Superconducting and Dissipative Characteristics of Overdamped SNIS Josephson Junctions for Sensing Applications

SUPERCONDUCTING AND DISSIPATIVE CHARACTERISTICS OF OVERDAMPED SNIS JOSEPHSON JUNCTIONS FOR SENSING APPLICATIONS

Vincenzo Lacquaniti, Cristina Cassiago, Natascia De Leo, Matteo Fretto, Paolo Durandetto, Elena Zhitlukhina, and Mikhail Belogolovskii

Abstract

Josephson-junction devices such as suitably designed nanoSQUIDs can provide a sensing element for micro and nanoelectronics. In this paper, the properties of such device must be tailored in order to have an optimal response. In particular, it relates its temperature stability, and a comparatively weak dependence of the critical supercurrent Ic on temperature T in the working range. To realize it, a concave upward Ic-versus-T curve is required. The aim of this paper was to study conditions when such temperature dependence can be realized in four-layered S/N-I-S Josephson junctions, mantaining the overdamped behavior. We show how the shape of the Ic-versus-T dependence can provide important information about the strength of the S/N proximity coupling.

Index Terms

Overdamped Josephson junctions, S/N-I-S structures, proximity effect, critical current-vs-temperature characteristic.

I - INTRODUCTION

Nanoscience and quantum metrology are frequently raising issues for single particle detection and measurement topics, including quantum information processes, nanomagnetism and spintronics as well as new circuits for the next generation of quantum standards. In this context, the Josephson junctions-based devices employed both as generators and detectors of radiation represent a suitable technology.

One definite advantage of tunnel junctions with respect to other technologies, such as micro- and nano-constrictions, apart the reliability of the fabrication process and the device robustness, is their improved sensitivity. As an example, Josephson tunnel junctions-based nano-SQUIDs provide typically a high critical current modulation depth (more than 70%) [1], [2]. So, it is possible to design and fabricate SQUIDs with high voltage modulation and consequently high voltage responsivity and low noise. On the other hand, the use of cryocoolers for voltage standards of the new generation raises new specific requirements for the Josephson junction characteristics.

The conventional Josephson junction is formed by two superconductors (S) coupled by a weak link that can consist in a thin insulating (I) barrier, a short section of a normal (N) metal, or in a physical constriction able to weaken the superconductivity at the contact point. The operating temperature affects the corresponding electrical parameters. The evaluation and minimization of this dependence is very useful both for voltage standards operating in a cryocooler system and for nano-SQUIDs employable in relaxation measurements of magnetic nanoparticles as a function of the temperature, and in the study of macroscopic quantum tunneling or magnetization of single nanoparticles [3], [4].

It is well known as a standard S-I-S trilayer is strongly underdamped. It has been shown [5], [6] that current-voltage (*I-V*) characteristics of a four-layered S/N-I-S structure (S = Nb, N = Al, I = Al_2O_3) can be made non-hysteretic and well controllable at 4.2 K due to the presence of an additional N interlayer and an ultra-thin I barrier. The parameters we can change in this case are the thicknesses of the S, I, and N layers and also the transparency of the S/N interface. In our previous experiments [5], [6] we used Nb films with a thickness (d_S) exceeding the superconducting coherence length and hence without any size effects and I barriers with a transparence expected to be locally fluctuating and following an universal distribution [7]. A single governing parameter that could be modified and substantially can affect the superconducting characteristic of the four-layered Josephson device is the thickness of the Al interlayer d_N. The physical mechanism behind it is the proximity effect, a mutual induction of physical properties from a superconductor into an adjacent N film (and *viceversa*) across the S/N interface [8].

A recent paper [9] attempted to bridge a gap between the two seemingly distinct proximity-phenomenon models in the N part of the S/N bilayer, introducing a nonzero pairing amplitude induced by Andreev-reflection events but without a superconducting gap and the opening of the gap due to the tunneling of Cooper pairs by considering the evolution of the induced superconducting gap with increasing d_N. The authors of [9] have shown that, besides the bulk gap value Δ_S, in the clean N layer there is a competing energy scale $\hbar^2/m_N d_N^2$ (m_N is the related effective mass of an electron). Due to it, a certain crossover thickness $d_c = \sqrt{\xi_S \lambda_F}$ (ξ_S

is the superconducting coherence length and λ_F is the Fermi wavelength in the N metal) appears in the problem that determines a scale of the excitation gap Δ_N in the normal part of the bilayer.

Note that the discussion above is related to a clean N film. In the dirty (diffusive) limit when electrons experience a huge number of elastic scatterings on impurities during the way from one surface to another, the size limiting the phase coherence length for electron-like and hole-like quasiparticles traversing a diffusive trajectory is the elastic mean free path $l_e = \sqrt{D\tau_e}$, here D is the diffusion constant in the normal metal, and τ_e is the elastic scattering time. If so, then for the motion of a quasiparticle across a dirty N layer we get the average time $\tau_e \sim d^2_N/D$. Using this value we can estimate the disorder-induced minigap Δ in the diffusive limit that is expected to be approximately $\overline{\Delta} \approx \hbar D/d^2_N$, see also [10].

Thus in both (clean and dirty) limits the energy gap should be induced in the N interlayer. In the following, we show that its presence as well as the size can be known by analyzing the temperature dependence of the critical current I_c in Josephson S/N-I-S samples. These measurements can be regarded as a noninvasive technique, which can provide important information concerning the quality of the Sand N layers and their interface in S/N-I-S devices with a comparatively thick N interlayer (about 100 nm). From a practical point of view, it is a way for designing Josephson junctions with improved temperature stability, i.e., reduced supercurrent sensitivity to temperature fluctuations. Such a property can be described by an absolute value of the normalized temperature derivative $|d(I_c(T)/I_c(0))/d(T/T_c)|$ [5].

Smaller values of this parameter imply superconducting currents less sensitive to thermal variations. The junctions discussed are expected to be used nearly and above 4.2 K, where they become non hysteretic [5]. Thus, concave upward I_c-vs-T curves at 4.2 K are required. Below we discuss how it can be achieved in the S/N-I-S devices. Our experimental results are analyzed within two models assuming totally different approaches to the proximity-effect problem; one considering the presence of the superconducting order parameter within the N layer [5], [11] and the other postulating its absence.

The paper is organized as follows. The sample preparation and the experimental setups are described in Section II. Section III compares two theoretical models mentioned above. In Section IV we discuss their relation to experimental I_c-vs-T data and Section V provides a conclusion.

II - EXPERIMENTAL

In this section we present data related to our overdamped Nb/Al-AlO_x–Nb Josephson devices with a fixed nominal thickness d_{Al} 120 nm of the Al interlayer. The thickness of Nb films was between 120 and 150 nm, the oxidation exposure, oxidation time per oxygen pressure, varied between 200 and 400 Pa • s. Two different deposition systems were used to realize the multilayer structure of the devices, a RF magnetron sputtering and a DC high vacuum sputtering. The base pressure of the systems was respectively 10^{-5} Pa and 10^{-7} Pa, while the sputtering power density during the Al deposition was 5.5 W/cm^2 and 7.6 W/cm^2, respectively. In both processes we used a cooling time of 15 minutes among the deposition of different layers and before oxidation.

In the S/N-I-S fabrication process the thick Al-layer sputtering deposition is critical due to the high rate of the film growth (>1, 3 nm/s). The RF process parameters coincided with those used in our previous papers [5], [6]. As was found in [5] (in agreement with the paper [12]) the transparency of the Nb/Al bilayers was mainly depending on the thickness d_N. The DC process used in this work probably induces a significant amount of roughness and the interdiffusion at the S/N interface due to the power density of the deposition process and the higher temperature reached (>200 °C). It is clear that the quality of the Nb/Al interface that strongly depends on the fabrication step and the interdiffusion of the two metals can change the junction properties. Here we refer to the paper [13] where the authors studied the influence of the interfacial roughness on the proximity effect in superconductor/ferromagnet (S/F) Nb/$Cu_{60}Ni_{40}$ bilayers. They found that the roughness factor induced by deposition on different substrates influences only the magnitude of the superconducting critical temperature T_c and does not affect the oscillating character of the T_c-vs-d_F (d_F is the thickness of the ferromagnetic layer) dependence, see Fig. 5 in the paper [13]. Note that such oscillations appear for highly transparent S/F interfaces. It means that the Cooper-pair transparency of the S/F interfaces (at least, in the Nb/$Cu_{60}Ni_{40}$ samples) is not noticeably affected by the interfacial roughness. It should be stressed that such a conclusion can be comparatively easily derived when one of the layers in the superconductor/normal-metal hybrid is ferromagnetic. The aim of our paper is to propose such a method for bilayers with a non-magnetic N layer.

Low-temperature measurements of the I-V curves have been carried out using a technique described in our previous papers, e.g., [5]. The samples were placed inside an insert of a He^3 cryostat with a static superconductive magnet whose field could be varied from 0 to 10 T. The temperature was increased from 1.5 K up to the superconductor-to-normal state, which ranged for our samples between 7 and 9 K. The DC and RF samples showed small differences in the electrical parameters at liquid helium temperature, J_c varied from 10 to 70 kA/cm^2 and R_N from 100 to 500 m Ohm, while junctions' dimensions were 16 and 25 μm^2.

III - MODELING

We discuss two theoretical models able to explain an effect of the S/N interface properties on the supercurrent-vs-temperature characteristics.

Our previous theoretical approach, named further the model *a*, that was developed in [5] is based on a model by Kupriyanov *et al.* [14] that describes stationary properties of double barrier S-I_1-S'-I_2-S junctions with arbitrary resistances of I_1 and I_2 interlayers which were identified in our case as the Nb/Al interface and the insulating AlO_x layer. The dirty-limit theory [14], which assumes the induced gap in the normal side of the S/N bilayer, contains two length-scale parameters for the Al interlayer, the electronic mean free path l_{Al} and the coherence length ξ_{Al}. A systematic study [12] of thin free Al films showed that l_{Al} is mainly controlled by charge scattering at their boundaries. Thus, in the multilayered structures l_{Al} would be further reduced due to the surface roughness caused by interdiffusion of several nm between Nb and Al layers [15]. Using an approximate formula (3) from [12] for the thickness dependence of the coherence length ξ_{Al}, we find that ξ_{Al} 150 nm in the free Al films of the thickness of 120 nm. Thus we are dealing with the inequality $d_{Al} < \xi_{Al}$ and hence with comparatively homogeneous (from the superconducting point of view) Al layers. In this case, a single fitting parameter is sufficient to compare model simulations to experimental I_c–vs–T is $\gamma_{eff} \approx \gamma_{\mathrm{Nb/Al}} d_{\mathrm{Al}} \sqrt{T_c^{\mathrm{Nb}}/T_c^{\mathrm{Al}}}/\xi_{\mathrm{Al}}$ where $\gamma_{Nb/Al}$ is the reduced Nb/Al interface resistance that for the bilayers fabricated in [12] followed a phenomenological relation $\gamma_{Nb/Al}(d_{Al}) = 0.111 d_{Al}$ (d_{Al} being in nm), T_c^{Nb} and T_c^{Al} are related critical temperatures.

From the results of [13] it follows that in the case of S/N rough interfaces, superconducting correlations could penetrate a relatively small depth into a non-superconducting layer. At the same time, despite the roughness, the S/N interface transparency is enough to have an essential impact of Andreev quasi electron-into-quasi hole (and *vice versa*) back scatterings [13]. It means that we are dealing with an abrupt S/N interface and it is just the case of the second model [16] which assumes that the Al interlayer is non-superconducting and the main proximity induced changes originate from the Andreev reflections at the interface between S and N films [8]. Of course, such approach named below model *b* is not limited by the rough N/S interfaces and can be applied to a wider range of samples as shown in [16]. Within the model *b* there is another governing parameter $\alpha = 2d_{\mathrm{Al}}\Delta_{\mathrm{Nb}}/(\hbar v_{\mathrm{Al}})$ where v_{Al} is the Fermi velocity in the Al interlayer, Δ_{Nb} is the energy gap in the S film. The α value controls the position of Andreev bound states $E_n(\phi)$ (ϕ is the phase difference between the two Nb electrodes) which are formed within the energy gap in the Al interlayer. The estimates for our samples show that it is less than unity and we may use a standard relation connecting the supercurrent $I(\phi)$ with the Andreev levels energies $E_n(\phi)$ measured with respect to the chemical potential and the Fermi-Dirac distribution function f_n (T): $I(\varphi) = \frac{2e}{\hbar} \sum_n \frac{dE_n(\varphi)}{d\varphi} f_n(T)$. Here n denotes a transverse channel and a state within the channel.

In Fig. 1 we compare results of related numerical simulations within the two models. We can see that with decreasing the barrier transmission D_I the temperature dependence of the critical current in the model *b* very quickly approaches to the behavior predicted by [17] for tunnel junctions whereas in the model *a* the shape of the related curve various considerably and continuously with increasing the Al-interlayer thickness.

IV - DISCUSSION

In this section we would like to turn attention to the shape of the I_c-vs-T dependence that can provide significant information concerning the conducting state of the Al film and that of the Nb/Al interface.

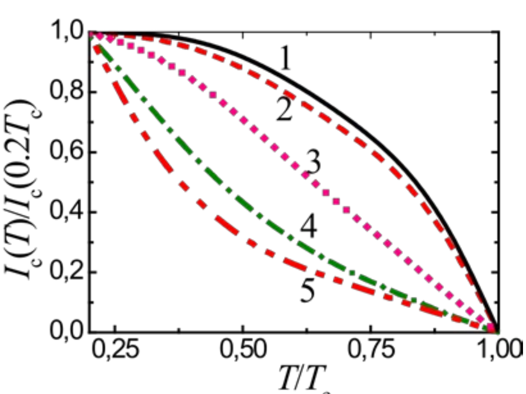

Fig. 1. I_c-vs-T curve simulations for a standard SIS junction [15] (curve 1); an S/N-I-S device with a non-superconducting and thick (d_{Al} = 120 nm) Al interlayer and an I barrier with the transparency D_I = 0.1, the model *b* (curve 2), and S/N-I-S heterostructures with a non-zero superconducting order parameter in the Al interlayer, the model *a* (d_{Al} = 60, 120, 200 nm for curves 3, 4, and 5, respectively).

Let us discuss both models qualitatively. A free Al film is superconducting up to T_c^{Al}= 1–2 K and the temperature dependence of the supercurrent in an Al-I-Nb trilayer would be that of the standard Ambegaokar-Baratoff [17] shape with I_c = 0 at $T = T_c^{Al}$. But in proximity with a Nb layer, superconductivity in Al will survive till T_c^{Nb} about 9 K. That is why at T 0.5 T_c^{Nb} the curve becomes flatter and extends up to T T_c^{Nb}. The resulting I_c-vs-T curve will be concave upward (Fig. 1, curves 3–5). Within the model *b*, we have Nb-weak link-Nb junction where the weak link consists of an ultra-thin insulating barrier and a normal Al film. It represents an intermediate case between Ambegaokar-Baratoff [17] and Kulik-Omelyanchuk [18] limiting solutions. The resulting I_c-vs-T curve will be concave downward (Fig. 1, curve 2).

All I_c-vs-T dependencies for the measured Nb/Al-Al oxide-Nb devices have been concave upward (representative data is shown in Fig. 2, squares) and well agreed with the results of the first approach (Fig. 2, solid line). This finding confirms the statement of [13] that even in the case of a rough S/N interface, its transparency remains comparatively high for Cooper pairs and that a minigap is induced in the Al interlayer.

This conclusion was obtained for a low-scale roughness of the S/N interface. We expect that with its increase the I_c-vs-T dependence can be modified since the electron mean free path l_{Al} will be limited by the d_{Al} value. Below we shall discuss how the model *b* will be modified in this case and what changes will be generated in dissipative characteristics of the four-layered tunnel S/N-I-S junctions. The feature to be discussed is a singularity appearing when the energies of the Andreev levels align by applying the external voltage bias V and consists of the current peak and a negative differential resistance region at voltages just above it. In our calculations performed for T 4.2 K we account for disorder by considering "generalized Bloch functions" with complex wavevectors k [19]. According to [19], imaginary components of k indicate evanescent decay in magnitude within the sample that was described by introducing the parameter $\beta = d\mathrm{Al}/l\mathrm{Al}$.

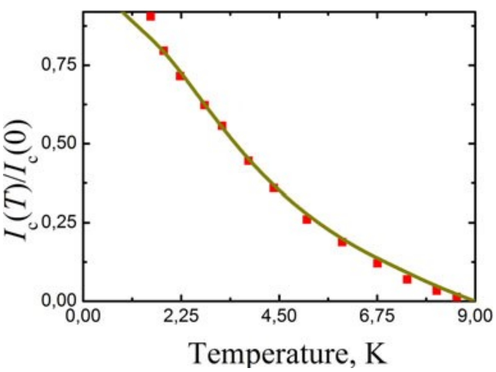

Fig. 2. Representative Ic-vs-T dependence for Nb/Al-Al oxide-Nb junctions with thick Al interlayers and ultra-thin Al-oxide barriers. Experimental data and results of numerical calculations within the model *a* are shown by squares and a solid line, respectively. In both cases the thickness $d_{Al} = 120$ nm.

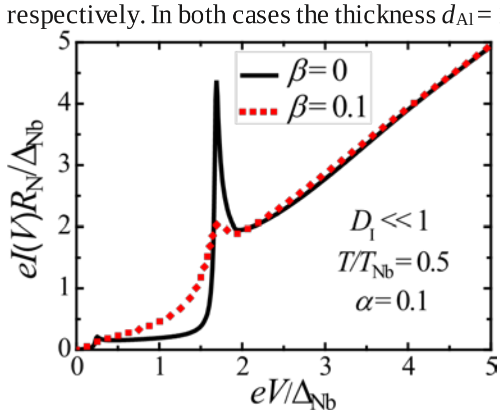

Fig. 3. Dissipative current-voltage characteristics of an S/N-I-S junction calculated within the model *b* in the tunneling regime (DI << 1), RN is its resistance in a normal state; the two curves show an effect of the electron mean free path in the N interlayer.

Related calculations have been done using a standard formula for tunneling current in an asymmetric S/N-I-S structure with a low transparent barrier $D_I \ll 1$. Scattering amplitudes were evaluated as a sequence of an infinite number of interface scattering events including Andreev electron-hole and hole-electron transformations at the S/N interface and the complex-valued phase shift acquired during an electron (hole) path from one edge of the N interlayer to the other [20]. For vanishing d_{Al}, we get a well-known singularity at $V = 2\Delta_{Nb}/e$ in the current voltage curve. With increasing d_{Al}, an Andreev- bound state is formed below this voltage bias due to the interference of electron and hole waves. It reveals itself as a peak followed by a pronounced dip (Fig. 3). As follows from Fig. 3 the discussed feature would be strongly smeared by disorder and hence its presence is the attribute of a comparatively clean N interlayer.

V - CONCLUSIONS

In this work, we have focused on Nb/Al based junctions with AlO_x barrier, the most reliable and most widely used materials for a complex and robust superconductive electronics.

A peculiar feature of this type of junctions, related to the presence of a thick (~100 nm) aluminum metallic layer, is a relatively smooth temperature dependence of the critical current I_c. We have discussed two possible models initiated by the proximity effect in the Nb/Al bilayer, the emergence of the induced energy gap in the dirty normal side of the S/N bilayer and the appearance of Andreev bound states in a clean N interlayer. It is shown that the main difference between them reveals itself in the shape of the temperature dependence of the supercurrent. The I_c-vs-T curves are concave upward in the first model and concave downward in the second one. Our experiments on overdamped Nb/Al-Al oxide-Nb devices have exhibited the first type of the superconducting characteristics and thus the presence of a minigap in the samples. These findings support the assertion of [13] obtained for superconductor/ferromagnet bilayers that the roughness factor does not radically affect the Cooper-pair transparency of the interface between a superconductor and a non-superconducting metal.

Finally, we argue that the measurements of the temperature effect on the critical supercurrent can serve as a good indicator of the quality of S/N interfaces in multilayered superconducting structures. To distinguish between the clean and dirty limits in the N interlayer, we propose another feature in S/N-I-S dissipative characteristics, a peak at voltage biases slightly lower the energy gap value followed by a pronounced dip that should reveal itself in comparatively clean N films and disappear in the dirty case. At last, we note that transport characteristics of superconducting junctions, in particular, temperature-induced changes (Fig. 1) strongly depend on the S/N boundary features. Unfortunately, direct experimental access to the interface is very challenging. The proposed approach to its characterization can extend our knowledge about the buried S/N interfaces in multilayered structures and will enable to design more effective Josephson nano-scaled devices with predetermined properties.

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