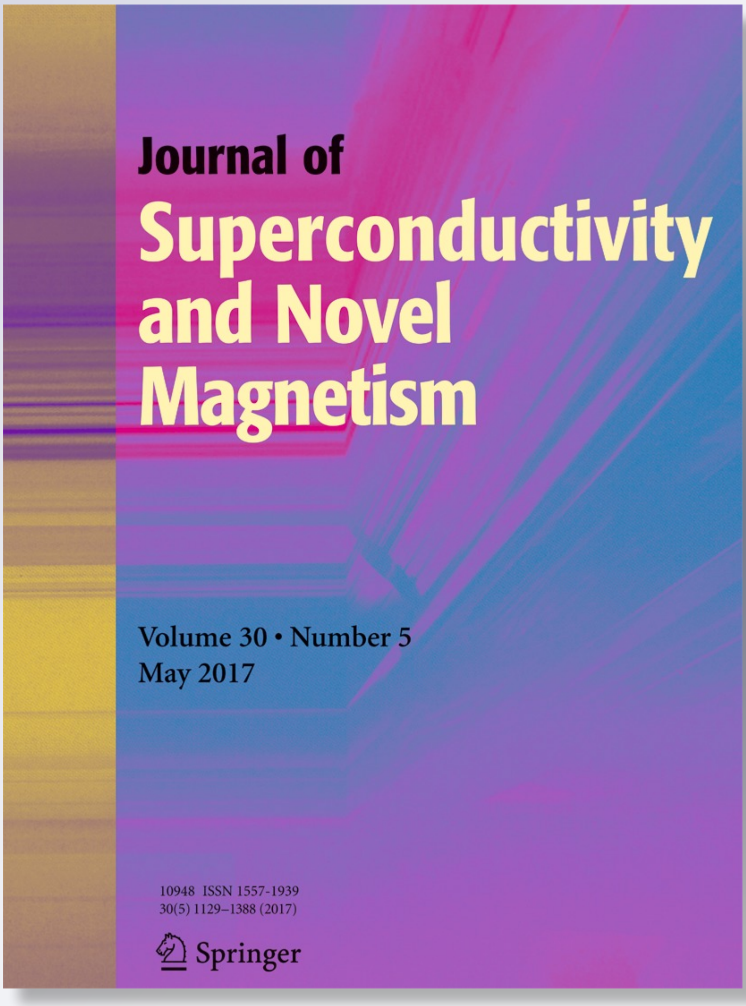
Temperature Dependence of the Phonon Escape Time Deduced from the Nucleation Time of Phase Slip Center in Superconducting NbTiN Thin Film

K. Harrabi, F. O. Bakare, F. Oktasendra & J. P. Maneval

Journal of Superconductivity and Novel Magnetism
Incorporating Novel Magnetism

ISSN 1557-1939
Volume 30
Number 5

J Supercond Nov Magn (2017)
30:1349-1352
DOI 10.1007/s10948-016-3833-3



J Supercond Nov Magn (2017) 30:1349–1352
DOI 10.1007/s10948-016-3833-3

ORIGINAL PAPER

Temperature Dependence of the Phonon Escape Time Deduced from the Nucleation Time of Phase Slip Center in Superconducting NbTiN Thin Film

K. Harrabi[1,2] · **F. O. Bakare**[1] · **F. Oktasendra**[1] · **J. P. Maneval**[3]

Received: 28 April 2016 / Accepted: 27 September 2016 / Published online: 24 October 2016

Abstract We have investigated the voltage response of superconducting NbTiN strips to a step-pulse of overcritical current in the range of temperatures $0.4 < T/T_c < 0.9$, where the critical temperature, T_c, is 8.7 K. The current-induced destruction of the Cooper pairs leads to the nucleation of a phase-slip center. The response appears after a certain delay time t_d, which we analyze through a Time-Dependent Ginzburg-Landau (TDGL) theory according to Tinkham's approach. The experimental findings can be fitted by inferring a film cooling time of about 1.8 ns for a 20-nm-thick film, very little dependent upon sample width and temperature. Assuming a definite ratio between the electron and phonon specific heats, one deduces an average phonon escape time of 90 ps per nm thickness of NbTiN film sputtered on sapphire.

Keywords 74.40.Gh Nonequilibrium superconductivity · 74.25.Kc Phonons

1 Introduction

The high demand of a reliable device that can detect a single-photon has been under the scope of many ongoing research since the first discovery of a new concept of detecting single photon using superconducting device by Gol'tsman et al. [1]. Superconducting detectors based on niobium nitride is a promising candidate compared to other available superconducting single-photon detectors (SNSPD), for their potential of having high sensitivity to single-photon in the regime of visible and infrared wavelengths, fast recovery and precision time [2]. The operating mechanism of an SNSPD is based on the creation of dissipative states in a localized spot in the superconducting nanowire. Under a current biased condition, when a photon is absorbed by a superconducting nanowire, a creation of a small resistive hotspot is observed. This phenomenon reduces the path available for the flow of superconducting current. Consequently, dissipative states are developed at a localized spot in the filament which is marked by the destruction of the superconductivity. These dissipative units are the phase-slip centers (PSC), and hot excited phonons or hot spot (HS) having a temperature larger than the critical temperature T_c of the superconducting film. The PSC is a quantum localized dissipative unit occurring in a periodical change in time between the normal and superconducting states. Its concept was first demonstrated by Webb and Warburton using tin whiskers [3] and later some group of researchers observed similar behavior in micro-strips [4]. In these states, electrons and phonons govern the propagation of heat along the filament; however, its evacuation toward the substrate is performed only by phonons. From the evacuated heat, one can obtain the recovery time of the photon detector. The heat will not be evacuated instantly, but it takes

---

✉ K. Harrabi
harrabi@kfupm.edu.sa

[1] Physics Department, King Fahd University of Petroleum and Minerals, 31261 Dhahran, Saudi Arabia

[2] Center of Research Excellence in Renewable Energy (CoRERE), Research Institute, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia

[3] Laboratoire de Physique LPA, Ecole Normale Supérieure, 75231, Paris 5, France

time to escape from the film, it is called the heat escape time τ_{esc} or phonon escape time. This time is an important parameter for determining the recovery time of the detectors. Herein, we report on the creation of PSC in NbTiN filaments using an electrical current pulse. The experimental data at different temperatures were fitted with the modified Time-Dependent Ginzburg-Landau (TDGL) theory [5] to deduce the cooling time of the film.

2 Sample Preparation and Experimental Set up

The NbTiN thin films, 20 nm thick, used in this experiment were deposited on sapphire in an argon-nitrogen plasma environment by employing DC magnetron sputtering (STAR-Cryoelectronics. NM, USA). Thereafter, the thin films were patterned with four gold contact pads, two lateral probes which are 1 mm apart, using standard photolithographic and ion milling process. The electrical measurements were performed in a 4.2 K closed-cycle cryostat under vacuum with a temperature controller. The operating temperatures T_b for these measurements were varied from 4.1 K to critical temperatures, T_c. Series of measurements were conducted on three different samples labeled as BK-NT3, BK-NT5, and BK-NT10 with their respective widths w = 3, 5, and 10 µm. The R-T measurements were conducted to measure the film resistivity and the transition temperature T_c using a four-point probe technique. The T_c corresponding to the three samples were deduced respectively to be 8.8, 8.7, and 8.8 K. The electrical residual resistivities ρ were found to be 182, 158, and 176.8 µΩ cm, respectively. We investigated the voltage response measurement of three filaments to rectangular voltage pulses at different temperatures. A pulse generator was used to send variable voltage pulse amplitude of 450 ns duration through a 50 Ω coaxial cable [10]. The voltage response was monitored as a function of time, we gradually varied the amplitude of the applied current until it exceeded the critical current value I_c. The reflected pulse was separated from the incident one by using a 240 ns delay line. The voltage responses were recorded using a 1-GHz oscilloscope. The additional 467 Ω resistors connected in series with the lateral probes were used to prevent any current leakage to the output circuitry (Fig. 1-top).

3 Nucleation of Dissipative State in Superconducting Filament by an Over-Critical Current

When a superconducting filament is fed with an electrical current larger than the critical current I_c, the order parameter falls to zero. As a result, a voltage is generated along the filament after a certain delay time t_d owing to the destruction of superconductivity [7]. Two dissipative states were generated in some localized spots in the filament, they are identified as PSC or HS. The PSC was interpreted as an oscillation of the order parameter at Josephson frequency rate, and once it occurs, the phase difference slips by quanta of 2π [4]. The destruction of the superconductivity appears when a thermal instability occurs, or might be caused by localized defect in the filament. However, the type of dissipation is influenced by few parameters and can be explained in the temperature dependence of two currents $I_c(T)$ and $I_h(T)$. The current I_h is defined as the minimum threshold current whose Joule effect is sufficient to maintain a localized normal zone above T_c. This type of dissipation depends on the location of to the value of the working temperature T_b compared to T^*, where T^* is the temperature that makes $I_c(T^*) = I_h(T^*)$ (Fig. 1-bottom). Harrabi [6] reported on the study of the dissipative states in NbTiN filaments at fixed temperature $T_b = 4.2$ K using a rectangular electrical pulse. The study showed the formation of HS, and its numerical reproducibility using the TDGL. The working temperature for two samples were located below and above T^*; therefore, the PSC ($T_b > T^*$) and the HS ($T_b < T^*$) were identified. A similar experiment performed on YBCO filament showed the transformation from PSC to HS [8].

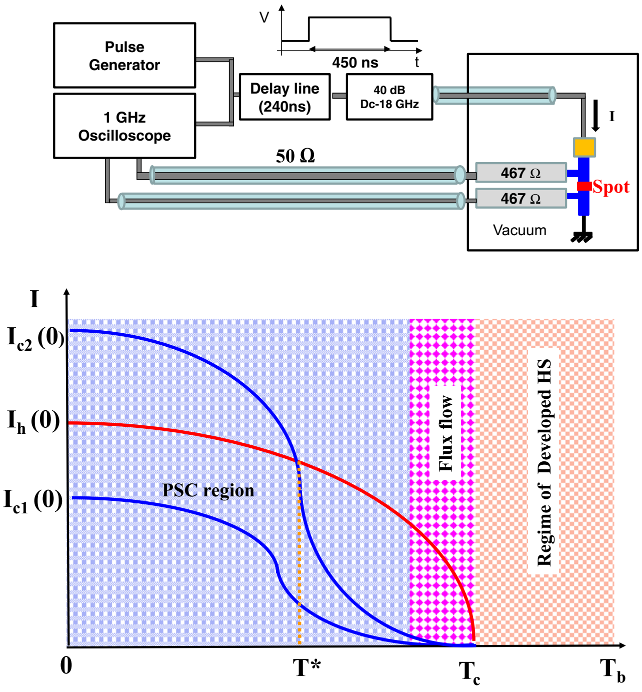


Fig. 1 *Top* sketch: experimental set-up used for pulse measurements. It consists of a pulse generator, a delay line needed to separate the incident pulse from the reflected one, and an oscilloscope to measure the voltage and the delay time t_d. *Bottom* sketch: Current temperature diagram of resistive states, showing $I_c(T)$ and the HS threshold current $I_h(T)$

However, the experiment presented in Ref. [9] showed the measurement of the crossing temperature T* and clear discrimination between the HS and PSC. Moreover, a HS is initiated by a PSC was proven in Nb filament.

Figure 2 depicts the resulting voltage response at $T_b = 4.2$ and 5.8 K for samples BK-NT5 and BK-NT10, respectively, and for current values exceeding I_c. It can be seen that as the current amplitude is increased, the delay time t_d is gradually reduced until it becomes immeasurable. In addition, the voltage response reaches a saturated value, which is one of the characteristic features of the PSC dissipative state [6]. We noticed in the whole range of investigated temperatures, the appearance of this dissipative mode for these three samples. This is explained in the current-temperature phase diagram shown in Fig. 1(bottom), it is a characteristic property of the sample where the critical current curve $I_c(T)$ lies below the hot spot current $I_h(T)$. On the other hand, the HS can be obtained when the biased current is increased until $I_h(T)$ is reached.

4 Determination of the Phonon Escape Time and its Temperature Dependence

In order to determine the phonon escape time τ_{esc} and its temperature dependence, we plotted the measured t_d at each T_b as a function of I/I_c and adjusted the function on the right side of (1) to match the experimental data through the prefactor τ_d from the one dimensional Time-Dependent Ginzburg-Landau (TDGL) equation. This equation describes t_d as a function of I/I_c:

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

where τ_d was interpreted as the inelastic electron-phonon relaxation time τ_E in the normal state close to the critical temperature and t_d is the time it takes for the normalized order parameter f to drop from 1 to 0. A quantitative interpretation of τ_d following the modification of (1) has been proposed by Tinkham [5] where τ_d is the temperature dependent gap relaxation time, and the integrand of (1) is also modified. This modified equation reveals that the t_d is a function of the two variables, T/T_c and I/I_c. It was studied previously in different types of superconductors Nb [11], YBCO [13], and NbTiN [6].

Figure 3 shows the experimental data of t_d as a function I/I_c of sample BK-NT5 at different temperatures fitted by using Tinkham's TDGL theory (red lines) with $T/T_c = 0.5$ and 0.7, respectively, for 4.2 and 5.8 K, and where the fitting parameter $\tau_d = 1.4$ ns for both temperatures. We interpret the prefactor time τ_d as the the time taking for film to cool on its substrate and can be identified with τ_{cool}.

The phonon escape time τ_{es} can be deduced from τ_d by considering the transfer of heat from the film to the substrate which is dominated by the phonon escape and along the film which is dominated by electrons and phonons. If the total specific heat of phonon C_ϕ and electrons C_{el} equals to $C = C_\phi + C_{el}$, then the phonon escape time is given by a relation $C_\phi/\tau_{es} = C/\tau_d$ [12].

The weak sensitivity of the cooling time to a temperature change below the critical value is illustrated in Fig. 4 for the three different samples. It is seen that τ_d is constant as the temperature is increased in the range of 4 to 7.75 K. This defines that prefactor τ_d is a T-independent parameter. The averaged τ_d values for samples BK-NT3, BK-NT5,

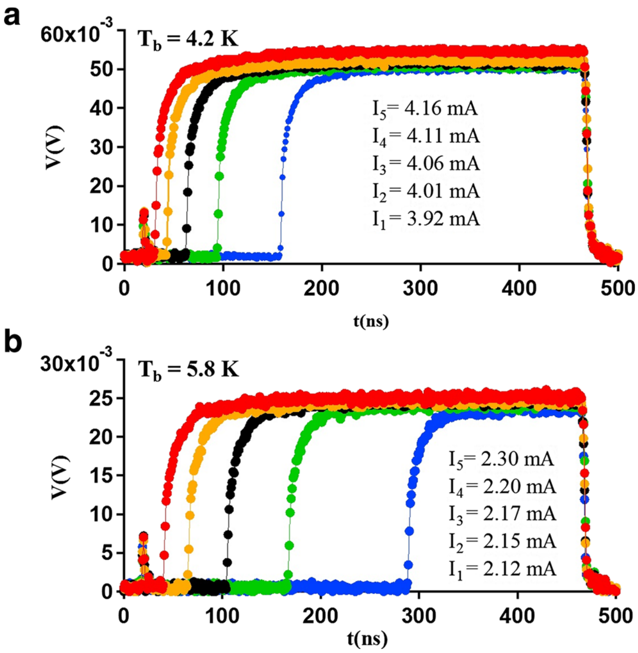


Fig. 2 Voltage responses as function of time and their corresponding current amplitudes through the filament for sample **a** BK-NT5 at $T_b = 4.2$ K and **b** BK-NT10 at $T_b = 5.8$ K

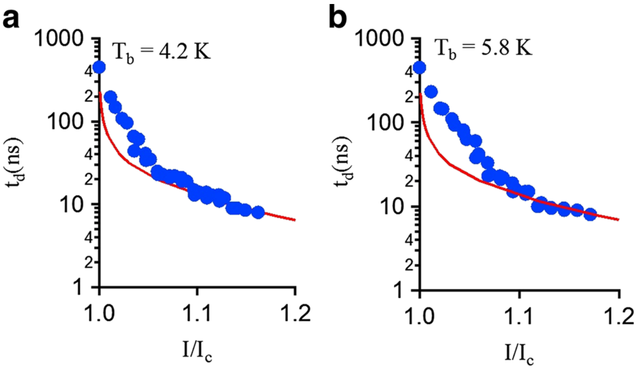


Fig. 3 Delay time t_d (in log scale) as a function of reduced current I/I_c fitted with Tinkham TDGL theory for different operating temperatures on sample BK-NT5 at **a** $T_b = 4.2$ K and **b** $T_b = 5.8$ K. The same prefactor ($\tau_d = 1.4$ ns) was chosen to draw the (*red*) solid curves

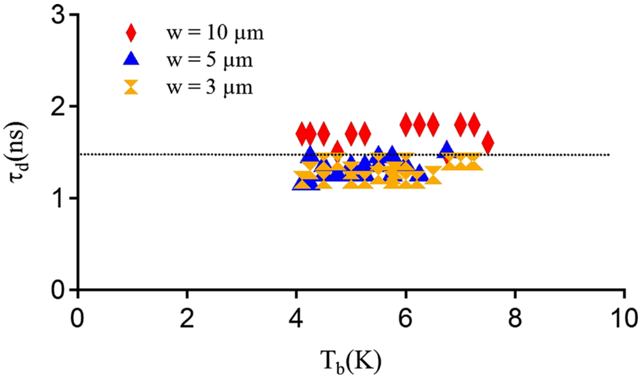


Fig. 4 Temperature dependence of the heat escape time (or cooling times) for the three samples BK-NT3, BK-NT5, BK-NT10

and BK-NT10 are, respectively, 1.4, 1.6, and 1.8 ns. They are a slightly different and can be compared to one performed in a pulse photo-resistance experiment in the normal state [15]. In addition, Semenov et al. [16] work led to the same conclusion. A recent study carried out recently on Nb [13] showed the same behavior as a function of temperature. However, the temperature dependence of the cooling time was performed on YBCO [14] as it presented different behavior, where the τ_d remains constant from 4.2 K till $T_b = T_c/2$ then increases.

The phonon escape from the film to the substrate is influenced by phonon-phonon scattering in addition to the acoustic mismatch between two lattices and the defects of the interface. If the average phonon energy reaches a rounding domain in the dispersion relation due to a temperature rise, many channels will open for phonon decay compared to that of the linear relation (Debye regime). Yet, at the same time, the phonon evacuation could also be decelerated because a temperature rise will create numerous phonons so that they impede one another causing phonon transport to become diffusive rather than ballistic [14]. Nevertheless, since the range of temperature of NbTiN is still in the Debye regime, the phonon dispersion relation is linear and phonon-phonon scattering is very limited. Thus, the elevation of temperature below T_C does not influence the phonon escape.

5 Conclusion

We have measured the heat escape time of an conventional superconducting material at different temperatures, by monitoring the destruction of superconductivity after an over-critical current pulse. The resistive voltage appears after a delay time t_d, which was interpreted using the TDGL equation. The heat escape time was subsequently deduced. We found that it is governed by the phonon transfer to the substrate and is constant throughout the operating temperatures below the T_c. Assuming proportionality to the thickness, we then deduce an average *phonon* escape time τ_{esc} for the three samples to be 90 ps nm thickness.

Acknowledgments Authors gratefully acknowledges the support of the King Fahd University of Petroleum and Minerals, Saudi Arabia, under the IN131034 DSR project.

References

1. Gol'tsman, G.N., et al.: Appl. Phys. Lett. **79**, 705–707 (2001)
2. Miki, S., Takeda, M., Fujiwara, M., Sasaki, M., Otomo, A., Wang, Z.: Appl. Phys. Express. **2**, 075002 (2009)
3. Webb, W.W., Warburton, R.J.: Phys. Rev. Lett. **20**, 461 (1968)
4. Skocpol, W.J., Beasley, M.R., Tinkham, M.: J. Low Temp. Phys. **16**, 145 (1974)
5. Tinkham, M.: Non-Equilibrium Superconductivity, Phonons and Kapitza Boundaries. In: Gray, K.E. (ed.) pp. 231–262. Plenum, New York (1981)
6. Harrabi, K.: AIP Adv. **5**, 037102 (2015)
7. Pals, J.A., Wolter, J.: Phys. Lett. A **70**, 150 (1979)
8. Harrabi, K., Salem, A.F., Ziq, K., Mansour, A.I., Kunwar, S., Maneval, J.P., Berdiyorov, G.: Appl. Phys. A **117**, 2033–2036 (2014)
9. Harrabi, K.: J. Supercond. Nov. Magn. **26**, 1865 (2013)
10. Harrabi, K.: J. Supercond. Nov. Magn. **28**, 573 (2015)
11. Berdiyorov, G., Harrabi, K., Oktasendra, F., Gasmi, K., Mansour, A.I., Maneval, J.P., Peeters, F.M.: Phys. Rev. B **90**, 134505 (2014)
12. Ladan, F.R., Harrabi, Kh., Rosticher, M., Villard, C., Mathieu, P., Maneval, J.-P.: J. Low Temp. Phys. **153**, 103 (2008)
13. Harrabi, K., Oktasendra, F., Gasmi, 1.K., Berdiyorov, G., Mekki, A., Maneval, J.-P.: IEEE Trans. Appl. Supercond. (2016)
14. Harrabi, K.: IEEE Trans. Appl. Supercond. (2016)
15. Bluzer, N.: Phys. Rev. B **46**, 1033 (1992)
16. Semenov, A.D., Nebosis, R.S., Gousev, Yu.P., Heusinger, M.A., Renk, K.F.: Phys. Rev. B **52**, 581 (1995)