Physica C: Superconductivity and its applications 589 (2021) 1353933

Contents lists available at ScienceDirect

Physica C: Superconductivity and its applications

journal homepage: www.elsevier.com/locate/physc

Phase slip center temperatures attained in superconducting NbTi filaments using an electrical pulse close to T_c

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ABSTRACT

We have investigated the dynamics of dissipative states in NbTi superconducting thin films using electrical step pulse excitations on a sapphire substrate close to T_c. Excitation of a superconducting wire with a current pulse larger than the depairing critical current, I_c, gives rise to a non-equilibrium superconducting state. We identified two dissipative states, the hotspot (HS) and the phase slip center (PSC). Both are signaled by a voltage that emerges after a certain delay time t_d. We focused on the phase slip phenomenon in the vicinity of T_c and measured the dependence of the delay times on the value of the applied current pulse; these were fitted with the time-dependent Ginzburg-Landau (TDGL) theory due to Tinkham. The film thermal relaxation times were deduced for the phase slip center close to T_c for different samples. In addition, the temperatures at the center of the PSCs were estimated from the blackbody radiation model, and the results are consistent with the PSC formalism.

1. Introduction

The quantum phenomenon of non-equilibrium superconductivity has attracted a great deal of interest in the field of fundamental condensed matter physics and in technological applications [1]. This phenomenon is of primary importance in superconducting nanodevices; in fact, the use of coherent quantum phase slip centers as the basic element (qubit) for quantum information processing was recently demonstrated [2,3]. The manipulation of these type of quantum systems is under the focus in many studies and remains a challenging task. Indeed, the most common application of non-equilibrium superconductivity appears in optical communication [4] and single photon detection. The fundamental concept of single photon detection relies on the creation of metastable states in a superconducting nanowire. When a single photon is absorbed by a superconducting nanowire biased with a current smaller than the depairing current I_c, a non-equilibrium state is generated in a localized spot [5–7]. The superconductivity is then locally destroyed and triggers an energy dissipative process. The non-equilibrium states are associated with the creation of dissipative zones in the superconducting filament, where two typical modes are being identified as a hotspot (HS) and a phase slip center (PSC) [8]. Moreover, the quantum and thermal phase slip centers were signaled as steps in the I-V characteristics of the superconducting nanowires [9,10].

Ref. [12] reported on the transition from thermally activated phase slips to quantum phase slip that occurs in zones having a size in the order of 10 nm in Al nanowires with constriction. The obtained negative magnetoresistance of the nanowire was reported as a fingerprint of phase-slips-dominated transport. This dissipation was caused by the suppression of the rate of activated phase-slips, as normal quasiparticle current is injected through the leads into the constriction. Moreover, the investigation of the point contact between two Al superconducting leads on Si/SiO2 with a constriction at middle and forcing the appearance of PS to be highly localized in space. The constriction allowed the control of migration of atoms, and permits the switch between strong and weak self-heating regimes after the switching process. The main dissipative mechanism was ascribed to a train of thermally driven phase slip events when the temperature of the constriction zone and that of the bath are close to each other. The formation of hot spot occurred when the constriction temperature is subsequently larger than the bath temperature [11].

The superconducting material NbN is one of the most promising candidates currently used for single photon detection. Different studies

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https://doi.org/10.1016/j.physc.2021.1353933
Received 6 March 2021; Received in revised form 20 June 2021; Accepted 26 July 2021
Available online 27 July 2021

have shown that substituting nitrogen by the titanium atom in NbN improved its physical properties, and modified both the electronic and crystal lattice structures [13,14]. It was found that the superconducting transition temperature of thin film NbTiN has been improved as compared to the thin film NbN [15]. In addition, the electrical conductivity and resistivity of NbN have been improved significantly by introducing Ti to it [16].The kinetic inductance of NbTiN superconducting nanowire single-photon detectors was lower than that of NbN and the recovery time of single photon response in NbTiN was improved as compared to NbN [17]. In the present work, we investigated the non-equilibrium dissipative states created by electrical pulses in NbTi bridges in the vicinity of T_c and identified these as PSCs. This type of PSC carries analogous information to the metastable state induced by single photon absorption in a superconducting nanowire. The experimental delay times t_d were analysed using the TDGL theory as modified by Tinkham [18]. The relaxation time of the film on its substrate close to T_c was deduced and turned out to represent an important asset for the reset time of the single photon detector using a superconducting nanowire. In addition, the temperatures reached at the center of the PSCs were consistent with the theoretical predictions using TDGL theory.

2. Experimental setup

The series of NbTi filaments used in our measurements had a thickness of 50 nm and were sputtered on sapphire substrate in argon nitrogen plasma rich environment (STAR- Cryoelectronics, NM, USA). The samples were designed to have four gold pads and were fabricated using photo-lithographic and ion milling processes for electrical contacts. The central parts had different widths $w_A = 1.8$ μm and $w_B = 2.3$ μm. The lateral probes and remaining parts of the samples were 40 μm wide, as shown in Fig. 1a. The transition temperatures were deduced from R-T measurement and were around $T_{cA} = 7.90$ K and $T_{cB} = 8.10$ K, respectively. The duration of the electrical current pulse step sent through the sample was 440 ns, with a repetition frequency of 10 kHz. The impedance of the different components of our circuit was 50 Ω. In the superconducting state, to treat the incident and reflected wave pulse differently in time domain, an air-delay line was incorporated. The

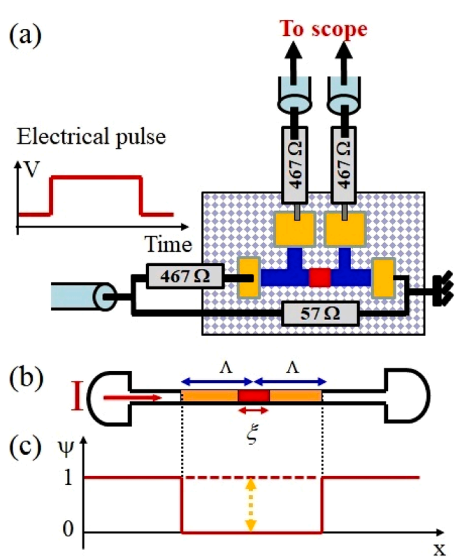

Fig. 1. (a) Sample layout, with lateral probes connected to the oscilloscope through 467 Ω resistors to ensure that the current flows to the ground. The filament was mounted in series with a large resistance (467 Ω), while a 57 Ω resistor was set in parallel in the opposite arm. (b) Schematic of a superconducting filament shows the destruction of the superconductivity over a length ξ and the diffusion length of quasi-particles, Λ. (c) The superconducting order parameter as a function of the position x.

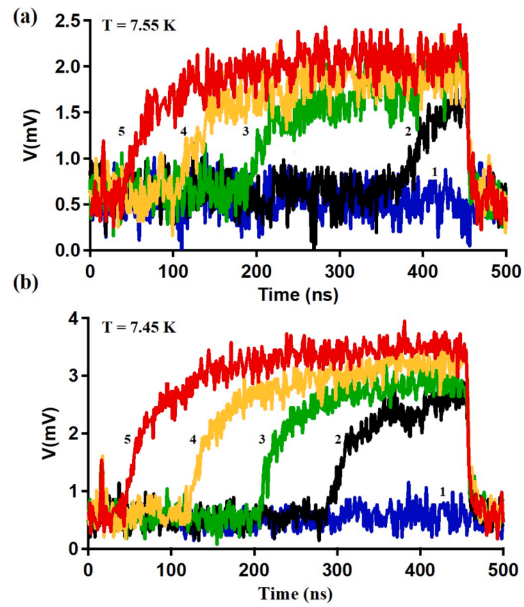

Fig. 2. Measured voltage response versus time in response to different current values for NbTi filaments, sample A: (a) T = 7.55 K: $I_c = I_1 = 112$ μA, $I_2 = 113$ μA, $I_3 = 117$ μA, $I_4 = 121$ μA, $I_5 = 124$ μA. (b) T = 7.45 K: $I_c = I_1 = 172$ μA, $I_2 = 178$ μA, $I_3 = 183$ μA, $I_4 = 187$ μA, $I_5 = 193$ μA.

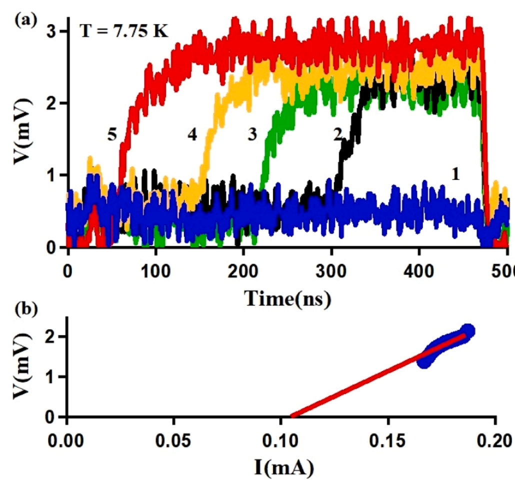

Fig. 3. Measured voltage response versus time in response to different current values for NbTi filaments, sample B: (a) T = 7.75 K: $I_c = I_1 = 166$ μA, $I_2 = 174$ μA, $I_3 = 178$ μA, $I_4 = 182$ μA, $I_5 = 187$ μA. (b) The PSC voltage versus the applied current value (blue color) fitted with a linear function (red); the excess current was determined, $I_s = 105$ μA. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

current flowing in the sample was then deduced from the following equation: $I = 0.09 \times V/50$, where V was the applied voltage value and the 0.09 factor originates from the parallel circuit configuration. The incident and reflected pulses were measured using a fast oscilloscope.

3. The phase slip center

The non-equilibrium state could be generated using different procedures, where the superconductivity is to be destroyed either locally or in the entire sample. Our technique allows the study of the local destruction of the superconductivity, as well as control of the thermal dynamics of the phase slip center using an electrical pulse. When a superconducting filament is biased with different current amplitudes larger than the critical value, non-equilibrium states are created. For sample dimensions comparable to the coherence length ξ, and at currents exceeding the depairing current I_c, the copper pairs being accelerated will acquire a kinetic energy that is sufficient for their local destruction. The superconductivity collapses in a zone of the order of ξ, the generated quasi-particles diffuse on both sides and then acquire a length scale given by $\Lambda = \sqrt{\tau \times D}$, ($\tau$ being the inelastic relaxation time and D the diffusion coefficient) [19]. This is known as the phase slip center dissipative phenomenon [8], and this zone is encapsulated between two superconducting areas, where the current transport is assisted by the superfluid density (see Fig. 1b). However, the PSC is interpreted as a local zone where the order parameter jumps back and forth between the normal and superconducting state (see Fig. 1c). Therefore, the current is carried simultaneously by the superfluid and the generated quasi-particles. An experimental investigation of the thermally activated phase-slip mechanism in superconducting nanowires was reported in a recent study [20]. This mechanism was reproduced in a filament having a width $w \gg \xi$ referred to as the phase slip line (PSL) and bearing similarity to a PSC. In contrast to PSCs, however, the PSLs occur in wide superconducting strips, where the order parameter may vary in two dimensions. Sivakov et al. [21] investigated PSLs in different materials where Shapiro steps were observed under microwave radiation. They noticed that the order parameter oscillates at the Josephson frequency.

In our experiment, the width of the NbTi superconducting filaments was much larger than the coherence length, so the occurrence of PSLs was anticipated. The filament was excited with a voltage pulse, and the voltage response was registered using lateral probes. The depairing current I_c is defined as the minimum value of current bringing the voltage in about 440 ns. For a current value $I < I_c$, the filament remains in the superconducting state, and a zero voltage was registered, as shown in trace of Figs. 2 a,b and 3a (trace #1). When the current amplitude exceeded I_c, a voltage emerged after a delay time t_d, which is interpreted as the time needed for local destruction of the superfluid density. The voltage response showed a step in voltage right after t_d, which is an indication of the nucleation of the PSL, which was a stable structure. We noticed that the time t_d was reduced by increasing the current amplitude. However, the change in the amplitude of the plateau was small; therefore, the length of the PSL remained the same. Measurements in the two samples illustrated the nucleation of a PSL close to T_c, in agreement with the theoretical study reported in Ref. [22].

4. Interpretation of experimental results using TDGL theory

The first experiment to report the destruction of the superconductivity using an electrical current pulse was performed on Al thin film [23]. The overcritical current ($I > I_c$) leads to the occurrence of a voltage after a delay time t_d, where energy dissipation occurs. The non-equilibrium state was described by the TDGL theory as modified by Tinkham [18]. It resulted in expressing t_d as an integral solution having the following form:

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

This functional depends on the applied current used as an excitation and the temperature through I_c. The quantity f is the normalized superconducting order parameter. In this metastable state, the quasi-particles acquire high energy and relax through two processes. The first one is due to the electron-electron scattering, which is a very fast process. However, the second one is related to the electron-phonon interaction, which occurs at the order of picoseconds. The constant term preceding the integral function *F(T,I)* is associated with the electron-phonon relaxation time. The YBCO [24] and Nb [25] films investigated using this pulse technique showed a strong correlation between τ_d and the film thickness. τ_d was associated with the time during which the superconductivity was restored as shown in the inset of Fig. 4 (i) & (ii).

Fig. 4 illustrates the dependence of the PSC delay time t_ds as a function of I/I_c for sample A. The experimental data of sample A was fitted with the temperature dependent *F(T,I)* modified by Tinkham for the corresponding different ratios of T/T_c. This leads to the determination of the film cooling times of NbTi on sapphire; these times are τ_{dA} (T = 7.70 K) = (6.5 ± 0.2) ns and τ_{dB} (T = 7.50 K)= (6.8 ± 0.2) ns.

5. Energy dissipation through PSC

For a current greater than I_c, the superconducting state collapses and the PSC occurs in a localized zone. Since the net current is the superposition of the normal and superconducting components, the dissipation differs from the HS. The energy dissipation rate is given by $\rho I(I - I_s)$, where I_s is the fraction of superconducting excess current that was initially estimated theoretically to be 1/2 I_c [19]. This can be measured experimentally from the linear extrapolation of the voltage that appeared across the filament versus the applied current, as shown in Fig. 3b. The dissipation process involves the contribution of the phonons and quasiparticles, and the energy dissipated in the filament has the same value as the energy evacuated toward the substrate. The heat generated in the filament remained for a time τ_d, and then escaped during certain time duration τ_{es} via phonons into the substrate: $\frac{\int c_e dt + \int c_p dt}{\tau_d} = \frac{\int c_p dt}{\tau_{es}}$. If we consider that the change in temperature is not large, we then get $(c_e + c_p)/\tau_d = c_p/\tau_{es}$.

The total specific heat in the superconducting state is, $C_S = \mu T^3 + \beta T^3$, for NbTi $\beta = 13.8\ J.m^{-3}.K^{-4}$ [26,27], which is close the Nb values [25]. If we consider the same ratio as Nb, $(c_e + c_p)/c_p \simeq 3$, we get $\tau_{es} \simeq \tau_d/3 \sim 2.2$ ns. The temperature at the center of the PSC was determined using the blackbody radiation theory, where the power radiated density is $P_R \propto (T^4 - T_b^4)$, and T and T_b are the temperatures at the center of PSC and the substrate, respectively. The PSC temperatures listed in Table 1 were determined using the following equation:

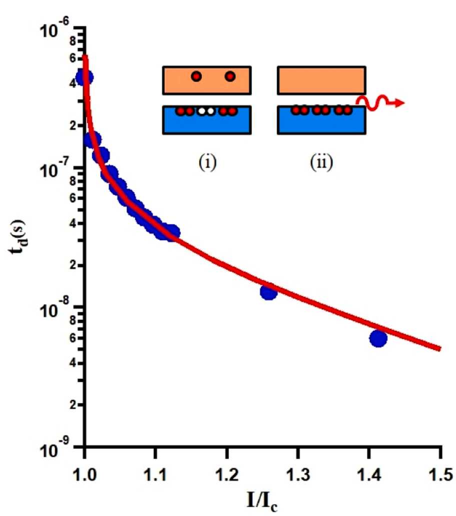

Fig. 4. Inset: The band energy diagram: (i)Non-equilibrium superconducting state and (ii) Relaxation of the excited state through electron-electron and electron-phonon interactions and evacuation of the heat toward the substrate. Delay time (blue dots) in a log scale as a function of the applied reduced current I/I_c for sample B close to T_c. The solid lines in red is the fitting function from Tinkham's TDGL. The film cooling time in equation 1, τ_d, was determined at T = 7.40 K τ_{dB} = (6.8 ± 0.2) ns. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Temperatures reached at the center of HSs for different values of the current and substrate temperatures T_b shown in Figs. 2 and 3.

Trace♯	w (μm)	τ_d (ns)	I(μA)	I_s(μA)	T_b(K)	T_c(K)	T(K)
2-Fig. 2a	1.8	6.5	113	84	7.55	7.90	**7.65**
5-Fig. 2a	1.8	6.5	124	84	7.55	7.90	**7.71**
2-Fig. 2b	1.8	6.5	178	120	7.45	7.90	**7.69**
5-Fig. 2b	1.8	6.5	193	120	7.45	7.90	**7.85**
2-Fig. 3b	2.3	6.8	234	105	7.75	8.10	**7.95**
5-Fig. 3b	2.3	6.8	262	105	7.75	8.10	**8.03**

$$\frac{\rho I \times (I - I_s)}{w^2 b^2} = \frac{\beta\left(T^4 - T_b^4\right)}{\tau_{es}} \tag{2}$$

where ρ represents the resistivity of the filament in the normal state where we used the value at 15 K ($\rho_A = 90\ \mu\Omega.cm$ & $\rho_B = 77\ \mu\Omega.cm$)

These estimates were achieved without adjusting any parameter, since all parameters involved in the calculation of Table 1 were measured experimentally. The results agree with the theoretical prediction that the temperature reached at the core is larger than the bath temperature but remains below T_c [18,19]. The measured excess current I_s that was used for the estimation of the temperatures was larger than $I_c/2$, even though using the predicted theoretical value $I_c/2$ results in temperatures at the core of the PSC that remained below T_c [28].

6. Conclusion

We investigated the electrical and thermal properties that resulted from the dynamics of dissipative non-equilibrium states in NbTi filaments and found that the nucleation of PSC dissipation occurred close to T_c. The experimental data for the dissipative states were fitted with the TDGL theory at temperatures close T_c. The thermal cooling time was subsequently deduced for the PSC in the vicinity of T_c. The temperatures attained at the center of the PSCs were estimated from the specific heat of the phonons, the quasi-particles generated, and the black-body radiation theory. The experimental results showed consistency with theoretical predictions.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

K.H., A.M. and H.B. gratefully acknowledges the support of the King Fahd University of Petroleum and Minerals, Saudi Arabia, under the SB 191013 DSR project.

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