A double junction superconductive detector based on a single material

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Abstract. We study a class of superconductive radiation detectors in which the absorption of energy occurs in a long superconductive strip while the readout stage is provided by superconductive tunnel junctions positioned at the two ends of the strip. This configuration has been extensively studied in the last years almost invariably using two superconducting materials one of which, with a lower gap, used to fabricate the junctions, has the role of a trap for the nonequilibrium quasiparticles. In this work we study in detail the signal formation and the performances of such a device based on a single superconducting material, i.e. one without traps. We show that the trap-free device is capable both of imaging and energy resolution. We calculate the detector response in the form of collected charges at the two junctions, for Ta and Al devices and discuss a few features, specific to the trap-free detector, which can facilitate a rapid characterization of the device before use under radiation.

1. Introduction
Single photon radiation detectors based on superconducting tunnel junctions (STJ) are attractive devices because they have nearly achieved the desired performance for energy-resolved detection of individual photons or particles. They cover a broad energy range and have high counting rates [1, 2]. Current work is presently directed toward the objective of scaling to cover large areas and provide imaging. This can be accomplished by substituting several single pixel STJs in an array with long and narrow strips where radiation is absorbed (as much as possible to cover the largest area). Each strip is readout through two STJs placed at the ends [3, 4, 5] realizing in such a way a double junction superconductive detector. The energy measurement in this Distributed Read Out Imaging Device (DROID) is obtained in the same way as for a single STJ by counting the total number of quasiparticles that tunnel through the barriers of the two junctions in time coincident pulses [6]; the position is obtained by measuring the quasiparticles separately collected by the two junctions. Since the very beginning when DROIDs were proposed, they were designed using a higher gap superconductor for the absorber and a lower gap superconductor for the STJ electrodes [3]. The idea was to exploit quasiparticle trapping and multiplication effects [7] to improve the collection efficiency. The presence of traps however is not a fundamental ingredient that underlies the DROID idea. The important issues are the large area coverage with imaging capability and the reduction of the readout channels, while maintaining good energy resolution. Moreover, single pixel STJ detectors have been made without traps; they are well proven examples of detectors that does not have traps but conserve excellent energy resolution.
[8]. We found the physics of a different DROID design, one that does not use traps, worth of deeper investigation.

2. Quasiparticle diffusion and signal formation in DROIDs

2.1. Detector response under radiation

In order to estimate the detector response we consider the diffusion of the excess quasiparticles in a strip absorber extending from $-L/2$ to $L/2$ made by a superconducting material characterized by a diffusion constant $D$ and a loss rate $\gamma_{\text{loss}}$.

$$\frac{\partial n(x,t)}{\partial t} = D \frac{\partial^2 n(x,t)}{\partial x^2} - \gamma(x) n(x,t), \quad -L/2 < x < L/2, \quad 0 < t < \infty$$

We assume that in correspondence of the junction regions, positioned at the two opposite edges of the absorber and extending between $-L/2$ and $-a/2$, $a/2$ and $L/2$ (inset of figure 1), the quasiparticles are subtracted from the initial population $N_0$ by losses and tunneling mechanisms while outside these regions only loss processes persist. In this way $\gamma(x)$ in (1) has the form:

$$\gamma(x) = \begin{cases} 
\gamma_{\text{loss}} + \gamma_{\text{tunn}} & -L/2 < x < -a/2 \\
\gamma_{\text{loss}} & -a/2 < x < a/2 \\
\gamma_{\text{loss}} + \gamma_{\text{tunn}} & a/2 < x < L/2
\end{cases}$$

The boundary conditions are i) the absence of leaking over $-L/2$ and $L/2$

$$\frac{\partial n(-L/2,t)}{\partial x} = \frac{\partial n(L/2,t)}{\partial x} = 0$$

and ii) the initial condition reflecting the localized radiation impact at $x_0$ generating $N_0$ quasiparticles

$$n(x,0) = N_0 \delta(x-x_0),$$

Reference [9] provides a separated series solution to (1)-(4) with many details. From $n(x,t)$ the collected charge in each tunnel junction $Q_{1,2}(x_0)$, as a function of the impact point $x_0$, can be obtained as

$$Q_{1,2}(x_0) = \gamma_{\text{tunn}} \int_{STJ_{1,2}}^{\infty} \int_{STJ_{1,2}} n(x,t) \, dx \, dt.$$
\[ \gamma(x) = \begin{cases} \gamma_{\text{loss}}; & -L/2 < x < a/2 \\ \gamma_{\text{loss}} + \gamma_{\text{tunn}}; & a/2 < x < L/2 \end{cases} \]

\[ S(x) = \begin{cases} S; & -L/2 < x < -a/2 \\ 0; & -a/2 < x < L/2 \end{cases} \]

Here the quasiparticle injection, represented by the source term \( S(x) \), occurs through the left junction whereas the junction on the right has the role of collector junction. Once solved (6)-(8) for \( n(x) \), [10], one obtain \( I_{\text{detect}}/I_{\text{inject}} \) as a function of \( D, \gamma_{\text{loss}}, \gamma_{\text{tunn}} \) and the geometrical parameter \( L, a \) by considering that

\[ I_{\text{detect}} = \gamma_{\text{tunn}} e \int_{STJ2} n(x) \, dx, \quad I_{\text{inject}} = e \int_{STJ1} S(x) \, dx. \]

3. Results and Discussion

The solution (5) allows the response under radiation of the no trap DROID to be quantified. We calculated the expected results for a long no trap DROID based either on tantalum or aluminum of various quality. The device geometry was characterized by an overall absorber length of 500\( \mu m \) with two 50\( \mu m \) junctions. For both materials we used two values of \( D \) and \( \gamma_{\text{loss}} \). Figures 1 and 2 show the response curves of the devices based on Al and Ta respectively. Table 1 provides for each curve the corresponding parameters used for the calculation.

| Curve | fig.1-1 | fig.1-2 | fig.1-3 | fig.1-4 | fig.2-1 | fig.2-2 | fig.2-3 | fig.2-4 |
|-------|---------|---------|---------|---------|---------|---------|---------|---------|
| \( D \) (cm\(^2\)/s) | 6.7 | 6.7 | 34 | 34 | 8 | 8 | 40 | 40 |
| \( \gamma_{\text{loss}} \) (s\(^{-1}\)) | \( 10^5 \) | \( 10^4 \) | \( 10^5 \) | \( 10^4 \) | \( 10^5 \) | \( 10^4 \) | \( 10^5 \) | \( 10^4 \) |
| \( \gamma_{\text{tunn}} \) (s\(^{-1}\)) | \( 10^6 \) | \( 10^6 \) | \( 10^6 \) | \( 10^6 \) | \( 1.3 \times 10^6 \) | \( 1.3 \times 10^6 \) | \( 1.3 \times 10^6 \) | \( 1.3 \times 10^6 \) |

**Figure 1.** Coincident expected charges in the two junctions for Al (see Table 1). \( L = 500\mu m, a = 400\mu m \). The geometry (Inset).

**Figure 2.** Coincident expected charges in the two junctions for Ta (see Table 1). \( L = 500\mu m, a = 400\mu m \).
It is evident that when the materials are chosen properly, as in curves 2, 4 of both figures, the absence of traps is irrelevant to the device performances and a device behavior comparable with the trap based devices is obtained.

We turn now to the response of the device to a dc current injection. The character of the solution of equations (6)-(9) and its possible relevance in the characterization of DROIDs is shown in figure 3 where \( I_{\text{detect}}/I_{\text{inject}} \) is plotted vs the absorber length \( L \) for three different aluminum devices made with junctions of increasing length. The three curves all show a similar decay of the detected current with the absorber length governed by the the diffusion and loss properties of the absorber. For fixed absorber length one can gain some current signal by using larger junctions. An \( I_{\text{detect}}/I_{\text{inject}} \) vs \( L \) curve could be used to characterize the absorber material on a chip with DROIDs of various lengths. Other types of curves can be calculated, as well, as a function of the junction size, \((L - a)/2\), or tunneling rate, \( \gamma_{\text{tunn}} \) and compared with the corresponding injection current experimental data.

In conclusion we have briefly illustrated the expected device performances for a novel no trap DROID based on either tantalum or aluminum of different diffusion constants and loss rates. We have shown that a performance similar to the one obtained using a trap-based device is possible with an extra ease of preliminary device testing before irradiation.

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