ELSEVIER
Nuclear Instruments and Methods in Physics Research A 444 (2000) 55–58
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.nl/locate/nima

Quasiparticle energy relaxation in superconducting tunnel junctions used as photon detectors

A. Poelaert[a], A. Golubov[b], A. Peacock[a], R. den Hartog[a,*], H. Rogalla[b]

[a]*Astrophysics Division of the European Space Agency, Noordwijk, ESTEC, Keplerlaan 1, 2200 AG, The Netherlands*
[b]*Low Temperature Group of the Faculty of Applied Physics, University of Twente, The Netherlands*

Abstract

We exploit the results of recent work (Poelaert, Ph.D. Thesis, University of Twente, 1999) showing that energetic quasiparticles in a superconductor relax to an energy, called *balance energy*, larger than the superconducting energy gap, despite of the large density of states available at the gap. This feature may have a major impact on the performance of superconducting tunnel junctions used as photon detectors. We show how the balance energy and the parameters for photon detection are sensitive to the superconducting proximity effect. In particular, we show that the balance energy also exists for non-proximized structures, obeying the BCS theory. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 85.25.Cp; 29.30.kv; 74.50. + r; 74.76.-w

1. Introduction

The energy of a photon absorbed in an electrode of a superconducting tunnel junction (STJ) is converted into a number of quasiparticles (QPs) proportional to the photon energy. QPs result from Cooper pair (CP) breaking in one of the superconducting electrodes of the STJ. They are excited states governed by the physics of free electrons in a superconductor (i.e. electrons not bound in a CP), and are therefore associated with charge carriers.

Recent theoretical and experimental evidence indicates that initial energetic QPs do not relax down to the superconducting energy gap [1,2]. During the photon detection process, QPs stay at a higher energy, called *balance energy*. The balance energy arises from a trade-off between processes that decrease QP energy (relaxation with phonon emission) and those increasing QP energy (phonon absorption and tunneling). In order to estimate the balance energy, it is important to establish the various characteristic times involved in the photon detection process as a function of QP energy. In this paper, we use the results of Ref. [1] to show (1) how the characteristic times are sensitive to the superconducting proximity effect in multi-layered electrodes and (2) that a balance energy larger than the energy gap is present in any structure, proximized or not. We start the discussions from an existing Ta/Al proximized device.

2. Device characteristics

The device is a $20 \times 20\ \mu m^2$ Ta/Al STJ deposited on highly polished sapphire. One hundred nanometer of epitaxial Ta was first deposited onto the sapphire, followed by 55 nm of Al. A 1.5 nm

* Corresponding author. Fax: + 31-71-565-4690.
E-mail address: rdhartog @astro.estec.esa.nl (R. den Hartog).

PII: S0168-9002(99)01327-3

thick AlO_x barrier with a resistivity $\sim 4.2\ \mu\Omega\,cm^2$ follows. The polycrystalline top electrode is deposited onto the barrier. It consists of 55 nm of Al and 100 nm of Ta, separated by 4 nm of Nb. A gap $\Delta_g = 450\ \mu eV$ was measured.

3. Proximity effect parameters

The superconducting proximity effect is the effect of the mutual interaction between two or more superconducting layers in electrical contact. The model used to determine the properties of proximized structures is fully described in Ref. [3]. For each sub-layer S_i in the proximized structure, the so-called Usadel equations can be solved, with the proper boundary conditions at the layer interfaces.

The boundary conditions for a bilayer S_1–S_2 are generally expressed in terms of the proximity effect parameters γ and γ_B [4]. γ_B represents the transparency of the S_1–S_2 interface, whereas γ quantifies the respective impact of S_1 and S_2 on the entire bilayer.

Estimating γ and γ_B provides the density of states in a given proximized electrode. These parameters can be determined by comparing experimental and theoretical values for the critical current J_c and for the gap Δ_g. The experimental values can be found as a function of temperature from the IV characteristics of the device. The theoretical gap can be extracted directly from the calculated density of states. The critical current has a direct analytic expression [3].

The results of such a fit for the device described in Section 2 is shown in Fig. 1. The best match has been found for $\gamma = 0.05$ and $\gamma_B = 3$. Typical examples of deviations of γ and γ_B are also shown (solid lines for γ and dashed lines for γ_B).

4. Characteristic times

The characteristic times of processes affecting the QP energy (and thereby determining the balance energy) are the tunnel time τ_{tun}, the relaxation time τ_e and the phonon absorption time τ_a. The expression for these quantities can be found in Ref. [5] in the frame of the BCS theory and in Refs. [1,3] for the general case considered in this paper. Numerical calculations, corresponding to the theoretical curves of Fig. 1, are shown in Figs. 2 (τ_{tun}), 3 (τ_e) and 4 (τ_a). All quantities are calculated for the whole proximized structure. Any position dependence within a structure is removed by averaging over the density of states.

Clear statements can be made from Figs. 2–4, noting the role of γ and γ_B on the QP density of states. In principle, in Ta most of the states are above Δ_{Ta}. However, if γ is large, the properties of Ta and Al are more efficiently averaged within the electrode thickness. As a consequence there are more states below Δ_{Ta} in Ta and less in Al. In case of a transparent Al/Ta interface (small γ_B) the states in Ta are easily reachable for the states in Al.

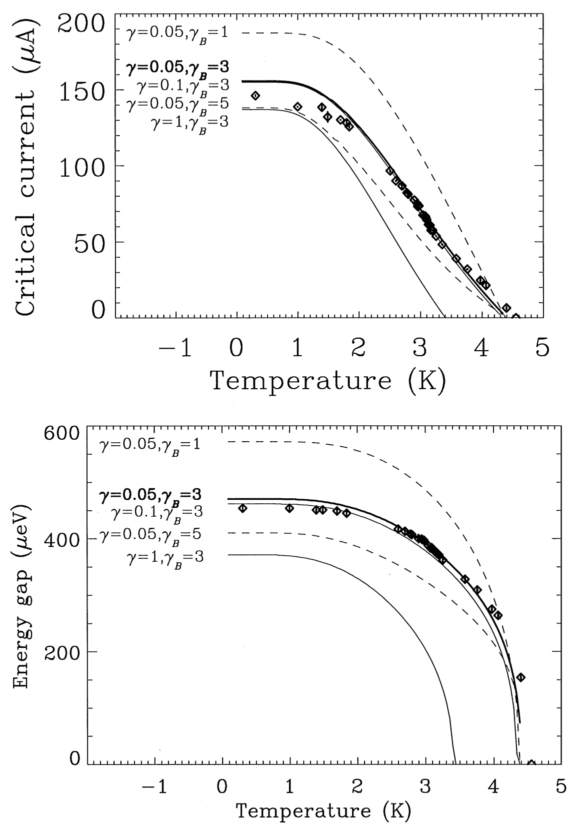

Fig. 1. Critical current (top) and energy gap (bottom) as a function of temperature: experimental data (diamonds) and theoretical curves.

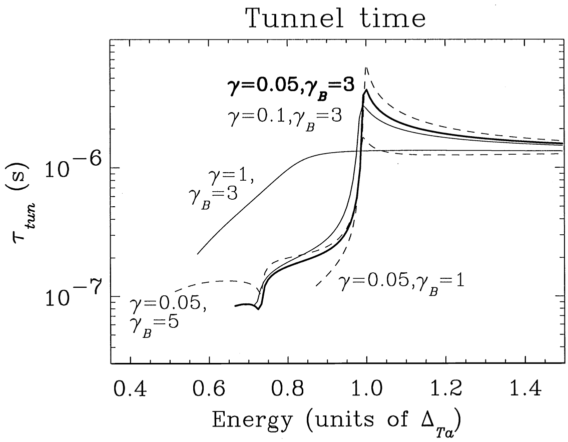

Fig. 2. Tunnel time as a function of QP energy for different values of γ and γ_B.

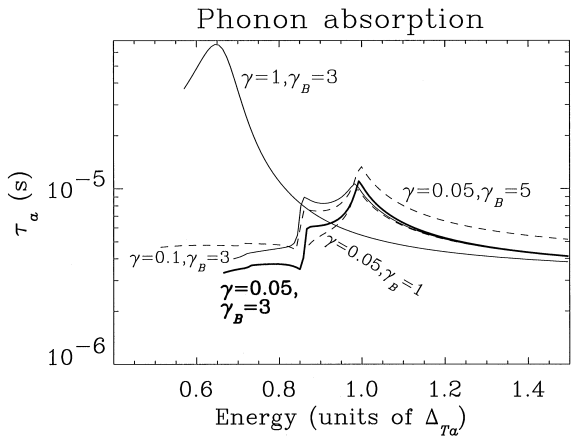

Fig. 4. Phonon absorption time as a function of QP energy for different values of γ and γ_B.

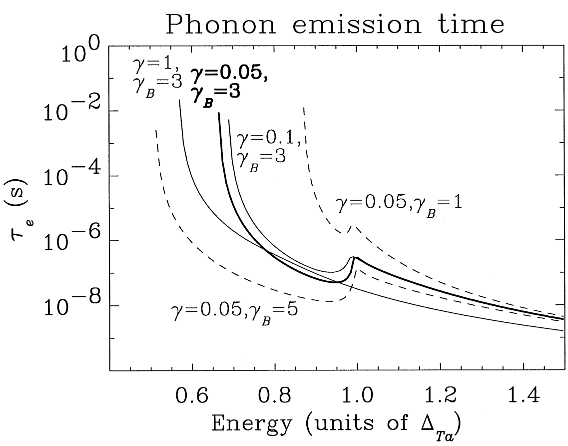

Fig. 3. Phonon emission time as a function of QP energy for different values of γ and γ_B.

In terms of tunneling (Fig. 2), in the case of large γ, these facts translate in a lower tunneling probability below Δ_{Ta}, since such low-energy states are also present in Ta. It is however easier to tunnel from states above Δ_{Ta}. In the case of small γ_B, it is now easier for QPs in Ta to 'feel' the presence of the barrier and tunneling is faster.

Relaxation (Fig. 3) is easier if all low-energy states are within reach of energetic quasiparticles. In principle, this is the case when γ is large (whatever the transparency, there are low-energy states available) and/or γ_B is small. The effect is clearly visible for large γ. For small γ_B however, the large value of Δ_g induces a smaller absolute number of states at lower energy and thereby slow relaxation times.

As for phonon absorption (Fig. 4), calculations show that at 300 mK low-energy phonons ($\sim$ 40 μeV) are mainly involved in the process. It can be shown as well that states in Ta below Δ_{Ta} are very difficult to populate after phonon absorption. This explains the slow absorption rate for large γ below Δ_{Ta}. If γ_B is large, the high-energy states within Ta are also out of reach for QPs in a low-energy state within Al and phonon absorption is generally a slow process.

5. Balance energy

The balance energy E_b is defined as the energy at which the processes enhancing the QP energy (excitation) exactly compensate for relaxation. In a STJ, relaxation is performed via phonon emission only, while excitation occurs via phonon absorption or tunneling. In other words, the balance energy $E_{b,STJ}$ in a STJ is such that

$$[\tau_{tun}(E_{b,STJ})]^{-1} + [\tau_a(E_{b,STJ})]^{-1} = [\tau_e(E_{b,STJ})]^{-1}. \quad (1)$$

In a system where tunneling is absent, such as a superconducting absorber, we simply have

$$\tau_a(E_{b,\text{absorber}}) = \tau_e(E_{b,\text{absorber}}). \quad (2)$$

In this paragraph we want to discuss the consequences of the proximity effect on the balance energy. Starting from the device described in Sections 2 and 3, the proximity effect is 'tuned' by changing the Al thickness only. The thickness and properties of the Ta layer and the resistance of the Al/Ta interface remain unchanged. In terms of the proximity effect parameters, it means that $\gamma/\gamma_B = \rho_{Ta}\xi_{Ta}/R_b$ is a constant and $\gamma \propto \sqrt{d_{Al}}$ for clean superconductors [1]. It must be stressed however that in practice, only the base electrode is in the clean limit and that the relation $\gamma \propto \sqrt{d_{Al}}$ is not entirely true. However, this does not seem to affect the conclusions of this work.

The balance energy (relative to the gap Δ_g) is plotted as a function of d_{Al} in Fig. 5. Line 1 corresponds to Eq. (1) and line 3 to Eq. (2). The dashed line corresponds to Eq. (1) where phonon absorption has been neglected. It appears that in a tunneling system, absorption is very slow, and excitation is mainly governed by tunneling. On the other hand, in the absence of tunneling, phonon absorption also inhibits QP relaxation to the gap. At a thickness of 2 nm of Al, the electrode can be viewed as an almost pure Ta layer, close to the BCS limit. Even in this case, QP relaxation to the gap cannot be achieved. In all cases, the balance energy is at least 5% above the gap. In a system with tunneling, it is 15–50% above the gap.

Fig. 5 shows that QP relaxation is more difficult in proximized structures than in BCS-like structures. The main consequence of this fact is that, in a proximized structure, QPs will be more widely distributed around the balance energy. This has direct implications on the intrinsic energy resolution of the device, due to statistical fluctuations of the energy-dependent parameters involved in the photon detection process.

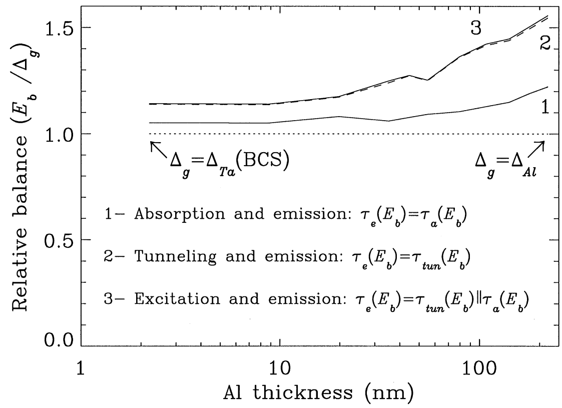

Fig. 5. Balance energy as a function of Al thickness for Ta/Al electrodes, with 100 nm of Ta and proximity effect parameters consistent with the real device measured in Fig. 1.

6. Conclusions

We have calculated the characteristic times for QPs involved in the photon detection process in a STJ, taking into account the superconducting proximity effect. A major outcome from this work is that QP relaxation does not occur down to the energy gap. A balance between relaxation processes (phonon emission) and excitation processes (phonon absorption and tunneling) is observed, and maintains the QPs at the balance energy. We have shown that the balance energy is significantly above the gap, even when tunneling does not take place, and even in a BCS, non-proximized structure. In future work, attention will be paid on the implications of the balance energy on the performance of STJs used as photon detectors, especially in terms of energy resolution.

References

[1] A. Poelaert, Ph.D. Thesis, University of Twente, 1999.
[2] K. Segall et al., IEEE Trans. Appl. Supercond. 9 (2) (1999) 3326.
[3] A. Golubov et al., Phys. Rev. B 51 (1995) 1073.
[4] A. Golubov et al., Phys. Rev. B 49 (1994) 12953.
[5] S.B. Kaplan et al., Phys. Rev. B 14 (1976) 4854.