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Energy Resolution of STJ X-Ray Detectors with Killed Electrode. Simple Model

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Abstract Superconducting tunnel junctions X-ray detectors Ti/Nb/Al,AlO$_x$/Al/Nb(2)/NbN with killed Ti/Nb electrode was studied as a function of bias voltage, energy of the absorbed quantum, and thickness of the Nb(2) layer. The data was compared with a simple diffusion model including the losses of excess quasiparticles due to self-recombination. It was shown that increasing of the electrode thickness reduces the self-recombination contribution and improves the linearity of the detector response.

Keywords Detectors · Superconducting tunnel junctions · X-rays · Quasiparticles · Recombination · Phonons · Energy resolution

1 Introduction

Detectors based on superconducting tunnel junctions (STJ detectors) have energy resolution of about 10–30 eV for the 5.9 keV X-ray line, that is substantially better than the resolution of 140–150 eV of typical silicon detectors [1]. Usually STJ-detectors consist of two identical superconducting electrodes separated by a thin insulating barrier and operate in multi-tunneling mode. In this case undesirable doubling of X-ray lines occurs in the measured spectra, caused by the absorption of quanta in both electrodes.

STJ-detectors with killed electrode have an alternative design in which the signals of one electrode are suppressed due to the presence of the trapping layer placed at the

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side opposite to tunnel barrier [2]. The main detector signal arises from the quantum absorption in the opposite electrode. The advantages of this detector type should be the absence of line doubling and short duration of the signals.

In our work [3], the STJ detectors with killed electrode on the basis of the additional titanium trapping layer were proposed. The general sequence of layers was described by the formula Ti/Nb/Al,AlO_x/Al/Nb/NbN. The bottom killed electrode consisted of two layers: a Ti trapping layer and a thicker Nb layer. The main top electrode had three layers: thin Al trapping layer, the main absorbing Nb layer, and the outer reflecting NbN layer. Unfortunately the achieved energy resolution was about 90 eV for 5.9 keV line. In this work the main parameters of these detectors were studied as a function of the bias voltage, the energy of the absorbed quanta, and of the thickness of Nb layers. Data are analyzed on basis of a simple diffusion model with quasiparticle self-recombination.

2 The Diffusion Model of STJ-Detectors

The main reason of degradation of energy resolution of X-ray STJ-detectors is spatial dependence of the detector signal on the photon absorption site. The amplitude of the signal is usually reduced as the photon absorption point approaches to the electrode edge. The data are considered in a framework of diffusion model of STJ-detectors. There are two main mechanisms of line broadening: the quasiparticle self-recombination [4, 5] and the edge losses of the excess quasiparticles [2]. The self-recombination causes the nonlinearity of the detector response versus the energy of the absorbed phonon as well.

Figure 1 shows the dependence of the signal amplitude Q on the coordinate of the quantum absorption x_0, obtained by a diffusion model for a single electrode. a is a linear size of an electrode. We remind that the signal amplitude is proportional to the total number of tunneled quasiparticles. If the edge losses and self-recombination losses are absent, then the signal Q does not depend on the coordinate x_0. In this

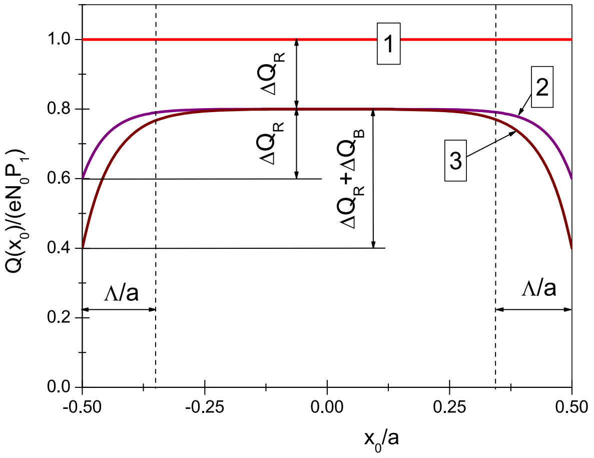

Fig. 1 (Color online) The dependences of the signal amplitude Q on the coordinate of a quantum absorption x_0, obtained by a diffusion model (scheme). (*1*) $\Delta Q_R = 0$, $\Delta Q_B = 0$. (*2*) $\Delta Q_R \neq 0$, $\Delta Q_B = 0$. (*3*) $\Delta Q_R \neq 0$, $\Delta Q_B \neq 0$

case the detector should have thin spectral line. Its width is determined by tunneling fluctuations and by an electronic noise.

The self-recombination losses reduce signal Q in the center of electrode by ΔQ_R and at the edge of electrode approximately by $2\Delta Q_R$ (curve 2 in Fig. 1). The edge losses additionally reduce the signal Q by ΔQ_B near the electrode boundary only (curve 3 in Fig. 1). The dependence of signal Q on the coordinate (x_0, y_0) causes strong broadening of the detector line. Changing of $Q(x_0)$ takes place in a strip near the electrode edge with the width approximately equal to the quasiparticle diffusion length $\Lambda = \sqrt{D\tau_d}$, where D is the quasiparticle diffusion coefficient and τ_d is the quasiparticle lifetime. The lifetime τ_d is determined by the quasiparticle tunneling rate γ_T and the loss rate γ_L: $\tau_d = (\gamma_T + \gamma_L)^{-1}$. To narrow the detector line it is necessary to reduce the values ΔQ_R, ΔQ_B and the ratio (Λ/a) (see Fig. 1).

The edge losses ΔQ_B depend on the methods of tunnel junction production. The ratio (Λ/a) first of all depends on the detector sizes. The recombination losses ΔQ_R can be described by the formula [6]:

$$\Delta Q_R = P_1\left(\frac{E}{1.75\Delta_t}\right)^2 \frac{R_{ef}}{2\pi D}\ln\left(\frac{\Lambda}{1.89a_0}\right), \tag{1}$$

where P_1 is the quasiparticle tunnel probability, E is the energy of the absorbed quantum, a_0 is the initial radius of the excess quasiparticles distribution, and R_{ef} is the effective recombination coefficient. In the case of a homogeneous electrode R_{ef} is equal to

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

where R is the recombination coefficient [7], η is the transparency of the electrode interface for 2Δ-phonons; $l_{2\Delta}$ is an average free path of 2Δ-phonons, $l_{2\Delta} = v_s\tau_{pb} \approx$ 13 nm, where v_s is the sound velocity and τ_{pb} is the pair breaking time for 2Δ-phonons [7]; d is the thickness of the electrode. From formulae (1) and (2) and Fig. 1 it follows that increasing of the electrode thickness d should decrease the recombination losses and consequently should improve the energy resolution. This conclusion was tested by experiment.

3 Experiment and Discussion

The samples of STJ-detectors Si-substrate/Ti/Nb/Al,AlO$_x$/Al/Nb(2)/NbN were fabricated by magnetron sputtering. Five rhomb-shaped STJ detectors with a ratio of diagonals of 2:1 or 4:1 and different electrode areas, $S = 400$, 400, 1600, 6400, and 20000 μm^2, were arranged on one chip. The scheme of the STJ-detector is shown in Fig. 2. The layer thicknesses were as follows: Ti and NbN (30 nm each), base Nb layer (100 or 150 nm), Al/AlO$_x$ oxide layer (4 nm/2 nm), top Nb(2) layer (150, 200, or 250 nm), and trapping top Al layer (11–13 nm). The width of current leads was about 10 μm. The superconducting gaps for the bottom and top electrodes were $\Delta_{\text{base}} = 1.36$ meV and $\Delta_{\text{top}} \approx 0.95$ meV. The normal resistance of the tunnel barrier was $R_N S \approx 400\ \Omega\,\mu\text{m}^2$. The best resolution was achieved for detectors with maximum areas $S = 6400$ and 20000 μm^2.

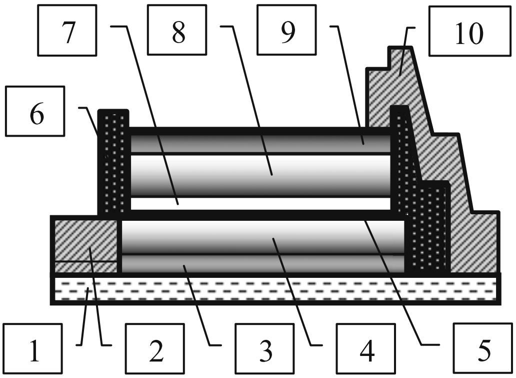

Fig. 2 Scheme of the STJ-detector: *1*—Si substrate; *2*—the base lead (Nb/Ti); *3*—Ti trapping layer; *4*—Nb base layer; *5*—isolating layer (Al_2O_3); *6*—SiO_2 isolation; *7*—Al trapping layer of the top electrode; *8*—Nb top layer; *9*—NbN outer layer; *10*—the top lead (Nb)

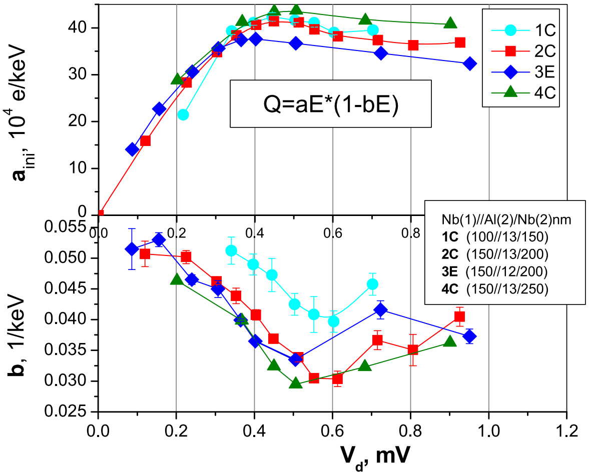

Fig. 3 (Color online) Bias voltage dependence of the initial slope a_{ini} (**a**) and the nonlinearity b (**b**)

The pulse height spectra were measured at different bias voltages V_d at the temperature 1.25 K. The samples were irradiated by MnK_α and MnK_β X-rays (5.9 and 6.4 keV) from a ^{55}Fe radioactive source, by fluorescent TiK_α and TiK_β X-rays (4.5 and 4.9 keV) from a Ti foil shield placed around the source and with fluorescent SiK_α X-rays from Si substrate [5].

The detectors had noticeable nonlinearity of the response relative the energy of the quantum. The dependence $Q(E)$ was determined at every bias voltage and was described by the formula [6]:

$$Q(0) = a_{\text{ini}} E(1 - bE), \tag{3}$$

where a_{ini} is the initial slope coefficient and b is the nonlinearity coefficient. Expressions for a_{ini} and b follow from formula (1):

$$a_{\text{ini}} = \frac{P_1}{1.7\Delta_t}, \qquad b = \frac{1}{1.7\Delta_t} \frac{R_{ef}}{2\pi D} \ln\left(\frac{\Lambda}{1.89 a_0}\right). \tag{4}$$

Figure 3 shows the dependences of coefficient a_{ini} and nonlinearity b on the detector voltage V_d for several samples. $a_{\text{ini}}(V_d)$ has a maximum and the $b(V_d)$ has a

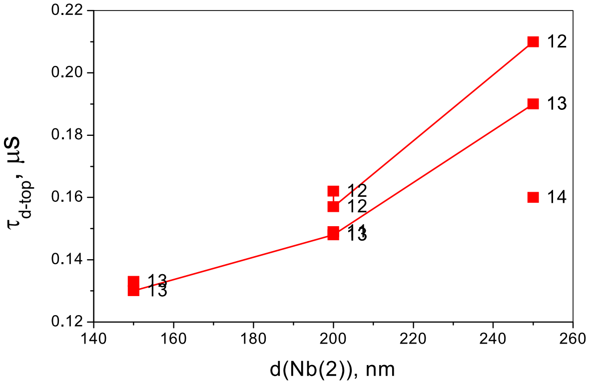

Fig. 4 (Color online) Quasiparticle lifetime $\tau_{d\text{-top}}$ as function of thickness of Nb(2)-layers. Labels show the thickness of Al-trapping layers in top electrodes in nm

minimum at the voltage $V_d \approx (\Delta_{\text{base}} - \Delta_{\text{top}})/e$. This behavior is explained by the maximum in the tunneling rate γ_T for the electrode with a narrower band gap in the asymmetric tunnel junction [6]. The maximum in γ_T is accompanied with the minimum in τ_d and Λ. One can see from Fig. 3b that detectors with thicker top electrode have lower nonlinearity b. This means that increasing of the electrode thickness d really decrease the recombination losses ΔQ_R.

Unfortunately changing of the electrode thickness did not improve the energy resolution. For all samples the best energy resolution at $V_d \approx (\Delta_{\text{base}} - \Delta_{\text{top}})/e$ was about 90 eV at 5.9 keV. This behavior can be explained by changing of quasiparticle lifetime τ_d. Figure 4 shows the dependence of the lifetime τ_d on the thickness of Nb layer. The lifetime τ_d was determined as a risetime of signal pulses at $V_d \approx (\Delta_{\text{base}} - \Delta_{\text{top}})/e$. One can see that the thicknesses of Nb layer and Al layer influence the quasiparticle lifetimes. In particular, increasing of the thickness of Nb layer increases the lifetime.

This means that the diffusion length Λ increases also. As the result, the factor (Λ/a) deteriorates the energy resolution. Changing of τ_d with the thickness of the layers is due to the tunneling rate γ_T. This means that the Al/Nb quasiparticle trap in this range of the layer thicknesses is not saturated. To exclude the dependence of τ_d on the electrode thickness one has to select thicker Al layers and consequently deeper quasiparticle traps.

4 Conclusion

The experimental data obtained for STJ-detectors with killed electrode are consistent with a simple diffusion model. It is shown that the self-recombination of excess quasiparticles gives the noticeable contribution to line broadening. Increasing of the electrode thickness reduces the self-recombination losses and improves the linearity of the detector response as a function of the photon energy. The improvement of energy resolution in STJ-detectors under study is blocked by decreasing of tunneling rate with increasing of the top electrode thickness. To improve energy resolution, the usage of thicker Al trapping layers is recommended.

The confirmation of the diffusion model was obtained in some other publications also [1]. The only exception is the series of the works performed by the low-temperature scanning synchrotron microscope method [8, 9]. The abnormal behavior observed in these works may be considered as an evidence of an additional mechanism of the resolution degradation which appears in STJ-detectors with large electrode sizes and deep quasiparticle traps.

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