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ABSTRACT

Measurements of the X-ray response of niobium-based superconducting tunnel junctions with Al trapping layers are presented. Signal amplitudes equivalent to as many as 2.3×10^8 tunneled electrons for a 5.9 keV photon are observed, corresponding to an amplification factor of ~ 100 per initially created quasiparticle in niobium. The detectors, however, exhibit a significant non-linearity in their energy response. The energy resolution is ~ 140 eV FWHM at 5.9 keV.

1. INTRODUCTION

Superconducting tunnel junctions (STJs) are investigated extensively because of their predicted high energy resolving power for X-ray radiation, compared to conventional semiconductor or gas-based detectors. The energy of a photon absorbed in the superconducting material will be partly converted into excited electronic states (quasiparticles) in excess of the equilibrium population, due to the breaking of Cooper pairs. The number of excess quasiparticles is proportional to the energy E of the incident photon: $N_0 = E/\epsilon$. For niobium, the average energy ϵ necessary to generate one excess quasiparticle has been calculated¹ to be $\sim 1.75\Delta$, where Δ is the bandgap of the superconductor. The advantage over conventional detectors arises from the small values of Δ in superconductors: typically 3 orders of magnitude lower than the bandgap for semiconductors. Thus, for a commonly used material as niobium, the limiting intrinsic resolution at 6 keV photon energy is predicted¹ to be ~ 4 eV (FWHM). In practical applications, this resolution is compromised by electronic noise and by (spatially non-uniform) loss of quasiparticles² and associated statistical fluctuations³.

In order to enhance the sensitivity of the STJs as radiation or particle detectors, Booth⁴ has proposed the concept of quasiparticle trapping: quasiparticles created in a superconductor S_1 , acting as an absorber, are trapped in an adjacent layer of superconducting material S_2 with a lower bandgap by rapid energy relaxation as a result of quasiparticle scattering. In an STJ of configuration $S_1/S_2/\text{barrier}/S_2/S_1$ with a sufficiently thin S_2 layer, the quasiparticles will be confined close to the tunnel barrier, thus

enhancing the tunnel probability and reducing the loss mechanisms such as diffusion into the leads and trapping at various interfaces. Good experimental results have been reported by Mears *et al.*⁵ (36 eV FWHM energy resolution at 5.9 keV for a niobium based STJ with 200 nm thick Al trapping layers at 70 mK) and Goldie *et al.*⁶. In this work we report experiments on niobium based STJs with 120 nm thick Al trapping layers at $T=0.3$ K.

Figure 1: SEM photograph of a typical $50 \times 50 \mu\text{m}^2$ STJ with $3 \mu\text{m}$ wide leads. The rim around the device is an insulating dielectric necessary for the fabrication of the top connecting lead.

2. DEVICE CHARACTERISTICS

The STJs used for this work have been fabricated by Oxford Instruments (Cambridge, UK). The detector chip (ID. 868.1.2) carries 8 STJs: four $20 \times 20 \mu\text{m}^2$ and four $50 \times 50 \mu\text{m}^2$ sized devices. The width of the leads is $3 \mu\text{m}$. They are Nb-Al-AlOx-Al-Nb multilayers deposited on polished sapphire substrates. The base and top electrodes of the devices have identical layer thicknesses: 100 nm of niobium and 120 nm of aluminium. The base film niobium is epitaxial, whereas the top electrode is polycrystalline. Figure 1 shows an SEM photograph of a $50 \times 50 \mu\text{m}^2$ device. The AlOx barrier has an estimated thickness of <1 nm and a resistance of $\sim 2.2 \times 10^{-6} \text{ Ohm cm}^2$. The bandgap of the devices, as derived from the onset of the increase to the normal resistance regime in the I-V curves and assuming equal gaps in top and base electrode, is 0.44 mV. In spite of the very high electron transmissivity, the junctions show low leakage currents. This is illustrated in figure 2, which shows the measured subgap current densities in the temperature range 0.3-1.1 K for a $20 \times 20 \mu\text{m}^2$ device. The solid line is the calculated subgap current density for a BCS-like temperature dependence using the above mentioned numbers for the bandgap and the barrier resistance. An additional leakage current density of $2.5 \times 10^{-4} \text{ nA } \mu\text{m}^{-2}$ is also included. The triangular data points refer to measurements of the subgap currents at $T=0.3$ K in different cooldowns.

They show a variation in current density over several orders of magnitude. This is attributed to different degrees of trapping of magnetic flux. From the lowest measured current density (which was similar for the best 20 and 50 micron devices) it is concluded that the real leakage current (as opposed to excess current induced by trapped flux) can only be established at $T < 0.3$ K. This leakage current density is of the same order of magnitude as in similar niobium-based devices with thin (5 nm) Al layers⁷.

Figure 2: Measured subgap current density (at $V_b = 0.1$ mV) versus T for the $20 \times 20 \mu\text{m}^2$ device. The solid and dashed lines are calculated current densities with and without leakage current added.

The characteristic times for trapping of quasiparticles from Nb into the trap formed by the proximitized Nb and the Al, as well as the characteristic times for excitation and tunneling from the trap have been estimated using the work of Golubov *et al.*⁸ on the proximity effect in dirty superconductors. From the ratio of measured bandgap and bulk niobium bandgap, the proximity parameter $\gamma_m \approx 6$ (see ref.8, figure 2) is derived. It then follows that the trapping time $\tau_{tr} < 1$ ns, whereas the excitation time is on the microsecond timescale. For the calculation of the tunnel time, one has to take into account that the quasiparticles are confined effectively in the Al layer as well as in the proximitized part of the Nb layer. The latter layer has a thickness of $\sim 0.9\xi_s$ for $\gamma_m = 6$ (see ref.8, figure 8), with ξ_s the coherence length in Nb. Thus, the tunnel times are estimated as^{8,9}:

$$\tau_{tun} = 4 \cdot e^2 \cdot R_n \cdot A [N_{Al}(0) \cdot d_{Al} + N_{Nb}(0) \cdot d_{Nb}^{trap}] \cdot \sqrt{\frac{(\Delta + V_b)^2 - \Delta^2}{(\Delta + V_b)^2}}$$

yielding $\tau_{tun} \approx 0.31 \mu\text{s}$. Here, R_n is the normal resistance, A is the area of the junction, $N_{Nb}(0)$ and $N_{Al}(0)$ are the normal state single spin densities of state of Nb and Al, d_{Nb}^{trap} and d_{Al} are the effective confinement lengths in the proximitized Nb (~ 12 nm) and the thickness of the Al layer, and V_b the applied bias voltage (0.2 mV). A lower limit for $\tau_{tun} \approx 0.21 \mu\text{s}$ is found if only the Al thickness is taken as the confinement length. Note that the proximity model used here does not strictly apply for the base

film Nb and the relatively thick Al layers.

The measurements described in section 3 were performed in a ^3He cryostat at its base temperature of 0.3 K. The detectors are clamped to the cold stage in the evacuated inner vacuum chamber of the cryostat. The read-out electronics, consisting of a charge sensitive amplifier and a shaping stage, are operated at room temperature and have an equivalent lower noise limit of about 2000 electrons rms. A radioactive ^{55}Fe sample, emitting Mn-K $_{\alpha}$ (5.895 keV) and Mn-K $_{\beta}$ (6.491 keV) line complexes, is used as a radiation source.

Figure 3: ^{55}Fe spectra from the a) $20 \times 20 \mu\text{m}^2$ and b) $50 \times 50 \mu\text{m}^2$ device.

3. X-RAY MEASUREMENTS AND DISCUSSION

X-ray spectra were taken with a $20 \times 20 \mu\text{m}^2$ and a $50 \times 50 \mu\text{m}^2$ device. In most of the X-ray measurements the subgap currents at $T=0.3$ K and 0.1 mV bias voltage were ~ 0.2 nA and ~ 20 nA for the 20×20

μm^2 and a $50 \times 50 \mu\text{m}^2$ device, respectively. Especially for the larger device this is almost 2 orders of magnitude higher than the lowest measured value in this configuration. Figures 3a and 3b show spectra of each of these devices at $T=0.3 \text{ K}$, and at bias voltages corresponding to maximum detected charge ($\sim 0.2 \text{ mV}$) in both cases. The magnetic field applied parallel to the junction barrier in order to suppress the Josephson current was $\sim 75 \text{ Gauss}$. Apart from a large contribution of events related to photons absorbed in the sapphire substrate, two sets of Mn-K_α and Mn-K_β peaks are distinguished. These are attributed to absorptions in the niobium of the top and base films, but there is no clear indication for the assignment of the individual peaks to each of the electrodes. The difference in charge between the two K_α peaks is $\sim 1.3\%$ for the 20 micron device and $\sim 2.3\%$ for the 50 micron device. Signals due to absorption in the Al layers are expected to be about an order of magnitude lower in countrate than those from the Nb, i.e. their K_α peaks should be comparable to the K_β peaks from absorption in Nb. The spectra in figure 3, however, show no clear features which could be attributed to absorption in the aluminium, probably due to the Al layer thickness being close to the primary electron range in Al^{10} .

Figure 4: Measured charge output versus bias voltage for the high pulse height K_α peak in the spectra of the $20 \times 20 \mu\text{m}^2$ and the $50 \times 50 \mu\text{m}^2$ device.

Figure 4 shows the dependence of the measured charge output on the bias voltage for both devices. The data refer to the electrode with the larger pulse height, but the two electrodes showed essentially the same dependence on bias voltage. The maximum charge output is about 2.3×10^8 electrons for the $50 \times 50 \mu\text{m}^2$ device and 0.85×10^8 electrons for the $20 \times 20 \mu\text{m}^2$ device and occurs at a bias voltage of $\sim 200 \mu\text{V}$. This is about 2 orders of magnitude higher than measured from similar devices with thin (5 nm) Al layers, where trapping effects are much reduced. The enhanced charge output can be attributed to two mechanisms: charge carrier multiplication and enhanced tunnel probability. Firstly, if quasiparticles are trapped in the proximitized Nb and Al layers they relax from the Nb bulk bandgap energy of 1.55 meV to the bandgap energy of 0.44 meV in the Al layers. This relaxation is accompanied by the emission of a phonon having an energy of $\sim 1.1 \text{ meV}$, corresponding to the bandgap difference. This

phonon has sufficient energy to break one other Cooper pair in the trap, yielding two extra quasiparticles. Thus, if all phonons would break a Cooper pair, a maximum signal enhancement by a factor of 3 would be obtained. The phonons, however can escape from the trap into the Nb, where they cannot break Cooper pairs, and subsequently be lost into the substrate, or decay to lower energy phonons. The transmission coefficients for phonons of the various interfaces are¹¹: $T_{\text{Al} \rightarrow \text{Nb}} \approx 0.8$, $T_{\text{Nb} \rightarrow \text{Al}} \approx 0.3$ and $T_{\text{Nb} \rightarrow \text{sapphire}} \approx 0.1$. If, as a first approximation, the Al-Nb interface is assumed to be perfectly transmissive and all phonons crossing this interface are considered as being lost, a lower limit for the signal enhancement is obtained. Following Goldie *et al.*⁶, the probability η that a phonon breaks a pair in the trap is given as $\eta = 1 - \exp(-2d/\tau_{\text{pb}}c_t)$, with d the total thickness of the trap (240 nm), τ_{pb} the pair breaking time in the trap (0.22 ns) and c_t the transverse phonon velocity in the trap (3.3×10^5 cm/s), yielding $\eta \approx 0.5$. Thus, about half of the phonons would contribute to the gain enhancement and the lower limit for this gain factor would be 2. Secondly, the loss rates for quasiparticles are reduced since they can no longer diffuse into the connecting leads or be trapped at interfaces. This, in combination with reduced tunnel times from the trap (see section 2), greatly enhances the tunnel probability. Assuming the trapping mechanism to be sufficiently fast to collect all quasiparticles that are created in the initial photon absorption process in the niobium (i.e. $\sim 2.2 \times 10^6$ quasiparticles for a 6 keV photon), and taking into account a gain factor of two due to the phonons, the average number of tunnels across the barrier, derived from the observed maximum charge outputs, is ~ 20 for the $20 \times 20 \mu\text{m}^2$ device and ~ 50 for the $50 \times 50 \mu\text{m}^2$ device. This is in reasonable agreement with the quasiparticle lifetimes, derived from the observed pulse decay times of $\sim 6 \mu\text{s}$ and $\sim 15 \mu\text{s}$ for the 20 and 50 micron device, respectively. These pulse decay times were measured with a dedicated preamplifier with a $0.5 \mu\text{s}$ integration time constant, which allows the true pulse shapes to be studied. In general, the pulses were not exponential but showed a combination of a fast decay ($\sim 3 \mu\text{s}$ and $\sim 8 \mu\text{s}$ for the 20 and 50 micron device, respectively) and a much slower decay (typically $15\text{--}20 \mu\text{s}$) which was bias voltage dependent. Figure 5 shows an example of a digitized pulse from the 50 micron device. The quoted pulse decay times were taken as the time at which the pulse amplitude has decreased to $1/e$ of its maximum value.

All spectra show a severe non-linearity in energy response, as can readily be seen from the inserts in figures 3a and 3b. The observed pulse height ratios Q_{p}/Q_{α} are 1.020 and 1.045 for the 20 and 50 micron device, respectively, much lower than the expected 1.10 for a linear response. The non-linearity in all cases is slightly more for the largest pulse height peak in the spectra. Also, the maximum pulse height from the substrate events compared to the film events is relatively larger in the 20 micron device than in the 50 micron device. Moreover, the non-linearity is found to be dependent on the bias voltage: at lower bias voltages the non-linearity is less severe. At this time, it cannot be completely excluded that the non-linearity as well as the pulse shapes are at least partly an artefact of the electronics. On the other hand, the non-linearity could also be caused by a high effective self-combination rate in these devices. Even though the recombination coefficient as defined by Kaplan *et al.*¹² in pure Al is about 50x lower than in pure Nb, the *effective* recombination rate could be significantly higher due to the relatively low phonon trapping factors¹³ in the trapping layers. This is due to the much slower pair-breaking rate in Al and the high transmissivity for phonons across the Al-Nb interface. Significant non-linearities in Nb-Al devices have also been observed by other groups, which attribute this effect to self-recombination⁶ or (partly) to electronic effects¹⁴. Note that the self-recombination should be more apparent in the 20 micron device than in the 50 micron device², because of the dependence of the recombination rate on the density of quasiparticles. Furthermore, if self-recombination is the dominant loss process immediately after the photo-absorption, the decay of the pulses is expected to be non-exponential since the loss rate will gradually decrease with decreasing quasiparticle density. Indeed both these effects are seen experimentally.

Figure 5: Measured pulse from the 50x50 μm^2 device, showing a decay characterised by two different time constants.

The best signal-to-noise ratio (FWHM) at 5.9 keV is seen for the electrode with the largest pulse height (see Fig. 3) for both devices and amounts to $\Delta Q/Q=0.0068$ for the 20 micron device and $\Delta Q/Q=0.011$ for the 50 micron device. The corresponding signal-to-noise ratios for an electronic pulser signal at the same pulse height are 0.0022 and 0.0033. After correcting the local energy scale for the non-linearity, this translates to energy resolutions (FWHM) of ~ 150 eV and ~ 140 eV for the 20 and the 50 micron device, respectively. This is a rather poor result in comparison with results obtained with conventional niobium devices, which showed about 2x better energy resolution⁷. Clearly, the electronic noise is not the dominating contribution to this rather poor energy resolution. Spatial non-uniformities in the response of the devices are thought to have a far smaller contribution to the resolution than in the conventional devices, due to the fast trapping mechanism. The contribution of statistical fluctuations in the number of electrons that actually tunnel³ is estimated to be ~ 10 eV. Possibly, bias voltage instabilities introduced by the large amplitude pulses in combination with the strong dependence of the pulse height on the bias voltage (see figure 4) causes the degraded resolution.

In experiments with an electronics chain optimized for low amplitude signals and low noise, the lowest achievable noise level for the 20x20 μm^2 device was ~ 4500 electrons FWHM, corresponding to ~ 0.3 eV (FWHM). This means that this device is a good candidate for single photon counting experiments at optical and UV photon energies ($E \approx 3$ eV). Results from such experiments, demonstrating the detection of single photons in the wavelength range of 220-500 nm, will be reported elsewhere¹⁵.

4. CONCLUSION

The response to 5.9 keV X-ray photons of niobium-based superconducting tunnel junctions with 120 nm thick Al trapping layers has been investigated at $T=0.3$ K. The devices exhibit extremely large signal amplitudes: up to 0.85×10^8 tunneled electrons for a 20x20 μm^2 device and 2.3×10^8 tunneled electrons for

a $50 \times 50 \mu\text{m}^2$ device. This is about a factor 40-80 higher than in conventional niobium-based devices with similar tunnel barrier properties but without trapping layers. The energy response of the devices is highly non-linear, which is attributed to self-recombination of quasiparticles and, possibly, to electronic effects. The energy resolution, corrected for this non-linearity, is at best ~ 140 eV. The contribution of the electronic noise from the detector and the electronics is insignificant and, with optimized electronics, could be reduced to ~ 0.3 eV FWHM. This will allow single photon counting experiments with these detectors in the UV and optical wavelength range.

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