Discontinuous hotspot growth related to the thermal healing length in superconducting NbN microstrips

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Abstract. Electrical transport measurements were performed on NbN multicontact microstrips in order to investigate the non-equilibrium dissipative states in highly disordered granular superconducting nanostructures. By applying a dc voltage-bias, a peculiar discontinuous normal phase propagation was observed in a current interval well below the switching point. These stabilized resistive states are explained within the framework of a localized normal hotspot maintained by Joule heating. The thermal healing length of our NbN microstrips is estimated by taking into account both kinds of heat transfer (i.e. by conduction within the microstrip and by surface heat transfer through the substrate). It appears that the estimated healing length properly matches the length associated with a normal region across the whole width and whose resistance is given by the difference of resistance between two nearest intermediate dissipative states as observed in the voltage-biased curves.

1. Introduction

Nowadays much attention is paid on the current-voltage characteristics of thin superconducting microbridges, especially for two-dimensional type-II structures of intermediate sizes $\xi < w < \lambda_\perp$ ($\xi$ is the coherence length, $w$ the width, $\lambda_\perp=\lambda^2/d$ the magnetic field penetration depth [$\lambda$ is the London penetration depth and $d$ the thickness]). The resistive state region that extents from the purely superconducting state to the fully normal state is intensively studied in such narrow structures due to the various competing dissipative mechanisms, namely those involving phase-slips phenomena and vortices [1, 2, 3, 4] as well as those involving normal phase propagation. The presence of voltage steps in current-biased curves is often attributed to phase-slip centers or phase-slip lines [5, 6, 7]. The investigation of such phase-slips phenomena requires that the heating level is small. When the heating level becomes sufficient, hotspot formation dominates and an abrupt transition to the normal state occurs when the instability current is reached. Thermal instabilities are thus preferentially studied by applying a voltage-bias in order to prevent structure damaging and to stabilize possible intermediate resistive states [8, 9, 10].

In the present work, we report on electrical transport measurements performed on multicontact superconducting NbN microstrips. Applying a voltage-bias allows us to evidence a peculiar normal phase propagation regime that occurs in a wide temperature range. We relate this discontinuous hotspot growth to the thermal healing length of our microstrips.
2. Materials and methods

The NbN thin films used to fabricate the samples were obtained by reactive dc magnetron sputtering. The films (75 nm and 25 nm thick) were deposited from a pure (99.9%) Nb target in a 8.9 mTorr Ar/N$_2$ gas-filled atmosphere (partial pressures of 88.8% and 11.2%, respectively). The 75 nm thick film was deposited onto a (100 nm SiO$_2$)/Si substrate and the 25 nm thick film onto a sapphire substrate. This process yields a critical temperature $T_c$ of 12 K and 9.5 K (the transition width is about 1 K) and a normal state resistivity of 1200 $\mu$Ωcm and 550 $\mu$Ωcm, respectively. The Ginzburg-Landau coherence length at zero temperature is calculated from the relation

$$\xi = \left[ \frac{\Phi_0}{2\pi B_{c2}(0)} \right]^{1/2},$$

where $B_{c2}(0) = 0.69 T_c \left| \frac{dB_{c2}(T)}{dT} \right|_{T=T_c}$ is the upper critical field at zero temperature determined with the dirty limit relation [11]. The obtained values are 2.2 nm and 3.5 nm for the 75 nm thick and the 25 nm thick films, respectively. The coherence length appears to be smaller than other reported values that usually range around 4 - 5 nm (see e.g. [4, 12]).

Multicontact structures were obtained by SF$_6$ reactive ion etching using a 40 nm thick Al$_2$O$_3$ mask patterned with standard e-beam lithography (see figure 1(a-b)). The microstrips width is 120 nm for the 75 nm thick film and 90 nm for the 25 nm thick film. The results reported here were obtained on 3 $\mu$m long segments. Our NbN thin films have an average grain size of about 14 nm as shown by the atomic force microscopy image of figure 1(c). Electrical transport measurements were performed in a He flow pulse-tube cryocooler. All the measurement lines were filtered using a combination of RC and LC filters operative up to 40 GHz. The bias is applied directly to the measured segment and the resulting voltage is probed using the nearest contacts on each side. The experimental setup used to apply the voltage-bias consists in a room temperature resistor of 1 $\Omega$ in parallel with a dc current source.

![Figure 1](image_url)(a-b) SEM images of a NbN multicontact microstrip. Here the 75 nm thick segments have a width of 120 nm with a length varying between 2 $\mu$m and 4 $\mu$m. NbN superconducting leads are used to perform electrical measurements. (c) Atomic force microscopy image (300 nm x 300 nm) illustrating the morphology of the NbN thin film.

3. Results and discussion

Figure 2 shows the typical low-temperature current-biased hysteretic behavior of our NbN multicontact microstrips (this is illustrated at 5.8 K for a 120 nm wide and 75 nm thick segment deposited onto a SiO$_2$/Si substrate). By increasing the applied dc current, the forward part of the curve is characterized by an abrupt transition to the normal state when the switching current is reached. The strong Joule dissipation that results from this thermal instability requires a significant decrease of the applied current before the sample goes back to the superconducting state. The current at which the sample starts to return to the superconducting state is called the retrapping current $i_r$ (see figure 2).

Applying a dc voltage-bias instead of a current-bias allows us to avoid the abrupt transition to the normal state at the switching current. By doing so it becomes possible to probe the resistive
Figure 2. Typical current-biased hysteretic behavior of our NbN microstrips at low temperature illustrated with a 120 nm wide and 75 nm thick segment (length: 3 µm) at 5.8 K. The dotted frame defines the superconducting resistive state which is studied in more details in figure 3.

part of the current-voltage characteristics which is not easily accessible in current-biasing mode. Figure 3(a) shows the voltage-biased curves of the same segment as in figure 2 (see the set of slanted segments with jumps between them marked by the dashed lines) for temperatures between 5.8 K and 7.8 K. The same features were observed in a larger temperature range, from 1.5 K up to around 2 K below the critical temperature. Numerous intermediate resistive states are pointed out, especially in the high-voltage part of the curves where they are stabilized in a larger current interval. Those results are very reproducible from one run to another. The current-biased transition from the normal state to the superconducting state is also shown (see the solid mostly vertical curves). We observe that the retrapping region of the hysteretic current-biased behavior coincide with the current range where the intermediate dissipative states take place in the voltage-biased curves. The figure 3(b) shows an enlargement of the high-voltage part of the voltage-biased characteristics (the evolution of the resistance is now presented as a function of the current). The difference of resistance between two nearest dissipative states in this part of the voltage-biased curves (noted $\Delta R_{V-bias}^{75nm}$) is determined to be around 120-230 Ω.

Figure 3. (a) Resistive parts of the (- - - -) voltage-biased and (——) current-biased characteristics of a 120 nm wide segment (thickness: 75 nm, length: 3 µm) at different temperatures. (b) Enlargement of the high voltage resistive regions displayed in resistance unit.

Figure 4(a-b) present similar measurements performed on a 90 nm wide 25 nm thick segment deposited onto a sapphire substrate (the length is the same as for the previous microstrip, namely 3 µm). The stabilization of several intermediate dissipative states is still observed when the voltage-bias is swept up and down. The retrapping current as determined from the backward
part of the current-biased characteristics (see the solid curves in figure 4(a)) also coincide with the current range where the intermediate dissipative states are stabilized. Based on the resistance vs current curves of figure 4(b), the difference of resistance between two nearest dissipative states appears to be slightly smaller, with $\Delta R^{25nm}_{V-bias}$ ranging between 90-160 $\Omega$.

Figure 4. (a) Resistive parts of the (- - - -) voltage-biased and (——) current-biased characteristics of a 90 nm wide segment (thickness: 25 nm, length: 3 $\mu$m) at different temperatures. (b) Enlargement of the high voltage resistive regions displayed in resistance unit.

The formation of a normal hotspot is known to be a competitive mechanism to phase-slip centers or lines phenomena [13, 14]. Here the slopes of the dissipative states presented in figures 3 and 4 are roughly the same for a given sample. When extrapolated to the zero-voltage level they intercept the current axis at less than 10-15% of the critical current whereas for phase-slip centers or lines phenomena this occurs at roughly half of the critical current [15]. Moreover the Joule heating is so high in our samples (notably due to the high normal state resistivity) that only hotspots prevail. It appears that the overall shape of the observed voltage-biased characteristics is well explained by the theoretical model of a localized normal hotspot maintained by Joule heating in a long bridge [16, 17]. This model is based on the assumption that the heat generated in the normal state in such a localized dissipative region is transferred by thermal conduction within the film and by surface heat transfer through the substrate. The thermal balance in the normal region is then given by the equation (1),

$$\rho_n \; j^2 = -\kappa \frac{d^2 T}{dx^2} + \frac{h(T_c) \; (T - T_s)}{d}$$  \hspace{1cm} (1)

where $\rho_n$ is the normal state resistivity, $j$ is the density current required to dissipate enough heat in order to maintain a normal region of a given size, $\kappa$ is the thermal conductivity of the film [Wm$^{-1}$K$^{-1}$], $x$ is the direction along the bridge, $h$ is the heat-transfer coefficient per unit area to the substrate [Wm$^{-2}$K$^{-1}$], $T_s$ is the temperature of the substrate and $d$ is the thickness of the bridge. The heat evacuated through the substrate is assumed to depend linearly to the temperature difference $T - T_s$ between the microstrip in the normal state and the substrate. Indeed, the microstrips being much smaller than the substrate, the latter is supposed to be at the sensed cooling temperature.

As mentionned, the model that fits the overall shape of the voltage-biased characteristics is the long bridge model, which means that the sample length under consideration is higher than the thermal healing length $\eta$ [17, 18]. This characteristic thermal length is defined by the
expression \( \eta = \sqrt{\frac{2d}{l}} \), which clearly reveals the two ways by which the dissipated heat can be transferred. In order to estimate the healing length associated with our microstrips, an accurate estimation of the parameters \( h \) and \( \kappa \) is needed. One can consider that in equation (1) the heat transfer through the substrate is much efficient than within the film [19]. The coefficient \( h \) can be determined by further assuming that the temperature of the microstrip at the retrapping current (i.e. when the sample goes back to the superconducting state as the bias is decreased) is close to the critical one. This is reflected in equation (2) that gives a heat-transfer coefficient \( h \approx 3 \times 10^5 \text{ Wm}^{-2}\text{K}^{-1} \) for the microstrip deposited on a SiO\(_2\)/Si substrate (a close value was also found by Wedenig et al [20]) and \( h \approx 6 \times 10^5 \text{ Wm}^{-2}\text{K}^{-1} \) for the microstrip deposited on a sapphire substrate. The higher heat-transfer coefficient \( h \) determined in the case of the sapphire is consistent with its better capacity of cooling compared to a SiO\(_2\)/Si substrate.

\[
\rho_n j_c^2 = \frac{h(T_c) (T_c - T_s)}{d} \tag{2}
\]

Furthermore the electrical and thermal properties of NbN films are seen to greatly differ from one sample to another, especially due to the polycrystalline structure, which is affected by the sputtering conditions [21, 22, 23]. Depending mainly on the deposition temperature and on the total sputtering pressure, the grains arrangement leads to various level of residual stresses and thus various amount of nitrogen vacancies. This material presents a nonmetallic behavior, with a high normal state resistivity \( \rho_n \) and a residual resistivity ratio \( RRR = R_{300K}/R_{15K} \) smaller than unity (i.e. a negative temperature coefficient of resistivity) [24]. For our samples the high normal state resistivity and the small \( RRR \) values (equal to 0.73 and 0.79 for the 75 nm thick and the 25 nm thick films, respectively) suggest that the thermal conductivity of the microstrips is strongly affected by the granular structure. An estimation of the coefficient \( \kappa \) is obtained based on finite elements calculations by fitting the resistance measured at current much larger than the switching one, knowing the resistance evolution with temperature. Doing this, we determined the thermal conductivity to be approximately 0.05-0.15 Wm\(^{-1}\)K\(^{-1}\). This relatively small value - compared for example with [20] - is consistent with the normal state resistivity (one often consider that \( \kappa \propto \rho_n^{-1} \) [25] even it is not straightforward to extract the coefficient \( \kappa \) directly from \( \rho_n \)). The mechanism for thermal conductivity is thus characterized by a low phonon mean free path and we notice that our minimum estimation is close to the electronic contribution \( \kappa_e \) determined with the Wiedemann-Franz law, which is valid at low temperatures \( (\kappa_e = \sigma_e L_0 T) \) where \( \sigma_e \) is the electrical conductivity in the normal state, \( L_0 = 2.44 \cdot 10^{-8} \text{ WOK}^{-2} \) and \( T \approx T_c \) in this case). With these estimated values for \( h \) and \( \kappa \), we obtain \( \eta_d=75nm \approx 110-190 \text{ nm and } \eta_d=25nm \approx 45-80 \text{ nm.} \) The healing length estimated for the 25 nm thick microstrip thus appears to be less than half of the \( \eta_d=75nm \) value. Let us note that Marsili et al estimate that the thermal healing length of their 100 nm wide, 7 nm thick NbN nanowires deposited on a MgO substrate is around 100 nm [26].

One can now calculate the length \( L^\Delta R_n \) of a normal region across the whole width and whose resistance would be given by the difference of resistance between two stabilized dissipative states \( \Delta R_{V_{bias}} \). These values are summarized in table 1. In both cases, there is a quite good agreement between the estimated values of the healing length \( \eta \) and the length \( L_n^\Delta R \) as determined with the voltage-biased characteristics. We previously noticed that the estimated \( \eta \) values were smaller for the 25 nm thick microstrip than for the thicker one. The same tendency is observed for the calculated values of \( L_n^\Delta R \). Since the healing length seems to be much larger than the average grain size of the our NbN films (about 14 nm in diameter as determined by AFM), it appears that the discontinuities in resistance are not directly related to our film structure or morphology. Neither are they related to the coherence length, which is small for NbN (here \( \xi \approx 2 - 3.5 \text{ nm} \). Even though the spatial extension of phase-slip centers or lines phenomena is linked.
to the quasiparticle diffusion length $\Lambda_Q$ [15], here we are in presence of a discontinuous hotspot propagation and the resistance variation scales rather well with the healing length.

**Table 1.** Main experimental characteristics of the NbN microstrips (thickness $d$, width $w$, normal state resistivity $\rho_n$, variation of resistance between two stabilized dissipative states $\Delta R_{V-bias}$), calculated normal length $L_{n}\Delta R$ associated with a variation of resistance $\Delta R_{V-bias}$ and estimated values for the healing length $\eta$.

| $d$ [nm] | $w$ [nm] | $\rho_n$ [$\mu\Omega$cm] | $\Delta R_{V-bias}$ [\Omega] | $L_{n}\Delta R$ [nm] | $\eta$ [nm] |
|----------|----------|--------------------------|-----------------------------|----------------------|------------|
| 75       | 120      | 1200                     | 120 - 230                   | 90 - 170             | 110 - 190  |
| 25       | 90       | 550                      | 90 - 160                    | 40 - 65              | 45 - 80    |

4. Conclusion

Electrical transport measurements on NbN multicontact sub-micron size structures are reported for samples that differ from their thickness and that were deposited onto different substrates. A thermal instability appears at low temperatures when the applied dc current exceeds the switching one. Applying a dc voltage allows us to avoid this abrupt transition to the fully normal state. It enables us to probe the resistive region that lies between the perfect superconducting state and the normal state. In this manner numerous intermediate dissipative states are stabilized in a current range well below the switching current. The discontinuous growth of a localized normal hotspot maintained by Joule heating is proposed to explain these features. Considering both kinds of heat transfer (i.e. by conduction within the microstrip and by surface heat transfer through the substrate), we show that the discontinuous normal phase propagation can be related with the thermal healing length $\eta$. Indeed there is a good agreement between the estimated healing length and the length $L_{n}\Delta R$ of a dissipative region across the whole width and whose resistance would be given by the difference of resistance between two nearest dissipative states in the voltage-biased curves.

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