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Superconducting Tunnel Junction Detectors for Optical and UV Astronomy

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Abstract. Astronomical detectors based on Superconducting Tunnel Junction (STJ) technology are the next logical step beyond CCD and MCP detectors for optical and ultraviolet astronomy. Rather than merely registering each photon event with high efficiency, these devices also measure the wavelength of the detected photons throughout the far-UV through near-IR. Large format STJ arrays promise to provide the ultimate '3D' astronomical detector capable of covering simultaneously more than a decade in wavelength. The STJ detector holds particular promise in space-based ultraviolet applications where its inherent spectral resolution is the highest and its naturally high quantum efficiency overcomes the sensitivity limit set by available UV photocathode materials. The capability to separate spectral orders on the detector also opens up exciting new possibilities for novel and highly efficient grating spectrometer designs.

1. Introduction

The employment of the Superconducting Tunnel Junction (STJ) as an astronomical detector has its roots in high energy astrophysics, where energy-sensitive detectors in the form of imaging proportional counters, and more recently rapid-readout CCDs, have a long history. Initial interest in STJs focussed on their potential use as an alternative to the X-ray bolometer. That the technology should be extendable to ultraviolet and visible energies was first argued theoretically by Perryman, Foden & Peacock (1993) and subsequently verified experimentally by Peacock et al. (1996, 1997a). This breakthrough holds particular promise in that an energy-sensitive detector has never before been available at UV and optical wavelengths.

This paper provides only a very superficial introduction to the STJ detector. More in-depth treatments with an astronomical slant can be found in Peacock et al. (1997b, 1998).

2. What's an STJ?

An STJ (or Josephson Junction) consists physically of two thin films of a superconducting metal (such as niobium, tantalum or aluminum) separated by a thin insulating layer (Fig. 2.). When operated at temperatures well below the

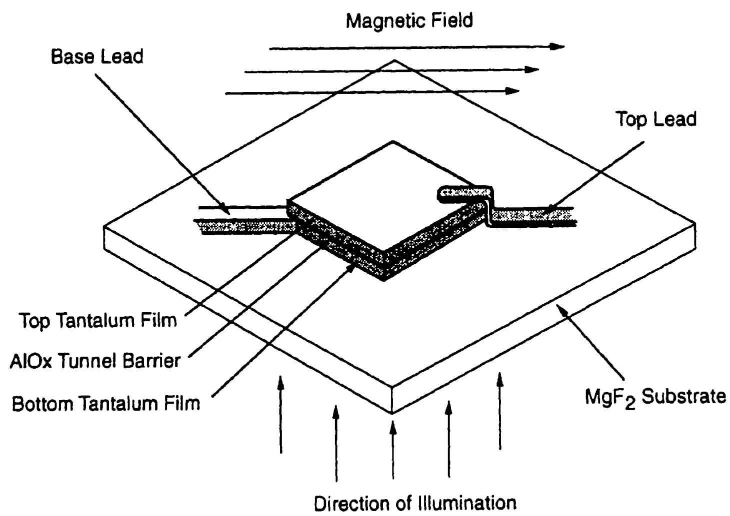

Figure 1. Schematic of a superconducting tunnel junction.

critical temperature of the superconductor (typically at $T \sim 0.1T_c < 1$ K), each photon absorbed by the junction generates an amount of free charge proportional to its energy through the breaking of Cooper pairs. By applying a small bias voltage across the junction and a suitable parallel magnetic field to suppress the Josephson current, this charge pulse can be extracted from the device, and the energy of the absorbed photon can be determined to an accuracy limited by the pseudo-Poissonian statistical fluctuations in the charge released. The STJ detector is therefore functionally similar to a proportional counter in that its energy resolution is proportional to the square root of the charge output which, in turn, is proportional to the input photon energy, i.e.

$$\delta E \propto Q^{1/2} \propto E^{1/2} \quad \text{or} \quad \delta\lambda(\lambda) = \alpha\lambda^{3/2} \tag{1}$$

where α is a constant specific to the material and design of the STJ.

The application of the STJ detector in conventional astronomy is the natural next step beyond photocathode-based and CCD detectors. In the latter devices, the band gap between the ground state and the state excited by the absorption of an optical photon is comparable to the photon energy. Consequently, only a single electron is extracted from the detector per absorbed photon - irrespective of its energy. In contrast, the equivalent energy gap in a superconducting metal is some three orders of magnitude lower, which means that of the order of one thousand electrons are generated per detected optical photon. Moreover, by suitable selection and engineering of the STJ materials and surface interfaces, the initial charge pulse can be further amplified by several orders of magnitude through the process of multiple tunneling – albeit at a modest factor $\simeq 2.4$ reduction in spectral resolution. The fascinating statistics of this (almost magical) tunneling amplification process have been explored by Goldie at al. (1994).

The factor of $\simeq 10^3$ lowering of the energy gap over a solid state CCD detector obviously comes at the price of having to lower the STJ operating temperature, kT, by the same factor in order to reduce the thermal noise in the device. Although not discussed here, the technology to achieve this has been developed for IR, sub-mm and X-ray applications and is largely in hand.

Table 1. STJ materials and performance

Material	$T_c(K)$	$T_{op}(mK)$[1]	$\delta\lambda(\text{Å})$[2]		
			1200 Å	2000 Å	5000 Å
Niobium	9.2	800	50	110	430
Tantalum	4.5	370	35	70	275
Aluminum	1.1	170?	16	35	140
Hafnium	0.13	30?	6	12	50

[1]Experimentally determined optimum operating temperature
[2]FWHM for tunnel-limited device

Table 1 lists the characteristic temperatures and predicted spectral resolution for several candidate superconducting metals. Of the four materials listed, functional STJs have so far successfully been manufactured out of niobium and tantalum, and the theoretical performance of these materials has been verified experimentally.

It is seen that the spectral resolution at visible wavelengths achievable with a tantalum detector is $R \sim 18$, which is comparable to that of conventional narrow band photometry. However, in the far-UV this rises to $R \sim 37$. Thus STJs are by their nature still inherently relatively low resolution devices. Provided the challenge of working at even lower temperatures can be overcome, STJs manufactured from hafnium promise to yield a factor $\sim$6 improvement in resolution over tantalum.

By arranging adjacent STJs in an array, a true 'three dimensional' astronomical detector can be manufactured. In practice, such STJ arrays are lithographically deposited on a thin optical window and backside-illuminated through the substrate, thereby leaving the topside free for lithographic deposition of the leads to each element Each detector pixel in the array is a functionally independent STJ operating in an essentially noiseless photon-counting manner. The charge pulses from each array element need to be amplified and digitized in total charge by the front-end analog electronics and then passed on to the digital processing unit for sorting in wavelength and storage.

The largest STJ array that has been manufactured so far has 6×6 elements (Fig. 2). However, STJ arrays of arbitrarily large size (and shape) are in principle possible; i.e. are mainly limited by the wiring and electronics required to handle many independent pixels.

Although the approach has not yet been fully demonstrated in practice, by reading out the charge from all four corners of the junction, the STJ in principle also lends itself to 'sub-pixel' event centroiding, thereby cutting down on the number of leads and processing channels – albeit at the expense of some loss of dynamic range and spectral resolution.

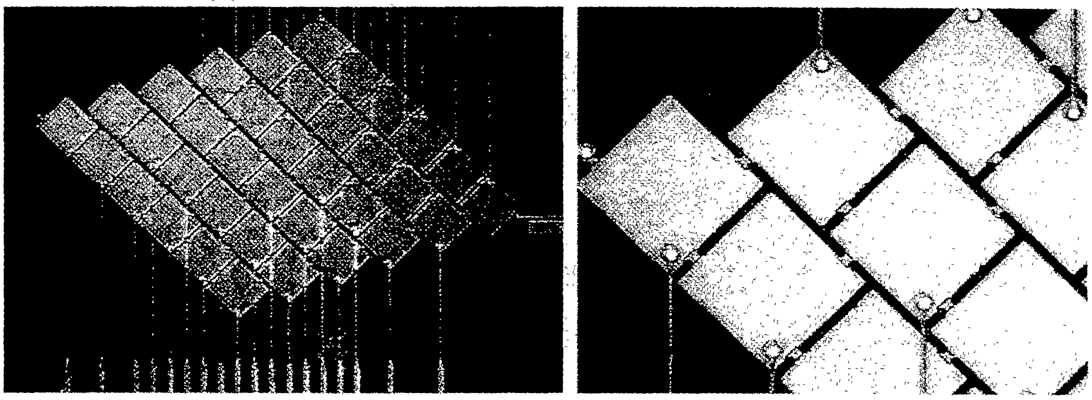

Figure 2. Closeup of 6 × 6 prototype 'S-CAM' tantalum on sapphire STJ array. Each STJ element is 25μm square in size. Note the niobium 'plugs' in the base lead which serve to eliminate cross-talk between pixels.

3. What's the Big Deal?

3.1. Wavelength Coverage

A key feature of the STJ is its huge simultaneous bandwidth. In principle, the STJ is capable of detecting single photons all the way from the near-IR (i.e., photon energies for which the output signal becomes large enough to distinguish above the electronic noise) and out into the hard X-rays (where the device starts to become transparent). In practice, however, the high energy limit of a 'back illuminated' STJ array designed for UV/optical applications is set by the natural short wavelength cutoff of the substrate material (i.e. $\lambda \sim 1150$ Å and $\lambda \sim 1450$ Å for MgF_2 and sapphire, respectively). A typical laboratory STJ spectrum spanning two full octaves in wavelength is shown in Fig. 3.

3.2. Sensitivity

The photon detection sensitivity of an STJ is almost entirely determined by the transmission and reflectivity losses in the optical interfaces between the substrate and the first film of the STJ proper. Figure 4 shows the predicted quantum efficiency curve for a UV-optimized STJ employing tantalum on MgF_2. The extremely high quantum efficiency in the far-UV is particularly noteworthy in that STJs for the first time promise to bring 'CCD level' detection efficiencies to these wavelengths.

Of the other three materials listed in Table 1, niobium and hafnium display similarly high quantum efficiencies. The very high reflectivity of aluminum on the other hand obviously renders this material unattractive for use in STJs for the visible and ultraviolet. However, since the STJ sensitivity limitations are entirely optical in nature, it is in principle possible to trade off bandpass for sensitivity by depositing suitable anti-reflection coatings on the front surface of the substrate.

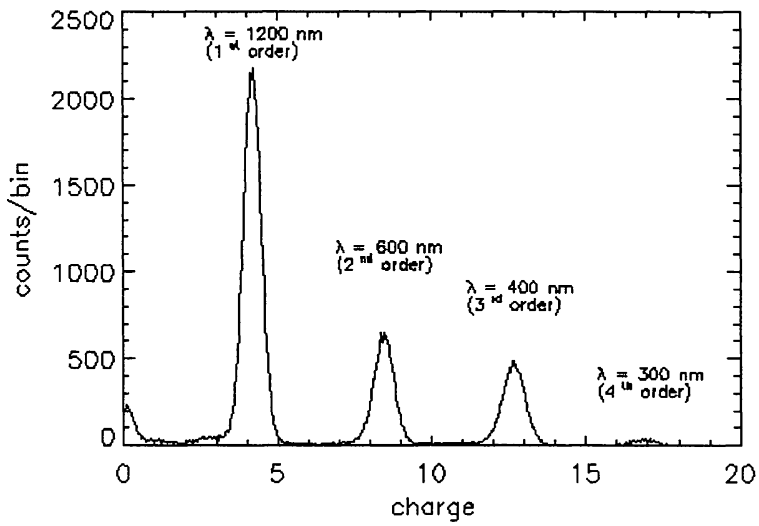

Figure 3. Laboratory spectrum obtained with a tantalum STJ showing the simultaneous detection of four spectral orders from a grating monochromator spanning wavelengths from 3000 Å in the near-UV to 1.2 μm in the near-IR.

3.3. Speed and Dynamic range

As a photon counter, the STJ is extremely fast, needing only a few tens of microseconds to recover between events. Because of this, the first ground-based astronomical uses of modest format STJ arrays are likely to focus on rapid photometry applications.

Like all photon counters, STJs are count rate limited at the bright end. The local pixel linearity range is set by the speed of the front-end analog electronics, which with current technology can relatively easily be designed to handle 10^3 counts s^{-1} per pixel or higher. The limit on the global event rate integrated over a whole array is set by the back-end processing electronics, which need to register and sort the detected events according to amplitude. Depending on the array size and degree of multiplexing adapted, total rates in excess of 10^5 counts s^{-1} should be readily achievable.

4. STJ-based UV Spectrographs

One potential application of STJ arrays of particular relevance to the topic of this conference is their use as detectors in UV grating spectrometers. In particular, the very high quantum efficiency of the STJ combined with its ability to sort light in energy permits inventive new types of extremely efficient echelle-type spectrograph designs to be contemplated.

As an example, Fig. 5 shows the spectral layout of a potential STJ-based spectrograph design employing a single concave grating as its only optical element. In this 'hybrid Rowland/Echelle' approach, the grating and STJ detector

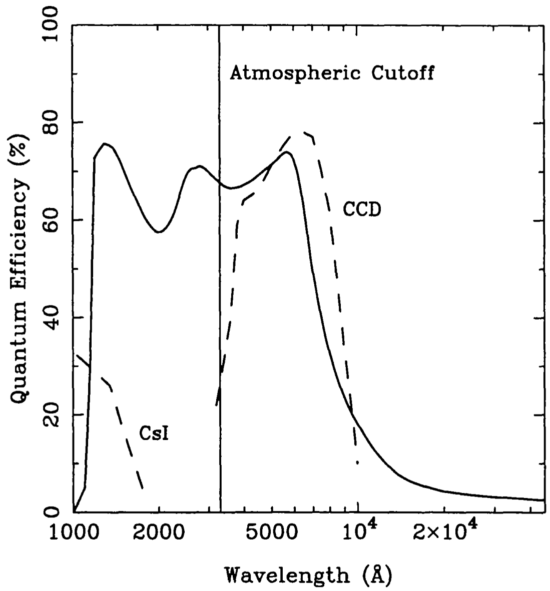

Figure 4. Calculated quantum efficiency of a bare tantalum on MgF_2 STJ compared to that of a typical CCD and a good quality cesium iodide photocathode. The exceptionally high efficiency predicted in the UV has been verified experimentally in the case of tantalum on sapphire.

are arranged as in the classical the Rowland circle mount, with the long dimension of the STJ array spatially sampling the dispersed image as in a conventional spectrograph. However, by operating the grating in relatively high spectral orders chosen to be resolvable by the STJ detector, the well-known problems of high groove density, excessive image length and off-axis aberrations of the (first order) Rowland mount can be alleviated.

In Fig. 5, the horizontal axis represents the 'conventional' dispersion direction sampled by the elongated format STJ array. The vertical axis shows the energy or wavelength dimension, with each horizontal bar representing one FWHM resolution element of the STJ material (in this case tantalum). Note that while the basic layout of the orders in this example are fixed by the requirement that the free spectral range at the shortest wavelengths equals twice the STJ resolving power, the spectral resolution is determined by the pixel sampling; i.e. by the number of detector pixels along the dispersion direction. In other words, provided the plate scale and grating aberrations are matched to the STJ pixel size, very high 'echelle type' spectral resolution is in principle achievable with a sufficiently long STJ detector. Making the STJ array several pixels high perpendicular to the dispersion direction will enable simultaneous monitoring of the adjacent sky background as in a conventional long slit spectrograph. However, since the background spectrum is already 'resolved' by the STJ detector, there is no need to employ a slit except in cases where one wants to observed an extended source or maximize the signal-to-noise ratio at wavelengths within an STJ resolution element of a strong airglow line. Most importantly, however, since an STJ-based spectrograph dispenses with the need for collimating and

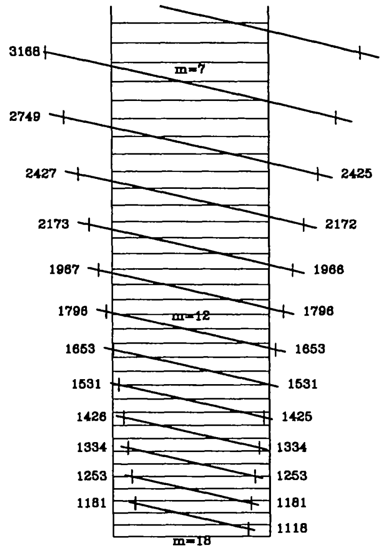

Figure 5. Possible layout of a far-UV grating spectrograph employing an elongated STJ array for photon detection and 'on chip' spectral order separation. The horizontal axis represents the conventional spatial dimension of the STJ array along which the dispersed spectrum is sampled, and the vertical axis its inherent wavelength resolution. The endpoint wavelengths of the free spectral range are marked along each spectral order and listed in the margin

cross-dispersing optics, it will have a significant advantage in throughput over a conventional design.

This economy of optics, together with its unprecedented high sensitivity clearly makes the STJ array a prime candidate for any future UV space observatory.

Acknowledgments. I am grateful to my colleagues Tone Peacock and Peter Verhoeve for their patience and efforts in enlightening me as to the inner workings of the STJ detector.

The ESA/ESTEC STJ detector development effort is further evangelized at `http://astro.estec.esa.nl/stj`.

Note added in proof: The announcement of an interesting alternative, but closely related, approach to employing superconductors as astronomical detectors has recently been made by Cabera et al. (1998, Appl. Phys. Lett., 73, 735).

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