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ORIGINAL PAPER

Temperature Elevation of Current-Driven Phase-Slip Centers in $YBa_2Cu_3O_7$ Strips

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Abstract We have studied the destruction of the superconductivity in narrow YBCO strips at different temperatures caused by an electrical current pulse. Different dissipative regimes can be distinguished, and phase slip center (PSC) are more likely to appear for an overcritical current and close to the transition temperature T_c. However, far below T_c, the dissipation generates a hotspot (HS). Temperatures reached in these modes were calculated based on the Joule effect. The results of these computations are consistent with all the specific cases, PSCs and HSs, measured experimentally. One of the most attractive applications of the superconductivity at non-equilibrium regime is the single photon detection. Its principle relies on the hotspot phenomena and mainly the heat evacuation, which can determine the reset time of the photon detection.

Keywords Superconductivity · Hotspot · Phase slip centers

1 Introduction

A renewed interest in non-equilibrium superconductivity has appeared since the advent of single photon detectors based on superconducting nanowires (SNSPDs) efficient up to the infrared wavelengths [1, 2]. The SNSPD consists of a superconducting film of a thickness less than the electron thermalization length, maintained at a temperature much lower than that of superconducting transition T_c and biased just below its critical current I_c. After photon absorption, a localized spot of destroyed superconductivity turns into a normal hotspot. Its size and its expansion rate are determined by parameters such as photon energy, superconducting material, electron thermalization time, and electron diffusivity. Our purpose in this work is to show that some of these thermal parameters can be deduced from a study of current-induced non-equilibrium states in microstrips [3].

In response to an overcritical current, a narrow strip develops several dissipation modes different from a homogeneous normal state. Working at low temperature excludes the flux flow (FF) due to pinning. One is left with localized resistive zones HS and PSC [3]. These dissipative modes were investigated using a current pulse technique in YBCO [4] and Nb [5, 6]. In this work, we have studied thin YBCO superconducting filaments at different temperatures. The heat escape times toward the substrate were determined, making it possible to evaluate the temperature inside the PSC and HS.

2 Sample and Experimental Setup

The YBCO thin films grown by thermal co-evaporation were manufactured by Theva GmbH (Germany). The R-cut sapphire substrates were coated with a 40-nm epitaxial cerium oxide buffer layer prior to deposition of the YBCO with thickness of 80 nm. On top of the YBCO film, a 100-nm gold layer was applied in situ to serve as contact. Afterwards, the devices were patterned using standard photo-lithography processes and ion milling. The measurement was performed in a 15 K closed cycle cryofree refrigerator with a temperature controller. The transition temperatures of the two samples THW3 and THW10 were, respectively, T_{0c} = (85 ± 1) K and T_{0c} = (86 ± 1) K, and

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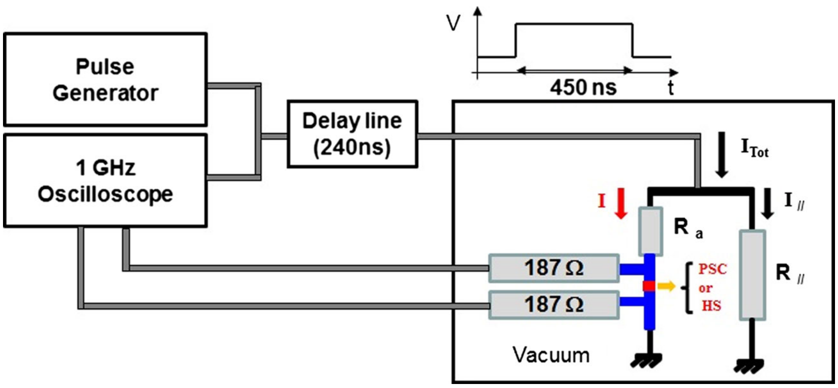

Fig. 1 Sketch of the experimental setup used for pulse measurements. It consists of a generator used to send a voltage pulse, a delay line is needed to separate the incident pulse from the reflected one, and an oscilloscope is used to measure the voltage and the delay time t_d. Two metallic resistances R_a and $R_\parallel$ are added to the circuit, so that, in the superconducting state, the line is terminated by a 50 Ω load

their resistivities at 100 K ρ_{100K}(THW3) = 73.1 μΩ cm and ρ_{100K}(THW10) = 121 μΩ cm. They had different widths w_{THW3} = 3 μm and w_{THW10} = 10 μm. Electrical pulses of 450 ns duration and 10 kHz repetition rate were sent through 50 Ω coaxial cables to the sample (Fig. 1). The bias current through the sample was maintained constant by using a large resistance in series R_a, while a resistor $R_\parallel$ is mounted in shunt across the combination R_a + sample. The equivalent impedance at the line's termination is 50 Ω, and as a consequence the reflected pulse vanishes. For an incident voltage V_i, the current flowing through the strip in its superconducting state is $I = I_{Tot}.R_\parallel/(R_\parallel+R_a)$, where the circuit impedance Z = 50 Ω and $I_{Tot} = \frac{V_i}{Z}$. The voltage response was recorded using a fast oscilloscope through lateral electrodes with 187 Ω connected in series (Fig. 1).

3 PSC Created by a Current Pulse

When driven by a step-pulse of current $I > I_c$, all our samples show a voltage response delayed with respect to the current, if we ignore the weaker flux flow (FF) response starting at time $t = 0$. Actually, the FF voltage can be reduced at will by lowering the temperature. That behavior

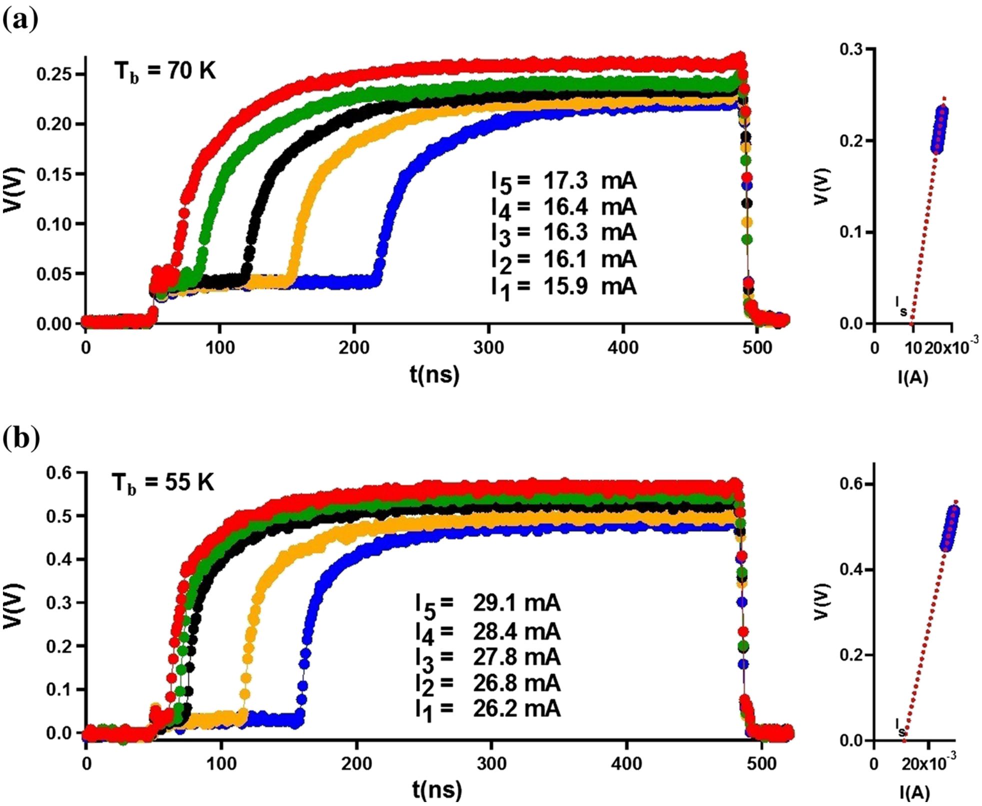

Fig. 2 Voltage response of THW3 to current pulses versus time at T_b = 70 K (*upper traces*) and 55 K (*lower traces*), here $R_\parallel$ = 56 Ω and R_a = 567 Ω. The step in voltage before the nucleation of PSC corresponds to the motion of flux lines. The critical currents are I_c(70 K) = 15.6 mA and I_c(55 K) = 26.0 mA. The right plot is V_{PSC} versus I_{PSC}. The values of the superconducting excess current are I_s(70 K) = 9.2 mA and I_s(55 K) = 11 mA

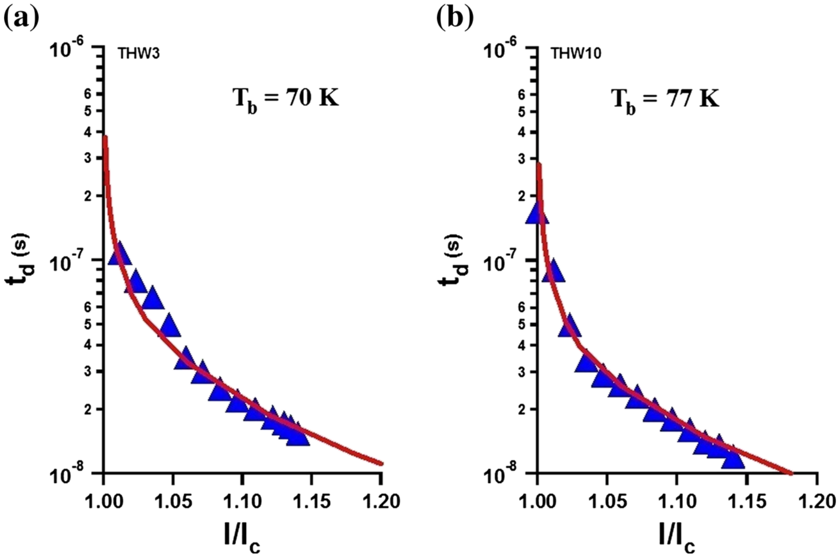

Fig. 3 Delay time t_d versus ratio of the applied current to the critical current I_c. The red traces are the Tinkham's fitting functions for $T/T_c = 0.8$ and 0.9, with, respectively, prefactors $\tau_d(70\text{ K}) = 6$ ns and $\tau_d(77\text{ K}) = 5$ ns

is reminiscent of the delay time t_d discovered and interpreted by Pals and Wolter [7] on the basis of a simplified time-dependent Ginzburg-Landau equation yielding:

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

The time parameter τ_d, originally related to the electron-phonon relaxation time, was found experimentally to be proportional to the film thickness, and actually to coincide with the cooling time of the film [4, 5]. Furthermore, instead of Eq. 1, we will use a more accurate treatment of the delay time due to Tinkham [8], where t_d is a function of the two variables (T/T_c) and (I/I_c).

Experiments performed at two temperatures (70 and 55 K) on sample THW3 (w = 3 µm) led to the two sets of traces of Fig. 2a, b. In addition to the FF voltage, and to the time delay decreasing with the intensity of the current, one notes a saturating voltage as a function of the time. That feature, already reported in low-T_c [6] and high T_c [4], was assigned to the formation of a PSC. Another proof comes from the linear dependence of the voltage upon the fraction ($I-I_c$) of the current, a very distinctive feature of PSCs [9–11]. The differential resistance of the PSC is extracted from the linear dependence of the PSC's voltage to the applied current (right plots of Fig. 2). As it is predicted by the PSC's theory, the extrapolated slope of V_{PSC} versus I_{PSC} intercepts the current axis at I_s [3], the remnant I_s being the superconducting excess fraction of the current. The cooling time τ_d to the substrate was subsequently deduced, for THW3 it is 6 ns (Fig. 3a).

The current flowing through the PSC is the superposition of the normal and superconducting currents. The heat dissipated in this localized zone per unit volume is $\rho I.(I - I_s)/(w.b)^2$ [12]. Increasing the applied current produces an increase in the output voltage without expansion of the

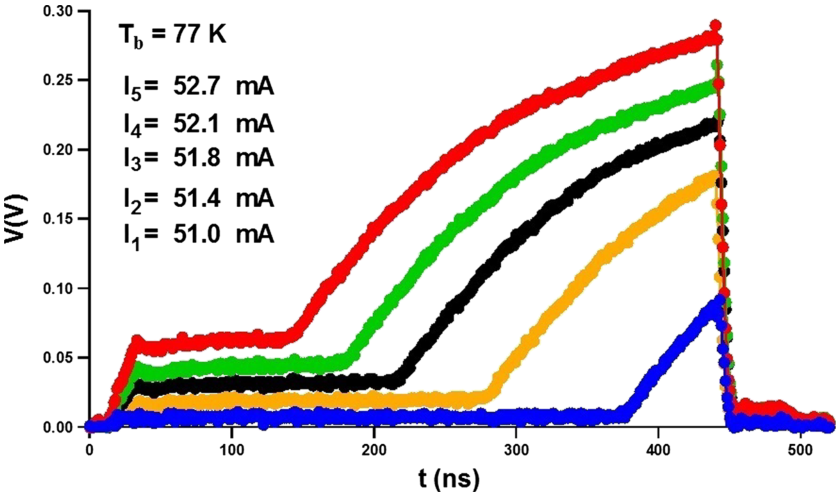

Fig. 4 Time dependence of voltage across THW10 in response to a rectangular current pulse at T_b = 77 K, where $R_\parallel$ = 67 Ω and R_s = 187 Ω. The step in voltage before the formation of HS is associated with the motion of vortices. The linear dependence of the voltage versus time shows the growth of the HS

PSC's length. We assume that the dissipation transferred to the substrate is given by:

$$\frac{\rho I(I-I_s)}{(w.b)^2}=\frac{E(T_{PSC})-E(T_b)}{\tau_d} \tag{2}$$

where E(T) is the energy density of the film at temperature T. For the case of YBCO films, one can identify the escape time τ_{esc} with the prefactor τ_d of Eq. 1 revisited according to [8].

The temperature is determined from the $\int CdT$ calculated from [13]. When the applied current exceeds I$_c$, the superconducting order parameter goes to zero and the quasiparticles diffuse to a certain length $\Lambda = wbR_u/\rho$ from both sides, and the length of the PSC is L$_{PSC}$ $= 2\Lambda$. When the temperature is reduced (T$_b$ $\ll$ T$_c$), the resistance due to vortex flow preceding the nucleation of PSC is reduced and the critical current increases Fig. 2b. We noticed that both the differential resistance and the excess current increased.

4 HS Created by a Current Pulse

In Fig. 4, different sample presented a different behavior, at T$_b$ = 77 K, and for I > I$_c$, a HS is formed. In the voltage response, after a delay time t$_d$, a linear increase of the voltage as a function of time is recorded. By raising the current, the delay time is reduced, the voltage increases, and the slope increases corresponding to the expansion velocity of the HS along the film. The normal zone expands and the current is purely normal. The heat generated par unit volume is $\rho I^2/(w.b)^2$ and escapes toward the substrate, where the temperature can be subsequently deduced from the following equation:

$$\frac{\rho I.I}{(w.b)^2}=\frac{E(T_{HS})-E(T_b)}{\tau_d} \tag{3}$$

The delay time t$_d$ in case of the HS is governed by the same equation used for the PSC. It led to a delay t$_d$(I/I$_c$) compatible with a cooling time to the substrate τ_d = 5 ns (Fig. 3b). We noticed that samples with the same thickness could lead to different dissipative modes either PSC or HS, this is reported in the ref. [4].

In Table 1, we note that the temperatures at the center of the PSCs are inferior to T$_c$ in all cases, as it should. A lower base temperature (55 K) requires higher currents and, consequently, leads to higher PSC temperatures. By rapid inspection, we note that an increment of only 10 % on τ_{esc} would be sufficient to heat the film up to T$_c$, and then blow up the PSC for the same values of the current. Ten to 20 % is about the accuracy that can be claimed in this type of experiment.

The traces of Fig. 4 bear the signature of hot spots (HS) at a temperature 77 K intermediate between the occurrences of PSCs in THW3. That is consistent with a longer τ_{esc} that we have determined at 6 ns in THW10. The minimum (measured) current generating a HS leads to a control of the parameters. The corresponding HS temperature is found to be 95.4 K, while the symmetric of the base temperature with respect to T$_c$ would fall at 95 K. According to [12], that is the property expected from the minimum HS for small temperatures deviations on both sides of T$_c$.

Table 1 Temperatures reached at the center of PSCs (Sample THW3) and HSs (Sample THW10) in current-driven YBCO strips for different values of the current and substrate temperatures T$_b$ shown in Figs. 2 and 4

T$_b$(K)	I(mA)	T(K)	Type	Trace♯
70	15.9	81.2 < T$_c$	PSC	1-Fig. 2a
70	16.1	81.5 < T$_c$	PSC	2-Fig. 2a
70	16.3	81.9 < T$_c$	PSC	3-Fig. 2a
70	16.4	82.0 < T$_c$	PSC	4-Fig. 2a
70	17.3	82.3 < T$_c$	PSC	5-Fig. 2a
55	26.2	83.1 < T$_c$	PSC	1-Fig. 2b
55	26.8	83.4 < T$_c$	PSC	2-Fig. 2b
55	27.8	83.7 < T$_c$	PSC	3-Fig. 2b
55	28.4	84.1 < T$_c$	PSC	4-Fig. 2b
55	29.1	84.5 < T$_c$	PSC	5-Fig. 2b
77	51.0	95.4 > T$_c$	HS	1-Fig. 4
77	51.4	96.3 > T$_c$	HS	2-Fig. 4
77	51.8	97.1 > T$_c$	HS	3-Fig. 4
77	51.4	98.0 > T$_c$	HS	4-Fig. 4
77	52.7	99.2 > T$_c$	HS	5-Fig. 4

5 Conclusion

We have studied the transport properties of high-T$_c$ superconducting material at different temperatures, using a current pulse technique. The dissipation modes due to a supercritical current were discriminated, between the HS and PSC. The heat escape times was determined from the delay time appearance of a PSC or a HS, once a PSC or a HS is created. This parameter plays an important role in determining the limiting performance of the SSPD. In addition, the temperature reached inside the dissipative zone was estimated. The results appear to be consistent with the prediction of T$_{PSC}$ < T$_c$ and T$_{HS}$ > T$_c$.

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