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Nuclear Instruments and Methods in Physics Research A 520 (2004) 237–239

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Diffusion-engineered single-photon spectrometer for UV/visible detection

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Abstract

We present predictions for a *diffusion-engineered*, single-photon spectrometer in the UV–visible range using a superconducting tunnel junction. Quasiparticles are created by photoexcitation, with charge Q_0. After tunneling through the junction, the quasiparticles can either backtunnel or diffuse away. With confinement by a higher gap or by narrow leads the quasiparticles in the counterelectrode dwell next to the junction and backtunnel, increasing the collected charge to $Q = pQ_0$, $p > 1$. For very narrow leads the dwell time is inversely proportional to the lead width, up to the recombination time of Al, 1 ms at 0.2 K. The new aspect of our work is the use of narrow leads to control the charge gain p, while minimizing self-heating. This charge gain will improve the energy resolution compared to the case $p = 1$, where the electronic noise is dominant, and compared to much larger charge gain, $p \approx 50$, where large self-heating resulted with extra noise.

PACS: 74.50.+r; 85.25.Am.; 85.25.Cp

Keywords: Photon detector; Tunnel junction; Backtunnelling

1. Introduction

Detectors using superconducting tunnel junctions (STJs) have been employed for detection of single photons from X-ray to IR energies. There are important applications in astronomy and biology for UV through IR detection, but the small size of the photon-induced (initial) charge, a few thousand electrons, limits the energy resolution that can be achieved with present amplifiers. To enhance the charge above that initially created, Q_0, one employs backtunneling which causes charge recycling. The collected charge is then $Q = pQ_0$. Backtunneling can be achieved by confinement of the quasiparticles near the tunnel barrier by a higher gap superconductor (Ta [1,2] or Nb [3] confines quasiparticles in Al), or by slowing down the diffusion away of the quasiparticles. It is this latter approach that we introduce in this work, for use with lateral structure devices. Such engineered outdiffusion can be used in other applications where non-equilibrium quasiparticles are detected, including kinetic inductance detectors [4].

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doi:10.1016/j.nima.2003.11.332

2. Engineered diffusion

We consider the lateral STJ geometry, Fig. 1. In this geometry the area of the junction can be optimized separately from that of the absorber. For example, it allows one to use a long absorber strip with two attached Al tunnel junctions to achieve one-dimensional imaging. Other groups use a stacked geometry, with either Ta [2] or Nb [3] as the higher gap superconductor/absorber, to confine quasiparticles in Al.

Our detector uses a Ta absorber ($\Delta_{Ta} = 0.7$ meV); $Q_o/e \approx 4000$ quasiparticles are created by a 4.89 eV photon [1]. These are trapped into the lower-gap Al trap electrode, $\Delta_{Al} = 0.18$ meV. For an electrode area $A_{electrodes} = 20\,\mu m^2$ ($= A_{trap-electrode} + A_{counter-electrode}$) there are ≈ 600 thermal quasiparticles in equilibrium at 0.21 K. The expected signal-to-noise (FWHM) for the case of no backtunneling ($p = 1$) for a 4.89 eV photon is the energy resolving power, $E/\Delta E = 50$, including the thermal quasiparticle current and intrinsic creation statistics. However, the amplifier and junction (quiescent) white noise will limit resolution to be a factor of ≈ 5 worse [1]. With backtunneling, the signal increases linearly with p, and the noise scales as $p^{1/2}$, for noise sources that remain the same. If $p = 20$, an improvement of the energy resolution is expected, to that limited by the noise of backtunnelling, $E/\Delta E = 25$. For many applications this would qualify the device.

For very large p (≈ 50) there is the heating due to the current. This increases the number of steady-state quasiparticles and gives extra noise [1]. Heat removal is poor due to Andreev reflection by the higher gap superconductor. Also, quasiparticles can multiply at energy $E > 3\Delta_{Al}$, and for pure Al, $\Delta_{Ta} > 3\Delta_{Al}$, so after repeating tunneling some quasiparticles do multiply. For intermediate values of p, say 3–20, heating does not appear to lead to significant extra noise [2,3].

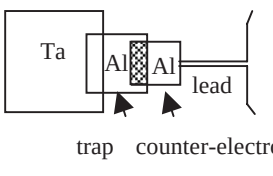

Fig. 1. Device geometry.

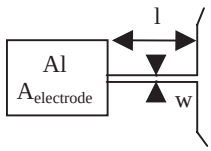

Fig. 2. Device Schematic.

We propose a method to achieve intermediate backtunneling ($p = 5$–20) in our lateral geometry. We use a geometric constriction to restrict outdiffusion, a thin Al lead which connects to a large pad (Fig. 2). The idea arose from experiments with X-ray devices, where the backtunneling was due to narrowed leads [5]. The signature was an extended current pulse, with a decay time constant of order 200 μs.

3. Diffusion simulation

We modeled quasiparticle diffusion away from the tunnel barrier for the geometry of Fig. 1 in the following limits: (1) the tunnel time is much smaller than the time for outdiffusion from the electrodes; each electrode has the same volume; (2) the internal diffusion time within the electrodes is short compared to the outdiffusion time; this means the electrodes can be treated as one volume; (3) the volume of the Al lead is not much larger than that of the electrode, and the length of the Al lead is such that the diffusion time along this lead, l^2/D, is shorter than the outdiffusion time from the electrodes; (4) $\tau_{inelastic} < \tau_{tunnel} < \tau_{outdiffusion} < \tau_{recombination}$. Under these fairly reasonable assumptions we find:

$$\tau_{outdiffusion} = A_{eff}(l/w)/D \quad (1)$$

and $p = (\tau_{outdiffusion}/\tau_{tunnel})$. The effective area of the electrodes is $A_{eff} = (A_{electrodes} + lw/2)$. The term $lw/2$ accounts for the approximate half filling of the volume of the lead by quasiparticles during the outdiffusion time. If (lw) is small, the effective area is just that of the electrodes, and also the signal is maximized. For example, consider a device with $l = 200\,\mu m$, $w = 0.05\,\mu m$, $A_{electrodes} = 20\,\mu m^2$, and $D = 20\,cm^2/s$. In that case, $\tau_{outdiffusion} = 50\,\mu s$.

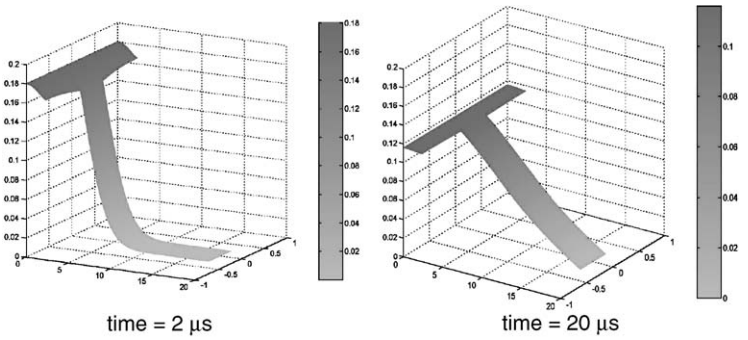

Fig. 3. Concentration profile in time.

With $\tau_{tunnel} = 2.5\,\mu s$, $p = 20$. This requires accurate lithography, which we have achieved. Much thicker, cleaner Al films ($d = 160\,nm$) have [6] $D \approx 60\,cm^2/s$.

Eq. 1 was discerned from simulations done in MATLAB of 2D diffusion, using 'pdetool'. These were originally done for our X-ray devices. The simulations presented above in Fig. 3 are for somewhat different device parameters. We plot the concentration profile in the electrode-lead plane at two times; $t = 2\,\mu s$, shortly after the quasiparticles are 'placed' in the electrodes; and $t = 20\,\mu s$, at which time the diffusion down the lead has occurred and has reached the steady-state linear distribution for Eq. (1). The decay of concentration in the electrodes is evident while the linear distribution is being established. The correction for finite lead volume given in Eq. (1) is found from our simulations to be accurate to 5% up to $lw = A_{electrodes}$.

Backtunneling occurs during the entire time that the density of quasiparticles is finite in the region of the junction, if the voltage bias is large [7]. STJ devices constructed with a lead width comparable to the width of the counter-electrode show only a slight enhancement of the charge, due to a small backtunneling effect.

Acknowledgements

This work was supported by NASA NAG5-11425. We thank A. Szymkowiak and M. Devoret for useful discussions.

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