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Simulation of two-photon events in a superconducting strip for different thermal bond lengths

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The results of the study of the evolution of two hot spots formed by the simultaneous absorption of two photons are presented. The lifetime of normal domains and the maximum resistance of the superconducting strip were estimated depending on the distance between the absorbed photons. The minimum distance between the edges of the temperature distribution of hot spots, leading to the loss of thermal coupling, is 28 nm, which is consistent with experimental data. The possibility of distinguishing two-photon events for different reading schemes was evaluated.

Keywords: superconductivity, SSPD, hot spot, NbN strip.

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1. Introduction

A superconducting single photon detector (SSPD) is sensitive to radiation from X-ray to middle infrared (IR) ranges. Its principle of operation is based on the local failure of superconductivity due to the photon absorption. SSPD combines low dark count rate (lower than 1 Hz), high count rate of single photons (higher than 1 GHz) and high quantum efficiency (99.5%) [1]. Such detectors are used in quantum cryptography [2], for integrated circuit failure analysis [3], and also are considered in other areas such as astronomy [4], time-of-flight spectroscopy [5], far-space optical communication systems [6]. Today, the single-photon detector based on the superconducting nanostrip is the fastest single-photon detector for photon counting [7]. In recent years, SSPD investigations have been performed in the multi-photon event detection and solution area [8].

One of the disadvantages of SSPD is their inability to distinguish the number of photons in the optical pulse. Distinguishing single-photon and two-photon events allows to expand the detector applications in such areas as quantum optics [9], metrology [10] and fluorescent microscopy [11], where superweak light shall be detected, and quantum cryptography system safety shall be ensured [12].

Using the electrothermal model, life times of normal domains, superconducting strip resistance and voltage photoresponse form were investigated depending on the distance between the absorbed photons. The minimum distance between the edges of the temperature distribution of hot spots resulting in the loss of thermal coupling of domains was determined [13–14]. Possibility of distinguishing single-photon and the described two-photon events was estimated using the known reading schemes.

2. Simulation and results

Photon absorption results in formation of normal region in the superconducting strip depending on the photon energy and in the quantum vortex breakdown. The vortex and antivortex exposed to the Lorentz force move to the strip edges perpendicularly to the detector shift current forming a waist with normal state of the superconducting film. For NbN, the waist width is approximately equal to 20 nm, and the time of formation is comparable with the electron-electron interaction time [15]. During formation of a normal waist, current in the superconducting strip is not changed due to the kinetic inductance of the detector and hot spots do not interact due to long phonon-phonon interaction time. This allows to consider formation of two normal regions as independent from each other provided that photons are absorbed simultaneously.

The used electrothermal model is based on solution of two differential equations one of which describes the hot spot evolution and the other describes the variation of current flowing via the superconducting strip [16]. As the investigations show, solution of a thermodynamic equation in the one-dimensional case is sufficient for representative results [17].

The test sample is a NbN strip with dimensions $0.1 \times 10\,\mu$m, 4.8 nm in thickness made by the electron-beam lithography and plasma-chemical etching methods. The critical temperature of superconductor $T_c = 10\,$K,

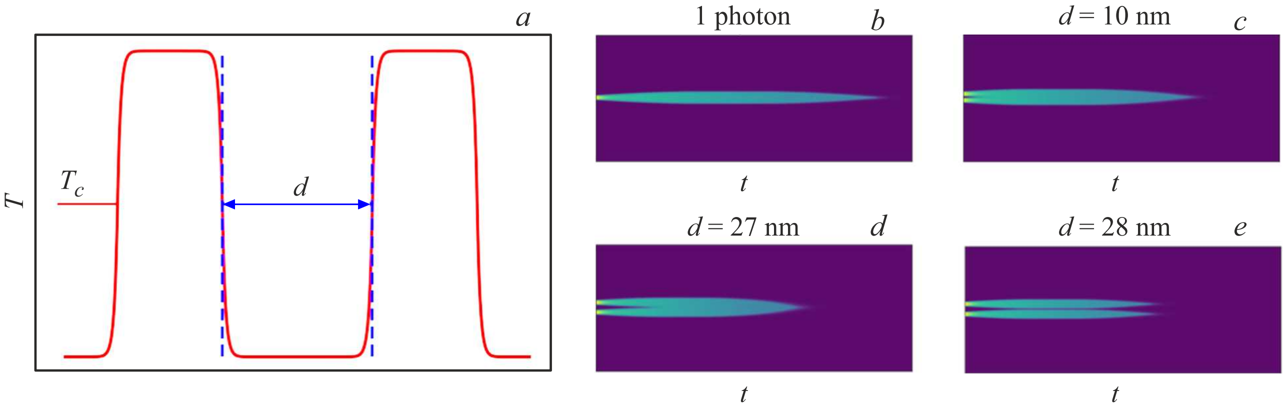

Figure 1. (*a*) The initial temperature profile of normal domains; (*b–e*) thermal maps of normal domain evolution over time for various d and temperatures were shown using colors.

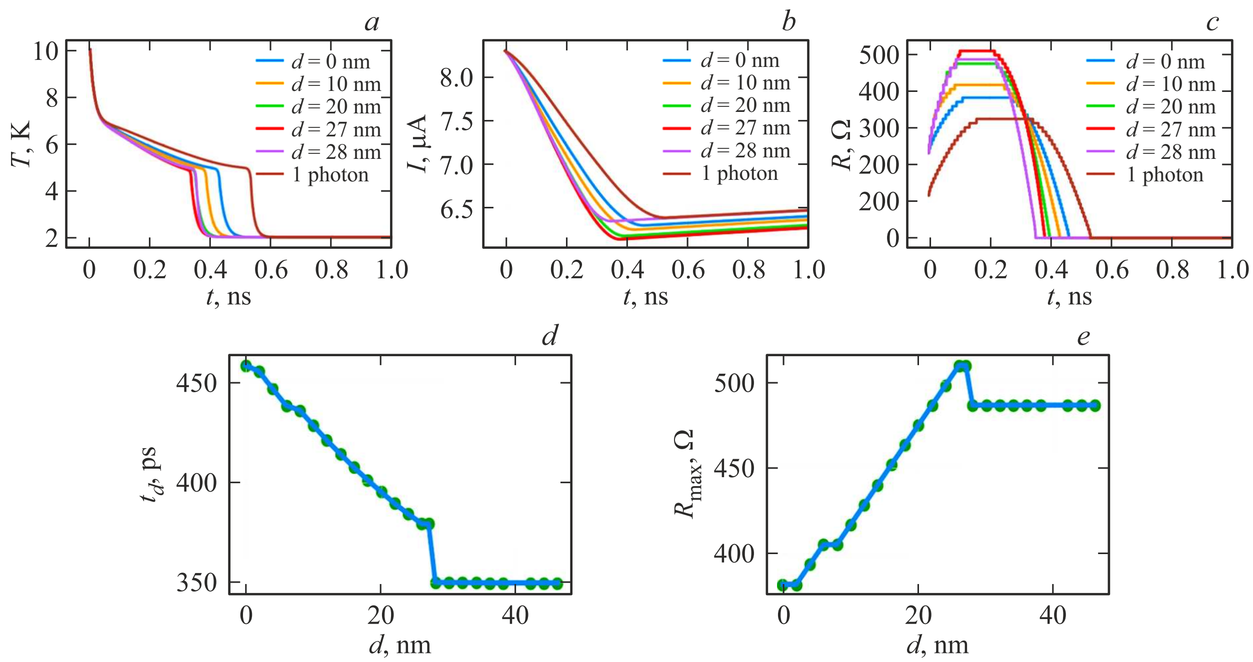

Figure 2. Dependence (*a*) Of temperature in the normal domain center, (*b*) current in the superconducting strip and (*c*) superconducting strip resistance on time for various values of d. Dependence (*d*) of normal domain lifetime t_d and (*e*) maximum superconducting strip resistance $R_{\max}$ on d.

liquid helium bath temperature at low pressure, i.e. substrate temperature, $T_{sub} = 2\,\mathrm{K}$, kinetic sheet inductance $L_h = 100\,\mathrm{pH}/\square$, sheet resistivity $R_s = 579\,\Omega/\square$, critical current $I_c = 10\,\mu\mathrm{A}$. Wave resistance of coaxial line parallel to the detector, $Z_0 = 50\,\Omega$.

Simulation starts from the time of formation in the superconducting strip of the normal domain. Initial conditions for the numerical solution: current in the superconductor is close to critical $I_{bias} = 0.9I_c$ and 20 nm normal domain have the temperature profile shown in Figure 1, *a*, the rest portion of the strip has a temperature equal to the substrate temperature. thermal conductivity equation was solved in the one-dimensional case for region $0.1 \times 0.6\,\mu\mathrm{m}$, which was enough, because the normal domain width id much smaller than the selected region.

Figure 1, *a* shows the parameter varied in this study d is the distance between the boundaries of the formed normal domains. Figure 1, *b–e* demonstrates the thermal maps of dimensions and temperature evolution of normal domains over time for various values of d. Simulation results for the studied characteristic of the superconducting detector are shown in Figure 2, single-photon absorption simulation is also shown for comparison.

From Figure 2, *a*, it can be seen that the normal domain lifetime decreases with increasing d. This is explained by the increase in resistance (Figure 2, *c*), which results in current reduction (Figure 2, *b*) in the superconducting strip and corresponding decrease in Joule heating. Also note that at $d = 28$ nm, the temperature profile shape approaches the constant view and is unchanged beginning from $d = 30$ nm, as shown in Figure 2, *a*.

Analysis of the dependences of normal domain lifetime and maximum superconducting strip resistance on the distance between the boundaries of formed normal domains shown in Figure 2, *d, e* shows a sharp transition from $d = 27$ nm to $d = 28$ nm. This is explained by the loss of thermal coupling between the domains as shown in Figure 1, *d, e*. When thermal coupling between domains exists, the heat diffusion occurs only in one direction, which increases their lifetime. Also, increase in dimensions of the normal region when thermal coupling is present increases the superconducting strip impedance.

The detected thermal coupling length between hot spots equal to 28 nm is close to 23 ± 2 nm obtained in 2012 by Renema et al. [13]. The authors used detector tomography and linear loss accounting method to obtain full statistics of the NbN detector response with additional intentional restriction for recording differences in the number of absorbed photons.

In the paper by Polyakova et al. as of 2019 the thermal coupling length was equal to 17 ± 2 nm [14]. It was counted using the detector tomography method to obtain the set of dependences of count probability on the mean number of photons in laser pulse.

Figure 3 shows the voltage pulses of a single-photon detector recorded from a coaxial line at various values of d. It can be well seen that the photoresponse amplitude grows with the growing distance between the normal domains due to the growth of superconducting strip resistance (Figure 2, *e*). With loss of thermal coupling, the photoresponse amplitude decreases significantly and becomes poorly distinguishable from the single-photon detection. Also note that the photoresponse rise time decreases with the increasing distance between the normal domains. These dependences may be used in practice to distinguish two-photon events with different distances between the formed normal domains from single-photon events. However, direct measurement of the detected dependences is limited by the accelerators used for the experiment: thermal noises of reinforcements operated at room temperature exceed the amplitude difference, and the reinforcement strip restrict the differentiation of the photoresponse leading edges.

The method offered in 2020 for the agreement of the coaxial line impedance and normal domain resistance allows to distinguish single-photon (matched) and two-photon (unmatched) events [18]. But, as shown in Figure 2, *c, f*, resistances of two normal domains with and without thermal coupling differ considerably from one another and from the resistance of one normal domain, which will prevent effective use of the presented method.

Other method to distinguish the number of photons by the photoresponse of the superconducting detector was offered in 2021. It is based on the use of a high-frequency

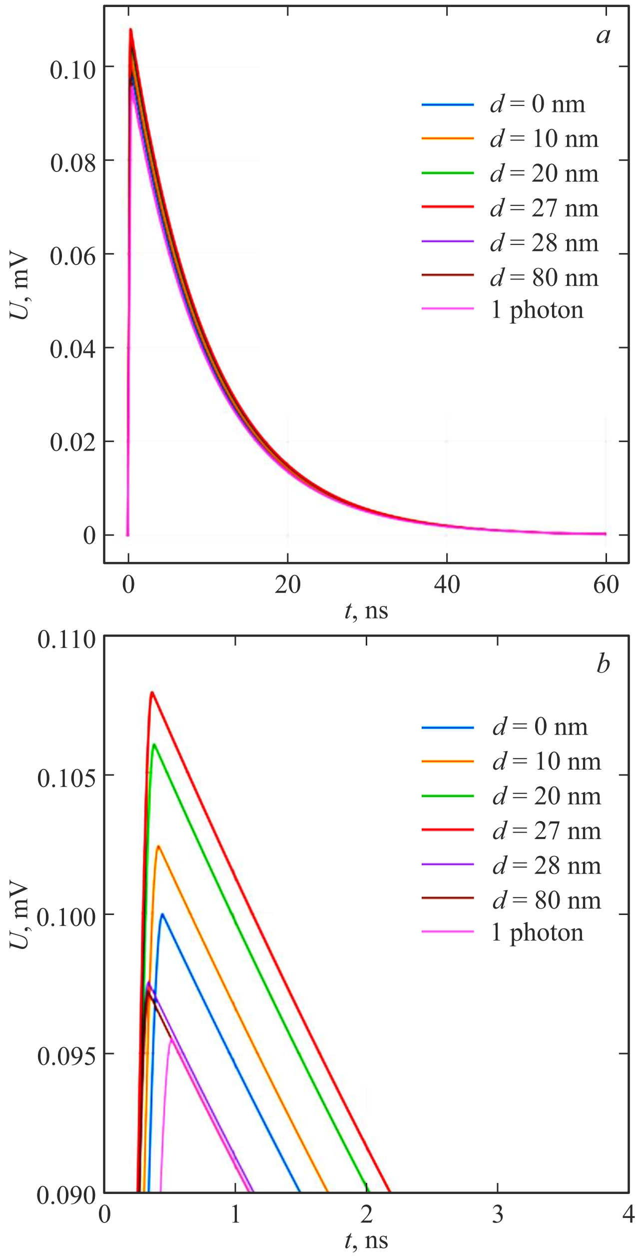

Figure 3. (*a*) Detector photoresponses for various values of d; (*b*) Region near the photoresponse amplitudes.

circuit recording a signal with high signal-to-noise values followed by their software processing by comparing with the reference pulses measured before [19]. This solution is more preferable and allows to distinguish photons with and without thermal coupling, however, the processing system requires preliminary calibration.

3. Conclusion

According to electrothermal model, the domain lifetime decreases with the increasing distance between the domain edges and does not vary after the loss of thermal coupling between the domains.

Simulation provided the coupling length between hot spots equal to 28 nm, which agrees with the experimental data.

It is deduced that the voltage pulses in two-photon and single-photon events received by instruments cannot be identified without the use of additional detection methods.

Conflict of interest

The authors declare that they have no conflict of interest.

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