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Measurement of the gap relaxation time of superconducting NbTi strips on a sapphire substrate

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Abstract

We report on the study of the transient voltage response of superconducting NbTi strips to an over-critical current pulse ($I > I_c$, where I_c is the pair-breaking current). In this experiment, a localized normal spot appeared for a current amplitude larger than the critical current. The induced metastable superconducting state was identified as either a hotspot or phase-slip center. These two dissipative modes share the feature of the voltage response occurring after a delay time t_d, a solution of the time-dependent Ginzburg–Landau (TDGL) theory developed by M. Tinkham. The gap relaxation time was subsequently deduced from fitting the experimental data with the TDGL theory. An agreement was found by choosing an effective gap relaxation time $\tau_\Delta = 4.75$ ns for a thickness of 50 nm. Assuming the proportionality to sample thickness, this indicates a thermal relaxation time of 96 ps/nm for a NbTi film sputtered at room temperature on polished crystalline Al_2O_3. If we assume that the electron and the phonon specific heats have the same ratio as for pure Nb, then it results in a phonon heat escape time $\tau_{es}/d = 32$ ps/nm.

1 Introduction

Non-equilibrium superconductivity has drawn the attention of researchers in the past few years after it was abandoned for a while. It occurs in one-dimensional superconducting wire as a fascinating quantum phenomenon, where dissipation takes place, which is referred to a phase-slip center (PSC) [1, 2]. The non-equilibrium dissipative state is generated when the flowing current in the filament exceeds the pair-breaking current of the cooper pairs [3]. The most spectacular dissipation is caused by the created quasi-particles [3, 4]; this is due to PSCs in one dimension. Based on the Skocpol–Beasley–Tinkham model [5, 6], the order parameter oscillates between zero and one value, where the cooper pairs condensate collapses and restores itself in time. To ensure the continuity of the order parameter, at the extreme edge of the PSC, the phase of the order parameter changes by a quanta of 2π. The possibility of overheating this localized spot tends to lead to a normal zone referred to a hot spot (HS), where the superconductivity collapses [7, 8].

The non-equilibrium region can be initiated in a superconductor by energy absorption; the formation of the HS drives the detection mechanism in different devices. Upon photon absorption by a superconducting nanowire biased with a current slightly below its critical current, the formation of a resistive zone is triggered and produces a response pulse voltage [9]. This resistive state can be either a PSC or HS, where the temperature at its center exceeds the transition temperature T_c of the superconducting wire. The heat that is generated in the normal spot sandwiched between the two parts of the superconducting filament is evacuated to the substrate after a certain time [3]. It is known as the reset time of a photon detector, during which the detector is insensitive to the upcoming photon.

Herein, we report on the study of the dissipative zones caused by an electrical current in an NbTi filament, which conveys information in a similar way to photon detection. We noticed the appearance of PSCs at temperatures close to T_c, and localized HSs at lower temperatures. These two dissipative structures are discriminated from vortex flow dissipation by their delay time in response to an electrical current pulse [3]. Moreover, they are distinguished between themselves from their specific voltage versus time signal

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shapes. Based on an analysis of the delay time versus the various values of the applied current, the gap relaxation time was deduced by fitting the experimental data with time-dependent Ginzburg–Landau (TDGL) theory.

2 Experimental setup

The NbTi filaments (thickness $b = 50\,\text{nm}$ and widths $w = 1$ and $2\,\mu\text{m}$) used in this experiment were deposited on sapphire in an argon–nitrogen plasma environment by employing DC magnetron sputtering (STAR-Cryoelectronics, NM, USA). Standard photo-lithographic and ion-milling processes were used to pattern four gold contact pads. For the present sample, the current is sent through an NbTi filament 600 μm long, and two lateral probe 400 μm apart from each other were used for voltage measurement. The samples were cooled under vacuum in a 4 K closed-cycle cryostat with a temperature controller.

In the superconducting state, the filaments were excited by a step current pulse from a pulse generator with a duration of 450 ns and with a repetition frequency of 10 kHz. In this experiment, 50 Ω coaxial cables and high-frequency variable attenuators were used. In the superconducting state, a pulse reflection from the sample is expected with a negative amplitude. Therefore, a delay line was deployed to separate the incident pulse from the reflected one. In the circuit, two 467 Ω resistors were incorporated into the laterals voltage probes to reduce any current leakage once a resistive state appear in the filament, and the latter ones served to pick up the voltage across the filament.

3 Localized resistive state created by a current pulse

The samples were mounted on the sample holder close to the temperature sensor and investigated at different cool-down rates. The measurements of the resistance of the sample versus the temperature $R(T)$ were performed using the standard four-probe measurements. The DC excitation for this measurement was biased with a current value about 1 μA to avoid the overheating of our samples. The transition temperatures were measured and found to be $T_c \simeq 7.6$ and 8.2 K for 1 and 2 μm, respectively. From the measurement of the resistance versus the temperature, we found a similar electrical resistivity for both samples, where $\rho \simeq 114\,\mu\Omega\,\text{cm}$. The current density J_c of the filament at 3.6 K reaches $3.12\,\text{MA cm}^{-2}$; it reflects the good quality of the film.

The samples were investigated at different temperatures and in the current pulse modes, as shown in Fig. 1. In pulse measurement, superconductivity does not usually disappear in the entire filament once the critical current value is exceeded, but it appears in a localized zone. The first experiment investigated an Al filament using an electrical current pulse and was reported the appearance of a voltage after a certain delay time t_d [10]. The stimulated dissipative states in superconducting filaments are governed by flux flow motion, the nucleation of a PSC, and the formation of HS. The PSC is considered an alternation in time of normal and superconducting states, the order parameter bouncing periodically from zero up to its maximum value. PSCs usually occur in filament in one dimension ($w < \xi$, where ξ is the coherence length) for a current value larger than the critical current. Such induced phenomena could be caused by thermal fluctuations [7, 11]. In addition, in the switching current event, a step is induced in the I–V characteristics [4, 12]. However, a similar dissipation that takes place in wide filaments ($w \gg \xi$) has the same behavior as the PSC and called a phase-slip line (PSL) [13–15]. For current values exceeding the critical current, a voltage appears after a certain delay time t_d, where a localized zone dissipates and a transition from the superconducting to the normal state occurs. The type of dissipation is identified by different parameters, and its nature can be discriminated in a phase diagram of two currents versus the temperature, with the pair-breaking current I_c and the hot spot current I_h, which is defined as the minimum current that can maintain a localized normal spot above the transition temperature T_c. This type of dissipation is determined by the bath temperature compared to the crossing temperature (T^*) between I_c and I_h. The two dissipative modes can be easily discriminated using the current pulse technique. Both are created with a current larger than the critical current I_c, and a voltage appears after a certain delay time t_d for each. If the substrate temperature is larger than

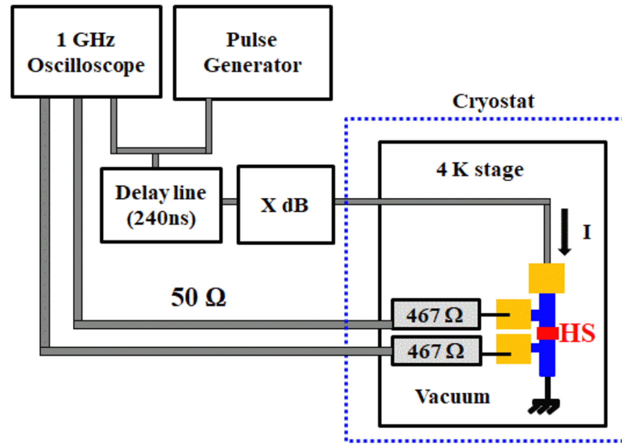

Fig. 1 Experimental setup: a pulse generator is used as an electrical pulse excitation source, and an oscilloscope is used to trace the voltage and the delay time t_d. Once the superconductivity is destroyed locally, its resistance becomes larger than the 50 Ω cable impedance. Two 467 Ω resistors are incorporated into the lateral probes to reduce any current leakage to the oscilloscope

the crossing temperature, then the dissipation is governed by the nucleation of the PSC, for which a voltage appears after a delay time t_d and where a non-monotonic behavior versus time occurs for $t > t_d$ (shown in Fig. 2a by a plateau voltage: constant voltage in time). However, for lower bath temperatures, the dissipation is initiated by a PSC that is transformed instantly to a HS. The HS is considered an unstable mode and has the tendency to expand along the filament. It presents a monotonic behavior of the voltage versus time, as shown in Fig. 2b ($t > t_d$). For $T = 7$ K, we noticed that the voltage has a tendency to saturate; this is mainly caused by the high resistance that appears in the filament due to the high resistivity material. However, a for low-resistive material, such as Nb, where a growing hotspot was reported [16]. A similar behavior reported for superconducting point contact, where a DC measurement unveils the existence of two distinct thermal regimes for a current larger than the switching value. One dissipative regime where the temperature reached a corresponding value was close to the bath temperatures. In other cases, the constriction temperature

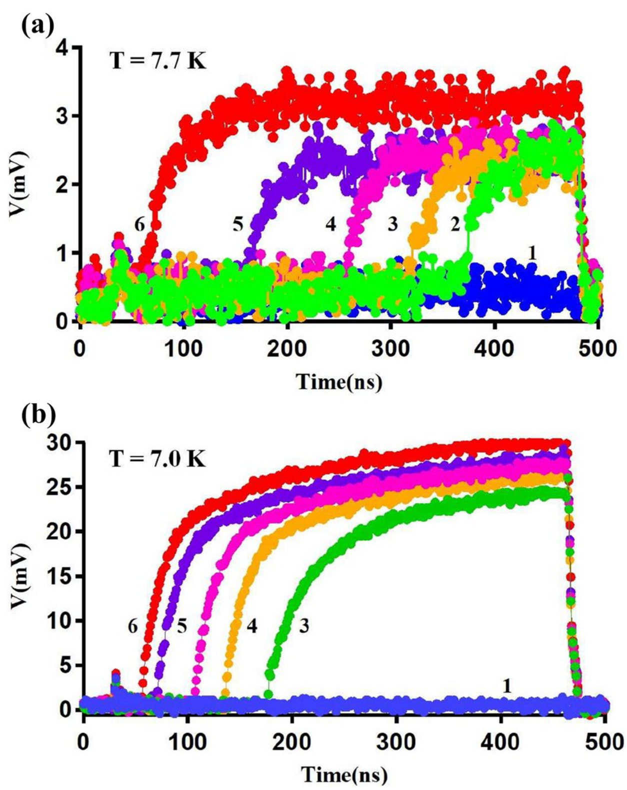

Fig. 2 Voltage response of the NbTi filament (w = 2 µm) versus time to different current values at two different temperatures. **a** The blue curve shows the recorded voltage at the critical current value $I_c = I_1 = 0.170$ mA, and other colors show increases in the current amplitudes (from minimum value I_c to maximum value $I_6 = 0.188$ mA) as the delay times are reduced for $T = 7.7$ K. **b** For $T = 7.0$ K, an expanding hotspot is obtained for several current amplitudes from $I_c = I_1 = 1.56$ mA to $I_6 = 1.74$ mA

can be substantially larger than the bath temperature, leading to the formation of a hot spot [17]. We emphasize that this method can not efficiently discriminate between these two dissipative states.

4 Measurement of the thermal relaxation time

When the substrate temperature is set below the transition temperature T_c, the response of the filament to an over-critical step current pulse is accompanied with the destruction of superconductivity in a localized zone and translated into the voltage that occurs after a certain delay time t_d. The expression of the delay time t_d is a function that depends on the applied current and a solution for the TDGL theory:

$$t_d(I/I_c) = \tau_d \int_0^1 \frac{2f^4 \mathrm{d}f}{\frac{4}{27}\left(\frac{I}{I_c}\right)^2 - f^4 + f^6}, \quad (1)$$

where f is the normalized order parameter, and I_c and I are the critical and applied currents, respectively. A current excitation larger than the critical current value drives a superconducting filament to the non-equilibrium regime in the absence of a magnetic filed. In two dimensions, Berdiyorov et al. [19] investigated (relying on Kramer‘s theoretical study) the time evolvement of the collapse of the superconductivity and numerically elaborated the solution to the equations [20, 21]: $\frac{u}{\sqrt{1+\gamma^2|\psi|^2}}\left(\frac{\partial}{\partial t} + \frac{\gamma^2}{2}\frac{\partial|\psi|^2}{\partial t}\right) = (\nabla - i\mathbf{A})^2\psi + \left(1 - |\psi|^2\right)\psi$, and $\frac{\partial \mathbf{A}}{\partial t} = Re[\psi^*(-i\nabla - \mathbf{A})\psi] - \kappa^2 \mathrm{rot}\,\mathrm{rot}\mathbf{A}$, where the length was expressed in units of the coherence length ξ and the vector potential is scaled to $\Phi_0/(2\pi\xi)$ (where Φ_0 is the magnetic flux quantum). Time is in units of the Ginzburg–Landau relaxation time $t_0 = 4\pi\lambda^2/c^2\rho_n$ (ρ_n is the normal-state resistivity, and c is the velocity of light). The parameters u and γ are the measures of the different relaxation times. It confirmed that both the flux-flow state and the phase-slip line state are dynamically stable dissipative units with temperature smaller than the critical one. And the hot spots are localized normal regions that expand in time. Also, it showed that a voltage appears after a delay time t_d for the PSC and HS.

The factor τ_d preceding the integral in Eq. (1) is the gap relaxation time (τ_Δ), limited by the inelastic electron–electron interaction, possibly relayed by the electron–phonon interaction. Eventually, the gap relaxation time can be determined by the characteristic cooling time of the film on its substrate. It is then proportional to the sample thickness, as it has been shown on YBCO filaments [18].

We investigated our sample at 3.6 K, and the current values were varied every 0.1 dB above the critical current to reach 1 dB for a relatively long delay time. However, for

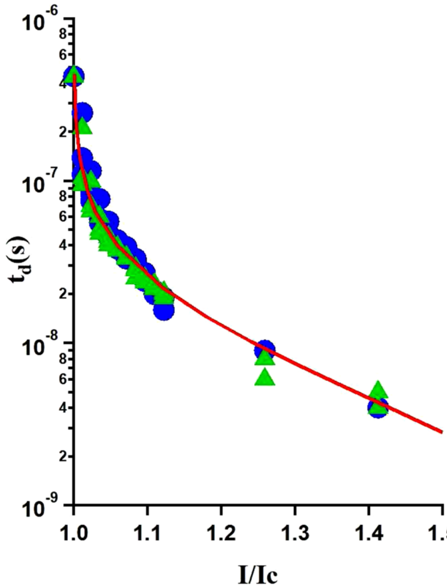

Fig. 3 Delay times in log scale as a function of the applied reduced current I/I_c at $T = 3.6\,\mathrm{K}$ for two different strips (green triangles $w = 2\,\mu\mathrm{m}$ and blue circles for $w = 1\,\mu\mathrm{m}$). The red curve is the fitting function of the Tinkham's TDGL giving the determination of the parameter τ_d in Eq. (1) with the fitting parameters $\tau_d(w = 2\,\mu\mathrm{m}) = (4.7 \pm 0.2)\,\mathrm{ns}$ and $\tau_d(w = 1\,\mu\mathrm{m}) = (4.8 \pm 0.2)\,\mathrm{ns}$ under a vacuum

a short delay time, we changed the current values every 1 dB. The delay time t_d is shortened by enhancing the applied current amplitude. The corresponding delay times were recorded and plotted in Fig. 3 as a function of the ratio of the applied current to the critical current (I/I_c). The experimental data were fitted with the TDGL theory (modified later by Tinkham) [22] for the ratio $T/T_c = 0.5$ at 3.6 K, and the fitting pre-factor τ_d was determined. For the film thickness $b = 50$ nm, we deduced $\tau_d = \tau_\Delta = 4.8$ ns and 4.7 ns for 1 and 2 μm, respectively, as shown in Fig. 3a, b. It is considered the cooling time of the filament on its substrate, for which the superconducting state is regained.

In general, for a dissipative state (either a PSC or HS), the heat generated is transferred along the filament, where both electrons and phonons contribute in different ways based on their specific heat, and is evacuated toward the substrate, thanks to the phonons only. The specific heat, based on the Debye model of electrons, and the phonons are, respectively, $C_{el} = \gamma T$ and $C_{ph} = \beta T^3$ [22, 23]. Therefore, the phonon escape time is given by $(C_{el} + C_{ph})/\tau_d = C_{ph}/\tau_{es}$. The phonon escape time τ_{es} depends on the quality of the interface between the filament and the substrate. In the present sample, for NbTi filament sputtered on sapphire, we measured an averaged value of $\tau_d = 4.75$ ns for a thickness of $b = 50$ nm. Assuming the proportionality to the thickness, one gets $\tau_d = 95$ ps/nm, and we assume that the electron and the phonon specific heats have the same ratio; as for the pure Nb, the resulting phonon escape time of ~ 32 ps/nm. This ratio is slightly different from the results obtained from the NbTiN on the sapphire substrate, which is 1.6 ns for a thickness of 20 nm, giving a film cooling time of 80 ps/nm [24]. The NbTiN film, despite the fact that it is a more resistive material compared to NbTi, showed a faster cooling time and was more suitable in the usage in photon detection.

5 Conclusion

We characterized the resistive singularities induced by an over-critical current pulse in an NbTi filament, and the dissipative states PSCs and hot spots were found to have, respectively, a high temperature (close to T_c) and a low temperature. Using Tinkam's TDGL theory, we deduced the thermal relaxation time of superconducting NbTi strips from the formation of a HS , and the normalization of the heat escape time to the filament thickness was determined to be 32 ps/nm.

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