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Bias Voltage Dependence of Quasiparticle Recombination in STJ Detectors with Killed Electrode

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Abstract Superconducting tunnel junction X-rays detectors Ti/Nb/Al/AlO$_x$/Al/Nb/NbN with the Ti/Nb/Al/ killed electrode has been studied under irradiation by X-rays photons of different energies produced by the fluorescence method. The nonlinearity of the STJ-detector response versus photon energy has been studied as a function of the bias voltage. The minimum of the nonlinearity is observed when the tunneling probability P_1 has maximum and the detector signals have shortest rise times. The experimental data were analyzed on the basis of the diffusion model taking into account the quasiparticle self-recombination. The simple approximate expression for the self-recombination contributions to STJ-detector signal was obtained. The nonlinearity of the response depends on the ratios of the recombination constant to the diffusion coefficient R/D and the diffusion length to the initial radius of the quasiparticle distribution Λ/a_0 and is inverse proportional to the thickness of the electrode.

Keywords Superconducting tunnel junction · Detector · Quasiparticles · Diffusion · Recombination

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1 Introduction

Superconducting tunnel junction (STJ) X-rays detectors have very good energy resolution of about 20–30 eV for 5.9 keV quantum. The best energy resolution of 11 eV is achieved with Al-base STJ [1]. Unfortunately, this resolution is several times worse than the theoretical limit. The main reason of line broadening is spatial dependence of the detector signal on photon absorption site. The amplitude of the signal is usually reduced as the photon absorption point approaches electrode edge. There are two main mechanisms of line broadening: edge losses of the excess quasiparticles [2] and the quasiparticle self-recombination [3, 4]. The self-recombination causes the nonlinearity of the detector response versus the energy of absorbed phonon as well.

The quasiparticle recombination is the two steps process. In the first step two excess quasiparticles joint to Cooper pair and emit 2Δ-photon. In the second step the 2Δ-photon escapes from electrode. In the case of the multitunneling mode of the STJ-detector the analysis of the quasiparticle recombination is the complex one due to 2Δ-photon exchange between the electrodes [5]. In [4] the STJ detectors of special construction with only one active electrode were proposed for studying of the quasiparticle recombination. In these detectors behavior of the other electrode is suppressed by the additional trapping layer placed at the side opposite to the tunneling barrier (killed layer) [2].

Within present work we studied the quasiparticle self-recombination in STJ-detectors with killed electrode as a function of bias voltage. The data were analyzed on the basis of the diffusion model [3, 4, 6]. The contribution of the quasiparticle self-recombination was described by the simple approximate formula.

2 Experiment

STJ detectors with multilayer structure Ti/Nb(1)/Al(1)/AlO_x/Al(2)/Nb(2)/NbN (thicknesses 30/150/6/2/13/200/30 nm respectively) were fabricated in IRE RAS by magnetron sputtering. The top Al(2)/Nb(2)/NbN electrode with proximity Al-trapping and NbN-reflecting layers was the main absorbing electrode. The bottom Ti/Nb(1)/Al(1) electrode had Ti trapping layer at the surface opposite to the tunnel barrier and worked as killed electrode for excess quasiparticles. Five STJ detectors with areas S 400, 400, 1800, 6400 and 20000 μm^2 were patterned on a chip. The detectors were of rhombus shape with diagonal ratio (1:2). The barrier resistance was $R_N S \approx 4.1\ \mu\Omega\ cm^2$. Superconducting gaps were $\Delta_b = 1.33$ eV for the base electrode and $\Delta_t = 0.95$ eV for the top electrode. The samples and the experimental setup are described in Ref. [4].

The detectors were irradiated by radioactive sources ^{55}Fe. In order to study the detector response as a function of photon energy in one run, we used the method of X-rays fluorescence for the additional X-ray lines generation. The experimental geometry with X-rays Ti screen was applied [4]. Pulse height spectra were measured at temperature $T = 1.3$ K. Better results were obtained for detectors with large areas: A-sample $S = 6400$ and B-sample $S = 2 \times 10^4\ \mu m^2$. The lines width for 5.9 keV X-rays were $w = 95$ eV with the electronic noise contribution 30 eV for A-sample

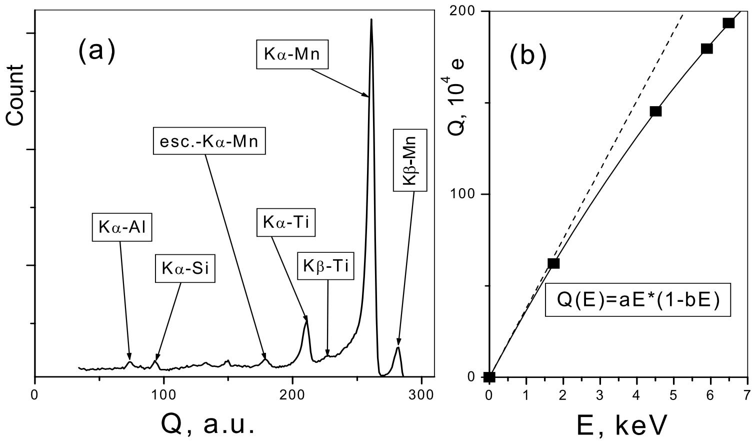

Fig. 1 (**a**) The spectrum of ^{55}Fe source in geometry with Ti-screen. (**b**) The energy calibration at $V_b = 0.55$ mV. *Squares* are the experimental data. The errors of Q do not exceed 10^4 e and are much less than the size of the symbols. *Solid curve* is fitting of the data by (1). *The dash line* shows the initial slope

and $w = 136$ eV with noise 79 eV for B-sample. Excess line broadening was observed for smaller detectors. The main reason of the line broadening is the dependence of a detector signal on the photon absorption point.

Figure 1a shows the spectra obtained by STJ detectors with the area 2×10^4 μm^2 for bias voltage $V_b = 0.46$ mV. There are several sharp lines in the spectrum. Besides X-ray lines from the sources (Kα and Kβ Mn) and the screen (Kα and Kβ Ti), there are additional weak Si Kα and Al Kα lines which were excited by the source radiation in the Si substrate and Al-layer of the source window. The line of the escape peak of Mn Kα from Nb-layer of the top electrode is also observed.

The calibration of the detector response on the photon energy was done for different bias voltages. Only good defined lines of Mn Kα and Mn Kβ, Ti Kα and Si Kα were used for calibration (Fig. 1b). Fitting of the data has been done by the formula:

$$Q(E) = aE(1 - bE), \tag{1}$$

where Q is the detector signal (collected charge), E is the energy of the quantum, a is the initial slope of the curve and b is the nonlinearity of the detector response. The data indicates strong nonlinearity of the calibration curves (Fig. 1b).

3 Data Analysis

The dependence of the initial slope a and the nonlinearity b on the bias voltage V_b are shown in Figs. 2a and b. The initial slope a is proportional to tunnel probability P_1

$$a = \frac{1}{1.75\Delta_t} P_1 = \frac{1}{1.75\Delta_t} \frac{\gamma_T}{\gamma_T + \gamma_L}, \tag{2}$$

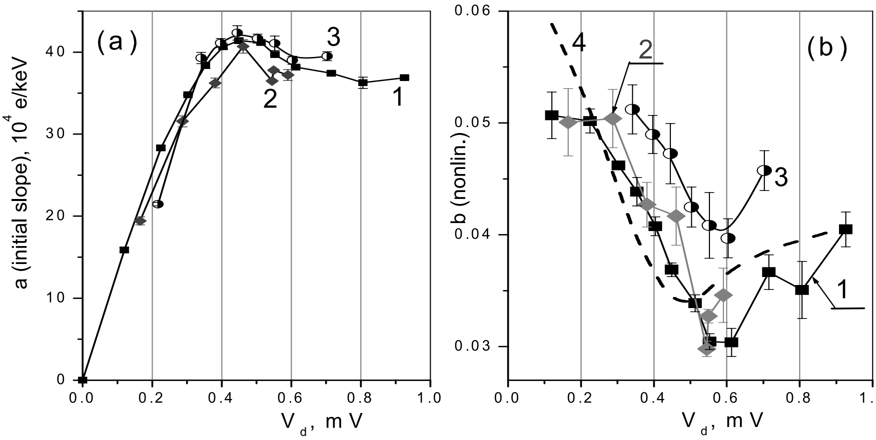

Fig. 2 Bias voltage dependence of the initial slope (**a**) and the nonlinearity (**b**). (*1*) Sample A, $S = 6400\ \mu m^2$, $d(\text{Nb}-2) = 200$ nm. (*2*) Sample B, $S = 2 \times 10^4\ \mu m^2$, $d(\text{Nb}-2) = 200$ nm. (*3*) Sample C, $S = 6400\ \mu m^2$, $d(\text{Nb}-2) = 150$ nm. (*4*) Fitting by formula (3)

where γ_T is the quasiparticle tunneling rate and γ_L is loss rate. The observed dependence of P_1 on V_b is typical for asymmetric tunnel junctions. The maximum of $P_1(V_b)$ is at $V_b = (\Delta_b - \Delta_t)/e$ (Fig. 2a). At the same range of bias voltages the detector signals have maximum of the amplitude and minimum of the rise times τ_d (0.15 μs for sample A and 0.14 μs for sample B). The best energy resolution is also observed near the same bias voltage. The dependence of the nonlinearity b on the bias voltage V_b shows a minimum near voltage $V_b = (\Delta_b - \Delta_t)/e$ (Fig. 2b).

The data were analyzed on the basis of the diffusion model of the detector with one active electrode [6]. The recombination losses of the excess quasiparticles were described by quadratic term ($-\text{R}_{\text{ef}} n^2$), where R_{ef} is the 2D-effective recombination constant and n is 2D-density of the excess quasiparticles. The nonlinearity of the calibration curves was described by the simple approximate formula:

$$Q = \frac{E}{1.75\Delta_t} P_1 \left(1 - \frac{E}{1.75\Delta_t} \frac{R_{\text{ef}}}{2\pi D} \ln\left(\frac{\Lambda}{1.89 a_0}\right)\right), \tag{3}$$

where Q is the detector signal (a collected charge), D is the diffusion coefficient, Λ is the diffusion length $\Lambda = \sqrt{D\tau_d}$, where τ_d is the quasiparticle decay time, $\tau_d^{-1} = \gamma_T + \gamma_L$, a_0 is the initial radius of the excess quasiparticles distribution.

The formula (3) was obtained for the case that the diffusion length was much less than the dimension of the electrode, and the absorption of the quantum was in the center. Self-recombination was considered as a first perturbation. It is follows from formula (3) that the contribution of the self-recombination depends on the two ratios: R_{ef}/D and Λ/a_0.

When the bias voltage is changed, the values of R, D and a_0 are constant. The diffusion length Λ is changed only with V_b due to the variations the quasiparticle tunneling rate γ_T. The curve 4 in Fig. 2b was obtained by fitting of the data for the sample A with formula (3), where values of τ_d were taken from experiment and R

and D were the variable parameters. It is seen from Fig. 2b that in a qualitative sense the model may describe the experimental data. Unfortunately the detail coincidence is absent.

The 2-dimential value R_{ef} is used in formula (3). To transfer to the standard recombination constant R [7] it is necessary to take into consideration thickness of the electrode d_0. The following expression can be obtained:

$$R_{\mathrm{ef}} = \frac{R}{d_1}\frac{\eta}{4}\left(\frac{l_{2\Delta}}{d_0}\right)\left(1+\frac{\eta}{4}\left(\frac{l_{2\Delta}}{d_0}\right)\right)^{-1}, \tag{4}$$

where η is the transparency of the electrode interface for 2Δ-phonons; $l_{2\Delta}$ is an average free path of 2Δ-phonons, $l_{2\Delta} = \upsilon_s \tau_{\mathrm{pb}}$, where υ_s is a sound velocity and τ_{pb} is the pair breaking time for 2Δ-phonons [7]; d_1 is the effective thickness of layer where the quasiparticles were trapped, $d_1 \approx 2\xi + d_{\mathrm{Al}}$, where ξ is the coherence length in Nb-layer and d_{Al} is thickness of Al layer.

The expressions (3) and (4) can be used for the estimation of the self-recombination contribution in the STJ-detector signal. In particularly it follows from (3) and (4) that the nonlinearity b of the detector response increases when thickness of the electrode d_0 decreases. That was confirmed by our experimental data (the curves 1 and 3 in the Fig. 2b).

4 Conclusion

The nonlinearity of the STJ-detector response has been studied as a function of the bias voltage. The minimum of the nonlinearity is observed when the tunneling probability P_1 has maximum and the detector signals have shortest rise times.

The simple expression for the self-recombination contributions to STJ-detector signal was obtained. The nonlinearity of the response depends on the ratios R/D and Δ/a_0 and is inverse proportional to the thickness of the electrode.

References

1. M. Huber, S. Bechstein, B. Beckhoff, F. v. Feilitzsch, J. Jochum, M. Krumrey, A. Rudig, G. Ulm, Nucl. Instrum. Methods A **520**, 234 (2004)
2. O.J. Luiten, M.L. Van den Berg, J. Gomez Rivas, M.P. Bruijn, F.B. Kiewiet, P.A.J. de Korte, in *Proc. 7th Int. Workshop of Low Temperature Detectors, LTD-7*, ed. by S. Cooper (Munich, 1997), p. 25
3. A.G. Kozorezov, J.K. Wigmore, R. den Hartog, D. Martin, P. Verhoeve, A. Peacock, Phys. Rev. B **66**, 094510 (2002)
4. V.A. Andrianov, L.V. Filippenko, V.P. Gorkov, V.P. Koshelets, Nucl. Instrum. Methods A **559**, 683 (2006)
5. V.A. Andrianov, P.N. Dmitriev, V.P. Koshelets, M.G. Kozin, I.L. Romashkina, S.A. Sergeev, V.S. Shpinel, Nucl. Instrum. Methods A **444**, 19 (2000)
6. V.A. Andrianov, L.V. Filippenko, V.P. Gorkov, V.P. Koshelets, Semiconductors **41**, 215 (2007)
7. S.B. Kaplan, C.C. Chi, D.N. Langenberg, J.J. Chang, S. Jafarey, D.J. Scalapino, Phys. Rev. B **14**, 4854 (1976)