Characterization of Resistive Hotspots induced in Superconducting NbTi thin film by an electrical current pulse

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Abstract
We report on the creation of resistive states in NbTi superconducting filament on polished crystalline Al2O3 using the current driven pulse technique. A current pulse larger than the depairing current (Ic) initiates a dissipation in a localized spot. The non-equilibrium state described by the two dissipative mechanism pinpointed as hotspot and phase slip center. A time dependent voltage response exposes the collapse of superconductivity that occurs after a certain delay time td. We found that hotspots occur at temperatures much lower than the transition temperature. This can be clearly seen in a current versus temperature diagram. The thermal cooling and heat escape times were extracted from fitting the experimental data of the delay time to Tinkham’s amended version of the Time-Dependent Ginzburg-Landau (TDGL). The temperatures reached at the core of hotspots were determined without any parameter adjustment.

1. Introduction

The superconductivity phenomenon had various applications in different fields, the fascinating superconducting qubits based on Josephson junction has been adopted for use in quantum algorithms [1]. The superconductivity in the non-equilibrium regime emerged as a promising candidate for many technological applications. Coherent qubits were constructed from superconducting quantum phase slip centers (PSCs) and efficiently demonstrated in solid state physics [2, 3]. In addition to being used in the field of optical communication, non-equilibrium was investigated in single photon detection through superconducting nanowires (SSPD). It relies on the dynamics of hotspots in superconducting nanowire. A current flowing in one-dimensional superconducting filament can cause different type of dissipative regimes. The PSC is a well-known energy dissipative phenomenon that occurs once the Cooper pair-breaking current has been exceeded [4]. The hotspot is a second dissipative state made of a normal region; usually it occurs when a superconducting nanowire is biased with currents close to Ic and irradiated by a photon [5]. In this region, superconductivity is destroyed and this leads to the creation of normal quasi-particles. The non-equilibrium superconducting state is exposed in the I–V characteristics [6, 7] and could be also created by thermal fluctuation [8, 9]. Various studies of niobium-based materials had positive results and were regarded as good candidates for SSPDs [10, 11].

In this study, we report on non-equilibrium states generated by electrical wave voltage pulses in NbTi bridges. This bears a similarity to single photon detection in that once a photon is absorbed in the superconducting nanowire, a hotspot may then be created. Our experimental investigation revealed the presence of a single dissipative state: HS. The experimental data were analysed based on the TDGL, which was later modified by Tinkham [12]. The cooling time for the film on its substrate was determined, and the temperatures reached at the HS center were estimated without any parameter adjustment.
2. Samples and experimental setup

Samples made out of superconducting NbTi wires were investigated. They had a width \( w \) (A: 1.8 \( \mu \)m & B: 9.2 \( \mu \)m) and a thickness \( b \) of 50 nm. The growth took place in argon nitrogen plasma inside a high-vacuum chamber (STAR-Cryoelectronics, NM, USA) sputtered on a sapphire substrate. Four 100 nm thick gold pads were patterned using photo-lithographic and ion milling processes and were used for electrical contacts. The laterals probes were 40 \( \mu \)m wide and the central part is 450 \( \mu \)m long (figure 1(a)). The duration of the electrical voltage wave pulse used to excite the superconducting filament was 440 ns, with a repetition rate of 10 kHz. In the experimental set-up, we used 50 coaxial cables and attenuators. The line was terminated by zero impedance in the superconducting state. To extract the incident wave from the reflected one, a 240 ns air-delay line was used in the circuit. Two lateral probes were connected in series with two resistors \( R = 547 \Omega \) to minimize the outgoing current. The resistance of the samples were measured as a function of the temperature, using a dc current with an excitation of 1 \( \mu \)A (figure 1(b)). The transition temperatures were approximately \( T_A = 7.80 \text{ K} \) and \( T_B = 7.60 \text{ K} \), and the resistivity at 15 K was \( \rho = 87 \mu \Omega \text{cm} \) (figure 1(c)). The current was calculated using \( I_1 = 0.09 \times V/50 \), where \( V \) is the applied voltage and the 0.09 factor is due to the fact that the circuit is being terminated by 50 \( \Omega \) resistor.

3. Resistive state created by current pulse

The phenomena of superconductivity results from carrying a current in material cooled below its critical temperature \( T_c \) without any dissipation. The Cooper pairs are responsible for carrying the current below its critical value \( I_c \). Initially, the Cooper pairs are accelerated, and once they reach a critical value, the superconductivity collapses. The order parameter goes to zero value, and quasi-particles are generated in a zone that is the size of the superconducting coherence length \( \xi \). The normal spot expands by the diffusion of quasi-particles where the dissipation occurs. This phenomenon is the origin of the well-known dissipative mechanism governed by the phase slip center \([4, 12]\). This phenomena occurs consistently in one-dimensional superconducting filament, where the width is comparable to the coherence length. However, the same phenomena takes place in a filament that has a width that is larger than the coherence length. This is known as the phase slip line (PSL) \([13]\) and is a hybrid state of normal and superconductor zones.

To discriminate between these two dissipative mechanisms, we used the pulse technique. The voltage pulse was sent along the filament, and the voltage response was recorded. A voltage develops after a delay time \( t_d \) that signals the destruction of the superconductivity locally. The breakdown of superconductivity requires a current that is slightly larger than the depairing current \( I \propto I_c \), which initiates dissipation and is known as a PSC current. Moreover, the hotspot current \( I_h \) is defined as the margin current that is capable of maintaining the temperature inside the core of a dissipation larger than \( T_c \)[14, 15]. Depending on the sample specification, different
behaviour were anticipated for these two currents. The [16] illustrated close to $T_c$, a voltage that appeared showed steady behaviour after $t_d$, as a stable state is attributed to the PSC and the HS at lower temperature as a growing structure. The present specimens behaved differently in the entire temperature region where the dissipation is governed by the HS and is explained in the current diagram in figure 1(a). For all the temperatures $I_b$ remains below $I_c$ in controversy to the study of NbTiN that showed the presence of anti-crossing of the two currents [17]. Figure 2 depicts the nature of the HS, which, similar to PSC, appears after a delay time $t_d$ that is reduced as the current amplitude increases. The style of the dissipation speculates that there is a growing voltage for the remaining time after $t_d$. This non-equilibrium superconducting state dissipates energy, and its temperature is higher than the critical temperature $T_c$. When the applied current increases, the delay time is reduced, and the HS expands along the filament. The creation of the normal spot in the superconducting filament is similar to the absorption of a photon by a superconducting nanowire. A study indicated that there was an agreement between a model developed for the dissipation and the voltage switching caused by two different mechanisms. Depending on the temperature, a hotspot-assisted suppression of the edge barrier was caused by the transport current, and phase-slip centres appeared in the nanowire [18].

4. Theoretical fitting

The collapse of superconductivity due to the excess current was indicated by the voltage determined after the delay time $\tau_d$. The TDGL theory provided an analytical method for describing this phenomena, which was later modified by Tinkham [12]. The solution of the equation is given in integral form:

![Figure 2. Measured voltage response versus time in response to different current values for NbTi wire of width $w_A = 1.8 \mu m$. (a) $I_1 = I_1 = 741 \, \mu A$, Increasing the current amplitudes the delay times were reduced and are respectively $I_2 = 794 \, \mu A, I_3 = 832 \, \mu A, I_4 = 933 \, \mu A, I_5 = 1.04 mA$. & (b) $I_1 = I_1 = 0.984 mA, I_2 = 1.05 mA, I_3 = 1.13 mA, I_4 = 1.18 mA, I_5 = 1.23 mA$.](image)
The integral depends on the ratio of the applied current to the critical current $I_c$ and the normalized superconducting order parameter $f$. The constant term preceding the integral function is associated with the electron-phonon relaxing time. The study of the non-equilibrium states in Nb [15] and YBCO [19] reported the dependence of $t_d$ on film thickness. The constant $\tau_d$ is identified as the film cooling time on its substrate. Figure 4 spotlights the dependence of the HS delay time $t_{ds}$ as a function of $I/I_c$. The experimental data is well fitted according to the TDGL theory modified by Tinkham, which allows the film cooling time of NbTi on the sapphire $\tau_{da} (7.50 \text{ K}) = (6.1 \pm 0.2) \text{ ns}$ and $\tau_{db} (7.45 \text{ K}) = (6.3 \pm 0.2) \text{ ns}$ to be deduced and reveal a small variation of temperature for these two specimens. This variation is associated with the increase of the population number of phonons as the temperature increases and gets closer to $T_c$.

A non-equilibrium state was created as a consequence of photon energy being absorbed by the superconductor, where quasi-articles are excited at a higher temperature than the Cooper pairs. In this process, the superconducting equilibrium state was regained by means of successive relaxation mechanisms. The inelastic scattering of electron-electron interactions was followed by electron-phonon interactions, and ended by phonon evacuation of the heat toward the substrate. This happened in addition to the generation and recombination processes that take place in the superconductor. Each relaxation mechanism possesses temporal characteristics of time constants [5]:

$$t_d(I/I_c) = \tau_d \int_0^1 \frac{2f^4 df}{\sqrt{\left( \frac{1}{\tau_d} \right)^2 - f^4 + f^6}}$$  \hfill (1)
where $c_e$ and $c_p$ are the electron and phonon specific heat respectively, $T_b$ is the bath (substrate) temperature, $\tau_{e-p}$ is the electron-phonon interaction time, $\tau_{p}$ is the phonon escape time, and $P(t)$ is the absorbed radiation power in the unit volume of the film. The hotspot created by photon energy absorbed into the superconductor is analogous to the one created by an electrical current pulse. The heat escape time can be deduced by equalizing the energy dissipated in the filament and the energy evacuated toward the substrate. The heat dissipated in the filament persisted for $\tau_d$ and involved the phonons and the quasi-particles generated. However, the heat was evacuated into the substrate via phonons within a certain time $\tau_{es}$.

\[
\frac{c_e}{\tau_{e-p}} \frac{dT_e}{dt} = -\frac{c_e}{\tau_{e-p}} (T_e - T_p) + P(t)
\]

\[
\frac{c_p}{\tau_p} \frac{dT_p}{dt} = \frac{c_e}{\tau_{e-p}} (T_e - T_p) + \frac{c_p}{\tau_{es}} (T_p - T_b)
\]

where $c_e$ and $c_p$ are the electron and phonon specific heat respectively, $T_b$ is the bath (substrate) temperature, $\tau_{e-p}$ is the electron-phonon interaction time, $\tau_{p}$ is the phonon escape time, and $P(t)$ is the absorbed radiation power in the unit volume of the film. The hotspot created by photon energy absorbed into the superconductor is analogous to the one created by an electrical current pulse. The heat escape time can be deduced by equalizing the energy dissipated in the filament and the energy evacuated toward the substrate. The heat dissipated in the filament persisted for $\tau_d$ and involved the phonons and the quasi-particles generated. However, the heat was evacuated into the substrate via phonons within a certain time $\tau_{es}$.

\[
\int \frac{c_e dT_e}{\tau_d} + \int \frac{c_p dT_p}{\tau_{es}} = \int \frac{c_p dT_p}{\tau_{es}}
\]

If we consider the linear regime, equation (3) becomes $C_{tot}/\tau_d = (c_e + c_p)/\tau_d = c_p/\tau_{es}$. The total specific heat in the superconducting and normal states are, $C_S = \mu T^3 + \beta T^3$ and $C_N = \gamma T + \beta T^3$, respectively, and NbTi $\gamma = 13.8 J \cdot m^{-3} \cdot K^{-1}$ and $\beta = 870 J \cdot m^{-3} \cdot K^{-4}$ [20], which are close the Nb values [15]. If we consider the ratio to be the same as Nb $C_{tot}/c_p = 3$, the heat escape time is given by $\tau_{es} \approx \tau_d/3 \approx 2$ ns. The temperature reached at the center of the hotspot is estimated based the blackbody radiation, where the power radiation density is
\[ P_b = \sigma_p (T^4 - T_b^4) \]. Here, \( \sigma_p \) is the Stefan constant used for the acoustic phonon approximation. This term is evaluated from the second term of equation (3), \( \int_{t}^{\infty} \frac{dT}{\tau_p} = \sigma_p (T^4 - T_b^4) \), which leads to the temperature dependent equation:

\[
\frac{\rho \mu^2}{w^2 b^2} = \frac{\beta (T^4 - T_b^4)}{\tau_p} \quad (4)
\]

The temperature at the core of the hotspot of different traces in figures 2 & 3 are illustrated in the table:

These estimations were achieved without adjusting any parameters, and all the parameters involved in the calculation of table 1 were experimentally measured. This supports the main characteristic feature of the HS: the temperature reached at its core is greater than \( T_c \).

5. Conclusion

We investigated the HS non-equilibrium states in NbTi specimens and found that dissipative HSs were formed due the excess current in the vicinity and away from \( T_c \). The film cooling time was subsequently determined by fitting the delay times \( t_{ds} \) for the HS using the TDGL theory, and the heat escape time was estimated from the specific heat of the electrons and phonons in the linear regime. The temperatures inside the HS cores were estimated based on the phonons, and quasi-particles, contributions to heat dissipation in the filament and the heat evacuation toward the substrate.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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