Superconducting tunnel junctions as detectors for UV astronomy

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ABSTRACT

Superconducting tunnel junctions (STJ)¹ have now reached a state of maturity where small arrays have for the first time been used in practical applications in ground based astronomy. Future generations of devices are now under construction to enhance the current capability. For example larger format arrays, higher readout speeds, and improved spectral resolution are all issues being addressed. In this paper we present specifically the performance at ultraviolet wavelengths from 100- 500 nm of the current generation of STJ arrays based on tantalum. Recent results on such tantalum based photon counting superconducting tunnel junctions (STJ) which are now suitable for use as broad-band low resolution spectrometers for ultraviolet astronomy are presented. These STJs, operated at a temperature of ~ 0.3 K, have demonstrated a limiting resolution of ~ 8 nm at 200 nm. These devices can be designed to be extremely linear in response with photon energy while measuring the individual photon wavelength and arrival time. The quantum efficiency for single photons is over $\sim 50\%$ at ~ 200 nm. Such an STJ has been packaged into a small prototype 6×6 array and shown to have good uniformity of response across all pixels. Larger arrays are under development which could contribute significantly to many fields of ultraviolet astronomy being able to provide efficiently and simultaneously the broad band spectrum and photon arrival time history of every single object in the field over a very wide dynamic range. With lower energy gap superconducting materials the resolution should become higher and possibly for hafnium based devices as high as ~ 1 nm at 200 nm. If such devices can be developed then imaging spectrometers which can simultaneously record the image and spectra of objects in a large field and therefore provide an object's red-shift may become a reality.

Keywords: Superconductivity - tunnel junctions - ultraviolet spectroscopy

1. INTRODUCTION

A variety of astronomical observations at ultraviolet wavelengths require an efficient detector covering a wide wavelength range from the Lyman limit to the optical which can simultaneously provide the wavelength, time of arrival and location of every single photon falling upon the detector from the widest possible field. A detector which possesses the ability to measure the wavelength of individual optical photons has not previously existed.

A superconductor is theoretically capable of detecting individual UV photons and also measuring the photon energy^{1,2}. This ability simply arises from the very small energy gap Δ , of order meV, in a superconductor between the ground state, as represented by the bound Cooper electron pairs, and the first excited state, containing broken Cooper pairs. The experimental demonstration of photon counting at optical wavelengths, by Peacock et al.³⁻⁵ and Verhoeve et al.⁶, has clearly shown the validity of this concept in niobium and tantalum.

In this paper we report on the development of superconducting tunnel junctions for use in ultraviolet astronomy. The wavelength resolution of these detectors may well provide a contribution in fields as diverse as fast spectro-photometry to deep field imaging. Indeed since these detectors have been packaged into arrays their existing performance may already be such that they could allow the simultaneous measurement of broad band low resolution spectra of very faint extragalactic

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sources to be obtained for all objects in the field. Such spectra containing emission line complexes or continuum absorption features (the Lyman edge) in very faint extragalactic objects may allow the direct determination of red shifts ^{5,7}.

2. THE STJ PRINCIPLE OF OPERATION

The absorption of a photon of wavelength $\lambda(\text{nm})$ in a superconductor is followed by a series of fast processes in which the photon energy is converted into a population of free charge carriers known as quasiparticles in excess of any thermal population. For typical transition metal superconductors this conversion process is of order of a few nanoseconds ⁸. At sufficiently low temperatures (typically about an order of magnitude lower than the superconductor's critical temperature T_c) the number density of thermal carriers is very small and the number of excess carriers N_0 created as a result of the absorption of a photon of wavelength λ is inversely proportional to the photon wavelength. In general N_0 can be written:

$$N_0(\lambda) \sim 7 \cdot 10^5 / \lambda \Delta(T) \quad (1)$$

Here the wavelength is in nm and the energy gap Δ is in meV. Thus in a tantalum superconductor at a temperature well below the critical temperature, $T_c \sim 4.5 \text{ K}$ and $\Delta_{Ta} \sim 0.664 \text{ meV}$, the initial number of free charge carriers $N_0(\lambda)$ created by the photoabsorption of an ultraviolet photon is of order $\sim 5 \cdot 10^3$ for a photon with $\lambda \sim 200 \text{ nm}$ ⁵.

The quasiparticles produced after photoabsorption in a superconducting thin film can be detected by applying a d.c. potential across two such films separated by a thin insulating barrier; forming a superconducting tunnel junction (STJ). This potential favours the transfer of quasiparticles from one film to the other through quantum-mechanical tunneling across the barrier. The detector signal is therefore represented by the current developed by this tunnel process. The situation is shown schematically in Figure 1. The superconducting films are deposited on a highly polished substrate which for optical and ultraviolet applications is sapphire but could be magnesium fluoride if a shorter wavelength response below the sapphire cut-off of 145 nm down to 115 nm is required. Illumination of the device is through this substrate onto a high quality epitaxial film. While front illumination is possible for single devices it is not favoured for large format arrays where the top surface is coated with a dielectric necessary to insulate the large amount of top wiring (see section 6). Note a magnetic field also has to be continuously applied in the plane of the barrier to suppress the Josephson current (the tunneling of Cooper pairs at zero bias voltage (see Figure 1)

Figure 1: A schematic of a tunnel junction together with the orientation in a parallel magnetic field necessary to suppress the Josephson current. The device is operated in the ultraviolet in a back illuminated mode where the UV response is limited by the cut-off of the substrate.

After initial tunneling, a quasiparticle can tunnel back, therefore contributing many times to the overall signal⁹. On average each quasiparticle will contribute $\langle n \rangle$ times to the signal. Hence the number of effective charge carriers N which appear to have been created is $N = \langle n \rangle N_0$. The initial fluctuation in the number of charge carriers created in the photoabsorption process combined with the tunnel noise, associated with the multiple tunnelling of charge carriers across the barrier, leads to an overall limiting resolution for a perfectly symmetrical junction of the form^{10,4}:

$$d\lambda_T (\text{nm}) \sim 2.8 \cdot 10^{-3} \lambda^{3/2} \Delta^{1/2} [F + 1 + (1/\langle n \rangle)]^{1/2} \quad (2)$$

Here the Fano factor F can be assumed to be ~ 0.22 , considered typical of many of the transition metal elemental superconductors such as tantalum⁸. Thus for a tantalum based STJ the tunnel limiting resolution for the case when $\langle n \rangle \rightarrow \infty$ is ~ 7 nm for $\lambda \sim 200$ nm^{4,5}.

3. THE DETECTOR RESOLUTION

At least two other components due to the readout noise of the analogue electronics ($d\lambda_E$) and spatial non-uniformities ($d\lambda_S$), must also be added in quadrature reducing somewhat the resolving power. Figure 2 illustrates the experimentally determined device limited resolution (obtained after subtraction of the electronic noise) at ultraviolet wavelengths for devices based on niobium and tantalum. The theoretical limiting resolution based on equation 2 is also indicated both for these materials as well as for lower energy gap materials such as molybdenum and hafnium currently under development. Clearly good agreement between the theoretical tunnel limited resolution and the experimentally determined device limited resolution is observed. At 200 nm the theoretical tunnel limited resolution for a device based on molybdenum or hafnium is only 2 and 1 nm respectively compared to ~ 7 nm for tantalum. Figure 3 illustrates the typical charge spectra obtained for a tantalum STJ when back illuminated with ultraviolet radiation with $\lambda \sim 400$ (a) and 250 nm (b). For each wavelength the main peak spectrum is quite symmetrical. The pulser peak in this figure refers to an electronic stimulation of the preamplifier used to determine noise contribution.

Figure 2: The tunnel limited resolution of a number of elemental superconductors at ultraviolet and optical wavelengths. Experimental data (with electronic noise subtracted) derived from niobium and tantalum devices is also shown.

Figure 3: Typical spectrum from a back illuminated tantalum device obtained at ultraviolet wavelengths (a) 400 nm and (b) 250 nm.

4. THE DETECTOR EFFICIENCY

Theoretically the tantalum STJ has a remarkable efficiency to the absorption of photons at ultraviolet wavelengths. Figure 4 (a) (inset) illustrates schematically the principal sources of photon loss for the case of a tantalum based device deposited on a sapphire substrate.

Figure 4: (a) The theoretical detector efficiency for a tantalum based STJ illuminated through a sapphire substrate. The total reflectivity at both the vacuum-sapphire (R_{sap}) and sapphire-tantalum (R_{Ta}) interfaces are, together with any multiple reflections, as well as the attenuation in the sapphire (A_{sap}), included in the estimate of the detector efficiency. A 100 nm thick tantalum base film transmits (T_{Ta}) less than 1 % of all photons not reflected at the interface. The inset illustrates the optical configuration where the detector efficiency is simply defined as $1 - R_{sap} - R_{Ta} - A_{sap} - T_{Ta}$. (b) As for (a) but the sapphire substrate is replaced by magnesium fluoride. Here the total reflectivity is also shown ⁵.

For $\lambda > 145$ nm the most significant factor effecting the detector efficiency is the reflection of photons from the vacuum - sapphire (R_{sap}) and sapphire-tantalum (R_{Ta}) interfaces in the back-illuminated mode. Figure 4 shows the total detection efficiency, resulting from reflections, including multiple reflections, at both these interfaces, and absorptions. These data are based on the optical constants for sapphire and tantalum from Palik ¹¹ and Weaver et al. ¹². The absorption (A_{sap}) of the

photon flux through the 0.5 mm thick R-plane sapphire is dramatic at short wavelengths ($\lambda < 140$ nm). These effects therefore limit the overall detection efficiency of the device. Note nearly all the photons entering the base epitaxial tantalum film will be absorbed. Figure 5 shows the measured ultraviolet efficiency for such a tantalum device deposited on sapphire.

Figure 5: The measured efficiency at ultraviolet wavelengths of a tantalum based device illuminated through a sapphire substrate. The solid line represents the predicted detection efficiency.

While a detector efficiency predicted theoretically to be over 50 % from $200 < \lambda < 700$ nm, peaking at ~ 75 % at $\lambda_{\text{peak}} \sim 550$ nm, is more than adequate for ground-based astronomical applications, the UV response is inadequate due to the cut-off of the sapphire substrate at 145 nm. An alternative for a space based telescope taking advantage of the UV response, would be to replace the sapphire substrate with one of magnesium fluoride. Figure 4(b) illustrates the system reflectivity (vacuum - MgF_2 and MgF_2 - tantalum including multiple reflections) together with the predicted detector efficiency assuming a 0.5 mm thick MgF_2 substrate. The short wavelength response has now been extended down to the cut-off of the MgF_2 (~ 115 nm) while the long wavelength optical response is largely unchanged.

5. DEVICE SPEED

As a photon counter the STJ is extremely fast and currently limited not by the intrinsic time resolution of the device but rather the speed of the signal processing electronics. Currently rates as high as 5 kHz per device can be achieved. The limiting temporal response of current tantalum based devices is typically a few microseconds. This response is governed by the effective tunnel time which itself is dependent on the thickness of the films and the tunnel barrier conductance, and by the loss processes in the junction. It should be noted that due to the modest spectral resolution of tantalum devices the first astronomical uses at optical wavelengths of a 6x6 tantalum STJ array focussed on rapid photometry applications such as the 33 ms Crab pulsar where each photon was time tagged with an accuracy of $5 \mu\text{s}$ ¹³.

6. DEVELOPMENT OF ARRAYS

A number of approaches can be considered to ensure an adequate field coverage for such UV detectors. The first and simplest is to package individual devices into a close packed nxm pixel array as shown in figure 6(a). This approach was used for the first astronomical application of STJs¹⁵. Of course the drawback to this approach is that each individual junction has its own wiring and signal processing electronics. A second approach – the matrix readout, connects the base film of all devices in an array from the same row and the top films from the same column as shown in figure 6(b). Events are then readout using a coincidence technique between signals from the base and the top films. Such an approach reduces the amount of wiring for individual devices and the signal processing chains to only $m+n$ ¹⁴.

Figure 6: A 6x6 tantalum based array (left) deposited on a sapphire substrate. Each pixel has its own signal processing chain. All wiring and plugs on this chip are in niobium. Right (b) a reduced readout chip of 12x8 pixels again deposited on a sapphire substrate¹⁴. In this case the devices are based on vanadium while all wiring and plugs are in niobium.

Figure 7 illustrates the variation of the charge output from a 6x6 tantalum based array when illuminated with 300 nm ultraviolet photons.

Figure 7: The responsivity of the 6x6 Ta based array when illuminated by 300 nm radiation. The variation over all pixels is < 5%

An alternative approach to ensure a large field coverage is also under study. Here the ultraviolet photons are not absorbed directly by a junction but rather are absorbed in a 100 nm thick epitaxial tantalum film. The quasiparticles are detected as they diffuse away from the photoabsorption site by four tantalum based junctions placed at the corners of the absorber. The photons energy is simply the sum of all coincident signals from the four junctions while the position depends on their ratio. Figure 8 illustrates the case in one dimension. Here (Figure 8(a)) the coincident signals from two 50 μm junctions deposited at the ends of a 400 μm tantalum bar are shown when the bar was uniformly illuminated with 300 nm photons. Figure 8(b) shows the charge spectrum from a selected region of the bar. The selected region is shown in Figure 8(a) based simply on the signal ratio. The wavelength resolution is ~ 30 nm and the estimated position resolution is ~ 40 μm .

Figure 8:(a) The reconstructed pulseheight ($s1+s2$) vs photon absorption position ($x \sim s1-s2$) obtained from two junctions at the end of a 400 μm tantalum bar when uniformly illuminated with 300 nm ultraviolet photons. (b) The pulseheight spectrum for the selected region of the bar indicated with dashed lines in Figure 8(a).

7. CONCLUSION

In conclusion the STJ has now been developed to a stage where practical applications using small format arrays can be considered at ultraviolet wavelengths. Already at optical wavelengths such arrays are now being used by ground based astronomers. Future developments will increase the format of tantalum based arrays from the current generation under development of up to 50×16 pixels to even larger format of 10^4 pixels. At device level the spectral resolution should improve towards a goal of ~ 1 nm at 200 nm through the introduction of lower energy gap materials.

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REFERENCES

1. G.H. Wood, B. White, *Appl. Phys. Lett.* **15**, pp.237-238, 1969.
2. M.A.C. Perryman, C.L. Foden, A. Peacock, "Optical photon counting using superconducting tunnel junctions", *Nucl. Instr. Meth.* **A325**, pp.319-325, 1993.

3. A. Peacock, P. Verhoeve, N. Rando, A. van Dordrecht, B.G. Taylor, C. Erd, M.A.C. Perryman, R.Venn, J.Howlett, D.J.Goldie, J.Lumley, M. Wallis, "Single optical photon detection with a superconducting tunnel junction", *Nature* **381**, pp.135-137, 1996.
4. T. Peacock, P. Verhoeve, N. Rando, M.A.C. Perryman, B.G. Taylor, P. Jakobsen, "Superconducting tunnel junctions as detectors for ultraviolet, optical, and near infra-red astronomy", *Astron. and Astrophys. Suppl. Ser.* **123**, pp.581-587 1997.
5. T. Peacock, P. Verhoeve, N. Rando, C. Erd, M. Bavdaz, B.G. Taylor, D. Perez, "Recent developments in superconducting tunnel junctions for ultraviolet, optical and near-infrared astronomy", *Astron. and Astrophys. Suppl. Ser.* **127**, pp.497-504 1998.
6. P. Verhoeve, N. Rando, A. Peacock, A. van Dordrecht, A. Poelaert, D.J. Goldie and R. Venn, "Superconducting tunnel junctions as photon counting detectors in the infrared to the ultraviolet", *IEEE Trans. on Supercond.* **7**, pp.3359-3362 (1997).
7. P. Jakobsen, "Superconducting tunnel junction detectors for optical and UV astronomy", *ASP Conf. Series* **164**, pp.397-404, 1999.
8. N. Rando, A. Peacock, A. van Dordrecht, C. Foden, R. Engelhardt, B.G. Taylor, P. Garé, J. Lumley, C. Pereira, "The properties of niobium superconducting tunneling junctions as X-ray detectors", *Nucl. Instr. and Meth.*, **A313**, pp.173-195, 1992.
9. K.E. Gray, "A superconducting transistor", *Appl. Phys. Lett.* **32**, pp.392-395, 1978.
10. D.J. Goldie, P.L. Brink, C. Patel, N.E. Booth and G.L. Salmon, "The statistical noise due to tunneling in superconducting tunnel junction detectors", *Appl. Phys. Lett.*, **64**, pp.3169-3171, 1994.
11. E.D. Palik, ed., *Handbook of optical constants of solids*, Academic Press Inc, 1985.
12. J.H. Weaver, C. Krafka, D.W. Lynch, E.E. Koch, *Physik Daten* **18-1**, 1981.
13. M.A.C. Perryman, F. Favata, A. Peacock, N. Rando, B.G. Taylor, "Optical STJ Observations of the Crab Pulsar", *Astron. and Astrophys.* **346**, L30, 1999.
14. D.D.E. Martin, A. Peacock, P. Verhoeve, A. Poelaert, R. Venn, "Matrix readout scheme for superconducting tunnel junction arrays", submitted for publication in *J. Appl. Phys.*, 1999.