On the Factor Governing the Energy Resolution of Ta-based Superconducting Tunnel Junctions

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The spectral response of Ta-based superconducting tunnel junctions to monochromatised synchrotron radiation in the photon energy range between 15 eV and 1.7 keV has been investigated with a view to establishing the physical processes contributing to the energy resolution. The resolution over the whole spectral range is only a factor of two or three above the expected intrinsic tunnel limited resolution. Between 15 eV and 60 eV peak widths of ~1 eV have been achieved. Spanning over two orders of magnitude in photon energy the high resolution has allowed us to isolate the various intrinsic components contributing to the spectral response and in essence confirm the validity of models describing the photo-absorption and tunnel processes in an STJ.

Keywords: Superconductivity, Superconducting Tunnel Junctions, Detectors, X-ray spectroscopy

Superconducting Tunnel Junctions (STJs) have shown good performance as broad band low resolution energy dispersive photon counting spectrometers in the optical and ultraviolet spectral range. This development has resulted in the first application of a Ta-based 6x6 array for optical astronomy [1]. In the extreme ultraviolet (EUV ~10 eV to 100 eV) and soft x-ray band (SXR ~100 eV to 2 keV) tantalum STJs offer high spectral performance with high resolving power [2]. The aim of the current investigation is to extend the practical useful spectral range of these types of detectors into the EUV and SXR. As has been previously discussed [3] the STJ energy resolution depends on a few factors: I) Fano noise resulting from the fluctuations in the initial number of charge carriers created by the photo-absorption process and described by the variance $\sigma_F^2 = \epsilon FE$, where $\epsilon = 1.7\Delta$ is the mean energy required to produce a single quasiparticle (QP) in a superconductor having an energy gap Δ , $F=0.22$ is the Fano factor [4] and E the photon energy. II) Tunnel noise resulting from the statistical fluctuations in the average number of tunnels $\langle n \rangle$ a single charge carrier makes across the barrier and described by the variance $\sigma_T^2 = \epsilon E(\langle n \rangle + 1)/\langle n \rangle$ for a symmetrical tunnel junction geometry [5,6]. III) Electrical noise with a variance σ_N^2 depending not only on the size and type of junction but also on the experimental configuration. IV) A spatially dependent gain variation introducing a variance of the form $\sigma_S^2 \propto E^2$ due to traps at the perimeter and other spatially dependent charge loss regions such as the leads. This is

the major contribution to the energy resolution at medium x-ray energies above 2 keV. Thus the total variance (σ_{tot}) which contributes to the measured resolution ($\Delta E \sim 2.35\sigma_{tot}$) can be written as $\sigma_{tot}^2 = \sigma_F^2 + \sigma_T^2 + \sigma_N^2 + \sigma_S^2$. The intrinsic resolution given simply by the physics of the photo-absorption and tunnel process is known as the tunnel limited resolution whose related variance is simply $\sigma_{Tun}^2 = \sigma_F^2 + \sigma_T^2$. At harder x-ray energies of e.g. 6 keV this tunnel limited resolution ΔE_{Tun} would be 7 eV whereas the measured resolution ΔE is typically 35 eV. In this situation σ_N is a minor contribution to the overall measured resolution which is totally dominated by the spatial contributor σ_S . At optical/UV wavelengths however the spatial variance is unimportant and a measured energy resolution of ~0.2 eV ($\Delta\lambda \sim 40$ nm) at a photon energy of 2.5 eV ($\lambda \sim 500$ nm) has been obtained for the case where $\sigma_N \sim 0.06$ eV. With $\sigma_N \rightarrow 0$ the resolution would reach the theoretical tunnel limited resolution of 0.13 eV. In summary the EUV and SXR spectral region between 10 eV and 2000 eV represents an important photon energy range where the physical mechanisms associated with the photo-absorption and tunnel process in an STJ can be studied and compared with current models. In this letter we investigate the spectral response from high quality tantalum based STJs and show that at EUV energies the energy resolution is dominated by the tunnel and electrical noise rather than any major spatial contribution.

Fabrication of the Ta-based STJs has been performed at Oxford Instruments Scientific Research Division in Cambridge, UK. A Ta-Al-AlO_x-Al-Ta multi-layer has been deposited onto a polished sapphire substrate. The base and top electrical connections were made using 3 μm wide polycrystalline niobium. This type of connection reduces the degradation in the junctions overall spectral response arising from the influence of the leads. The shorter QP lifetime and lower diffusion in niobium reduces the QP leakage into the junction due to photons absorbed in a lead. The higher Nb energy gap also reduces the QP loss through diffusion into the lead for the case when the photon is absorbed in one of the two films. The measured layer thicknesses of the top and the base films were 95 and 110 nm respectively. At EUV energies and part of the SXR band up to ~ 400 eV practically all photons are absorbed in the top film. Above this energy the measured spectral response arises from photons absorbed in both films. In this case the observed response comprises two somewhat different signal amplitudes arising from a difference in the micro-structure of the films since the base film is epitaxial and the top film polycrystalline. The micro-structure effects the charge production, the transport and QP diffusion properties which then also give rise to different signal pulse shapes as well as signal amplitudes. This effectively means that a pulse length or risetime discrimination can be applied to the measured signal so as to better separate photons absorbed in different films. Here we present detailed spectral data from a junction of $30 \times 30 \mu\text{m}^2$ size, which allow us to clearly identify the key physical processes controlling the energy resolution of tunnel junctions.

During the experiment the STJs are located in a ^3He cryostat providing a base temperature of 440 mK and with a hold time of about 6 hours. Since the STJs are sensitive to infrared (IR) radiation, which not only increases the thermal current but seriously degrades the energy resolution [7], it is necessary to use a cold filter for blackbody IR shielding of the STJ from the outer warm environment. For this purpose a 75 nm Al filter with a Ni mesh support has been installed. The demonstration of the extremely high energy resolution of the STJs was carried out using monochromatised synchrotron radiation provided by the SX700 beamline [8] of the PTB radiometry laboratory at BESSY I with a resolving power of the monochromator of between 500 and 1000. An energy range from 15 eV to 1.7 keV has been covered. For each photon absorbed, either in the top or bottom film or the substrate, a charge sensitive amplifier operating at room temperature measures the signal amplitude. The integrated signal simply is a measure of the total number of QP tunnels across the barrier. The signal risetime at the output of the charge sensitive amplifier, which is a measure of the QP loss time, in these Ta based devices is typically 8 μs for a $30 \times 30 \mu\text{m}^2$ device.

FIG. 1: The STJ signal amplitude-risetime distribution in the vicinity of the photo peaks showing the top and base film response when illuminated with 1.5 keV photons. The signal amplitude and risetime units are arbitrary

FIG. 2: Observation of the multiple harmonic order radiation in the EUV spectral range (left side of the dashed line). At 45 eV the FWHM is as low as 1.3 eV. The influence of an aluminium filter caused a lower number of counts in the harmonic at 90 eV. The diagram also shows the spectra obtained at photon energies 500, 800, 1000 and 1500 eV (right side of the dashed line).

From 15 to 400 eV the detector response shows a single pulse height peak since most of the photons are absorbed in the top film. At higher energies a second peak generated by photons absorbed in the base film appears since the top film becomes more transparent for these x-rays. The risetime distribution around the main two peaks as shown in figure 1 has a small but clear difference of the top and base film peak risetime. In order to separate the two peaks a risetime selection was applied in the form of a smooth function allowing the spectral response of both films to be evaluated individually.

The spectroscopic performance of the STJ in the EUV is shown in figure 2. The monochromator was set to a 15 eV nominal photon energy with no suppression of the harmonic orders, so that the photons with multiple

energies up to 205 eV could be resolved. All photons are absorbed in the top film. The figure shows as well the spectral response in the SXR when illuminated by photons with energies ranging from 500 eV to 1500 eV. A risetime filter has been applied in order to select events absorbed in one film or the other. Resolutions of 5.9, 5.8 and 10 eV were obtained at 800, 1000 and 1500 eV respectively for the base film while the top film had a resolution of 8.4 eV at 500 eV. The measured resolution across the complete spectral range from the EUV to the soft x-rays is shown in figure 3 for both the top and the base film. The high quality of the base film leads to an energy resolution approximately a factor 2 better than the top film. For example at 1 keV the measured base film resolution was 5.9 eV compared to a tunnel limited resolution of 3.0 eV for $\langle n \rangle = 10$ and an electronic contribution of $\Delta E_N \sim 0.7$ eV. Since the measured charge Q due to multiple tunneling is $Q = \langle n \rangle Q_0$ with $Q_0 = E/\epsilon$, $\langle n \rangle$ can be determined across the whole spectral range and was found to slowly increase from $\langle n \rangle \approx 9$ below 100 eV to $\langle n \rangle \approx 13$ at 2-keV. This non-linearity in the energy response is consistent with earlier observations and theoretical considerations [3,9]. Based on the equation for σ_{tot} , the measured noise contribution σ_N and σ_T derived from $\langle n \rangle$ assuming $\epsilon \sim 1.7\Delta$ and $\sigma_F^2 \sim \epsilon EF$, we can derive the spatial contribution to the overall resolution by fitting the parameter a in $\sigma_S = a \cdot E$ to the experimental results. We find $a = 6$ eV/keV for the base and $a = 15$ eV/keV for the top film. Figure 3 also shows the various components which make up the measured resolution for each film across the complete spectral range.

FIG. 3: The measured energy resolution ΔE_{tot} for both the top and the base film as a function of photon energy. The various components which contribute to this observed resolution are shown together with the energies of some important astrophysical lines.

The energy dependence of the resolution of the detector over the whole energy range from the EUV to the soft x-ray range has been determined and the resolution shown to be as good as within a factor of 3 of the tunnel limited resolution. Introduction of a risetime filter allows the separation of the response from both the base and top

film which arise at photon energies above 400 eV. The resolution particularly of the top film is rather well described from the EUV to the SXR by the model discussed above. Further geometry improvements relating to the film thickness should allow the double film response to be further optimised. For example reducing the thickness of the top film to ~ 20 nm say, which is equivalent to the mean penetration depth for 70 eV photons in Ta, would now extend the base film response down into the EUV. In conclusion the observed energy resolutions covering the wide energy range from the EUV to the SXR can be described by a model in which the key components to the total variance are the individual variances associated with the tunnel and photo-absorption process together with an additional variance linked to spatial variations in the STJ response. This latter component probably arises from local traps at interfaces and boundaries throughout the junction.

REFERENCES

- [1] N. Rando, P. Verhoeve, S. Kraft, R. den Hartog, A. Peacock, D.J. Goldie, R. Hart, Proc. SPIE 3445, 247 (1998).
- [2] S. Friedrich, J.B. le Grand, L.J. Hiller, J. Kipp, M. Frank, S.E. Labov, S.P. Cramer, A.T. Barfknecht, IEEE Trans. Appl. Supercond. 9, 3330 (1999).
- [3] P. Verhoeve, N. Rando, J. Verveer, A. van Dordrecht, A. Peacock, P. Videler, M. Bavdaz, D.J. Goldie, T. Lederer, F. Scholze, G. Ulm, R. Venn, Phys. Rev. B 53, 809 (1996).
- [4] N. Rando, A. Peacock, A. van Dordrecht, C.L. Foden, R. Engelhardt, B.G. Taylor, J. Lumley, C. Pereira, Nucl. Instrum. Meth. A 313 173 (1992).
- [5] D.J. Goldie, P.L. Brink, C. Patel, N.E. Booth, G.L. Salmon, Appl. Phys. Lett. 64, 3169 (1994).
- [6] C.A. Mears, S.E. Labov, A.T. Barfknecht, Appl. Phys. Lett. 63, 2961 (1993).
- [7] J.B. le Grand, C.A. Mears, S.E. Labov, P. Jakobsen, P. Verhoeve, M. Bavdaz, A. Peacock, Proc. of the 7th International Workshop on Low Temperature Detectors (1997) 106, Munich, ISBN 3-00-002266-X.
- [8] F. Scholze, M. Krumrey, P. Müller, D. Fuchs, Rev. Sci. Instr. 65, 3229 (1994).
- [9] A. Poelaert, A.G. Kozorezov, A. Peacock, J.K. Wigmore, Phys. Rev. Lett. 82, 1257 (1999).