).

As we will see later, this set of currents $I_1(T)$, $I_h(T)$ determines three domains of current: For $I < I_1$, no hot spot can exist, even in a transient state. For $I > I_h$, we have expanding HS, and regressing HS in the intermediate region $I_1 < I < I_h$.

3. EXPERIMENTAL

We have studied mainly epitaxial $YBa_2Cu_3O_7$ films. *C*-axis oriented films were deposited on crystalline MgO by laser ablation. Then, the bridge pattern (width $\approx$ 5–40 μm) was obtained by ion-milling after a photolithographic process. The contact pads were covered with evaporated gold. We thus obtained ohmic contacts, of about 30 mΩ in the best cases. Although we have investigated niobium films in parallel, the corresponding results will be deleted till a later report.

To observe the response on the nanosecond scale, we used a 50-Ω coaxial circuit (Fig. 2) including a delay-line (250 ns), so that the input pulse is separated from the zero-impedance bridge response by at least 500 ns. The input current excitation came from one or a combination of two pulse generators selected for the flatness of their pulse output. The observation of voltage signals usually required no amplification and was performed using a fast numerical scope.

4. DETERMINATION OF THE HOT SPOT CURRENT I_h

We apply the technique of the superposed current pulses to first excite the film into an HS state, quite recognizable from the rapidly increasing voltage, and then come back to a lower current. Figure 3 shows the resulting behavior of the thin film resistance. According to the intensity of the residual current I_r, the signal can be increasing or decreasing. The HS current defined as I_h is the value of I_r which keeps the HS voltage constant.

5. ESTIMATES OF THE VELOCITY OF GROWTH

If considered as a thermodynamic system, void of any microstructure, a superconducting film sustaining a hot spot can be characterized by the set of three quantities, d (thickness), $D = \kappa/C$ (thermal diffusivity), and $\tau = C \cdot d \cdot \alpha^{-1}$. For simplicity, we will not distinguish between the superconducting and the normal values. Only the electrical resistivity will be taken as ρ (normal value above T_c) independent of T, and zero in the superconducting zones.

From dimensional analysis, with L = length and t = time, we can form a velocity $U_0 = L/t$, and a

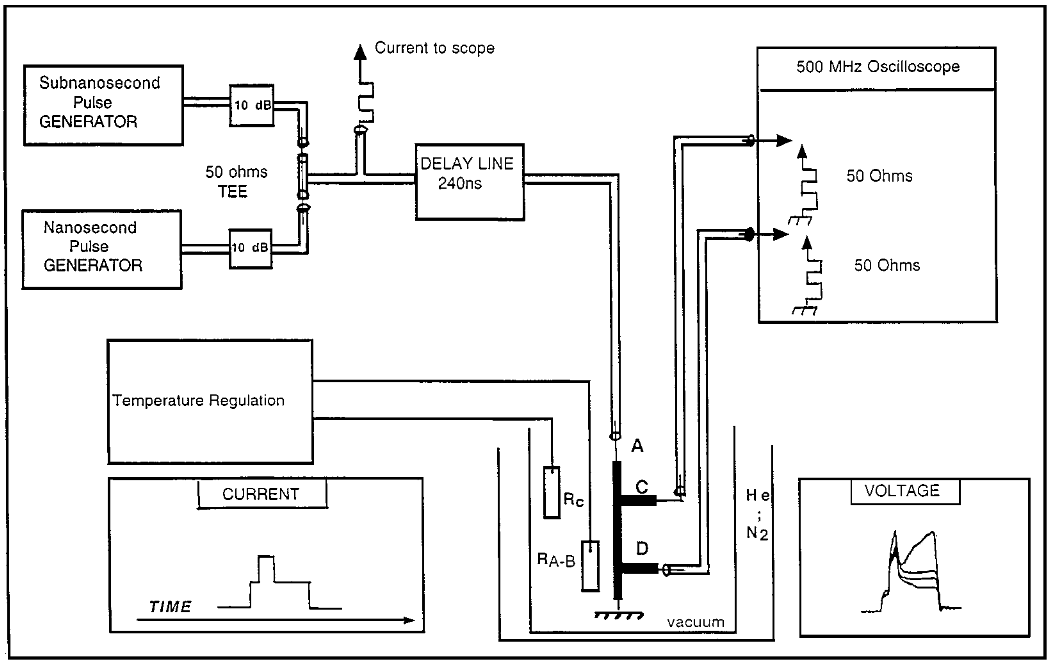

Fig. 2. Experimental setup for monitoring transient responses on the nanosecond scale. Typical input and output signals are shown in separate boxes.

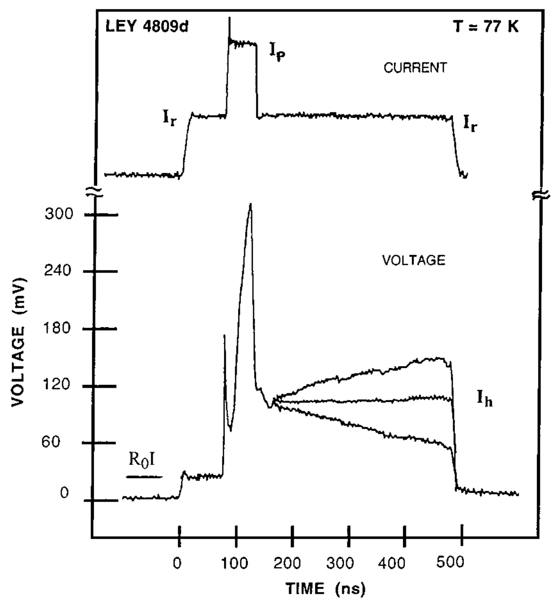

Fig. 3. YBCO film LEY 4809d (thickness: 120 nm; width: 10 μm) submitted to a superposition of two current pulses (upper graph): I_P to create the HS state, and I_r to monitor its velocity of growth. I_h is defined as the value of I_r which keeps the HS voltage constant (middle trace). $R_0 I_r$ is the voltage drop at the contacts.

length with $(D \cdot \tau)^{1/2}$, since $[D] = L^2 t^{-1}$ and $[\tau] = t$. This length is similar to the characteristic healing length η of SBT-74 [2].

From an exact model (see [5]), the HS velocity of growth U and minimum normal length m are given respectively by

$$U = \frac{j^2 - 2}{\sqrt{j^2 - 1}} \cdot \sqrt{\frac{D}{\tau}} \quad \text{and} \quad m \approx 2\eta = 2\sqrt{D \cdot \tau}, \qquad (3)$$

where the reduced current j is the ratio I/I_1.

Typical values for YBCO films on MgO can be derived using D (90 K) = 3.2 mm^2/s from the graphs of Onuki *et al.* [7], and τ from the data of Harrabi *et al.* [6], which can be summarized as $\tau/d = 75$ ps/nm. We then find $U_0 = 20$ m/s and $\eta = 0.15$ μm for films a few tens of nanometers in thickness.

Although we do not report on Nb films, let us anticipate the situation. Now, the diffusivity of heat is dominated by the electron mobility, so that we take $D = (1/3) v_F \cdot l_e$, where v_F is the Fermi velocity, about 10^6 m/s, and l_e is the electron mean free path, about 3 nm, as it is determined by the normal resistivity at low T. With a bolometric time τ of the order of

10^{-8} s, we find U_0 around 300 m/s, and η of the order of 3 μm. These values are 10 to 20 times the corresponding values for YBCO, and should serve as a test of the model when compared to YBCO results.

6. EXPERIMENTAL OBSERVATIONS

6.1. Velocity of Growth

In Fig. 4, we show the rise of hot spot signals in YBCO sample LEY 4553 w ($d = 120$ nm; $w = 10$ μm) for a bath temperature $T = 77$ K. This implies that all currents are above I_c (77 K) > I_h (77 K). The signals are composed of an initial rise corresponding to a contact resistance of about 0.4 Ω. Then the rising signals corresponding to each current occur at the specific nucleation time t_d determined by the ratio I/I_c [4,6]. The fast rising parts are preceded by slow rising voltages having a significance which will not be developed here.

The velocities have to be measured at the onset (see interrupted lines) as the upper bending is due to the finite value of the film impedance compared to the source impedance 50 Ω. In the present set of data, only modest changes of currents were selected for clarity. Actually, much faster velocities obtain in higher currents, but the signals have then the property of accumulating at $t_d = 0$.

6.2. Velocity of Regression and Minimum or Healing Length

According to Eq. (3), the velocity of growth becomes negative for $j = I/I_h < 2^{1/2}$, which corresponds to a regression of the normal zone, which should result in a decrease of the voltage in constant current. However, the film has to be launched into the HS state by a strong current. That is performed by the superposition of a "turn-on current" I_P on an otherwise small current I_r. The strong pulse is sufficient to produce a normal zone a few micrometers long. Then the expected decrease (Fig. 5) of the voltage in current I_{P1} is observed. We note for instance $U = -0.7$ m/s on trace 3. We are presently pursuing detailed measurements of the velocity $U(I, T)$ to check the relevance of Eq. (3) in this problem.

Together with the gradual voltage decrease with time, one observes a sudden drop of the signal from a roughly constant value of about 15 mV which, for currents around 38 mA, would indicate a final resistance of 0.45 Ω. Trace 4 stands as an apparent exception, only due to the limited time range recorded. Considering the normal resistance of this film for a total length 0.6 mm, this amounts to a final length 0.31 μm before coalescence.

Based on Eq. (3), an estimate using $D = 3.4$ mm^2/s from Onuki *et al.* [7] and $\tau/d = 75$ ps/nm with $d = 120$ nm gives $\eta = (D\tau)^{1/2} = 0.17$ μm, and a value of $2\eta = m$ very close to the experimental determination.

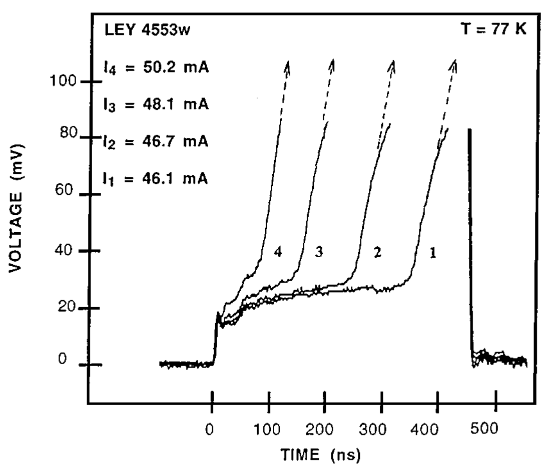

Fig. 4. Voltage signals along YBCO film LEY 4553w at $T_b = 77$ K show hot spot growth for several values of the current. Decreasing nucleation times follow from increasing currents. The velocity U is deduced from the rate of voltage increase (interrupted lines), and from the normal resistivity of the film.

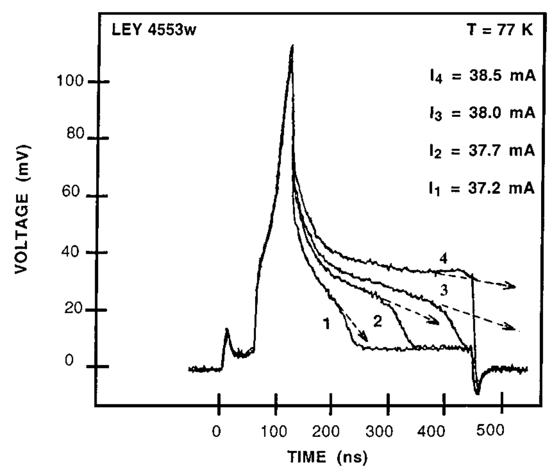

Fig. 5. Voltage signals along YBCO film LEY 4553w at $T_b = 77$ K show hot spot regression (interrupted lines) for several values of the current below the HS limit I_h. The HS state is triggered by a superposition of two pulses. The final jump down corresponds to a length of normal material very close to the prediction of Eq. (3), that is $2(D\tau)^{1/2}$.

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