Superconducting Tunnel Junctions as Photon Counting Detectors in the Infrared to the Ultraviolet

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Abstract—Photon counting experiments with Ta/Al superconducting tunnel junctions are presented. Single photon detection is demonstrated in the wavelength range $\lambda \approx 200\text{--}2000$ nm with a resolving power $\lambda/\Delta\lambda \approx 22\text{--}4$. The response of the detector shows good linearity with photon energy.

I. INTRODUCTION

Superconducting tunnel junctions (STJs) are being investigated as photon counting detectors because of their predicted high energy resolving power. This quality arises from the low energy required to break Cooper pairs and to generate free charge carriers (quasiparticles) in a superconductor. Quasiparticles can be detected by the tunneling of electrons across the insulating barrier of the STJ. Calculations for Sn and Nb indicate that the initial number of quasiparticles $N(E)$ generated by the absorption of a photon with energy E is given as [1], [2]:

$$N(E) = \frac{E}{\epsilon} \pm \sqrt{F \frac{E}{\epsilon}} \quad (1)$$

Here $\epsilon \approx 1.7\Delta$ (with Δ the bandgap of the superconductor) is the average energy required to generate one quasiparticle and $F \approx 0.2$ is the Fano factor. Fano-limited energy resolution would be obtained if each initial quasiparticle would be detected by exactly one tunnel process across the barrier. In practice, the energy resolution is degraded by statistical variations in the number of tunnel processes per quasiparticle (tunnel noise), electronic noise and spatial nonuniformity in the response of the detector.

Equation (1) implies that even for a detector based on a relatively high-bandgap material like Nb ($\Delta = 1.5$ meV), photon counting with moderate energy resolution should be possible in the UV and visible. This has been demonstrated for Nb-based STJs with Al trapping layers [3]. This quality makes the STJ an attractive competitor to semiconductor-based detectors for astronomical application [4].

In this paper photon counting experiments with tantalum/aluminium (Ta/Al) STJs in the UV-IR are presented. The energy resolving power and response linearity are discussed. No data on detection efficiency are available yet, although measurements of the reflectivity and transmission confirm theoretical models. Experiments at X-ray wave-

lengths with these devices will be reported elsewhere.

II. DETECTOR DESCRIPTION

The STJs used in this work are fabricated by Oxford Instruments Scientific Research Division (Cambridge, UK). The detector chip consists of a sapphire substrate on which 10 square STJs are made in five different sizes: 10×10 , 20×20 , 30×30 , 50×50 and $100 \times 100 \mu\text{m}^2$. The symmetrical STJs are made from Ta/Al/AlOx/Al/Ta multilayers with 100 nm thick Ta and 30 nm thick Al. The base electrode Ta is epitaxial (RRR=33), whereas the top electrode is polycrystalline. The contact leads are $\sim 2 \mu\text{m}$ wide and made of Nb, in order to prevent the diffusion of quasiparticles out of the lower bandgap Ta electrodes. The sum energy gap (2Δ) at the barrier, as measured from the I-V curves at $T = 300$ mK, is 1.05 meV. This is significantly lower than twice the energy gap for bulk Ta ($2\Delta = 1.4$ meV), due to the Al proximity layers. Their thickness was chosen such that the resulting energy gap would allow operation of the devices at the base temperature of the cryostat without being limited by excessive thermal currents. The reduced energy gap in the Al causes these layers to act as quasiparticle traps [5]. This enhances the tunnel rate and reduces loss rates, by confining the quasiparticles close to the barrier, away from possible loss sites such as the surfaces and interfaces. The AlOx tunnel barrier has a resistivity of $2.6 \times 10^{-6} \Omega \text{cm}^2$. The leakage current densities, as measured at $T = 300$ mK, are $50\text{--}100 \text{ fA}/\mu\text{m}^2$ and independent of the size of the device. The I-V characteristics of the STJs are dominated by leakage currents up to $T \approx 400$ mK. Typical operating conditions for a $30 \times 30 \mu\text{m}^2$ device are: $T = 0.30$ K, $V_{\text{BIAS}} = 0.10$ mV, $I = 120$ pA, $R_{\text{DYN}} \approx 0.8 \text{ M}\Omega$.

III. EXPERIMENTAL SET-UP

The experiments have been performed in a ^3He cryostat with a base temperature $T = 0.30$ K and the possibility of stable operation at temperatures up to ~ 1.2 K. The detector chip is clamped to a cold finger in the inner vacuum chamber of the cryostat. A superconducting magnet is available to provide the magnetic field parallel to the plane of the tunnel barrier, which is required to suppress the Josephson

current and Fiske steps. The light source is a Xenon lamp combined with a grating monochromator. The wavelength range 200-5000 nm can be covered with the use of two gratings. Additional filters are used if the suppression of the light in higher orders of the monochromator is desired. A UV-grade silica fiber is used to couple the light into the cryostat and onto the detectors. The fiber limits the available wavelength range to 200-2000 nm. In the present experiment, the end of the fiber was in close contact with the backside of the sapphire substrate, thus illuminating the base electrode of the detectors. Since the sapphire is transparent and the 100 nm thick Ta transmits $<2\%$ of the light in the available wavelength range, essentially only the base electrode is stimulated in this experiment. The source intensity is adjusted with the entrance slit of the monochromator, such that the event rate on the detector is ~ 300 cts/s.

The STJs are read-out with a charge sensitive amplifier ($RC=350$ μ s) at about 1 m distance and a shaping stage, both at room temperature. Each detected photon gives rise to a pulse at the output of the preamplifier. The amplitude and the rise time of this pulse correspond to the total number of tunneled electrons (charge output) and the decay time of the signal, respectively, and are stored on a PC. The limiting noise level of the electronics chain with open input is ~ 400 electrons rms. The electronic noise is monitored through the width of the response to an electronic pulser fed into the electronics.

IV. MEASUREMENTS AND RESULTS

A. Spectra and Detector Responsivity

Single photon pulse height spectra have been recorded with STJs of all five sizes at $T=300$ mK, $V_{\text{BIAS}}=0.10$ mV and $B\approx 0.0075$ T, and for wavelengths ranging from 200-2000 nm ($E=6.2$ - 0.62 eV). Examples of spectra from a 20×20 μm^2 device are shown in Fig.1. The measured responsivities (defined as the charge output per eV of photon energy) and the pulse decay time for each device size are given in Table I. They showed only minor variations in the bias voltage range $V_{\text{BIAS}}=0.05$ - 0.30 . Also variation of temperature and magnetic field strength induced no significant changes. The signal-to-noise ratio is expressed as the minimum detectable photon energy, defined as $5\sigma_{\text{NOISE}}$ (with σ_{NOISE} derived from the width of the electronic pulser signal). Clearly, the responsivity and the quasiparticle lifetime are strongly dependent on device size. This, together with the good energy linearity (see section IV.B), indicates that loss of quasiparticles occurs predominantly at the edges of the devices, rather than at interfaces/surfaces or in the bulk material.

Nevertheless, the optimum signal-to-noise ratio is found for the 20×20 μm^2 devices. This is due to higher noise levels for larger device areas, because of larger STJ capacitance, higher bias currents and possibly a higher sensitivity

Fig.1. Single photon spectra at four wavelengths recorded with a 20×20 μm^2 STJ ($T=0.30$ K, $V_{\text{BIAS}}=0.10$ mV, $B=0.0075$ T). The broad structure at lower pulse heights in the 246 nm spectrum is caused by false light from the monochromator. The three peaks in the 983 nm spectrum correspond to three grating orders of the monochromator ($\lambda=983$, $983/2$ and $983/3$ nm).

to acoustic noise. In addition, the electronics sensitivity decreases for increasing pulse decay time. Fig.2 shows a digitised pulse from a 20×20 μm^2 device, recorded at the output of the charge sensitive preamplifier. The solid line is the result of a least squares fit of the measured pulse shape to an exponentially decaying pulse from the STJ, convoluted with the response function of the preamplifier ($RC=350$ μ s). The dashed line is the predicted signal in case of $RC=\infty$, illustrating the reduced sensitivity of the electronics for signals with relatively long decay times.

Assuming that the initial number of quasiparticles is given as $N(E)=E/\epsilon$, with $\epsilon\approx 1.7\Delta_{\text{Ta}}$, the observed responsivities correspond to an average number of tunnel processes

TABLE I
MEASURED RESPONSIVITY, PULSE DECAY TIME AND ENERGY RESOLUTION FOR THE 5 DEVICE SIZES ($T=0.30$ K, $V_{bias}=0.10$ mV, $B=0.0075$ T).

device size (μm^2)	responsivity (electrons/eV)	$\langle n \rangle$	decay time (μs)	minimum detectable photon energy (eV)	FWHM @ $\lambda=500$ nm (eV)
10x10	0.5×10^4	6	2.8	0.51 ($\lambda=2.4 \mu\text{m}$)	0.31
20x20	2.5×10^4	30	12.5	0.30 ($\lambda=4.1 \mu\text{m}$)	0.19
30x30	5.5×10^4	65	26	0.32 ($\lambda=3.9 \mu\text{m}$)	0.20
50x50	10×10^4	119	46	0.42 ($\lambda=3.0 \mu\text{m}$)	0.22
100x100	16×10^4	190	70	0.80 ($\lambda=1.6 \mu\text{m}$)	0.39

Fig.2. Digitised pulse from a 300 nm photon on a $20 \times 20 \mu\text{m}^2$ device, recorded at the output of the charge sensitive preamplifier (see text).

per quasiparticle ranging from $\langle n \rangle = 6$ for the smallest device, to $\langle n \rangle = 190$ for the largest device (see Table I). The tunnel times, derived as $\tau_{TUN} = \tau_{decay} / \langle n \rangle$ are $\sim 0.4 \mu\text{s}$.

B. Linearity of the Energy Response

In principle, the linearity of the energy response could be evaluated from the spectra recorded at different photon energies. The accuracy of such an evaluation, however, tends to be limited by the drifts in operating temperature or detector response. The distribution of the monochromator output over several grating orders provides a much more rigorous test of the response linearity, since the grating equation guarantees that the output in the various orders are exact multiples of the same wavelength. The top panel of Fig.3 shows a spectrum recorded with a $20 \times 20 \mu\text{m}^2$ device, illuminated with light from the monochromator set for $\lambda = 2383$ nm. While the orders 2-9 (corresponding to $\lambda \approx 1192$ -265 nm) can easily be distinguished, the first order is cut off by the low transmission of the optical fiber. The middle panel shows the measured peak positions of the various orders as a function of the corresponding photon

Fig.3. Linearity of the energy response. Top: the charge output spectrum of a $20 \times 20 \mu\text{m}^2$ device when illuminated with multiple orders from the monochromator (set for $\lambda = 2383$ nm). Middle: measured peak positions versus photon energy. The solid line is a best fit of the data to a linear relation. Bottom: residuals of the fit. Superimposed is the $1/e$ absorption depth in Ta (solid line).

energy. The solid line is the best fit of the data to a linear relation. The offset of -31 ADC channels is an electronic offset. The residuals (measured-calculated) of the fit, shown in the bottom panel of Fig.3, are $< 0.6\%$. The trend for negative residuals at higher photon energies could be an indication for non-linearity due to self-recombination of

quasiparticles, which was found to be a significant process at X-ray photon energies [6]. The positive residual just above 2 eV is reproduced at other wavelength settings of the monochromator, with completely different intensity ratios in the various orders. It happens to coincide with a maximum in the $1/e$ absorption depth in Ta (superimposed in the bottom panel of Fig.3). This may be indicative of either enhanced quasiparticle and pristine phonon loss for absorptions close to the sapphire/tantalum interface, or a dependence on photon energy of the average energy ϵ required to generate one quasiparticle.

C. Energy Resolution

The energy resolution (FWHM) has been measured as a function of photon energy for all 5 device sizes. The measured resolution at $E=2.5$ eV ($\lambda=500$ nm) is given in the last column of Table I. For the device size with the best results ($20 \times 20 \mu\text{m}^2$) the measured energy resolution ΔE as a function of photon energy is shown in Fig.4, together with the measured electronic noise ($\Delta E_{\text{NOISE}} \approx 0.14$ eV) and the derived device-limited resolution $\Delta E_{\text{LIM}} = (\Delta E^2 - \Delta E_{\text{NOISE}}^2)^{1/2}$. The solid line in Fig.4 represents the predicted device limited resolution for a symmetrical device [7],[8]:

$$\Delta E = 2.355 \sqrt{\epsilon E (F + 1 + \frac{1}{\langle n \rangle})} \quad (2)$$

Here, $\epsilon=1.7\Delta$ and the Fano factor $F=0.22$ have been chosen the same as for Nb [2], and the average number of tunnel processes per quasiparticle $\langle n \rangle = \infty$. The dashed line is the predicted resolution, if an additional contribution of 0.014 eV per eV of photon energy, arising from spatial nonuniformities in the response of the device, is included. Clearly, the device-limited energy resolution derived from the measurements is very close to the tunnel-noise-limited performance in this wavelength range.

V. CONCLUSION

The photon counting capabilities of Ta based STJs with Al trapping layers have been demonstrated in the wavelength range $\lambda=200$ -2000 nm, with detector sizes ranging from $10 \times 10 \mu\text{m}^2$ to $100 \times 100 \mu\text{m}^2$. The best signal-to-noise ratio is obtained with a $20 \times 20 \mu\text{m}^2$ device, which should allow photon counting up to $\lambda \approx 4 \mu\text{m}$. While the response of the detectors is linear with photon energy to within 0.6% in the wavelength range $\lambda=200$ -2000 nm, the deviations from linearity may suggest a small effect of quasiparticle self-recombination, and a correlation with the absorption coefficient in Ta. The measured wavelength resolving power is $\lambda/\Delta\lambda=22$ -4, for $\lambda=200$ -2000 nm. The derived device-limited resolution is in good agreement with the predicted Fano- and tunnel-noise-limited resolution for a symmetrical Ta device, assuming the same energy conversion efficiency

Fig.4. Measured energy resolution as a function of photon energy for a $20 \times 20 \mu\text{m}^2$ STJ.

and Fano factor as for Nb.

The performance of Ta/Al devices is found superior to Nb/Al devices [3]. This is a combined effect of the much longer quasiparticle life time and the lower energy gap in Ta, which results in larger signal amplitudes and a higher intrinsic energy resolving power.

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