Temperature- and field-dependence of critical currents in NbN microbridges

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Abstract. We report measurements of the critical current of nano- and micrometer-sized NbN bridges as a function of temperature and magnetic field. The bridges were fabricated from 4 to 10 nm thick, sputtered NbN films using standard photo- and e-beam lithography. The detailed temperature- and field-dependence is strongly influenced by the bridge width. We interpret our data taking into account geometrical edge barriers for vortex entry and conclude that sub-micrometer wide bridges remain free of vortices in zero-field and measured critical currents are the depairing currents. The situation is much more complex in micrometer-wide bridges. For certain conditions such bridges may even show non-monotonous dependence of the critical current on temperature. We develop a qualitative model that explains our main observations.

1. Introduction

Magnetic vortices in type-II superconductors have attracted a lot of interest from both theoreticians as well as experimentalists ever since the seminal work by A. Abrikosov 50 years ago [1]. Whereas their behaviour in bulk and extended two-dimensional superconductors is quite well understood, many open questions remain to be answered in the case of meso- and microscopic superconducting structures. These issues also come into play in electronics and detector applications if the typical dimensions of the superconducting structures become of the order of the magnetic penetration depth \( \lambda \) and/or the superconducting coherence length \( \xi \). This is the case in superconducting single-photon detectors (SPD) and hot-electron bolometer (HEB) mixers, for example [2].

The central element of a HEB mixer is a rectangle a few micrometers wide and 200 - 300 nm long made from a few nanometer thick superconducting film. This rectangle is embedded into an antenna structure and biased with a current along the shorter edge. In these detectors the presence of vortices can significantly influence the intermediate frequency bandwidth [3, 4]. SPD, on the other hand, consist of an approximately 100 nm wide and several micrometer long superconducting meander. They achieve their best performance when they are biased with 90 to 95% of the depairing-critical current [5]. Basically, this requires them to be free of vortices, although the self-field of the biasing current certainly exceeds the bulk lower critical field \( H_{c1} \). Otherwise, the maximum dissipation-free bias current would be limited by the vortex depinning current, which is typically at least a factor of two smaller than the depairing current.
Very early on it was realized in the study of magnetic vortices in superconductors that vortices have to overcome an additional energy barrier for either vortex entry or exit [6]. This so called Bean-Livingstone barrier is a consequence of boundary conditions at the surface of a superconducting specimen. In small samples with dimensions approaching $\lambda$ the overall effect becomes hysteretic, thereby prohibiting the entry of magnetic vortices, but still allowing their exit from the sample [7].

In this paper we present systematic measurements of the critical current density as a function of temperature and field of few nanometer thin NbN bridges of varying widths $W$ and lengths $L \approx 10W$. We interpret our results as a consequence of a geometrically enhanced edge barrier for vortex entry and discuss the consequences for the design of small-scale superconducting devices, e.g. SPD and HEB light sensors.

2. Sample preparation and setup

The superconducting bridges were fabricated starting with NbN films deposited onto polished sapphire substrates by dc reactive magnetron sputtering of pure Nb targets. Base pressure in the sputtering chamber was of the order of $10^{-7}$ mbar. For deposition of the NbN films the substrates were heated to 750°C. A mixture of Ar and $N_2$ was used as sputtering gas at a total pressure of $\sim 5 \cdot 10^{-3}$ mbar. Based on predetermined deposition-rate data nominally $d = 4$ to 10 nm thick NbN films were deposited. The films were cooled to ambient temperatures before exposing them to air.

Using standard photo- and e-beam lithography the films were patterned into bridges of widths $W$ ranging from 100 nm to 10 $\mu$m. Etching was performed by ion-milling or reactive ion-etching. A 4-point resistivity measurement configuration was used, where the distance between the voltage contacts was $\sim 10$ times the bridge width. Layout and dimensions of the bridges were measured using electron microscopy and atomic force microscopy (AFM), compare inset of Fig. 1. With the AFM the film thickness could also be verified.

The measurements were performed in a Quantum Design Physical Properties Measurement System with a superconducting 9 T solenoid. To characterize the samples and determine essential parameters of the bridges resistance $vs.$ temperature curves were taken in zero-field and up to the maximum field. In zero-field the transitions into the superconducting state were smooth and sharp. Resistance data above $T_c$ could be well fitted taking into account contributions from fluctuation conductivity in two-dimensional films [8]. Such fits resulted in $T_c(0) \approx 14$ K with variations of about $\pm 0.1$ K from one bridge to the other. Taking $R_n/2$, with $R_n$ the normal-state resistance, as a criterion to determine $T_c(H)$ we found a linear relation between $H_{c2}$ and $T$. Linear extrapolation to zero temperature gives $\mu_0H_{c2}(0) \approx 25$ T. Taking into account deviations from a linear relation at low temperatures [9] we calculate a zero-temperature coherence length $\xi_0 \approx 4.3$ nm. Furthermore, using results of our resistivity measurements we are able to estimate the magnetic penetration depth $\lambda(0) \approx 250$ nm [10], very much in line with published data for NbN films [11, 12].

Critical currents were measured using the same setup. In the superconducting state a dc current was applied and increased linearly in equal steps until a predetermined voltage drop across the bridge was measured. The corresponding current value was taken as the critical current. Except for temperatures very close to $T_c$ the voltage rise was extremely sharp and determined critical-current values almost independent of the chosen voltage level. Typically, the voltage level was set to a value that was equivalent to a resistance $\sim 10^{-3}R_n$. The precision of the critical-current data is about 1%. As we will show below, even very small magnetic fields had distinct consequences on the value of the critical current. Therefore, we took great care to minimize the magnetic field for zero-field measurements. Nevertheless, the accuracy of the magnetic field was limited to the equivalent of about $\pm 100 \mu$T.
3. \( j_c(T, H) \) measurements

The dimensions of all of our bridges ensure a homogeneous current density. The effective penetration depth \( \lambda_{\text{eff}} = 2\lambda^2/d \) for thin films with \( d < \lambda \) is always larger than the bridge width. Moreover, we have to assume that the effective superconducting cross-section of our bridges is slightly smaller than the geometrical one. The etching process during fabrication usually causes some damage to the strip edges and the top and bottom layer of the film are structurally and chemically different from the inner parts of the film [13]. We estimate the maximum reduction in film thickness to be about 1 nm and 5-10 nm for the bridge width. On the other hand, the bridges are wide enough to allow for the existence of vortices [14]. Only if the width \( W < 4.4\xi(T) \) the occurrence of vortices inside a bridge is impossible. This limit is reached only very close to \( T_c \), especially for the micrometer wide bridges. Thus, if the absence of vortices is not excluded by another mechanism we have to expect to measure the vortex depinning-critical current density.

In Fig. 1 we present critical current densities of four bridges of different width. The data are plotted as a function of the reduced temperature \( t = T/T_c \) for comparison. Current densities were calculated using the geometrical cross-section of the bridges and a film thickness \( d = 8 \text{ nm} \). It is obvious that the temperature-dependence is very different for the narrow bridge with \( W < 1 \mu m \) compared to the micrometer wide bridges. Within Ginzburg-Landau (GL) theory one can calculate the expected temperature-dependence for the depairing-critical current density [15]

\[
    j_c(t) \propto (1 - t^2)^{3/2} (1 + t^2)^{1/2}.
\]

This temperature-dependence fits the experimental data of the 0.3 \( \mu m \) wide bridge very well (see solid line in Fig. 1). From a fit to the data we conclude a critical current density at zero temperature \( j_c(0) = 1.5 \cdot 10^7 \text{ A/cm}^2 \). All bridges wider than 1 \( \mu m \) show a qualitatively different behaviour that does not fit Eq. (1) over the whole temperature range. Close to \( T_c(0) \) the measured \( j_c \)-values are very similar to each other. However, below \( t \approx 0.8 \) to 0.7 the critical current densities in the micrometer-wide bridges appear to level off at approximately 0.5\( j_c(0) \) of the narrow bridges. This maximum current density in the wider bridges does not depend on the strip width.

4. Discussion

The data suggest that sub-micrometer wide bridges remain free of vortices, despite the self-field at the strip edges due to the applied current \( H_s \approx H_c \gg H_{cl} \). Assuming a rectangular cross-section one can calculate the maximum field at the strip edges for the 0.3 \( \mu m \) wide bridge to be
roughly 1.3 mT. We have to take into account the geometrical edge barrier for vortex entry in narrow superconducting strips, however. Recently, Stan et al. have shown [16] in experiments with externally applied fields, that the minimum field for vortex penetration $H_p$ can significantly exceed $H_{c1}$. These experiments suggested that for vortex entry the field has to be larger than

$$H_p = \frac{2\Phi_0}{\pi \mu_0 W^2} \ln \left( \frac{\alpha W}{\xi} \right),$$

(2)

with $\Phi_0 = h/2e$ the flux quantum and $\alpha$ a constant factor close to unity [17, 18]. Inserting the parameters of the 0.3 $\mu$m-bridge in Eq. (2) the magnetic flux density has to exceed $\approx 40$ mT for $t \leq 0.9$. Thus, we argue that such narrow NbN-bridges remain vortex free and the measured critical current is the depairing current.

We calculate the maximum fields at the strip edges of the micrometer-wide bridges also compute to approximately 1 mT. The penetration fields in those bridges, however, are now also of the order of mT or even smaller. For the following discussion we introduce three different current densities. The first one is the depairing-critical current density $j_0$ with a temperature-dependence according to Eq. (1), at which the momentum of Cooper-pairs reaches its maximum. A further increase of $j$ breaks the Cooper-pairs and destroys superconductivity. The next one is the depinning-critical current density $j_{\text{pin}}$ at which the Lorentz-force acting on vortices exceeds the pinning forces. It is always smaller than $j_0$. The third and last one is the penetration-critical current density $j_{\text{pen}}$, which is the current density that causes a self-field at the strip edge large enough for the penetration of vortices. This last current density is only logarithmically dependent on $t$ (Eq. (2)), thus varying much slower than $j_{\text{pin}}$ and $j_0$. We can then distinguish three different situations:

(i) $j_{\text{pen}} > j_0 > j_{\text{pin}}$: The strip remains vortex-free and the measured critical current density is $j_0$, the absolute maximum for a superconductor. This situation may be encountered at high temperatures just below $T_c(0)$.

(ii) $j_0 > j_{\text{pen}} > j_{\text{pin}}$: At the applied current $j = j_{\text{pen}}$ vortices enter the superconductor. Because $j > j_{\text{pin}}$ the vortices (and anti-vortices at the opposite edge) are never pinned, but immediately start moving across the strip. This leads to a resistive state and the experimentally determined critical current density is $j_{\text{pen}}$.

(iii) $j_0 > j_{\text{pin}} > j_{\text{pen}}$: Vortices enter the strip at an applied current $j < j_{\text{pin}}$, i.e. at first they are pinned at pinning centers near the strip edge. Further increase of current causes more and more vortices to enter the strip because of the increasing self-field. When $j \geq j_{\text{pin}}$ vortices become unpinned and the strip becomes resistive, with $j_{\text{pin}}$ the measured critical current density. Provided that $W$ is not too small, this situation may be realized at low temperatures.

Situations (i) and (iii) can be easily identified in Fig. 1. At high temperatures, for $0.8 < t < 1$, the critical current closely follows the temperature-dependence of Eq. 1 and those values correspond to $j_0$ even for the micrometer-wide bridges. For those wider bridges and below $t \approx 0.5$ critical currents are nearly constant and independent of their width and significantly lower than extrapolated depairing current densities. Pinning forces are independent of the strip width; their temperature variation depends on the details of the pinning mechanism [19], but at low fields and temperatures they should be nearly constant, i.e. situation (iii) is probably realized below $t = 0.5$.

It cannot be conclusively decided based on the available data whether we can identify the temperature range $0.5 \lesssim t \lesssim 0.8$ with situation (ii) or if it is simply a cross-over from (i) to (iii). We do not expect a very good quantitative agreement between the penetration fields calculated using Eq. (2) and the self-fields when the experimental data start to deviate from the
temperature-dependence of Eq. (1). Relation (2) was derived for equilibrium situations with no applied current, contrary to our case where we have strong currents. However, further evidence for our model comes from measurements of the critical current in weak external magnetic fields. In Fig. 2 we show $I_c(T)$-data for different external magnetic fields from nominally zero up to 5.3 mT. These measurements were made on the 4.9 µm wide bridge, and for comparison a fit of Eq. (1) to the high-temperature, zero-field data is also plotted (dashed line). At high temperatures the data at different fields are almost identical and can be described by the temperature-dependence of the depairing-critical current, i.e. situation (i). With increasing external fields the critical currents are reduced compared to the zero-field critical current at higher temperatures. This trend reflects that lower current-generated self-fields are needed for vortex-entry, as one might expect within our model.

Turning to the low-temperature data below $\approx 6$ K, the maximum critical current is only weakly field-dependent. While the critical currents at fields $B = 1.8$ and 2.5 mT still reach a plateau that can presumably be associated with $j_{\text{pin}}$, the 5.3 mT-data do not saturate at a well defined plateau anymore. The moderate increase of $j_c$ at low temperatures might reflect the temperature-dependence of $j_{\text{pen}}$. However, an improved model that is adapted to our particular experimental situation will be needed to draw more quantitative conclusions. Such a model should include both the effects of the high bias currents and of the externally applied fields.

The 1.8 and 2.5 mT-data show an astonishing effect at around 7 K. The critical current increases in certain bridges and in specific external magnetic fields by about 10% with increasing temperature (see Fig. 2). This effect is well reproducible. However, it could not be observed in all micrometer-wide bridges and was absent in bridges, for which the critical current followed the GL temperature-dependence. A satisfactory explanation of these steps in $j_c$ might require a model that even includes details of the pinning, edge roughness, and non-homogeneous vortex distribution.

In conclusion, we have presented critical-current data of nano- and micrometer wide NbN bridges as a function of temperature and magnetic field. The geometrical edge barrier is very efficient in prohibiting flux entry into sub-micrometer wide bridges. For those bridges the measured critical currents are most likely associated with the depairing of Cooper-pairs. This is of great importance for the operation of superconducting SPD where this situation has always been assumed to be realized, but, to our knowledge, has never been experimentally verified. In wider bridges competing effects of vortex exclusion and motion lead to a temperature-dependence of the critical current that is much richer in detail, showing even non-monotonic behaviour. Our results may also be of interest for other applications of small superconducting structures where either the exclusion of vortices or maximized critical currents are desirable.

Figure 2. Critical current $I_c$ versus temperature $T$ of a 4.9 µm wide bridge in different applied magnetic fields. For comparison the temperature-dependence of the GL-critical current is also plotted (dashed line). The field-dependence can be explained with our qualitative model (see text). Note the non-monotonic features at around 7 K in fields of 1.8 and 2.5 mT.
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