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for use in astronomy

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Superconducting Tunnel Junctions (STJ) have now been under development for a number of years for a wide range of astronomical applications. Devices based on niobium-aluminium or tantalum-aluminium have been shown to be efficient photon counting energy dispersive spectrometers from the near infra-red to X-ray region of the spectrum. The basic performance characteristics of tantalum based devices, in terms of detection efficiency, spectral resolution and signal linearity with photon energy, are provided for each wave band of astronomical interest, namely: the near infra red (NIR [1-5 μm]), optical [400-1000 nm], ultraviolet (UV [100-400 nm]), extreme ultraviolet (EUV [10-100 nm]), soft X-ray (SXR [100-2000 eV]) and medium X-ray (MXR [2-10 keV]) regions of the spectrum.

Although design issues which allow the optimization of the performance for a specific waveband are of importance, we show that current generations of tantalum based STJs have already very good performance over the whole spectral range. A particular improvement in the resolving power and a description of the role played by various mechanisms in degrading the energy resolution from the theoretical tunnel limited value is given based on specific measurements at relevant photon wavelengths. Additional astronomical characteristics for future applications, such as the time resolution and imaging capability are also presented, based on experimental data and the performance of the first small format 6x6 pixel STJ array described. Finally an assessment is provided on the possibility for further improvements, particularly in the area of higher spectral resolution, through the use of lower band gap superconductors.

Key words: Superconductivity, high resolution spectroscopy, cryogenic detectors, astronomy

1 Introduction

After absorption of a photon in a superconductor the generated hot electrons are thermalised by excitation of phonons which have generally sufficient energy to break Cooper pairs into quasi-particles (qp) - the charge carriers. The whole process occurring on a time scale ranging from ns as in niobium to ms in hafnium is essentially determined by the critical temperature T_C and therefore by the energy gap Δ of the electrode material used to form the Josephson junction. A small Δ gives high resolving power and a high charge signal amplitude. The resolving power of an STJ is theoretically limited by statistics of the qp generation and the tunnel process [1]. For a tantalum based STJs one finds $E/\Delta E = \lambda/\Delta\lambda = 11.1 \cdot \sqrt{E} = 390/\sqrt{\lambda}$. Here the Fano factor of 0.2 [2] and a mean energy of $2\Delta=1.2$ meV required to break a Cooper pair has been assumed. The tunnel statistics associated with the back-tunneling of the qp's across the thin oxide barrier are also included in these simple formulae. A single charge carrier tunnels in our tantalum devices on average about 10 times across the barrier. Development of Hf based STJs [3] would, compared to Ta based STJs, reduce the energy gap from 0.664 meV to 0.021 meV improving the resolving power by a factor of 5.6, such that at 1 keV (1.2 nm) it could be ~ 2000 .

Tantalum based STJs with a T_C of 4.5 K have been developed which reach the theoretically predicted resolving power [4,5] in the optical spectral range and approach it almost in the EUV and soft x-ray region where additional charge losses deteriorate the detector response. In this paper we summarize the results of the experiments with tantalum based devices covering the spectral range from the NIR to the MXR. The presented data will characterize the spectroscopic capabilities of the detectors with respect to resolving power, line shape properties and detection efficiency. Since imaging and time resolution are also of importance for astrophysical applications, results obtained with an 6x6 tantalum based STJ array are included in the presentation.

2 Broadband performance of tantalum based STJs

2.1 NIR and optical spectral range

Operation of STJs for detection of NIR and optical photons allows back-illumination of the devices through the substrate on which the Josephson junction has been deposited. The substrate, which is usually a sapphire window, acts as a natural filter with a band pass open between 6 μm and 140 nm. It is clear that for tantalum based STJs in the optical spectral range the resolving power is limited to about 20. Figure 1 shows some spectra obtained using monochromatised optical and NIR radiation. The photons are transmitted by an optical fiber to the STJ located in a

Fig. 1. Optical spectra at photon wavelengths of 300 nm, 400 nm, 750 nm, 1 μm and 2 μm as a function of photon energy.

cryostat with a base temperature of 300 mK. Scintillation of the fiber gives sometimes residuals at lower pulse height, especially for the 300 nm radiation. The spectra clearly demonstrate the spectroscopic performance in the NIR and optical spectral range.

2.2 EUV and soft x-ray range

For the use of STJs in the EUV and x-ray spectral range it is necessary to front-illuminate the device. Because of the STJs sensitivity to high rate (piled-up) long wavelength photons, it is necessary to protect the STJ from blackbody IR radiation. This is possible by either a strong limitation of the solid angle open to the outside or by a suitable filter. For the EUV and SXR a 75 nm Al filter with a Ni mesh support has been used, which was located at the radiation entrance port of a cryostat with a base temperature of 440 mK. In this way external radiation sources could be used. The spectroscopic capability is demonstrated in figure 2 showing a spectrum from a tantalum based STJ illuminated with 15 eV photons and its associated multiple harmonic order radiation up to 210 eV delivered by the SX700 grating monochromator of PTB at the electron storage ring BESSY in Berlin [6]. The harmonic orders have deliberately not been suppressed. In the same picture some spectra in the SXR taken using the same monochromator show the detector response at higher energies. In this spectral range STJs provide their most powerful performance and the measured resolving power at e.g. 1000 eV is 170, compared to the theoretically tunnel limited resolving power of 350 (see figure 7).

Fig. 2. Observation of the multiple harmonic order radiation in the EUV spectral range (on the 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 (on the right side of the dashed line) with resolving powers of 60, 135, 170 and 150 respectively.

2.3 Medium x-ray energy response

The nature of the detection process and the limitations in the device fabrication set practical constraints for the device thickness to below 500 nm. The detection efficiency is therefore $<20\%$ at say 6 keV if no intermediate absorber material is introduced. A major part of the radiation in the MXR is thus not absorbed in the electrodes of the STJ but in the substrate below. Such an event creates phonons in the substrate which can enter the STJ and break Cooper pairs, so that an unwanted signal is generated. It is possible to reject such events by signal processing, effectively filtering the events with a typical signal risetime associated with substrate events. Figure 3 shows a spectrum without any discrimination taken with a ^{55}Fe radioactive source. In the SXR the different signals from the top and the base electrode give rise to two peaks for each emission line in the spectrum.

2.4 Imaging capability

Fabrication of STJ arrays with close packed pixels (see figure 4) requires the electrical leads to be isolated from the underlying detector pixels or counter electrodes. A SiO_x layer is therefore deposited onto the whole pixel array before the leads are

Fig. 3. Spectrum of a ^{55}Fe source with the photo peaks of the $K\alpha$ and $K\beta$ lines at 5.9 keV and 6.4 keV. In the spectrum the response of the detector from both base and top film as well as from the substrate can be seen.

deposited with contact to small interconnections on positions where SiOx has been etched away. Photons absorbed in the isolation layer generate, like in the substrate, signals which show up as low energy events in the spectrum. The pulse risetime determination and discrimination can therefore assist in the rejection of events created by photons absorbed in the SiOx isolation. This approach can be applied in the whole SXR and MXR [7]. Figure 6 demonstrates the technique by showing a spectrum obtained from monochromatic photons of 1 keV energy with and without a pulse risetime discrimination together with the distribution of the pulse length (typically $10\mu\text{s}$) as a function of the pulse amplitude.

In back-illumination mode used at NIR and UV wavelength this SiOx isolation plays no role in the overall response to individual photons. A first generation 6x6 pixel camera operating in the optical spectral range between 300 and 700 nm has been developed for a ground based astrophysical application [8]. The pulse height uniformity of the array element is demonstrated in figure 5, which shows a homogeneity of about 5%. The detection efficiency is determined by the substrate transmittance and by the reflection of the electrode surface. A calibration of the detector revealed a detection efficiency of around 70% [4].

Fig. 4. Optical microscope photograph of a 6x6 tantalum array with $25\ \mu\text{m}$ pixel size and a filling factor of 74%. The pixels have a common ground and each one signal wire.

Fig. 5. The distribution of the responsivity/charge-output uniformity for a 6x6 array illuminated with optical or x-ray radiation.

Fig. 6. Comparison of the spectra obtained by illuminating a pixel of the array with (lower) and without (upper) application of pulse risetime filter. The accepted events are between the two solid lines in the pulse risetime distribution in the middle.

2.5 Overall resolving power and detection efficiency

The resolving power obtained from the analysis of the measured spectra is compared to the theoretical tunnel limited resolving power. The derived resolving power has been corrected for electronic noise which contributed typically a σ of 0.06 eV in the optical spectral range in back-illumination mode and 0.3 eV in the EUV to MXR

Fig. 7. Theoretical tunnel limited resolving power compared to the experimental data obtained with tantalum based STJs. The jump at $\lambda \sim 150$ nm to lower resolving power by changing from back- to front-illumination indicates the material quality change from epitaxial (base film) to polycrystalline (top film). This causes also the second jump of resolving power at the transition from top to base film at $\lambda \sim 15$ nm. The prospects for Mo and Hf STJs have been included.

in front-illumination mode. Since the charge output or average number of tunnels is non-linear in energy [9], the data had to be corrected for this effect. It can be seen in figure 7 that the data can be well described by the theoretical resolving power in the optical spectral range and approaches the theoretical limit closely in the EUV to MXR.

At 5.9 keV a resolving power of 370 obtained in an experiment with a collimated beam has also been included [10] into the data set. The collimation minimizes the main contribution to the resolving power at higher energies, which arises from spatial inhomogeneities in the junction [11]. With the collimation the resolving power increases by a factor of 3.

3 Discussion and conclusion

The current status of the performance of our tantalum based STJ detectors as high resolution spectrometers in the broadband from the NIR to the medium x-ray range has been demonstrated. Use of lower T_C material together with improved electronics and data processing techniques could make these detectors suitable for spectroscopy with extremely high resolving powers and fast response times. Array sizes of about

10^3 pixels should be readily achievable with the current fabrication techniques which are particularly based on the early experience with small format 6x6 arrays. Such detectors would open completely new fields of investigation especially for astrophysical applications in the next century.

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