A New Noise Source in Superconducting Tunnel Junction Photon Detectors

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***Abstract*— We report on the development of an "all-in-one" detector that provides spectroscopy, imaging, photon timing, and high quantum efficiency with single photon sensitivity: the optical/UV single-photon imaging spectrometer using superconducting tunnel junctions. Our devices utilize a lateral trapping geometry. Photons are absorbed in a Ta thin film, creating excess quasiparticles. Quasiparticles diffuse and are trapped by Al/AlOx/Al tunnel junctions located on the sides of the absorber. Imaging devices have tunnel junctions on two opposite sides of the absorber. Position information is obtained from the fraction of the total charge collected by each junction. We have measured the single photon response of our devices. For photon energies between 2 eV and 5 eV we measure an energy resolution between 0.47 eV and 0.40 eV respectively on a selected region of the absorber. We see evidence that thermodynamic fluctuations of the number of thermal quasiparticles in the junction electrodes leads to current noise that far exceeds the expected shot noise of the dc bias current. We believe that this may limit the resolution of our present generation of detectors at the operating temperature of 0.22 K.**

***Index Terms*—Detectors, imaging, noise, spectroscopy, superconducting devices.**

I. INTRODUCTION

THERE has been great interest in the concept of single photon spectroscopy in recent years. Two competing technologies are Superconducting Tunnel Junctions (STJ) and Transition Edge Sensors (TES) [1]-[2]. These technologies may offer "all-in-one" detectors that provide spectroscopy, imaging, photon timing, and high quantum efficiency with single photon sensitivity at energies ranging from the infrared to the gamma ray. In the optical/UV region, much attention has been focused on imaging spectrometers. The general approach pursued to date in other labs is a large format array of single-pixel detectors [3].

We propose to develop STJ detectors with intrinsic imaging, meaning that the detectors have many more pixels than read out channels [4]-[5]. We propose to do this using an STJ detector with lateral trapping. This work is an extension of successful x-ray work, where we have made detectors with a resolution of 13 eV FWHM for a 6 keV X-ray [6]-[8].

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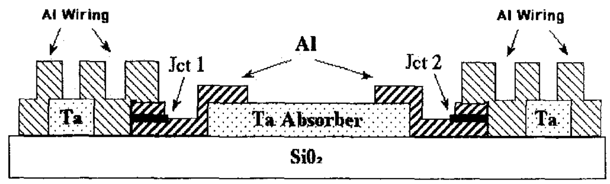

Fig. 1. Schematic of an imaging STJ detector using lateral trapping and backtunneling. Not shown is an insulating SiO layer between the trap and wiring, which has a via for contact between the two layers. The Ta plugs are omitted for devices designed without backtunneling. Courtesy of Elsevier Science B.V. [4].

II. OPERATING PRINCIPLE

Fig. 1 shows a schematic drawing of an imaging STJ detector. Many physical processes are involved in the operation of these detectors [9]. First, an incident photon is absorbed in the central Ta film breaking Cooper pairs and creating quasiparticles. The quasiparticles diffuse until they reach the Al. In the Al, they can scatter inelastically, losing energy until they approach the Al gap. Once the quasiparticles scatter below the gap of Ta, they are "trapped" in the Al electrode. The quasiparticles then tunnel and are read out as an excess sub-gap current. The current pulses are integrated to obtain a charge from each junction, Q_1 and Q_2.

We have the relation

$$Q_1 + Q_2 = eN_\gamma \propto \frac{E_\gamma}{\Delta_{Ta}} \tag{1}$$

where E_γ is the photon energy, N_γ is the number of quasiparticles created by the photon, and Δ_{Ta} is the energy gap of Ta.

The fraction of charge collected in each junction tells us the location of the absorption event. If the photon is absorbed in the center, then the charge divides equally. If the photon is absorbed at one edge of the absorber, then the closest junction collects most of the charge.

An important process in our detectors is backtunneling. Consider one half of Fig. 1. We have a lateral Ta/Al/AlOx/Al/Ta tunnel junction. Excited quasiparticles enter the Al trap from the Ta absorber. At high bias voltages, quasiparticles in the Al trap can only tunnel directly to the counter electrode. The high Ta gap then confines excited quasiparticles near the tunnel barrier. The confined quasiparticles in the counter electrode can then undergo a pair-mediated tunneling process called backtunneling. When a quasiparticle backtunnels, a pair in the trap is broken. One electron from the pair tunnels to the counter electrode and recombines with the quasiparticle in the counter electrode. The remaining electron in the trap is promoted to be a quasiparticle in the trap. So, it appears that a quasiparticle is transferred from the counter electrode to the trap against the bias. However, a *charge* is transferred in the forward direction, with the bias. Although backtunneling seems like a complicated process, it has the same probability as direct tunneling.

Keeping both processes in mind, we see that a confined quasiparticle can circulate, first tunneling and then backtunneling. Because both tunneling and backtunneling transfer a charge in the forward direction, this effect gives the junction charge gain. Thus, we measure an integrated charge many times greater then the number of quasiparticles initially created.

We have designed our present devices to maximize backtunneling by interrupting the Al wiring with Ta plugs. The absorber and the plugs confine the quasiparticles near the junction.

III. Experimental Conditions

All devices have been fabricated at Yale in a high vacuum deposition system with in-situ ion beam cleaning. We start with an oxidized Si substrate. The Ta absorber and plugs are then sputtered at 750 °C. Next a Nb ground contact is sputtered. The Al trilayer is then evaporated in one vacuum cycle. A SiO insulating layer is evaporated and finally Al wiring is evaporated. An in-situ ion beam cleaning is performed before each metal deposition to ensure good metallic contact. All layers are patterned photolithographically using either wet etching or lift-off.

Measurements are made in a two stage ^{3}He dewar. The base temperature is 220 mK.

To measure the photo-response of our junctions, we use a room temperature JFET current amplifier. We use an Amptek A250 amplifier with a 2SK146 input transistor. Extra circuitry is added that allows the A250/2SK146 to be dc coupled to the junction [11]. The amplifier thus provides an active voltage bias for the junction.

We illuminate the detectors using a small Hg lamp calibration source. A bandpass filter selects one photon energy at a time. We bring light into the dewar using an optical fiber. The fiber is UV grade fused silica. The fiber is Al coated to enhance UV transmission up to energies of 6 eV. The filtered light passes through a fiber splitter that divides the light equally between two fibers. One of these fibers is fed into the dewar. The other fiber is fed into a photomultiplier tube that simultaneously measures the intensity.

IV. Results

We have made high quality junctions. Two characteristics are important for low noise. First, junctions should have a low sub-gap current to minimize shot noise. They should also have a large sub-gap resistance to minimize the contribution of amplifier voltage noise. Fig. 2a shows the sub-gap I-V curve of a 400 μm^2 junction with a normal state resistance of R_{NN}=2.3 Ω. At 220 mK we measure a sub-gap current of ~5 nA and a sub-gap resistance of 880 kΩ. The sub-gap resistance exceeds our expectations by an order of magnitude.

We do not always observe these nearly ideal I-V curves when the junctions are integrated in to a complete detector with backtunneling. Fig. 2b shows the sub-gap curve of a 100 μm^2 junction from a different fabrication run, which is

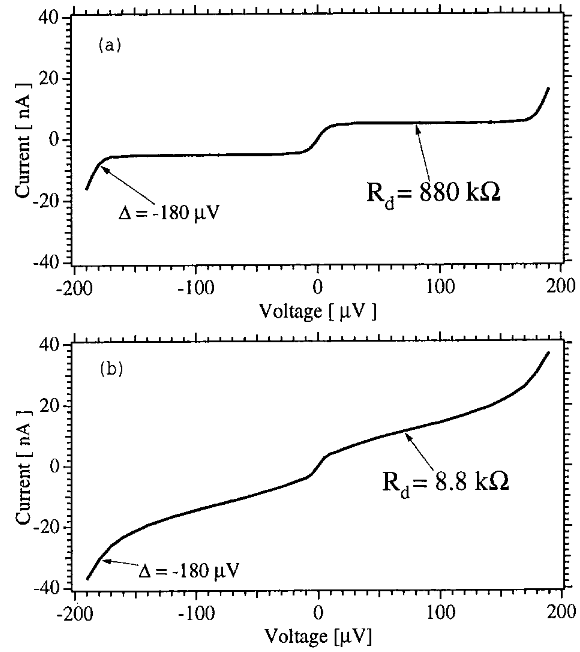

Fig. 2. Sub-gap I-V curves of two junctions. Both measurements are made at T=220 mK. The junction parameters are: (a) Area=400 μm^2, R_{NN}=2.3 Ω; (b) Area=100 μm^2, R_{NN}=13.8 Ω. Courtesy of Elsevier Science B.V. [4].

integrated into a working detector. This junction has a normal state resistance of R_{NN}=13.8 Ω. In this figure, the sub-gap resistance is only 8 kΩ. We do not believe that flaws in the tunnel barrier cause this excess current. Devices from the same wafer with nominally identical junctions, but no Ta plugs in the wiring do have nearly ideal I-V curves. Also, in some junctions with Ta plugs and curves initially similar to Fig. 2b, we were able to reduce the excess current by as much as a factor of 3 by placing the dewar in an electromagnetically-shielded enclosure. We will discuss a possible cause for the excess current in the analysis section.

We have detected optical and ultraviolet photons using a detector with junctions as in Fig. 2b. This device has a Ta absorber 10 μm wide by 100 μm long by 0.6 microns thick. Each Al trap overlaps the absorber by 5 μm. In Fig. 3, we show two histograms of events recorded with this detector. Fig. 3a and Fig. 3b are the response to illumination with 4.89 eV ultraviolet photons and 2.27 eV green photons, respectively. We have plotted the number of events versus the collected charge. The raw current pulses were digitally filtered before being integrated to obtain the charge measurements.

The full width at half maximum (FWHM) of the histogram for 4.89 eV photons is 0.4 eV. The full width at half maximum (FWHM) of the histogram for 2.27 eV photons is 0.47 eV. The histograms in Fig. 3 contain events from a limited range of the absorber. This gives us a resolving power of R=12 at 4.89 eV and of R=4.8 at 2.27 eV. These resolving powers can be compared to the theoretical limit for devices with backtunneling: R=25 and R=17 at 4.89 eV and 2.27 eV respectively.

The resolution over the whole absorber, under UV illumination, is 1.5 eV, for a resolving power of R=3.5. An energy resolving power of R=3.5 in the UV implies that the detector can resolve 5 spatial pixels [4]. This particular detector has an active absorber area 70 μm long by 10 μm

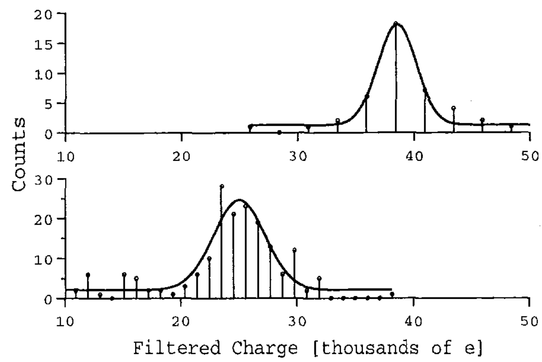

Fig. 3. Histograms of single photon events. Incident photon energies for plot (a) and (b) are 4.89 eV and 2.27 eV respectively.

wide. This is achieved with only two readout channels. The degradation of the resolution when events from the whole absorber are included may be caused by variations of the Ta gap energy near the Nb ground contact. We have observed this effect in our x-ray detectors.

We have measured the fall time of the photon-induced current pulses by averaging 2000 single UV photon pulses and fitting an exponential to the waveform. The fall time of the pulse should be the effective quasiparticle recombination time in the Al junctions. Since the quasiparticles are confined near the junctions by the Ta plugs, they continue to tunnel and backtunnel until they are lost. We measure an effective quasiparticle recombination time of τ_{rec}=159 μs.

The average number of times that a quasiparticle tunnels is $n=\tau_{rec}/\tau_{tun}$, where τ_{tun} is the tunnel time. We can extract the tunnel time from measurements of R_{NN}. We find τ_{tun}=2.46 μs. With this we find that n=65. We estimate that the initial number of quasiparticles created by a 4.89 eV photon is about N_o=4000 [12]. The total number of electrons we collect is about N_{total}=240,000. So, the addition of the Ta plugs in the wiring does produce a large charge gain.

V. Analysis

We have measured the noise spectra of both junctions with no illumination and they are consistent with the measured resolution. However, the noise spectra contain excess noise. The excess noise is clearly dependent on the excess current that we see in the junctions; the excess noise increases as the excess current increases. However, the power spectral density of the noise exceeds the expected shot noise density ($2eI_{dc}$) of the excess current by more than an order of magnitude. In addition the noise is not white, but instead rolls off above a few kilohertz. This roll-off frequency varies with the bias condition.

We recently reported that the excess noise and low-frequency roll-off were consistent with the excess current being generated by stray photons with energy E_γ>2Δ striking the device and creating non-equilibrium quasiparticles [13]. We proposed that the stray photons were coming from blackbody radiation from surrounding parts of the dewar or photons coupling down the leads. We have recently performed measurements of devices in a light-tight sample holder connected to room temperature by rigid SMA cables with cold, copper powder filters. Both the sample holder and powder filters were at the base temperature of 256 mK. The cut of frequency of the powder filters was approximately 200 MHz, well below the gap frequencies of Ta and Al, 350 GHz and 80 GHz respectively. We saw essentially no change in either the excess current or excess noise of the devices. We believe this measurement conclusively proves that *stray photons are not the source of the excess current and noise.*

We now propose another explanation for the excess noise. Since the number of thermal quasiparticles in our junctions is only about $N\sim10^5$, the thermodynamic fluctuations of the number of thermal quasiparticles should be of order $\sqrt{N}\sim0.3\%$ of N. Since the tunneling current is proportional to the total number of quasiparticles in both electrodes, the fluctuation of the number of thermal quasiparticles should lead to a current noise that substantially exceeds the standard shot noise in our devices. In addition, the fluctuation in the number should happen on a time scale of order the recombination time for the quasiparticles, τ_{rec}. This would lead to a noise spectrum that rolls off above $1/\tau_{rec}$. This type of noise has been studied in semiconductors and is often refered to as thermal generation-recombination noise in the literature [14].

To develop a quantitative theory of this noise, we assume that the balance of a thermal generation current and thermal recombination current determines the number of thermal quasiparticles. The recombination current is $I_{rec}=N_{eq}/\tau_{rec}$, where N_{eq} is the number of quasiparticles and τ_{rec} is the recombination time. In equilibrium, the generation current must equal the recombination current. Now, both recombination and generation are random processes, so both the recombination and generation current should have an associated shot noise. If we assume that the magnitude of the average generation current is only weakly dependent on the number of thermal quasiparticles, then we can write the following Langevin equation for the response of the number of the thermal quasiparticles to the generation-recombination shot noise:

$$\frac{d(\delta N_{eq})}{dt} + \frac{\delta N_{eq}}{\tau_{rec}} = i_{g-r}(t) \tag{2}$$

where δN_{eq} is the deviation of the number from the average value and i_{g-r} is a particle current with units s^{-1}.

If we assume that the generation and recombination current are standard white, shot-noise process, then we get the following power spectral density for the fluctuations of the number:

$$\left| \mathcal{X}(\nu) \right|^2 = 2\left(\alpha_g + \alpha_r\right) \tau_{rec} N_{eq} \left(\frac{1}{1 + \left(2\pi\tau_{rec}\nu\right)^2} \right) \tag{3}$$

where N_{eq} is the average number of quasiparticles and $\alpha_{g(r)}$ is the effective magnitude of the carriers in the generation (recombination) current. For instance, if we assume the two currents are independent and that quasiparticles are always generated and recombine in pairs, then $\alpha_g = \alpha_r = 2$. If we integrate this power spectrum, we predict an rms fluctuation of the number

$$\sigma_{\delta N} = \left(\frac{\alpha_{tot}}{2} N_{eq} \right)^{1/2} \tag{4}$$

where $\alpha_{tot}=\alpha_g+\alpha_r$. This result agrees with our expectation that the thermodynamic fluctuations of N_{eq} should be of order $\sqrt{N_{eq}}$.

If the tunnel time of the junction is much shorter than the recombination time, then the tunneling current "measures" the fluctuations of the number of quasiparticles on both sides of the junction. The fluctuations of N_{eq} therefore lead to a current noise in the junction

$$\delta I_{eq}(t) = e\,\frac{\delta N_{eq}(t)}{\tau_{tun}} \tag{5}$$

where τ_{tun} is the tunnel time. Here we are assuming that the junction is biased at a voltage V>>kT/e, so that only electron-like quasiparticles can tunnel from the trap and only hole-like quasiparticles can backtunnel from the counter-electrode. This implies that τ_{tun} here is twice the normal-metal tunnel time. This current noise will have a power spectral density

$$\left|\mathcal{I}_{\delta N}(\nu)\right|^2 = 2\left(\alpha_g + \alpha_r\right)\frac{\tau_{rec}}{\tau_{tun}}\,eI_{eq}\left(\frac{1}{1+\left(2\pi\tau_{rec}\nu\right)^2}\right) \tag{6}$$

We notice two things. First the noise indeed rolls off above $1/\tau_{rec}$. Second, the magnitude of the noise is larger than the standard shot noise by the factor $\alpha_{tot}(\tau_{rec}/\tau_{tun})$. We recognize $n=\tau_{rec}/\tau_{tun}$ as the backtunneling multiplication factor.

When we read-out a photon induced current pulse, this current noise will be integrated for a time of order the fall time of the pulse which is τ_{rec}. The rms fluctuation in the collected charge due to this noise will therefore be

$$\sigma_{N_{eq}} \approx \left(\frac{\alpha_{tot}}{2}\,N_{eq}\right)^{1/2} \tag{7}$$

where there is a factor of order unity neglected that would account for the effect of filtering, etc.. This noise is referred to the input of the junction. We can also compare this to the statistical noise added by the backtunneling process itself, which is $\sigma_{back} = \sqrt{N_\gamma}$ in the limit of large n. Basically, we see that the fluctuation of the thermal quasiparticles will degrade the energy resolution compared to the backtunneling limit if $N_{eq} \geq N_\gamma$. This is the case in our measurements where $N_{eq} \approx 2N_\gamma$.

This result is surprising. It had not been previously understood that backtunneling multiplication would also effectively multiply the shot noise due to thermally excited quasiparticles. It was believed (incorrectly) that backtunneling could increase the signal of the detector over the noise of thermal quasiparticles to the point that the detector should be limited by the backtunneling noise of N_γ. This is clearly not the case. The only way to eliminate the noise associated with thermal quasiparticles is to cool the detector to lower temperatures or raise the effective gap of the junction.

This surprising result arises from the fact that the Ta plugs in our wiring isolate the quasiparticle system of the Al electrodes. At our operating temperatures, there are basically no thermal quasiparticles in the Ta and few of the quasiparticles in the Al are excited over the gap of Ta. We can think of the quasiparticles as a system that can exchange particles and energy with a reservoir, its thermodynamics described by the grand canonical ensemble. The reservoir is conceptually divided into two parts that are in equilibrium with each other. The phonon system is the energy reservoir, while the Cooper pairs form a particle reservoir. In addition, since there are few quasiparticle excitations in the Al at this temperature, we have a *small*, isolated system. The diminutive size of the system leads to relatively large fluctuations of its thermodynamic quantities.

Given this explanation for the excess noise, the bias dependence of the roll-off frequency of the excess noise is consistent with the excess current being caused by self-heating of the junctions. In this scenario, the excess current represents additional thermal quasiparticles excited by the Joule power dissipated in the junction by the bias current and voltage. These additional quasiparticles decrease the recombination lifetime of quasiparticles in the junction, causing the roll-off of the noise to move to higher frequency. This is indeed what we observe. Devices with Ta plugs are more prone to self-heating because the Joule power added by the bias cannot be carried away by quasiparticles diffusing into the leads.

VI. Conclusions

We have begun the development and testing of imaging, single photon spectrometers. Our devices use superconducting tunnel junctions with lateral trapping. Our preliminary fabrication results are very promising. We have detected single optical and UV photons with these first detectors. Our results suggest a that a new noise source exists for small, isolated tunnel junctions: thermodynamic fluctuations. The existence of this noise suggests that whether an STJ detector uses backtunneling for charge gain or not, it must be operated at a very low temperature compared to the superconducting transition temperature of the junctions. The temperature must be low enough that the number of thermal quasiparticles in the junction is small compared to the number produced by an incident photon.

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