Distributed readout detectors using superconducting tunnel junctions

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Abstract

Superconducting tunnel junctions (STJs) are able to measure the energy of single photons in the range from near infrared to X-rays. They provide simultaneous information of the impact time and wavelength of an absorbed photon. The main difficulty of these detectors compared with conventional imaging detectors lies in their limited pixel number. Each STJ has to be connected independently and therefore the wiring becomes technologically more demanding as the number of STJs increases. One approach to solving this problem is to use a single large absorber and to distribute STJs for position sensitive signal readout. This configuration is able to detect single optical photons with an energy resolution close to that of a single STJ pixel.

We have produced a Ta absorber strip with Ta/Al/AlO\textsubscript{x}/Al/Nb/Ta junctions at either end. The energy and position of single photons were measured simultaneously. The energy resolving power approaches the theoretical limit. We will present a simple Monte Carlo simulation which reproduces the measurement exactly.

Key words: Distributed readout, Monte Carlo simulation, superconducting tunnel junction

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1. Introduction

Superconducting tunnel junctions (STJs) can be used as single photon detectors with a moderate energy resolution from near infrared to X-rays. However, a drawback of this technology is the limited number and size of the junctions available in one detector.

One approach to this problem is to separate the absorption and the read-out processes by the use of one large absorber and several distributed junctions for readout [1,2,3]. The sum of the signals of all junctions measures the energy of the photon and the difference of the signal amplitudes allows to calculate the position of the photon impact.

In this paper we will present the response of a strip detector to optical photons and compare it with a Monte Carlo simulation.

2. Experiment

We deposited a 135 µm long, 31.5 µm wide and 100 nm thick Ta absorber layer (\textit{RRR} \approx 25) on a sapphire substrate. At each end, on top of the absorber, we fabricated 25 × 25 µm\textsuperscript{2} Ta-Al junctions.
with 38 nm thick Al layers (including an intermediate thin Nb seed layer). The device was cooled down to a temperature of 0.32 K. We biased each junction independently at about 100 µV where the thermal current was ~ 200 pA. A pulsed 592 nm LED (17 nm FWHM) served as light source. We read out the signals with a charge-voltage-conversion amplifier. The signals were digitalized and stored in a file for offline analysis.

Figure 1 shows the response (black dots) of the two junctions to the absorption of 592 nm photons in the Ta layer. The black spot near zero is noise. The first and second banana curves correspond to the absorption of one and two photons, respectively. The small curving of the middle part means that the quasiparticles diffuse very fast (compared to the loss processes) across the entire strip. The increase of the signal amplitudes at the end of the strip is due to a degradation of the gap under the junctions which results in a higher number of initially created quasiparticles [2].

Figure 2 shows the same measurement by displaying the sum of the signals (energy) as a function of the normalized difference (position). The histogram of the center values of the single photon events has a FWHM of 6460 charges. An electronic noise of 4490 charges was measured by applying a test pulse. The width of the light source amounts to 1440 charges. By subtracting these external noise sources from the total noise we obtain an intrinsic noise of 4240 charges which corresponds to a 0.19 eV resolution or a resolving power of 11. The theoretical resolving power obtained by taking into account the Fano factor and the tunnel noise only and by assuming that all the created quasiparticles take part in the tunnel process is 16 [2]. However, this theoretical value cannot be reached since a significant fraction of the quasiparticles is lost before contributing to the signal by tunneling.

3. Monte Carlo simulation

We propose a simple two-dimensional Monte Carlo simulation for modeling our strip detector. The absorption of a photon will create \( N_0 = \frac{E_{\gamma}}{1.7\Delta} \) quasiparticles, where \( E_{\gamma} \) is the photon energy and \( \Delta \) the Ta gap energy. To this number \( N_0 \) we added a Gaussian noise corresponding to the bandwidth of the light source and the Fano noise. At each simulation step every single quasiparticle moves a distance \( d \) in an arbitrary direction. The distance \( d \) is a model parameter chosen to be small compared to the junction dimensions.
If a quasiparticle would move out of the Ta strip it is set back to the borders of the layer (i.e. it is not reflected and will move in an arbitrary direction again at the next simulation step). During each step there is a certain probability that a quasiparticle will be lost \((P_{\text{loss, Abs}} \text{ and } P_{\text{loss, STJ}})\) or, if it stays within the junction borders, that it is trapped \((P_{\text{trap}})\). There are two loss probabilities to take into account that the quasiparticle lifetime in the STJ is higher than in the absorber area because in the junction area one has to consider the mean lifetime of quasiparticles in Ta and Al [4]. Once a quasiparticle is trapped it can’t move out again in our model. Finally there is a certain probability that a quasiparticle staying within the junction borders contributes to the signal \((P_{\text{sig}})\) whereupon it is taken out of the simulation. To the number of read out charges the tunnel noise is added to obtain the final signal. Since the Ta gap is slightly reduced in the junction area we introduced also a parameter \(F < 1\) taking into account that the number of charges created outside the junctions is smaller.

Agreement between experimental data and Monte Carlo simulations (black and grey points, respectively, as shown in Figs. 1 and 2) was obtained by empirically tuning the simulation parameters, yielding the best fit parameters: \(d = 6 \mu\text{m}, P_{\text{loss, Abs}} = 7 \cdot 10^{-4} \text{ and } P_{\text{loss, STJ}} = 5.1 \cdot 10^{-4}, P_{\text{trap}} = 3 \cdot 10^{-3}, P_{\text{sig}} = 2 \cdot 10^{-3}, F = 0.875\). Because the loss probabilities are calculated per simulation step for a given quasiparticle propagation length \(d\), one could, in principle, determine the corresponding loss rates and the diffusion speed via diffusion model if one of those values were known.

4. Summary

Our measurements confirm the results of Ref. [2], proving that a good energy resolution can be achieved with a distributed readout scheme. We have also shown that a simple Monte Carlo simulation reproduces the experimental values. From the simulation parameter \(F = 0.875\) we conclude that the relevant energy gap for absorption in the Ta layer under the junction is about 12.5% smaller than in the strip. This energy difference of \(88 \mu\text{eV}\) is on the order of the thermal energy \((k_B T = 28 \mu\text{eV})\) and thus the quasiparticles are not expected to be trapped totally in the junction area. This agrees with the fact that the photons absorbed at one end of the strip are also detected by the junction at the opposite end. Furthermore, this indicates that the mean energy of the quasiparticles which are created after absorption of a photon in the Ta layer under the junction is higher than the gap energy at the barrier as measured by the \(IV\) curve which is about \(450 \mu\text{eV}\). This agrees with the 4-quasiparticle-populations model presented in our former work [4,5].

Combining that model with a three-dimensional Monte Carlo simulation would allow us to calculate and, by variation of simulation parameters, to optimize the responsivity and energy resolution of STJ distributed readout detectors. As an example, we found that a moderately thicker Al trapping layer is favourable. On the other hand, the less significant contribution of the absorber quality to the device performance as found in our experiments could be verified.

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