On the development of a superconducting tunnel junctions as Photon counting spectrometers for application in astrophysics

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The current state of development of superconducting tunnel junctions as photon counting spectroscopic detectors is reviewed and their application to a broad range of astrophysical problems discussed. Arrays of Tantalum based junctions have now reached a state of maturity such that serious astronomical applications can be considered over the wavelength range from 0.5 nm to 2 µm. The agreement between the theoretical resolution, as defined by the tunnel limited resolution, and measurements over this waveband, for both niobium and tantalum based devices, provides a good indication that lower critical temperature elemental superconductors may provide an even improved resolution in the near future. Such devices based on hafnium with a critical temperature of ~ 130 mK are already under development.

Keywords: superconducting tunnel junctions, spectral resolution, astrophysics

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1. Introduction

The absorption of a photon of a wavelength $\lambda$ (nm) in a superconductor is followed by a series of fast processes which involve the breaking of Cooper pairs by energetic phonons created by the hot electrons produced as the atom relaxes after the initial photoabsorption. The result of this cascade essentially is that the photon's energy is converted into a population of free charge carriers known as quasiparticles in excess of any thermal population. For typical transition metals this conversion process ranges from nanoseconds (niobium) to microseconds (hafnium). At sufficiently low temperatures (typically about an order of magnitude lower than the superconductors critical temperature $T_c$) the number density of thermal carriers is very small while the average number of excess carriers $N_e$ created as a result of the photoabsorption process can be written as: $N_e(\lambda) \sim 7 \times 10^5 / \lambda (\text{nm}) \Delta(T/T_c)$. Here the wavelength is expressed in nm and the temperature dependent energy gap $\Delta(T/T_c)$ is in meV. Thus in a superconductor such as tantalum with $T << T_c$ (4.5 K) the initial mean number of free charge carriers created $N_e(\lambda)$ is $\sim 10^6 \text{ nm} (10^3 \text{eV})$.

The variance on $N_e(\lambda)$ depends on the variance in the partition of the photons energy between productive phonons (phonons with an energy $\Omega > 2\Delta$ which can break Cooper pairs) and phonons which are essentially lost from the system ($\Omega < 2\Delta$). The population of $\Omega < 2\Delta$ phonons evolves with time as the average energy of the increasing quasiparticle population relaxes, through quasiparticle phonon emission, towards the bandgap. The variance $\langle N_e^2 \rangle$ depends on the superconductors bandgap $\Delta$ and its Fano factor $F$ such that $\langle N_e^2 \rangle \sim 7 \times 10^4 F / [\lambda (\text{nm}) \Delta(T/T_c)]$. Expressing this variance in terms of the wavelength resolution we have: $d\lambda_F (\text{nm}) \sim 2.8 \times 10^{-3} \lambda^{3/2} [F \Delta(T/T_c)]^{1/2}$. It has been shown that $F \sim 0.2$ for elemental superconductors such as niobium and tin [1,2]. This therefore represents the fundamental Fano limited resolution of any superconductor. Thus a superconductor such as tantalum with $T << T_c$ irradiated with photons of wavelengths covering the X-ray to the near infrared $\lambda \sim 1,10,100$ & 1000 nm then $d\lambda_F \sim 0.001, 0.033, 1.07$ and 34 nm respectively [3,4].

The quasiparticles produced through photoabsorption 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 bias favors 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. After initial tunneling, a quasiparticle can tunnel back, therefore contributing many times to the overall signal [5]. On average each quasiparticle will contribute \(<n>\) times to the signal through an average of \(<n>\) tunnels before it is lost from the system through traps etc. [6]. Hence the mean number of effective charge carriers \(N = n N_c\). The multiple tunnel process leading to \(n\) the average number of tunnels per quasiparticle is of course subject also to statistical fluctuation [7]. The fluctuations due to the Fano process and that arising from the tunnel process can be added in quadrature such that the overall limiting resolution for a perfectly symmetrical super conducting tunnel junction can be written as: \(d\lambda_T (\text{nm}) \sim 2.8 \times 10^3 \lambda^{3/2} \Delta(T/T_e)^{1/2} [F +1 + 1/n]^{1/2}\). For the case when \(n \geq 2\). Figure 1 illustrates this tunnel junction limited resolution for a number of elemental superconductors based on the parameters summarized in table I. Note this expression for the tunnel limited resolution \(d\lambda_T\) can be further generalised to any superconductor compound or proximised by-layer through the use of the approximate BCS relation in the weak coupling limit of \(2\Delta = 3.5kT_e\), where \(k\) is Boltzmann's constant. Deviations from this relation are small even for strongly coupled superconductors such as niobium and are also summarized in table I. Thus in terms of the critical temperature we can write: \(d\lambda_T (\text{nm}) \sim 1.1 \times 10^3 \lambda^{3/2} T_e^{1/2} [F +1 + 1/n]^{1/2}\) (\(n \geq 2\)). Typically \(n\) is of order 10-100 and depends on the size and nature of the STJ.

2. Astrophysical rationale

Having established the limiting wavelength resolution \(d\lambda_T\) of an STJ it is worth considering the applications of such a resolution within such fields as astrophysics.

2.1 X-ray wavelengths

Any plasma at a temperature above ~ \(10^6\) K radiates the bulk of its energy as X-rays from collisional excitation line emission and thermal bremsstrahlung continuum processes. At low temperatures (< \(10^7\) K) the bulk of this photon emissions is in the form of emission lines radiated in the Soft X-ray band (SXB) with \(\lambda > 0.5\) nm (~ 2 keV) while at higher temperatures the continuum emission processes dominate. This only arises as a result of the fact that since at higher temperatures the majority of ions with a low
atomic number are completely stripped of their electrons while the remaining ions are hydrogenic or helium-like species of sulphur and iron.

High resolution x-ray spectroscopy provides the ability to determine the electron and ion temperatures the electron density and the relative abundance of the elements as well as establishing the degree of thermal and ionization equilibrium. While the measurement of the intensity of the hydrogenic and helium like lines from the same element is an important ion temperature indicator, it is the ability to resolve the satellite lines e.g. the resonance, forbidden and intercombination lines from helium-like species which can determine the key characteristics of the X-ray emitting plasma in a model independent manner. Table II summarizes these key transition wavelengths for some of the most abundant elements expected to be present in an astrophysical plasma together with a tantalum based STJ's tunnel limited resolution at these wavelengths. Clearly such an STJ, provided it can achieve a measured resolution close to $d\lambda/T$, should be capable of resolving these key transitions. To illustrate this point figure 2 shows the response of a tantalum STJ to the large complex of lines (the Fe-L complex) around 1 nm, expected to be radiated from an optically thin plasma having a temperature $\sim 10^7$ K. In this example solar abundance's and ionization equilibrium were assumed and for clarity the continuum emission has been suppressed. The majority of lines are easily resolvable with such a tantalum STJ enabling, through the measurement of the relative intensity of the lines from the same ion, the temperature to be uniquely determined, and also, through the relative intensity of lines from different elements such as Fe and Ne, the relative abundance's can be established. Note the intensity ratio of resonance lines from different ions of the same element together with line centroids allows one to deduce either the degree of ionization equilibrium or possibly distance to the object, through the determination of the red-shift $z$. Needless to say a high spectral resolution is required for such observations. This resolution can be achieved using a tunnel limited tantalum STJ but is completely impossible with conventional solid state devices.

To illustrate the high degree of sensitivity of various emission line strengths to plasma temperature figure 3(a,b) show the simulated tantalum STJ response to emission line spectra from a hot solar abundant
optically thin plasma in equilibrium over the wavelength region covered by the hydrogenic and helium-like oxygen lines ~ 2nm. Again for clarity the continuum has been suppressed. The ion temperature $T$ was taken to be $\log(T) = 6.4$ and 6.8 respectively. This temperature can be established directly from the line intensities without recourse to modeling the underlying continuum bremsstrahlung spectrum which anyway provides only a measure of the free electron temperature.

2.2 UV/Optical wavelengths

In optical and UV spectroscopy high resolution normally implies a resolving power $\lambda/d\lambda > 10^4$. From figure 1 it is clear that none of the classical superconductors forming the basis of current STJ's under development (those based on Nb,Ta, Al,Mo or Hf ) could achieve such a resolving power. In fact a superconducting critical temperature $T_c << 100 \mu K$ is implied to achieve a resolving power of $10^4$ leading to the development of STJ's based on such elemental superconductors as rhodium. Of course things are not quite this simple with the temporal characteristics associated with the production of the free excess charge carriers being a function of the critical temperature (see table 1) while the phonons with $\Omega > 2\Delta$ have wavelengths significantly larger than the thickness of the film. Thus such low temperature superconductors may well be significantly slower in their overall in response.

Given that the resolution of a typical STJ based on tantalum is not appropriate for high or even medium resolution spectroscopy what are the alternative key attributes which such a device can bring to the field of optical/UV astronomy. Two features are important: (a) the timing characteristics ($\leq 10 \mu s$) coupled to the broadband spectral capability may make this the ideal spectrophotometer. Objects such as pulsars and flare stars may be ideal objects with which to observe with narrow field small arrays, (b) the efficiency at UV wavelengths which, if coupled to a large format array (a panoramic detector), may allow for the development of an efficient broadband imaging spectrometer with which to determine the low resolution spectra of very faint objects allowing for very deep field surveys. Such surveys could allow the determination in a single exposure of the broadband spectra and possibly therefore the redshift $z$ (and therefore age) of all objects in the field through the measurement of the Lyman edge and the Lyman
emission lines - the Lyman forest. Note that the observed wavelength $\lambda_o = \lambda_R (z+1)$, where $\lambda_R$ is the rest wavelength. Thus the classical Lyman edge would appear at $\sim 400$ nm at a $z \sim 3$. This is close to the optimum performance for a tantalum based STJ where it has an efficiency of $\sim 70\%$ and a resolution of $\sim 20$ nm. It is however clear that STJ devices based on lower temperature superconductors such as hafnium would allow the clear evaluation of redshift.

3. Current Performance of STJ's

The key factors described in this section involve the basic performance of tantalum based STJ's building on the earlier work in niobium. The validation of the basic equations discussed in section 2 relating to both $N_e$ and $d\lambda_T$ with both tantalum and niobium devices give some confidence in the ultimate successful development of lower temperature elemental superconducting tunnel junctions such as those based on hafnium [8].

3.1 X-ray Wavelengths

The efficiency of any detector is an important parameter when considering practical applications. Figure 4 illustrates the efficiency of a tantalum based STJ as a function of photon wavelength for the case when one film $\sim 100$ nm thick is used as the primary detection element. For comparison the efficiency of a hafnium film is also shown. Little difference exists between such films given there similar atomic numbers although their tunnel limited resolution should be very different. At a wavelength of 2 nm the efficiency is $\sim 75\%$ however the situation rapidly degrades at shorter wavelengths with an efficiency of only $5\%$ at 0.2 nm. While the thickness of these films can undoubtedly be increased to 200-300 nm, beyond this various loss mechanisms may become important such that the spectral resolution could be expected to degrade. Of course in practice the efficiency at the longer wavelengths will be lower than that indicated in figure 4 due to the fact that unlike in the optical/UV where back illumination is the mode of operation, at X-ray wavelength the photon enters the detector through the front (front illumination). This means that some fraction of the X-rays at long wavelengths are absorbed in the top film oxide layer and also the top film, if the bottom film is used as the primary detection film, as well as the top contact. This latter point is
important when considering arrays in which a significant amount of top contact wiring together with a SiOx insulation layer is required.

While the resolution in the Medium X-ray Band (MXB ~ 0.1-0.5 nm) has not yet reached the tunnel limits indicated by figure 1, the situation in the Soft X-ray Band (SXB ~ 0.5-10 nm) is close. Figure 5 illustrates the measured spectra from a tantalum STJ forming part of a 6x6 element array illuminated by monochromatic radiation of various wavelengths in the SXB [10]. Each device was 25x25 µm and consisted of two films each 100 nm thick. Only those photons absorbed in the base film, which are separated from top film and substrate events by their distinct signal risetime are shown here. Typical resolutions dλ ~ 0.015 nm (3.5 eV) at λ ~ 2.4 nm (~500 eV) were measured and are indicated in figure 1. While these data have not yet achieved the tunnel limited resolution (dλ_T ~ 0.01 at λ ~ 2.4 nm) the cause is determined to be a spatial variation in the detector gain which provides an additional variance dependent on the square of the photons energy and which contributes to the overall variance [10,11].

3.2 UV/Optical Wavelengths

At optical and UV wavelengths, where the photons energy is very small, spatial effects on the resolution are unimportant. Here it is rather that the signal is low such that the signal to noise ratio is the dominant factor governing the measured resolution. At these wavelengths the photons enter the detector through the substrate, which can either be sapphire or magnesium fluoride depending on the short wavelength cut-off required [4]. The theoretical efficiency of a tantalum device deposited on a sapphire substrate with this mode of illumination is very high. All photons are absorbed in the high quality epitaxial tantalum base film. Efficiencies of ~ 70% from 200 - 600 nm are expected limited at the short wavelength by the cut-off of the sapphire substrate. Such efficiencies have been experimentally confirmed.

To illustrate the broad band response of this type of photon counting spectroscopic detector Figure 6 shows the charge spectrum from a single tantalum based device when illuminated with optical light via a grating monochromator. This grating response covers four orders from 296 nm to 1183 nm - i.e. from the
UV to the NIR. Not only are the various orders well resolved but the charge output as a function of wavelength can be precisely determined leading to a wavelength linearity which is very high. These types of measurements allow the determination of the wavelength resolution across a broad waveband and are shown for both tantalum and niobium based devices in figure 1.

4. Conclusion

The STJ based currently on tantalum or niobium has now been developed to a stage where practical small format arrays (3x3 and 6x6 pixel) have been produced which provide similar performance to optimised single devices. Such arrays are already now being developed into instruments for ground based optical astronomy [12]. The performance of these arrays at UV and SXB wavelengths are such that practical instruments can now be considered for space based applications. The key specific points which have been experimentally demonstrated can be summarized as:

a) Tunnel limited resolutions have been achieved at optical and UV wavelengths
b) High efficiency has been shown at UV wavelengths
c) Resolutions are within a factor of 2 of the tunnel resolution in the SXB
d) High speed photon counting has been realised (10 kHz)

Areas where development of the basic tantalum device are still required can be summarized as:

a) Reduction of the spatial contribution to the resolution allowing for the demonstration of tunnel limited resolution in the MXB.
b) Improvement in the efficiency of the device in the MXB
c) Reduction in the various absorbing materials (contacts, SiOx etc.) which reduce the efficiency in the SXB.
d) Production of very large format arrays
e) Development of large format application specific readout electronics
Acknowledgments

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References

Table I: Key properties of elemental superconductors used in the fabrication of STJ's

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$ (K)</th>
<th>$\Omega_D$ (meV)</th>
<th>$\Delta$ (meV)</th>
<th>$\tau_{qp}$ (ns)</th>
<th>$\tau_\Omega$ (ns)</th>
<th>$H_c$ (G)</th>
<th>$2\Delta/kT_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niobium</td>
<td>9.20</td>
<td>23.7</td>
<td>1.550</td>
<td>0.149 (0.386)</td>
<td>0.004 (0.009)</td>
<td>1980</td>
<td>3.9</td>
</tr>
<tr>
<td>Vanadium</td>
<td>5.30</td>
<td>32.7</td>
<td>0.800</td>
<td>5.3 (4.8)</td>
<td>0.013 (0.012)</td>
<td>1420</td>
<td>3.5</td>
</tr>
<tr>
<td>Tantalum</td>
<td>4.48</td>
<td>20.7</td>
<td>0.664</td>
<td>1.8 (2.4)</td>
<td>0.023 (0.016)</td>
<td>830</td>
<td>3.4</td>
</tr>
<tr>
<td>Aluminium</td>
<td>1.14</td>
<td>36.9</td>
<td>0.172</td>
<td>100 (453)</td>
<td>0.242 (0.246)</td>
<td>105</td>
<td>3.5</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.92</td>
<td>38.8</td>
<td>0.139</td>
<td>2077 (2963)</td>
<td>0.405 (0.579)</td>
<td>95</td>
<td>3.5</td>
</tr>
<tr>
<td>Hafnium</td>
<td>0.13</td>
<td>21.7</td>
<td>0.021</td>
<td>~ (8000)</td>
<td>(20)</td>
<td>13</td>
<td>3.9</td>
</tr>
</tbody>
</table>

1 The Debye energy
2 The quasiparticle ($\tau_{qp}$) and phonon ($\tau_\Omega$) characteristic times taken from reference 8. Data in () are based on recent data on the phonon related characteristics of these materials.
3 The critical magnetic field

Table II: The principle line transitions of the most abundant helium-like lines

<table>
<thead>
<tr>
<th>Element</th>
<th>$1s^2-1s2p^3P$ (R)</th>
<th>$1s^2-1s2p^3P$ (I)</th>
<th>$R-I$ (nm)</th>
<th>$1s^2-1s2p^3P$ (F)</th>
<th>$I-F$ (nm)</th>
<th>$d\lambda_T$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>0.1850</td>
<td>0.1859</td>
<td>0.0009</td>
<td>0.1867</td>
<td>0.0008</td>
<td>0.0002</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.5039</td>
<td>0.5067</td>
<td>0.0028</td>
<td>0.5099</td>
<td>0.0032</td>
<td>0.0009</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.6650</td>
<td>0.6690</td>
<td>0.0040</td>
<td>0.6737</td>
<td>0.0047</td>
<td>0.0014</td>
</tr>
<tr>
<td>Oxygen</td>
<td>2.1602</td>
<td>2.1804</td>
<td>0.0202</td>
<td>2.2100</td>
<td>0.0296</td>
<td>0.0083</td>
</tr>
</tbody>
</table>

R =Resonance line, I = Intercombination line and F = Forbidden line transition. All line wavelengths in nm.
$d\lambda_T$ (nm) the tantalum tunnel limited STJ resolution determined at the resonance line wavelength.
**Figure Captions**

**Figure 1**: The tunnel limited resolution of a number of elemental superconductors as a function of wavelength from the X-ray to the near infrared. The experimental data derived from niobium and tantalum STJ's is also shown.

**Figure 2**: The simulated response of a tantalum based STJ to the Fe-L complex of lines around 1 nm from a hot optically thin plasma at a temperature of $10^7$ K. Practically all the lines are resolvable by such a detector.

**Figure 3**: The simulated response of a tantalum based STJ to the helium and hydrogenic lines of oxygen at a temperature $T$ of (a) $\log(T) = 6.4$ and (b) $\log(T) = 6.8$, from an hot optically thin plasma. Note the difference in scale between the two spectra as well as the radically different line ratios when the temperature has changed by only a factor of 2.5.

**Figure 4**: The efficiency of a tantalum and hafnium 100 nm film to the absorption of X-rays as a function of wavelength. Some key emission lines are indicated.

**Figure 5**: The spectra from a single pixel of a 6x6 tantalum array illuminated by monochromatic soft X-rays.

**Figure 6**: The charge spectrum from irradiation of a tantalum STJ by photons of wavelength 1183 nm. The various orders from the grating monochromator are easily discernible and provide a excellent technique with which to establish the linearity of the device.
Figure 1
Figure 3
Figure 4
6x6 pixel Tantalum array irradiated with 525 eV radiation
25x25 micron pixels - single pixel response

Count/#

Charge Output Q (ADC #)

FWHM = 0.016 nm (3.5 eV)

6x6 pixel Tantalum array irradiated with 1 keV radiation

Count/#

Charge Output Q (ADC #)

FWHM = 0.08 nm (6.8 eV)

Figure 5