Temperature Dependence of the Heat Escape Time Deduced From the Nucleation of a Dissipative Zone in Superconducting $YBa_2Cu_3O_7$ Filament

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***Abstract*—The application of an overcritical current pulse $I > I_c(T)$ to narrow $YBa_2Cu_3O_7$ strips generates a phase-slip center after a certain delay time t_d. By analyzing this function $t_d(I/I_c)$ through a time-dependent Ginzburg–Landau theory, one can extract the time of heat escape τ_{esc} from the film to the substrate. The parameter τ_{esc} was found to remain constant in the range from 5 to 40 K, but to increase notably above 40 K and up to T_c. We interpret this behavior as a manifestation of a Kapitza heat transfer by acoustic phonon radiation. The loss of transmissivity at higher temperatures is likely related to the rise of phonon–phonon decay processes.**

***Index Terms*—Superconducting thin film, critical current density, heat transfer.**

PACS numbers
74.78.Bz: High-Tc films
74.25.Sv: Critical currents
44.00.00: Heat transfer
63.20.Kr: Phonon-electron and phonon-phonon interactions.

I. Introduction

In the past decade, superconducting nanowires have emerged as promising candidates for single photon detection in the infra-red range. They are capable of high sensitivity with very little dark count rate [1], [2] when they are biased away from the critical current limit. A repetition frequency of a few GHz is made possible by the thinness of the device and its correspondingly short thermal recovery time (a fraction of a nanosecond). Immediately after the absorption of a photon, which reduces the width available to superconducting transport, the filament is in a situation comparable to a narrower one submitted to a larger than critical current. It is well established [3], [4] that a resistive discontinuity appears in the form of a Phase Slip Center (PSC) or of a Hot Spot (HS) if the bias current is maintained constant.

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Since its discovery by Pals and Wolter [5], it has been known that a delay time t_d, dependent upon the reduced current I/I_c and proportional to the gap relaxation time written here τ_d, is required before the filament switches into a resistive state. M. Tinkham [6] provided a more complete treatment of this problem which makes t_d dependent of the two variables T/T_c and I/I_c. In the case of epitaxial $YBa_2Cu_3O_7$ (YBCO) filaments, the quantity τ_d was found [7] to coincide with the cooling time of the film on its substrate. Considering the relevance of this parameter to determine the recovery time of the filament functioning as a single particle detector, we have extended the measurements of $t_d(T/T_c, I/I_c)$ to a wider temperature range, and used a substrate different from that used in [7].

In the present work, a step-pulse of constant current is applied to a superconducting YBCO filament in order to produce a resistive response after a delay t_d. From [6], one can build a set of functions $F_2(T/T_c, I/I_c)$ such that the delay time can be represented by $t_d = \tau_d\, F_2(T/T_c, I/I_c)$. The only parameter left to be determined is the prefactor τ_d. It is finally discussed by comparison with other similar physical situations.

II. Sample and Experimental Setup

The YBCO thin films were DC-sputtered and patterned on R-cut sapphire substrates by Theva GmbH(Germany). An epitaxial 40 nm buffer layer of cerium oxide was used for stoichiometric matching between the substrate and the 80 nm YBCO film. A 100 nm gold layer was then evaporated to serve as contact. Afterwards the devices were processed using standard photolithography and ion milling. The measurement was performed in a Janis closed cycle Cryofree refrigerator with a temperature controller. The series of measurements were performed on a sample of width $w_{\mathrm{THW3}} = 3\ \mu$m, having a transition temperature $T_c = 85$ K, and a resistivity at 100 K $\rho_{100\ \mathrm{K}}(\mathrm{THW3}) = 73.1\ \mu\Omega$.cm.

To measure the response of a superconducting filament to a rectangular electrical current pulse on the nanosecond scale, a 50 Ω coaxial circuit was used. The incident excitation was provided by a short rise-time pulse generator adapted to the circuit to measure the delay time t_d. We attempted to completely suppress the reflection and at the same time maintain a constant bias current in the sample. It is achievable by setting the equivalent impedance at the line's termination at 50 Ω. A large resistance R_a is mounted in series, while a resistor $R_\parallel$ shunts the combination R_a + Sample. The current flowing through the strip in its superconducting state is $I = I_{\mathrm{Tot}}.R_\parallel/(R_\parallel + R_a)$,

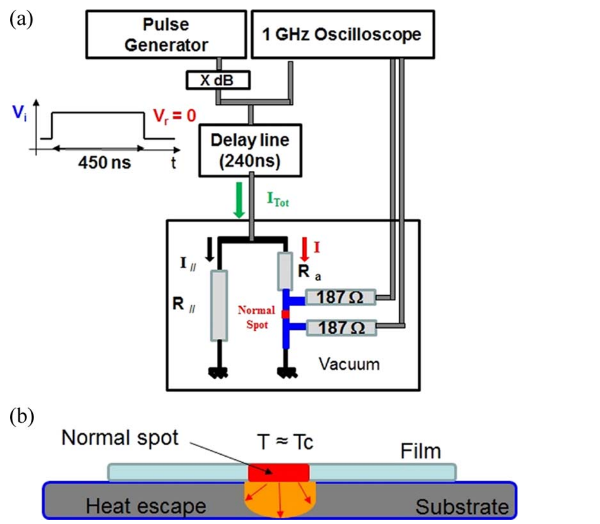

Fig. 1. (a) Illustration of the experimental setup used for pulse measurements. It consists of a pulse generator, a set of calibrated attenuators, and a delay line needed to separate the incident pulse from the reflected one. Two resistances R_a and $R_{\|}$ are added to the circuit, so that, in the superconducting state, the line is terminated by a 50-Ω load. (b) Schematic of the heat escape toward the substrate after the nucleation of a normal zone.

where the circuit impedance $Z = 50\ \Omega$ and $I_{\text{Tot}} = V_i/Z$. The voltage response was recorded using a numerical oscilloscope with 187 Ω connected in series (Fig. 1) [9].

III. Nucleation of a PSC by a Current Pulse

The most intriguing and less familiar process of dissipation in one dimensional micro-bridges, involves the PSCs, which are the substitutes of the vortex flow in very narrow filaments. In the standard model [3], [4], a PSC is described as the locus of periodic cancellations of the superconducting order parameter, each cycle being accompanied by a 2π change of the phase difference of its wave function. Each cycle also gives rise to an explosion of quasi-particles diffusing over an inelastic (or Pippard) length Λ (typically a few μm). The normal resistance R_u of the 2Λ zone determines the voltage drop along the filament. At constant current bias, the current oscillates between the two components, superfluid and normal flows. The existence of a delay time t_d between the application of a supercritical current and the appearance of a voltage, was demonstrated in Al filaments [5], and followed by similar observations in indium [10], YBCO [7], [9], [11], Nb [12], [13], [15], and NbTiN [14]. The delay time studied in [15] and [16] was reproduced numerically and showed a good agreement with the experiment.

In Fig. 2(a), the PSC voltage appearing after the delay time t_d is superposed to a flux flow voltage starting at $t = 0$. However, at low temperature the flux flow disappears due to pinning effect as shown in Fig. 2(b). The heat generated in the localized PSC raises its temperature above the substrate temperature T_b but remains below T_c [12].

IV. Determination and Temperature Behavior on the Phonon Escape Time

The delay time is identified with the time required to destroy the superconducting state by bringing the order parameter to

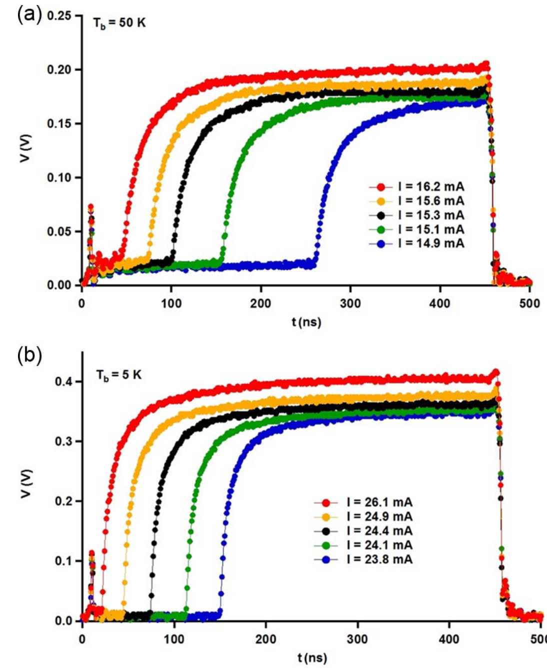

Fig. 2. (a) Time domain of the sample voltages response to a rectangular current pulses at $T_b = 50$ K, the vortex motion is illustrated by a step in voltage before the formation of PSC. (b) Voltages in response to a rectangular current pulses at $T_b = 5$ K. The instant $t = 0$ coincides with the sharp inductive peak on the left.

zero. It was originally derived [5] from a simplified Ginzburg Landau under the form:

$$t_d\left(\frac{I}{I_c}\right) = \tau_d \int_0^1 \frac{2f^4 df}{\frac{4}{27}\left(\frac{I}{I_c}\right)^2 - f^4 + f^6} \tag{1}$$

where τ_d is the gap relaxation time. This form admits no explicit dependence upon the temperature. In a more complete theory due to M. Tinkham [6], the gap relaxation time takes the form $\tau_\Delta \simeq 2.41\tau_E/(1 - T/T_c)^{1/2}$, where τ_E is the inelastic electron-phonon collision time at the Fermi level at $T = T_c$ [10]. The integrand, as well as the domain of integration become dependent upon temperature, so that t_d must be written as a function of two variables:

$$t_d = \tau_\Delta F_2\left(\frac{T}{T_c}, \frac{I}{I_c}\right). \tag{2}$$

For the case of YBCO film, it was found [7] the gap relaxation time τ_Δ must be replace by the phonon escape time τ_{esc}.

In Fig. 3, the delay times t_d were plotted as a function of the ratio I/I_c for different temperatures. The prefactor τ_Δ was deduced from the fit of the function $F_2(T/T_c, I/I_c)$. We found that the presumed phonon escape time $\tau_d = \tau_{\text{esc}}$ remains unchanged and constant for a wide range of temperature up to 40 K (see Fig. 4), but increases while approaching T_c. Far below T_c, in addition to the intrinsic relaxing mechanisms in the film (electron-phonon and electron-electron interactions), the relaxation of the gap is dominated by phonon trapping in the film (the heat cannot escape faster than the phonons at the interface). If we admit the identification of $\tau_d = \tau_{\text{esc}}$ the temperature behavior of τ_d can be understood qualitatively. At low temperatures, the τ_{esc} is defined by the acoustic mismatch

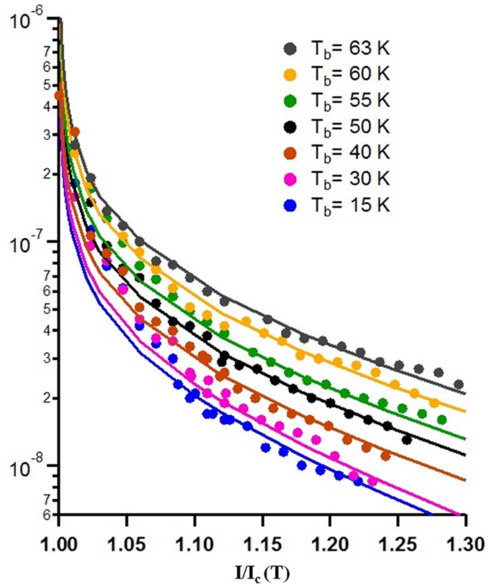

Fig. 3. Delay time t_d in log scale as a function of the reduced current I/I_c for several fixed temperatures. The fitting procedure consists of sliding vertically the theoretical function (Eq. (2) according to Tinkham [6]) to fit the experimental data.

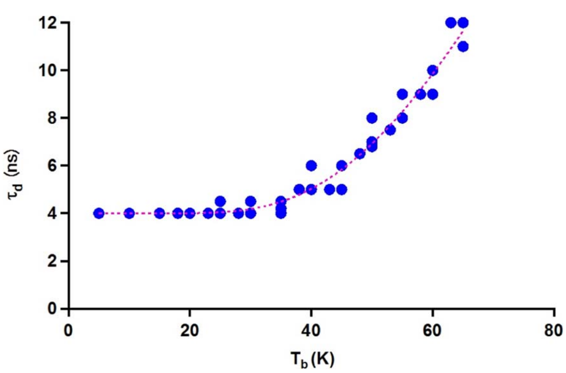

Fig. 4. Temperature dependence of the heat escape time. At low temperature, the heat escape time is constant and increases closer to T_c.

factor. Above 40 K the elevation of T might act in several ways [19]. First, the average phonon energy $hf \simeq 2.8$ kT reaches a domain of bending of the dispersion relation (hf vs. $q = 2\pi/\lambda$, where h, f and k are, respectively the Planck constant, the frequency and the Boltzmann constant). That dispersion reduces the energy velocity of the phonons. Secondly a larger number of phonons increases the rate of phonon-phonon interactions, causing the phonon transport to become diffusive. That reduces the evacuation of heat from the film and lengthens $\tau_{\rm esc}$.

For our present sample, for $T \preceq T_c/2 \sim 43$ K, the first mechanism is dominant, the phonon are still the Debye regime. The dispersion is linear and the phonon-phonon scattering is negligible, the heat escape time remains constant and short. However, for $T_c/2 \sim 43$ K $\preceq\ T \preceq T_c$, the average phonon has energy $\sim$120 K and phonon are numerous. We have two dominants mechanisms, the phonon-phonon scattering and the diffusion, causing the heat escape time to be long. It turns out, at low temperature that $\tau_d = \tau_{\rm esc} = 4$ ns for 80 nm film. Assuming the proportionality to the thickness we obtain $\tau_{\rm esc} =$ 50 ps/nm for YBCO on sapphire that can be compared to 75 ps/nm for YBCO on MgO [12].

V. Conclusion

We have measured the heat escape time of high-T_c superconducting material at different temperatures, by destruction of the superconductivity using a current pulse technique. The dissipation was initiated for a current exceeding the critical current I_c. The resistive voltage appeared after a delay time t_d, the later one was interpreted using the TDGL equation and the heat escape time was subsequently deduced. We found that the heat escape time is limited by the phonon transfer to the substrate, and is constant up to 40 K then it increases when getting close to T_c. This identified thermal parameter plays a major role in the re-set time of the superconducting single particle detector.

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