Recombination losses in STJ X-ray detectors with killed electrode

V A Andrianov*, L V Filippenko, V P Gorkov and V P Koshelets

1 Institute of Nuclear Physics, Lomonosov Moscow State University, 119992 Moscow, Russia
2 Institute of Radio Engineering and Electronics RAS, 103907 Moscow, Russia
3 Faculty of Computational Mathematics and Cybernetics, Lomonosov Moscow State University, 119992 Moscow, Russia

*andrva@srd.sinp.msu.ru

Abstract. Superconducting tunnel junction X-rays detectors Ti/Nb/Al/AlOx/Al/Nb/NbN with the Ti/Nb/Al killed electrode were studied under irradiation by X-rays photons of different energies produced by the fluorescence method. The nonlinearity of the detector response and the shape of the detector line were analyzed on the basis of the diffusion model taking into account the quasiparticle self-recombination and edge losses.

1. Introduction
Superconducting tunnel junction (STJ) detectors have excellent energy resolution. Now these detectors are used in precise X-rays analysis, astrophysics and in some other applications. In X-rays region the energy resolution of 11 eV for 5.9 keV line is achieved [1]. Unfortunately, this resolution is several times worse than the theoretical limit. The main reason of line broadening is the spatial dependence of the detector signal on the photon absorption site. There are two main mechanisms of this broadening: edge losses of the excess quasiparticles and the quasiparticle self-recombination. The edge losses are caused by quasiparticle trapping in the regions with a lower energy gap formed at electrode edges [2].

The recombination losses were considered in [3-5]. It was shown that the quasiparticle self-recombination could cause the signal dependence on the photon absorption site. Unfortunately, the analysis [5] was done in the complex case of the multitunneling mode of the detector.

In this work we propose to study the quasiparticle self-recombination in STJ detectors of special construction, when only one electrode is active and in the other one the excess quasiparticles are absorbed in the additional trapping layer placed at the side opposite to the tunneling barrier (killed electrode). Such STJ construction is best to reveal the self-recombination effects, as quasiparticle multitunneling is suppressed here.

2. Experimental data
STJ detectors with multilayer structure Ti/Nb(1)/Al(1)/AlOx/Al(2)/Nb(2)/NbN (thicknesses 30/100/6/2/13/150/30 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
The bottom Ti/Nb(1)/Al(1) electrode had Ti trapping layer at the surface opposite to the tunnel barrier and worked as a killed electrode for excess quasiparticles. Five STJ detectors with areas $S = 400, 400, 1800, 6400$ and $20000 \, \mu m^2$ were patterned on a chip. The detectors were of rhombus shape with diagonal ratio (1:2). The barrier resistance was $R_{NS} \approx 3.3 \, \mu \Omega \cdot cm$. The samples and the experimental setup are described in Ref. [6].

The detectors were irradiated by radioactive sources $^{55}$Fe and $^{57}$Co. 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. Two experimental geometries were used: with X-rays screen and with X-rays filter. In the first case the Ti cylindrical screen was placed so that its axis coincided with the line connecting the detector and the source. In geometry with the X-rays filter the thin KCl film was positioned between the source and the detector.

Pulse height spectra were measured at temperature $T \approx 1.35 \, K$. The better results were obtained for detectors with large area, $6400$ and $20000 \, \mu m^2$. The line width for 6 keV X-rays was about 100 eV and the electronic noise contribution was about 60 eV. Excess line broadening was observed for smaller detectors. The main reason of the line broadening is the dependence of a detector signal on the absorption point of a photon.

Figure 1a and 1b show the spectra obtained by STJ detectors with the area $6400 \, \mu m^2$ in the setups with the Ti screen and with the KCl filter. There are 5 sharp lines in every spectrum. Besides X-ray lines from the sources and the screen or the filter, there are additional weak Si $\alpha$ and Al $\alpha$ lines which were excited by the source radiation in the Si substrate and Al-layers of the detector. Both spectra were used for obtaining the dependence of the detector signal on the photon energy. The data displays the strong nonlinearity of this dependence (Fig. 2).

---

**Fig. 1.** Pulse height spectra of STJ detectors:

a) $^{57}$Co + Ti-screen; b) $^{55}$Fe + KCl filter.

**Fig. 2.** The dependence of the signal on the photon energy. Squares - $^{57}$Co + Ti-screen; triangles - $^{55}$Fe + KCl film. Curve 1 – the diffusion model calculations. Line 2 – the signal without recombination.
3. Data analysis

For describing of the experimental data we developed the mathematical model of STJ detectors. This model takes into account the quasiparticle diffusion in the active electrode, quasiparticle tunneling and losses, the additional losses at electrode edges and the quasiparticle self-recombination. The signal amplitude (collected charge, Q) was numerically calculated for different photon absorption points, and then the spectral line shape was calculated under conditions of the homogeneous irradiation.

The main parameters of the model were the tunneling probability 
\[ P_t = \gamma_T (\gamma_T + \gamma_L), \]
where \( \gamma_T \) and \( \gamma_L \) are quasiparticle tunneling and loss rates, the diffusion length 
\[ \Lambda_D = \sqrt{D/(\gamma_T + \gamma_L)}, \]
the edge losses parameter [2] and the quasiparticle effective recombination coefficient 
\[ R'_{ef} = R'_{eff} d_{eff} (\gamma_T + \gamma_L), \]
where \( R'_{eff} \) is given in [4, 7], \( d_{eff} \) is the effective width of Al/Nb bi-layer. Typical dependences of the detector signal \( Q \) on the photon absorption point are shown in Fig. 3. Photon energy equaled 5.9 keV; detector area \( S=1600 \, \mu m^2 \). Curve 1 corresponds to the case when only edge losses of quasiparticles are turned on. Curve 2 describes the self-recombination losses of quasiparticles when edge losses are absent. Curve 3 corresponds to the case when self-recombination and edge losses act simultaneously. The Fig. 3 demonstrates that both factors, the self-recombination and edge losses, induce the signal reduction for photo-absorption sites in edge regions and create line broadening.

Experimental data were analyzed in two steps. In the first step the dependence of the detector response on the photon energy was considered. The variable parameters were \( P_t \) and the ratio \( R'_{eff} / \Lambda_D \). The results of the fitting are shown in Fig. 2 by solid line. In the next step the line shape for the most intensive Mn \( \alpha \) line was fitted. The variable parameters were \( R'_{eff} \), \( \Lambda_D \) and . The parameters were selected in such manner that good description was simultaneously obtained for detectors of different sizes. Spectrum lines for detectors with areas 1600 \( \mu m^2 \) and 6400 \( \mu m^2 \) and results of the theoretical description are shown in Fig.4. It can be seen that diffusion model can reproduce all main futures of detector lines. Our calculations have
shown that the both factors, the quasiparticles self-recombination and the edge losses, broaden the experimental line.

4. Conclusion
The strong nonlinearity of the response of the detector with the killed electrode is due to the quasiparticle self-recombination which is strengthened by $2\Delta$-phonons absorption in the Ti trapping layer. An additional amplifying factor of the self-recombination is the slow diffusion of quasiparticles in the polycrystalline electrode [3].

The analysis has shown that the quasiparticle self-recombination reduces the signal amplitude, causes the nonlinearity of the energy dependence of the signal and induces broadening of the detector line. The diffusion model with a recombination term and edge losses is able to reproduce all main features of the detector line shape and to explain the dependence of the signal on the phonon energy.

References
[1] M. Huber, et al., AIP Conference Proceedings 605 (2002) 63.
[2] O.J. Luiten and et al., Proc. of 7-th Int. Workshop on Low Temperature Detectors (LTD-7) edited by S. Cooper, Munich, Germany (1997) 25.
[3] V.A. Andrianov and et al. Physics of the Solid State 41 (1999) 1063
[4] A.G. Kozorezov and et al., Phys. Rev. B66 (2002) 094510.
[5] R. den Hartog and et al., Phys. Rev. B66 (2002) 094511.
[6] M.G. Kozin and et al., Nucl. Instr. & Meth. A520 (2004) 250.
[7] S.B. Kaplan and et al., Phys. Rev. B14 (1976) 4854.