The role of phonon processes in the performance of superconducting tunnel junctions used as photon detectors

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The role of phonon processes in the performance of superconducting tunnel junctions used as photon detectors.

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Phonons play an important role in the photon detection process in a superconducting tunnel junction (STJ). The absorption of a photon in a STJ produces a cloud of charge carriers (quasiparticles). Phonons can thereafter be generated by relaxation of quasiparticles down to lower energy states, or by recombination of two quasiparticles into a Cooper pair. These phonons can be re-used to produce new quasiparticles or excite existing quasiparticles, or can be lost from the system. The balance between the re-use and the loss of phonons can affect the performance of the STJ, in terms of charge output, energy linearity and resolution. The attention is particularly focussed on the possibility for quasiparticles to significantly increase their energy via multiple tunneling, before they have time to relax by phonon emission. A model involving the basic balance equations is used to account for the significant non linear response as a function of photon energy observed in Nb-Al-AlO_x-Al-Nb STJs.

Keywords: particle detectors, superconducting devices, linearity.

1. Introduction

Superconducting Tunnel Junctions (STJs) are widely used as photon detectors, at wavelengths ranging from the near IR (4 μm) to the soft x-rays (0.2 nm $\sim$ 6 keV), due to their intrinsic capabilities in terms of signal amplitude and energy resolution [2,3]. Phonons play a crucial role in the photon detection process, mainly due to their ability for breaking Cooper pairs. The main effects are related to the emission of phonons following the recombination of charge carriers (quasiparticles = qps) in Cooper pairs. In addition, the average energy level of qps may be raised above the energy gap Δ after tunneling (Gray effect), thereby affecting the characteristic times involved in the photon detection. This paper summarizes the role of recombination, and studies the possibility of having qps maintained well above Δ . This study is based on the energy non-linearity of a specific case, using the very recent features pointed out in [1], which account for the existence of local potential wells, where qps may be trapped.

2. Photon detection by a STJ

The energy E of a photon absorbed in a STJ is used to generate a number N_0 of qps, via the relaxation of hot qps emitting phonons of energy $\Omega \geq 2\Delta$. Finally, $N_0 \approx E/\varepsilon$ with $\varepsilon = 1.75\Delta$ [2].

The qp population in the electrode where the photon was absorbed evolves in time from N_0 to 0, via quasiparticle transfer to the opposite electrode, or via loss from the system (see Fig. 1).

The transfer can be due to the tunneling of an electron through the insulating barrier separating the electrodes; the current developed by these tunneling processes can be integrated, to provide the STJ response or charge output. Moreover, the recombination of 2 qps in the electrode produces a phonon of energy $\Omega \geq 2\Delta$; this phonon is transmitted into the opposite electrode, where it breaks a Cooper pair; this transfer process assumes a Cooper pair breaking time much shorter than the recombination time.

Losses are due to diffusion into the leads, recombination, and trapping into local potential wells. Recombination is a loss process, only if the emitted phonon escapes the electrode without breaking a Cooper pair. Potential wells are mainly present at interfaces (Nb-Al, Nb-substrate, top surface, edges, barrier), whose imperfections can produce a local decrease of the order parameter. The proximity effect [4] suggests that these wells have the size of the system coherence length.

The population can also be increased, by transfer from the other electrode (tunneling or recombination phonon), or by excitation out of the potential wells (de-trapping). De-trapping mainly occurs via recombination. A trapped qp recombines with a free one, of energy large enough, such that the recombination produces a phonon of energy $\Omega \geq 2\Delta$; as a result, this phonon breaks a Cooper pair and generates two free qps. De-trapping via recombination can only occur if the free qps involved are distributed around energies larger than $\Delta + w$, where w is the potential well depth. Such energetic qps can exist. Due to the bias voltage V_b applied at the barrier, a qp tunneling raises its energy by eV_b (see Fig. 1).

The STJ response can be effectively described by the balance equations associated with the qp population in each electrode [1]. Tunneling, diffusive losses and local

trapping are characterized by the rates Γ_t , $\tilde{\Gamma}$ and Γ respectively, whilst recombination and de-trapping are quantified by the recombination coefficient R , typically expressed in $\mu\text{m}^3/\text{s}$.

3. Quasiparticles above the energy gap

The full set of balance equations can be found in [1]. They are used to fit the data showing the responsivity S of a $20 \times 20 \mu\text{m}^2$ Nb-Al-AlO_x-Al-Nb device, in the photon energy range 1 eV to 6 keV, at a temperature of ~ 330 mK, using $V_b = 0.18$ mV. The device is fully described in [3]. The Nb and Al layers are 100 nm and 120 nm thick, respectively. The energy gap is 0.44 meV. The responsivity is defined as the charge output per eV of the photon energy, normalized to its value at zero energy. Hence, $S = 1$ for optical photons, and any deviation from 1 is an indication of energy non-linearity. The data are fitted within 1.4% (see Fig. 2). The increase of S in the range 40-500 eV, is due to qp de-trapping. Note, the picture of Fig. 2 is very much dependent on the device layout. A device with thinner Al (50 nm) and thicker Nb (165 to 265 nm) layers is discussed in [5] and reveals a very linear behaviour in the range 70-700 eV. The main parameters used for our fit are: $\Gamma_t^{-1} = 90$ ns, $\tilde{\Gamma}^{-1} = 70$ μs , $\Gamma^{-1} = 1.7$ μs and $R = 1200$ $\mu\text{m}^3/\text{s}$. The trapping rate is close to the signal decay time at 1 eV (2 μs), where trapping is the main loss process. At such low energies, recombination is marginal due to the very low density of qps. The diffusive losses are mainly governed by the decay time at the maximum responsivity (47 μs), where recombination and trapping are both relatively weak. Using the proximity effect described in [4], the theoretical tunnel time is estimated at 90 ns for qps of energy Δ . R is equal to the ratio of the recombination rate to the density of qps. These two quantities are available analytically in thermal equilibrium, as a function of qp energy ϵ [4]. Using a Debye spectrum for the phonons, R can be estimated as ~ 600 $\mu\text{m}^3/\text{s}$ at $\epsilon = \Delta$, which is half the value used for the fit. The energy dependence of R is $R \propto (\epsilon + \Delta)^2$, and implies $\epsilon = 1.8\Delta$. With $V_b = 0.18$ mV, this energy is exactly reached after 2 tunnel processes. Eq (7b) of [4] shows that after one tunnel process qps need 250 ns to relax to any lower energy by phonon emission. Since the tunnel time is 90 ns, qps will tunnel at least twice. After two tunnel processes, the relaxation time is as short as 25 ns. The result is a distribution of qps well above the energy gap, implying a serious increase of R .

4. Conclusion

There is experimental evidence that qps, generated by photon absorption in a STJ, can be raised far above the energy gap, due to multiple tunneling. Typically, qps may tunnel several times before they relax back to the energy gap, by phonon emission. The main consequence, coupled to a stronger recombination than expected from qps distributed close to the energy gap, is the possibility of qp de-trapping. Recombination and de-trapping govern the energy non-linearity of the STJ, in opposite trends. When recombination produces a responsivity decrease, de-trapping yields an increase.

5. References

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Figure captions

FIG 1. Schematic of the processes involved in photon detection. The x-axis is the position into the device, showing part of electrode 1, the barrier and electrode 2. Qps are represented by black circles; Cooper pairs are encircled pairs of circles, at the Fermi level. The processes illustrated are detailed in the text.

FIG 2. Responsivity vs qp energy: data (+) and best fit using balance equations (solid line).

FIG. 4

FIG. 2