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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Injection–detection experiments to study quasiparticle losses in Nb, using a series array of Nb/Al junctions

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Abstract

Injection–detection experiments have been performed to study quasiparticle diffusion and quasiparticle losses in Nb strips using a series array of Nb/Al junctions. The *I–V* curve of the detector junction was measured as a function of the spacing between the (high-quality) detector junction and the simultaneously biased injector junction. For our sample geometry, the quasiparticle gas is described in terms of a one-dimensional diffusion model. It was found that trapping losses at the interface between the Nb base electrode and the anodised Nb_2O_5 dominate. In addition, a very low quasiparticle diffusion constant at 1 K, $D = 1.2 \times 10^{-4}$ m^2/s has been found. We estimate that this corresponds to an electron mean free path of $l \approx 7$ nm. Due to the difference between the bandgaps of the base and top electrode and to the peak in the density of states at the gap edge, the excess detector current shows a characteristic voltage dependence for bias voltages below 0.5 mV.

1. Introduction

X-ray detectors based on superconducting tunnel junctions are often operated with a superconductor as the absorber of the X-rays or other high-energetic particles. In order to be able to obtain a high energy resolution, it is necessary to first map out the quasiparticle diffusion and loss processes. The morphology of the film, in our case Nb, mainly determines the diffusion constant, whereas the quasiparticle losses are due to recombination and trapping. For Nb at very low temperatures, typically below 2 K, recombination is utterly negligible against quasiparticle trapping. Due to the very fast scattering rates in Nb [1], the latter process becomes very fast. A quasiparticle is trapped by energy relaxation under phenon emission in a region of lower bandgap. This usually happens at the boundaries of the absorber, where the superconducting bandgap is suppressed.

A population of excess quasiparticles, which is to be detected with a superconducting tunnel junction, can be created in a superconductor by means of high-energy particles, e.g. X-ray photons, by an electron beam, or by direct injection of quasiparticles with another tunnel junction. In this paper we describe results obtained with the latter method. Our main experimental goal was to quantify the quasiparticle trapping losses and to identify the regions where these quasiparticle trapping losses take place in our device. A recent injection–detection experiment was also motivated by the pursuit of superconducting tunnel junctions to be applied as particle detectors [2]. In contrast to that experimental study, we use a series array of tunnel junction on one superconducting strip, rather than a set of two functions. This configuration enables us to probe the quasiparticle density at multiple distances from the point of injection.

After a short outline of the experimental details and the one-dimensional quasiparticle diffusion model the results on the quasiparticle transport will be discussed.

2. Sample fabrication and experimental details

On an oxidised silicon wafer, layers of Al (5 nm), Nb (300 nm), and Al (5 nm) were deposited, followed by thermal oxidation at 10 mbar for one hour to form the barrier. Then 5 nm of Al and 200 nm of Nb finished the trilayer, which was structured with the lift-off technique. Subsequently, the trilayer was reactive ion etched down to the lower Nb layer, with the exception of rectangular patches of $L = 8.2$ μm by $W = 17.8$ μm, in order to structure the junctions. Fig. 1 shows the top view of the device. The horizontally shown strip has a width $W_s = 30.4$ μm, and a height $d_s = 300$ nm. The brighter lines, shown vertically, form the wiring to the junctions, deposited in the final step. Except for the window contracts, which can be seen as the "holes" on the strip (smaller than the junctions naturally), the strip has been anodised to prevent shorts between the wiring layer and the base electrode strip. Thus, the top side of the Nb base electrode is bounded by either Al/AlO$_x$/Al junction barrier, or by anodic Nb-oxide.

The procedure of the injection–detection experiments is

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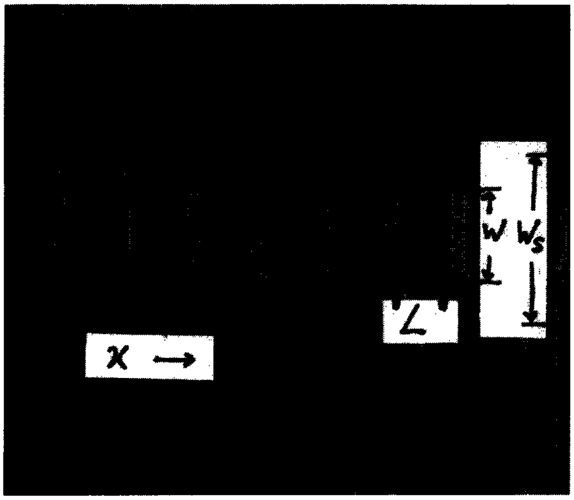

Fig. 1. Photograph of the top view of the prepared injection–detection device.

to measure the I–V curve of a junction, the detector junction, with and without another junction being biased at the injection current. From these curves, the excess detector I–V curve is calculated as a function of voltage by a subtraction off-line. An example is shown in Fig. 2.

3. One-dimensional quasiparticle diffusion model

For an injection current I_i at $x = 0$, density of quasiparticles per unit length n is governed by a one-dimensional diffusion equation, which is written as:

$$n_t \begin{cases} Dn_{xx} - \tau^{-1}n + \dfrac{I_i}{eL}, & |x| \le L/2\,, \\ Dn_{xx} - \tau^{-1}n\,, & |x| > L/2\,. \end{cases} \tag{1}$$

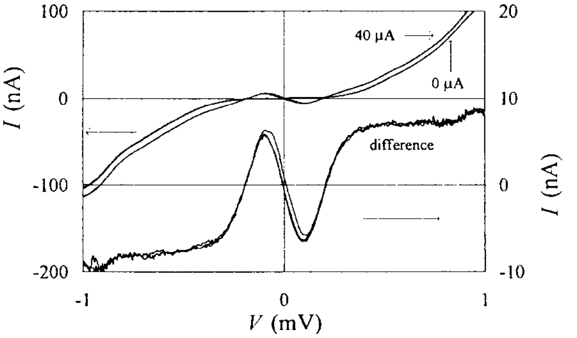

Fig. 2. I–V curves of the detector junction, with and without an injection current $I_i = 40\ \mu$A (upper curves), and the difference curve (lower curve), respectively. By using a bias circuit [3], the whole curve can be transversed. $T = 1$ K.

Herein, D is the diffusion constant and τ is the lifetime of quasiparticles against all loss processes. For $x > L/2$, n is a simple exponential function in x. In turn, n can be related to the detected excess current I_d, the junction normal state resistance R_N and the junction dimensions. For the excess detector current I_d, it can be shown that for $|x| > L/2$ [3]:

$$\frac{I_d}{I_i} = \frac{1}{4e^2 N_0 R_N W_s d_s L^2} D^{1/2} \tau^{3/2} [\mathrm{e}^{(D\tau)^{-1/2} L/2} - \mathrm{e}^{(D\tau)^{-1/2} L/2}]^2\, \mathrm{e}^{-(D\tau)^{-1/2}|x|}\,, \tag{2}$$

where N_0 is the normal state density of states of Nb for both spin directions. From Eq. (2) it is seen that by measuring the response I_d/I_i for more injector–detector separation values x, both D and τ can be determined independently. Eq. (2) is valid under the assumption of no quasiparticle multiplication, which occurs for injection at higher voltages. Otherwise a injector-voltage dependent factor must be incorporated. The one-dimensional approach also requires that the quasiparticles have distributed themselves evenly over the width W_s and the height d_s of the strip. For factors τ evaluated for strips with different geometries, it is even possible to distinguish the origin of the quasiparticle trapping losses [3].

4. Discussion of the results

The excess I–V curves for injection current values I_i = 20, 40, 60, 80, and 100 μA are shown in Fig. 3. The spacing x between the injector and the detector equals 12 μm. For somewhat larger bias voltages of the detector junction (>0.5 mV) the current is practically voltage-independent. To this regime Eq. (2) applies. A plot of the height of the plateau against the injection current shows a perfectly linear dependence. For higher values of the injection current, the injection junction is not anymore biased at the steep current rise at $eV_i = 2\Delta$, and quasiparticle multiplication comes into play. Applying Eq. (2)

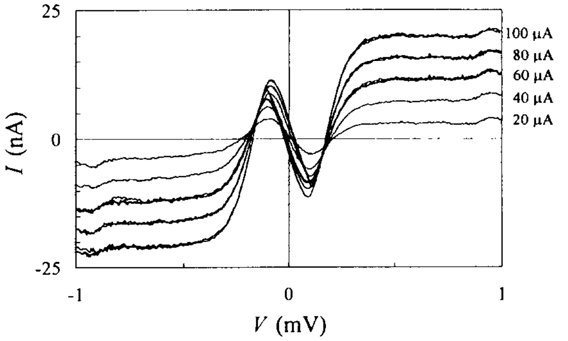

Fig. 3. I–V difference curves for I_i = 20, 40, 60, 80, and 100 μA. The injector–detector spacing is 12 μm. $T = 1$ K.

to the measured data, we have evaluated $D = 1.2 \times 10^{-4}\ \mathrm{m^2/s}$. It is assumed that the quasiparticle diffusion is limited by scattering at the boundaries of the single crystal grains or rather subgrains (see Ref. [4]) of which the polycrystalline Nb film consists. An electron mean free path of $l = 7$ nm has been estimated. This is well in agreement with the by TEM microscopy obtained size of the Nb single crystal grains [5] in our polycrystalline films. The established loss time is $\tau = 109$ ns. From the evaluation of samples with other geometries, we conclude that the losses are primarily due to quasiparticle trapping at the interface between the Nb base electrode and the anodised Nb, which is in accordance with previously found severe edge-effects in our SNAP-processed X-ray junctions [6]. Further we found that small magnetic fields, up to 30 mT, have little effect on the losses. Sample heating can be neglected for not excessively high injection currents.

For smaller bias voltages (<0.5 mV), a peculiar voltage dependence of the excess detector current is observed, in particular the sign-reversal at $V_d \approx 0.2$ mV, having an extremum at $V_d \approx 0.1$ mV. Due to the peak in the density of states near the gap edge, this is to be expected for an excess quasiparticle population in a base electrode that has a larger bandgap than the counter electron. The occurrence of negative excess currents for small bias voltages has been theoretically described in Ref. [7], for instance. Our experiment demonstrates the negative excess current and its dependence on the bias voltage in a very clear manner, although the absolute negative resistance due to excess quasiparticles has been previously demonstrated by Gershenzon and Falei [8]. A comparison of the voltage dependence of the excess current with theoretical curves, calculated for densities of states obtained from a microscopic proximity effect model [9], and incorporating the thermal quasiparticle distribution, has been calculated [3].

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