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Current-induced critical state in NbN thin-film structures

K. Il'in[1*], M. Siegel[1], A. Engel[2], H. Bartolf[2], A. Schilling[2], A. Semenov[3], H.-W. Huebers[3]

[1]Institute for Micro- and Nano-Electronic Systems, University of Karlsruhe, Hertzstrasse 16, 76187 Karlsruhe, Germany
[2]Physics Institute, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland
[3]DLR e.V. Institute of Planetary Research, Rutherfordstrasse 2, 12489 Berlin-Adlershof, Germany
**e-mail: k.ilin@ims.uni-karlsruhe.de*

The temperature dependence of the critical current of NbN thin-film bridges was experimentally studied. At low temperatures we observed significant enhancement (up to two times at 4 K) of the critical current density over depinning value in the sub-micrometer wide bridges. This enhancement can be described by an increase of the edge barrier for penetration of magnetic vortices into narrow superconducting strips.
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1. INTRODUCTION

In numerous electronic applications of superconductivity, a combination of narrow strips made from thin superconducting films is the most frequently used device layout. A typical operation regime, e.g. for superconducting radiation sensors working in the absence of an external magnetic field, is when the device is biased by the direct current that often has a value very close to the critical current value. The development of ultra-sensitive superconductive detectors and mixers, whose response is based on radiation induced heating of electrons, requires ultra-thin superconducting films that would allow one to reach the ultimate response-speed of these devices. The most popular material for detector applications are films from niobium nitride with thicknesses of approximately 5 nm. The superconducting transition temperature T_C of these films, as compared to T_C^0 of bulk NbN, drops by almost 50 % and amounts to ≈ 10 K. This sets the liquid-helium operation temperature of modern detectors, e.g. superconducting single-photon detector (SSPD) and hot-electron bolometer (HEB) mixer close to $0.5\,T_C$. However, detection mechanism in these devices and subsequently requirements for the superconducting structures differ significantly.

The response mechanism of SSPD, which usually represents a narrow superconducting strip with the width $W \leq 100$ nm, is the current assisted formation of a normal-conducting hot spot after absorption of an energy quantum. Detector performance improves significantly if the bias current approaches the critical value I_C. Homogeneous distribution of the supercurrent over the strip cross-section suits best for device operation and can be achieved in the absence of magnetic vortices already for $W << \lambda$, where λ is the magnetic field penetration depth. Since a magnetic vortex can not enter the strip less than about five times the coherence length ξ in width, the uniform current density can be achieved in such strip even in an external magnetic field. Particularly, SSPD made from NbN should be narrower than at least 50 nm in order to absolutely exclude vortices. Since motion of vortices is one of possible sources of intrinsic noise of SSPD device this should further improve their performance[1].

Typical HEB mixer is a few micrometers wide and 200 - 300 nm long superconducting rectangle embedded into an antenna structure made from a thick normal-metal layer. Contrary to an SSPD, the HEB mixer is biased along the smaller side of the superconducting rectangle. The resistive state is reached by combining the bias current and the local oscillator (LO) power. Depending on the LO frequency, vortex motion can more or less significantly change an intermediate frequency bandwidth of the mixer[2,3]. Additionally the SSPD and HEB devices differ in the substrate material. Silicon substrates are mostly used for fabrication of HEB for THz frequency range, while SSPD devices are made from NbN films deposited on sapphire substrates.

In this paper we analyze the formation of the resistive state in the regime relevant to the above applications: dc biased superconducting strip in "zero" external magnetic field. We present experimental results obtained for NbN strips with different width and thickness.

2. RESULTS

The superconducting NbN films were deposited by dc reactive magnetron sputtering of pure Nb target in the gas mixture of Ar and N_2 with total pressure $\approx 5*10^{-3}$ mbar. The films were deposited onto Si and Al_2O_3 substrates kept at 750°C during deposition. The thickness d of the films was varied in the range from ≈ 4 up to 10 nm. Single-bridge structures in four-probe configuration were made by standard photo- and electron-beam lithography and ion milling or reactive ion etching technique. For each film thickness the width of bridges was varied from ≈ 100 nm up to 9 µm. The actual width of each bridge was measured after patterning by SEM imaging.

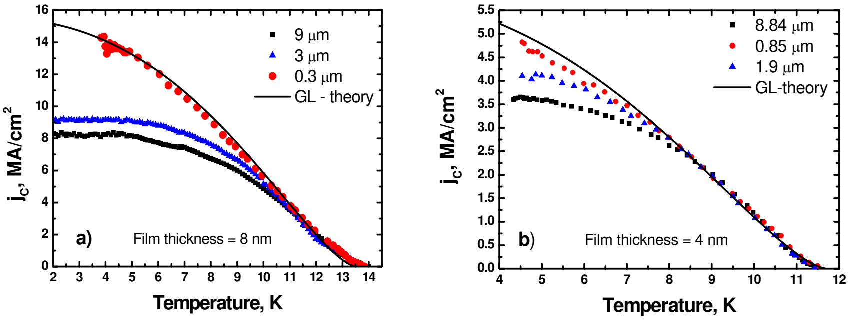

Fig. 1. (Color on-line) Temperature dependencies of the critical current density in NbN bridges on sapphire. Thickness and width of bridges are indicated on the graphs. Solid line is the temperature dependence of the de-pairing critical current density according to Ginzburg-Landau theory Eq. (1).

Measurements of current-voltage characteristics were made in current-bias mode and in the temperature range from 2 K up to T_C of the particular bridge. The critical current value I_C was defined as the current corresponding to the full switching of the structure from the superconducting to the resistive state. Current-voltage characteristics of all of our bridges were hysteretic except at temperatures very close to T_C.

The critical current density $j_C(T)$ was estimated as $I_C(T)/Wd$. The temperature dependence of j_C in NbN bridges on sapphire is shown in Fig. 1a and Fig. 1b for bridges made from 8 nm and 4 nm thick film, respectively. For all bridges $j_C(T)$ curves coincide at high temperatures in the range from T_C down to either ≈ 11 K or ≈ 8.5 K for thick and for thin film, respectively. At lower temperatures the $j_C(T)$ curves depart from each other showing different behavior. The bridges with a width of several micrometers show saturation of j_C at temperature below $T \approx 6$ K. In contrast, the sub-micrometer wide bridges demonstrate monotonic increase of j_C down to the lowest measured temperatures. The solid lines in Fig. 1 are the temperature dependence of the de-pairing critical current j_{pair} predicted by the Ginzburg-Landau (GL) theory[4]:

$$\frac{I_C(t)}{Wd} = j_C^0\left(1-t^2\right)^{3/2}\left(1+t^2\right)^{1/2}, \tag{1}$$

where $t=T/T_C$ and $j_C{}^0$ is the density of the de-pairing critical current at zero temperature. The experimentally measured $j_C(T)$ of the narrowest bridges follow the theoretical prediction over the complete temperature range.

The situation with NbN bridges on Si is somewhat different from that one with the NbN bridges on sapphire. For NbN bridges on Si, the $j_C(T)$ dependencies are similar to each other in a wide temperature range (see Fig. 2). Only at temperatures below $0.5\,T_C$ we obtained different dependencies for bridges with different width. The widest bridge with $W = 9$ µm shows the weakest dependence on temperature at $T \approx 0.4 - 0.5\ T_C$, while in the same temperature range the $j_C(T)$ dependencies for 2 µm and 0.6 µm wide bridges are a bit steeper.

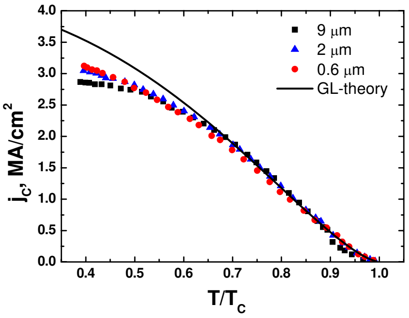

Fig. 2. (Color on-line) Temperature dependence of the critical current density in NbN bridges made from the 10 nm thick film on Si. The width is indicated in the graph. Solid line is the temperature dependence of the de-pairing critical current density according to Ginzburg-Landau theory Eq. (1).

3. DISCUSSION

There are two mechanisms of generation of the critical state in current carrying type II superconductors. The ultimate limit of the critical current value is the value of current, at which the velocity of the Cooper pairs becomes too high to carry any additional current without dissipation – the so called de-pairing critical current. The second mechanism is de-pinning of the magnetic vortices, when the Lorenz force acting on them exceeds the pinning forces. As it has been shown by Likharev[5], to reach the value of the de-pairing current the width of the superconducting strip has to be smaller than the effective magnetic penetration depth $\lambda_{eff}(T) = 2\lambda^2/d$ (for films with thickness $d < \lambda$) and smaller than $4.4\ \xi(T)$ ("Likharev's limit"). If the size of the structure is larger than "Likharev's limit" there is a possibility for penetration of magnetic vortices into the strip and their de-pinning once a large enough current has been applied. In NbN films with $d < 10$ nm, the value of $\xi(0)$ is not larger than 10 nm and the width of all our bridges exceeds the “Likharev’s limit”. The reported values of $\lambda(0)$ in NbN thin films are several hundred nanometers. Therefore all our bridges fulfill the first condition $W < \lambda_{eff}$. Therefore, we can assume as a first approximation a homogeneous distribution of the super-current over the cross-section of our bridges in the whole temperature range of the measurements.

The reason for penetration of the magnetic vortices into the bridges in the absence of an external magnetic field is the transport current j_{tr} applied along the superconducting strip. To get vortices penetrating into the strip, the magnetic field created by the transport current at the edges should exceed the critical value. In case of very wide bridges, this critical field is equal to the first critical magnetic field H_{C1}, which is inversely proportional to the value of $\lambda(T)$. Although H_{C1} is very small in NbN thin films, it remains larger than the Earth magnetic field.

In the case of a narrow bridge, the edge barrier for the vortex entry, which was first considered by Bean and Livingston[6], has to be taken into account. Following this model and recent works[7,8] on vortex dynamics, the density of the transport current required for penetration of magnetic vortices into a superconducting strip of the width W can be written as

$$j_{pen} = \frac{2\Phi_0}{\mu_0 W^2 \sqrt{dW}} \ln\left(\frac{2W}{\pi\xi}\right), \qquad (2)$$

where Φ_0 is the flux quantum and μ_0 is the magnetic permeability of free space.

To explain the observed experimental $j_c(T)$ dependencies for bridges with different width, we consider a three-currents model. We assume that for a given film of thickness d the values of de-pairing and de-pinning current, $j_{pair} > j_{pin}$, are independent of W and are exclusively determined by material and structural properties of the film. The third current is the vortex penetration current j_{pen}, which increases with the decrease of W (see Eq. (2)). For very wide bridges made from a thin NbN film the j_{pen} value is smaller than j_{pin}. In this situation the increase of j_{tr} first results in the penetration of magnetic vortices into the strip. Further increase of j_{tr} causes an increasing vortex density. When j_{tr} reaches the de-pinning current value the movement of vortices results in the switching of the bridge into the resistive state.

If the width of the bridge is smaller than the width W_1, which is defined by the condition $j_{pen} = j_{pin}$, the de-pinning current will not be the critical current value any more. In this situation the critical state will be generated at $j_{tr} = j_{pen}$, when the vortices penetrate into the bridge and immediately start to move since the Lorentz force is already larger then the pinning force.

Further decrease of W till the width W_2, at which $j_{pen} = j_{pair}$, results in the increase of the j_{pen} value according to Eq. (2) and correspondingly in the increase of the experimentally measured j_C. If $W < W_2$, the density of the current that is sufficient for vortex penetration exceeds the j_{pair} value. Hence the former is the absolute limit for the non-dissipating current-carrying ability of a superconducting bridge. In ideal bridges with $W < W_2$ the critical current density is $j_C = j_{pair}$ and is independent of W.

It is seen that in this model j_C with a value very close to the j_{pair} value can be achieved even in bridges, which are far from the "Likharev's limit". Nevertheless, the mechanism responsible for generation of the critical state in the bridges with $W > W_2$ is the de-pinning of the magnetic vortices.

In this work we consider superconducting bridges with width smaller than λ_{eff} but much larger than ξ. For the bridges with $W > \lambda_{eff}$ the non-homogeneous distribution of the super-current over the cross-section of the strip has to be taken into account. In the narrowest bridges the particular edge quality, e.g. shape, roughness, degree of damaging by fabrication process and width of oxidation resulting in suppression of superconductivity[9], are all comparable to the coherence length and play a significant role in defining the current carrying ability of the nanometer sized structures of ultra-thin superconducting films. The case of ultra-narrow superconducting strips is actual for analyzing the response mechanism of SSPD. On the other hand, in the micrometer wide thin-film structures the vortex penetration, movement and interaction with incident radiation are the phenomena important for the development of HEB mixers.

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