Non-equilibrium resistive states of superconducting NbN microstrips in a transverse magnetic field

S Adam¹, L Piraux¹, S Michotte¹, D Lucot² and D Mailly²

¹ Université catholique de Louvain, Unité de Physico-Chimie et de Physique des Matériaux, Place Croix du Sud 1, B-1348 Louvain-la-Neuve, Belgium
² Laboratoire de Photonique et de Nanostructures (LPN-CNRS), Route de Nozay, F-91460 Marcoussis, France
E-mail: sebastien.adam@uclouvain.be

Abstract. Applying current in type-II superconducting sub-micron size structures often leads to a discontinuity of the current-voltage characteristic as the instability current is reached. Also voltage-bias mode allows to avoid such an abrupt switch to the normal state, and gives a relevant outlook of the involved resistive phenomenons. Current and voltage-bias measurements on NbN microbridges with a constriction are reported here as a function of temperature and transverse magnetic field. Starting from a 75nm-thick sputtered film, 160nm-wide microstrips were patterned with an half-wide section constriction in their middle. From the current-bias curves it appears that the discontinuities are due to a flux flow instability that rapidly evolves in a hot-spot. Moreover applying the voltage reveals several dissipative states that leads to successive S-shaped current oscillations in a small current range. Formation of vortex channels can be considered to explain these features.

1. Introduction

NbN superconducting sub-micron size stuctures are frequently used in detection devices due to their intrinsic attractive properties: relatively high critical temperature, very good sensitivity as well as short response time [1]. Such devices (e.g. superconducting single-photon detector (SSPD) [2, 3], hot electron bolometer (HEB) [4] and recently detector for time-of-flight mass spectrometry [5]) take advantage of the sudden voltage rise that appears at the instability current.

Several mechanisms can lead to a voltage discontinuity in type-II superconducting microbridges. The main one is the formation and expansion of a normal hot-spot. Self-heating hot-spot occurs when heat dissipation becomes sufficient to rise a part of the sample above its critical temperature. Depending on the biasing-mode (voltage or current), the hot-spot can either be stabilised or expand itself in the whole sample [6]. This effect has been widely studied in superconducting thin films and microbridges [7].

Vortex motion is also a source of dissipation. As vortices are teared from the pinning centers by the applied current, flux flow appears at a velocity propotional to the electric field created over the sample. According to the Larkin and Ovchinnikov theory [8], a flux flow instability can be observed when this velocity reaches a critical value \( v^* \). In current-biasing mode, this electronic instability results in a switch into a dissipative normal state. Flux flow instabilities
have been observed in several thin films [9] as well as in microbridges [10]. Moreover it has been showed that flux flow instability can be strongly influenced by heating effects [11].

Many authors refer to the rearrangement of the vortex lattice due to flux flow instabilities, leading to the formation of vortex channels (i.e. localised regions where vortex can move very fast) [12, 13]. Many similarities have been pointed out between these channels and the formation of phase-slip lines (PSL) (i.e. the 2D equivalent of phase-slip centers) [13, 14] as these two mechanisms corresponds to a $2\pi$ phase difference across the extremities of the sample.

In this paper, current and voltage bias measurements on superconducting NbN microstrips with a constriction are reported. Our current-biased results are interpreted within the framework of flux flow instability, which results in the formation of a hot-spot. Voltage bias curves show particular features that could be interpreted as the successive formation of vortex channels.

2. Materials and methods

Samples were fabricated from NbN films obtained by dc reactive magnetron sputtering. The 75 nm-thick films were deposited onto a Si/SiO$_2$ substrate from a pure Nb target in an Ar/N$_2$ gas-filled atmosphere. This yields to $T_c \approx 12 K$ with a transition width of 1 K (resistivity is around 1200 $\mu\Omega$ cm). Films were patterned using standard electron beam lithography to obtain multisegment structures in four-probe geometry. Microstrip length ranges from 2 $\mu$m to 12 $\mu$m. The etching process was performed by SF$_6$ reactive ion-etching. Each 160 nm-wide segment has a 100 nm-long 80 nm-wide constriction at its middle (see the inset of Fig.1).

![Figure 1. SEM image of NbN multisegments microstrip (segment length ranging from 2$\mu$m to 12$\mu$m). Each 160nm-wide segment has a 100nm-long 80nm-wide constriction (see the arrow). NbN superconducting leads enable four-contacts measurements.](image)

Electrical transport measurements were performed in a 4.2K cryostat with an exchange gas. Each segment was measured in a 4-contact arrangement using the nearest superconducting contacts to apply the bias and the following ones to measure the voltage. By doing so, spurious transition of adjacent segment is avoided. Magnetic field was applied using a 4T superconducting magnet in the direction perpendicular to the microstrip.

3. Results and discussion

Fig.2 shows current-voltage (IV) characteristics of a 4$\mu$m-long microstrip. These curves were obtained at 4.2K by sweeping up and down the dc current at different magnetic fields ranging from 0T to 2T. Superconducting state is preserved up to the critical current (e.g. around 37 $\mu$A at zero field) at which a voltage appears and gradually increases. Then each curve presents a sharp transition to normal state when their instability current $I^*$ is reached. By sweeping down the current, intermediate dissipative states are pointed out (a detailed description of the encircled area will be done at Fig.4). The retrapping current, at which the microstrip returns to the superconducting state, does not depend on the magnetic field (unlike the instability current). The temperature evolutions of these currents at zero magnetic field are showed in Fig.3.
Fig. 2 shows that current-induced flux flow always develops in the microstrip, even at zero magnetic field. According to the temperature dependence of the instability current (see Fig. 3), a simple self-heating effect as the origin of the instability can be excluded (as the hot-spot model is described by a $(1 - T/T_c)^{1/2}$ dependence). Retrapping current is however well described by this joule heating model. A hot-spot formation can thus be considered after the electronic instability takes place, leading to the current-biased transition to normal state (a similar behaviour has been observed on YBCO-nanobridges by Kamm et al. [15]).

Applying a dc voltage bias instead of a current bias allows us to avoid the abrupt transition to the normal state at the instability point. Instead this leads to the stabilisation of several dissipative states shown in the current-voltage characteristics of Fig. 4 for current ranging from 6µA to 20µA. Fig. 4 is associated with the previous 4µm-long microstrip (left) and with a 12µm-long microstrip (right). For temperatures lower than 11K, current rapidly decreases at low voltage as the instability current is reached (as shown by the left-directed arrows). Several reproducible S-shaped current oscillations are observed when the voltage is raised up (grey curve) and then decreased (black curve). Their number increases with the microstrip length. The same structure persists in a non-zero magnetic field with just a slight shift to lower current values.

Fig. 3. Temperature dependence of the instability (○) and the retrapping (●) currents for a 4µm-long microstrip.
The constriction was especially designed to localise the first dissipative phenomenon. As previously mentioned, the electronic instability that takes place at relatively high currents (around 45µA at 4.2K for the 4µm-long strip) seems to rapidly evolve in a hot-spot. The low-voltage features of Fig.4 might then be associated with the stabilisation of a hot-spot around the constriction, but this probably does not impact the low-current high-voltage reported behaviour. Since they will tend to coalesce, many stabilised hot-spots are however highly unlikely to explain the numerous resistive zones that develop in the strip as the voltage is raised up. Another dissipative mechanism should then be considered. As each S-shaped current oscillation is associated with a particular resistive state, the formation of vortex channels could be proposed to explain the observed behaviour.

4. Conclusion

Electrical transport measurements on NbN microstrips with a constriction are reported for different temperatures and transverse magnetic fields. Current bias curves show evidences of flux flow instabilities, which rapidly evolve into a hot spot. That leads to the abrupt switch to the normal state. Moreover applying voltage points out several dissipative zones, which are characterised by S-shaped current oscillations. Vortex channelling is proposed to explain these features. To gather a more detailed understanding of the constriction impact, subsequent experiments are needed on segments with and without a constriction. These segments will be fabricated on the same sample to guarantee similar geometrical and structural properties.

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