Soft X-Ray Performance of Superconducting Tunnel Junction Arrays

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***Abstract*-A number of 6x6 element arrays of Ta-based superconducting tunnel junctions have been manufactured for photon counting applications with moderate energy resolution in ground-based optical astronomy. The individual array elements show low leakage, uniform responsivity across the array, good simultaneous Josephson current suppression and minor crosstalk between adjacent pixels. The same arrays have been characterized in the soft X-ray range (E=270-1500 eV). The base electrode response shows good energy resolving power (E/ΔE≈140). Unwanted spectral features originating from other parts of the detector can be largely eliminated by risetime filtering. Modifications in the layering are necessary in order to improve the soft X-ray detection efficiency.**

I. Introduction

Superconducting tunnel junctions (STJs) are developed as photon and particle counting detectors with a high intrinsic energy resolving power [1]. Photons absorbed in an STJ will break Cooper pairs into free charge carriers or 'quasiparticles' (QPs), which can be detected by the tunneling of electrons across the insulating barrier of the STJ. The initial number of quasiparticles N(E) is proportional to the energy E of the absorbed photon: $N(E)=E/\varepsilon$ [2], [3], where $\varepsilon \approx 1.7\Delta$ (with Δ the bandgap of the superconductor) is the average energy required to generate one quasiparticle. Typically, ε is of the order of meV, implying that STJs could be used as photon counting, energy resolving detectors for visible and IR photons. This has recently been demonstrated with Nb- [4] and Ta-based [5] STJs and has lead to the development of a camera based on a 36 element array of STJs for application in ground-based optical astronomy [6].

STJs are also attractive for astrophysical applications in the soft X-ray region (E≈100-2000 eV), since they could provide the required energy resolving power of $E/\Delta E \geq 200$. A resolving power of $E/\Delta E \approx 100$ has already been demonstrated with Nb-based STJs [7].

In view of future soft X-ray applications, the general performance and the response to monochromatic soft X-ray radiation of 6x6 element arrays of Ta-based STJs are presented in this paper. Preliminary results have been presented elsewhere [8].

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II. Description of the STJ Detector Array

The two detector arrays (referred to as #1 and #2) used in this work are fabricated by Oxford Instruments Scientific Research Division (Cambridge, UK). The detector chip consists of a sapphire substrate on which a 6x6 element array of 25x25 μm^2 square STJs is made. This layout was designed for the detection of single optical photons by illumination through the transparent substrate. Nomarski microscope images of such an array are shown in Fig. 1.

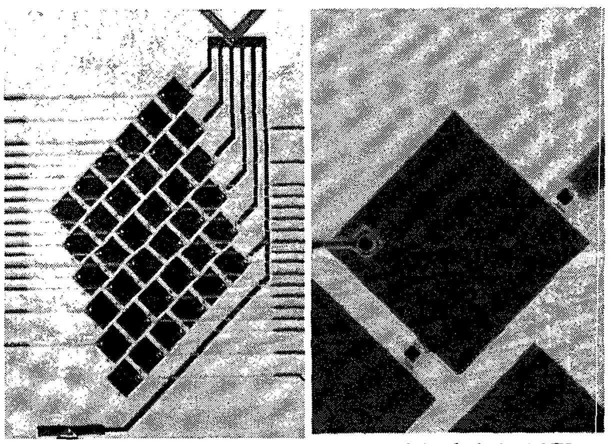

Fig. 1: Nomarski microscope photographs of the 6x6 pixel STJ array. Left: overview, right: detail.

The symmetrical STJs are made from Ta/Al/AlOx/Al/Ta multilayers with 100 nm thick Ta layers and 5 nm thick Al layers. The base electrode Ta is epitaxial (RRR=46), whereas the top electrode is polycrystalline. The entire array is covered with an insulating SiOx layer of 350 nm thickness. The contact leads for the top electrodes are 1.5 µm wide and made of Nb, in order to prevent the diffusion of quasiparticles out of the lower bandgap Ta electrodes. The top film electrical contact is made through a 1.5 µm via in the SiOx. The gaps between adjacent pixels is 4 µm, yielding a filling factor of 74%. The base electrodes of each 6 element column of the array are interconnected with 2 μm wide Ta bridges which are interrupted by a Nb plug (see Fig. 1), again to prevent diffusion of quasiparticles into neighbouring pixels. Eventually, the 6 columns are connected to a common return lead. The energy gap (2Δ) at the barrier, as measured from the I-V curves at T=300 mK, is 1.32 meV, close to the energy gap for bulk Ta (1.33 meV). The AlOx tunnel barrier has a resistivity of about 3 $\mu\Omega$ cm^2. The I-V characteristics of the STJs are dominated by leakage currents up to T≈500 mK. The pixels are in the 'diamond' orientation with respect to the magnetic field, to enhance the suppression of the Josephson current I_j. The six columns are offset by 0.5 pixel with respect to each other in order to allow the top contact leads to be routed as straight lines across the array, without overlapping each other.

III. Experimental Set-up

The performance verification experiments on the STJ arrays have been performed in a ^{3}He cryostat with a base temperature T=0.30 K. The detector chip is clamped to a cold finger in the inner vacuum chamber of the cryostat. A superconducting magnet is available to provide the magnetic field parallel to the plane of the tunnel barrier, which is required to suppress the Josephson current and Fiske steps. The base electrode of the STJs can be illuminated through the sapphire substrate with monochromatic UV and visible light, through an optical fibre. Alternatively, a small ^{55}Fe radioactive source, emitting Mn-K lines at 5.9 and 6.5 keV, can be used to stimulate both the top and base electrodes. The higher energy photons enable us to assess the energy resolution of the detector, as well as the level of crosstalk between pixels. Most of these tests were done on array #1.

The soft X-ray experiments were performed on array #2 at the synchrotron radiation facility BESSY in Berlin, Germany, using the SX700 beamline (E=10-1900 eV) at the radiometry laboratory of the Physikalisch-Technische Bundesanstalt (PTB). A dedicated ^{3}He cryostat, operated at T=450 mK, with a radiation access port and a 75 nm thick Al filter *to suppress IR background radiation* was used.

The STJs are read-out with a charge sensitive amplifier and a shaping stage, both at room temperature. Each detected photon gives rise to a pulse at the output of the preamplifier. The amplitude and the risetime of this pulse correspond to the total number of tunneled electrons (charge output) and the decay time of the signal pulse from the STJ, respectively, and are stored on a PC. The limiting noise level of the electronics chain with open input is ~600 electrons rms. The electronic noise is monitored through the width of the response to an electronic pulser fed into the electronics. Presently, up to four pixels can be read out simultaneously, which enables the verification of the level of crosstalk between pixels by means of coincidence measurements.

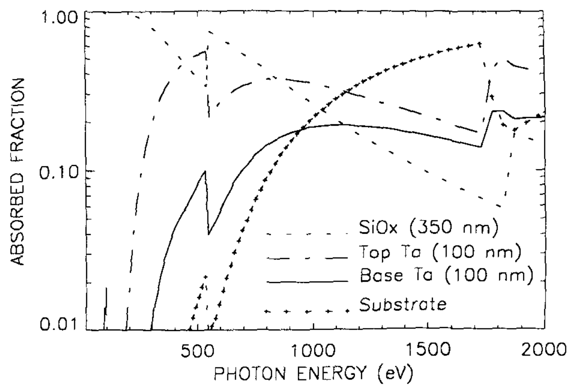

Fig. 2: Absorbed fraction in the respective layers of the present STJs.

IV. Measurements and Results

A. Array Performance

Extensive testing of the arrays, consisting of screening all pixels individually with respect to their leakage currents, Josephson current suppression and responsivity (= number of tunneled electrons per eV of photon energy), as well as simultaneous read-out of up to 4 pixels, has demonstrated:

- the responsivity of array #1 is ~6000 electrons/eV, corresponding to an average number of tunnel processes per QP of $<n>=7$, and is uniform over all pixels to within 10%. Array #2 has responsivity corresponding to $<n>=4$.
- all pixels of array #1 show leakage currents <0.2 pA/μm^2, except for one which has 1.6 pA/μm^2. This means that all pixels can be operated with noise levels $\Delta E_{NOISE}<0.3$ eV (FWHM).
- the bias voltage is not critical: only minor variations in responsivity between V_{bias} =100 and 200 μV are found.
- the Josephson current can be suppressed at the same magnetic field (B≈105 gauss) to <60 nA for each pixel, with an average of <10 nA. This is sufficiently low to allow stable voltage biasing in a low noise configuration.
- the crosstalk between adjacent pixels by diffusion of QPs across the connecting bridge is of the order of 8% for array #1 (with $<n>=7$). This is about an order of magnitude less than in an earlier version of the array without the Nb plugs in the bridges. In array #2 (with $<n>=4$), no measurable crosstalk was observed. The residual crosstalk in array #1 can be due to QPs at an energy equivalent to the Nb energy gap, which can diffuse across the Nb plug before they scatter down in energy [9]. In addition, an anomaly could have occurred in the fabrication of the plugs in array #2, leading to trapping of QPs at the plugs (rather than reflection) and lower responsivity.

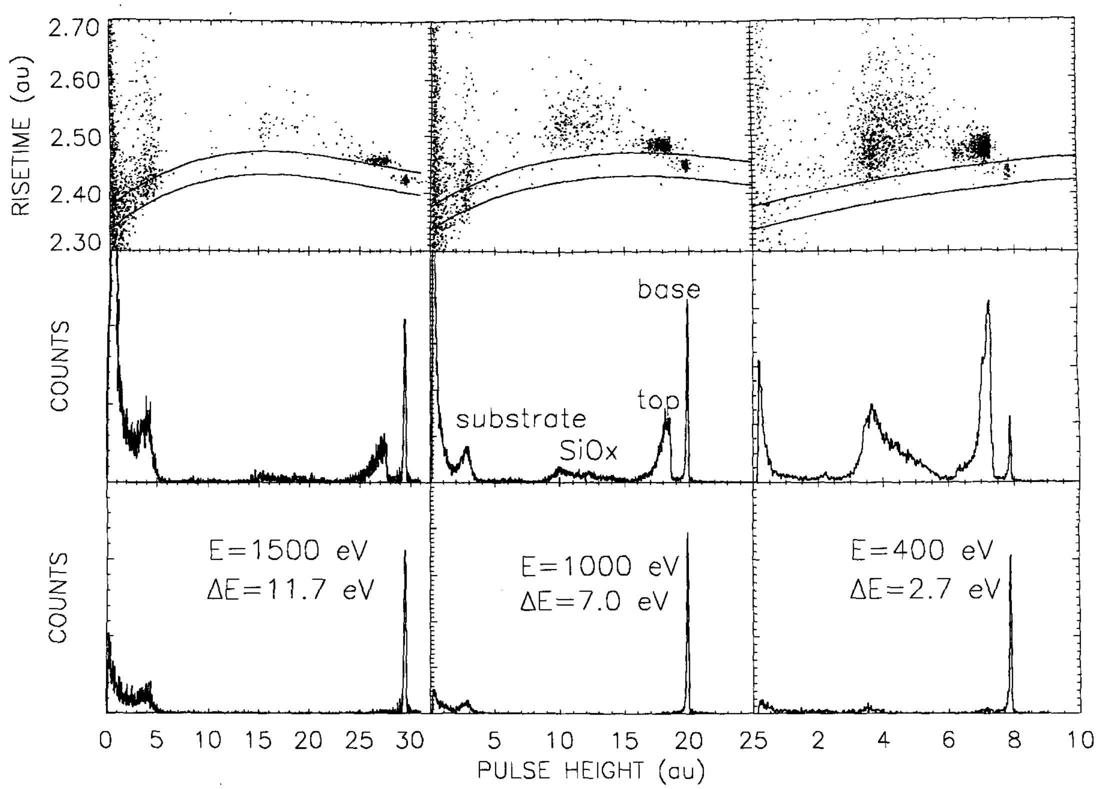

Fig. 3: Soft X-ray spectra at E=1500 eV (left), 1000 eV (middle) and 400 eV (right). Top: charge-risetime scatter plot, middle: full spectrum, bottom: risetime-filtered spectrum.

- photon absorptions in the substrate, which give rise to significant numbers of unwanted low pulse height events, can be rejected by using their coincident signals in neighbouring pixels. Rejection efficiencies of 30% and 45% when using one or two neighbouring pixels, respectively, can be achieved at E=1500 eV.

B. Soft X-ray Response

Fig. 2 shows the absorption efficiency in the SiOx insulation layer, the top electrode, the base electrode and the sapphire substrate for illumination with soft X-rays (E=100-2000 eV) at the front side of a STJ with layer thicknesses as described in section II. Note that the present devices were designed for the detection of UV and visible photons by illumination through the sapphire substrate, and hence, the layering is not optimised for X-ray detection.

Spectra have been acquired with the four-channel read out system for nine pixels of array #2 at photon energies in the range of 270-1500 eV. Sample spectra at E=1500, 1000 and 400 eV of one of these pixels are shown in Fig. 3 (middle row). Also shown are the corresponding *risetime-charge* scatter plots (top row), showing that the contributions from the various layers can be discriminated by their risetime signature. The spectra in the bottom row contain mainly base electrode events, and are obtained after application of a single risetime filter, as indicated by the curved lines in the scatter plots in Fig. 3. Especially at the higher energies, clean high-resolution spectra are obtained without loss of detection efficiency of base electrode events.

The measured energy resolution (FWHM) as a function of photon energy for base and top electrode is shown in Fig. 4, together with the measured electronic noise ($\Delta E_{NOISE} \approx 1.0$ eV). The solid line in Fig.4 represents the predicted statistically limited resolution for a symmetrical STJ [10],[11]:

$$\Delta E = 2.355\sqrt{\varepsilon E(1 + F + \frac{1}{<n>})} \qquad \textbf{(1)}$$

Here, the mean energy to produce a QP $\varepsilon=1.7\Delta$ and the Fano factor F=0.22 have been chosen the same as for Nb [3], and the average number of tunnel processes per quasiparticle $<n>=4$.

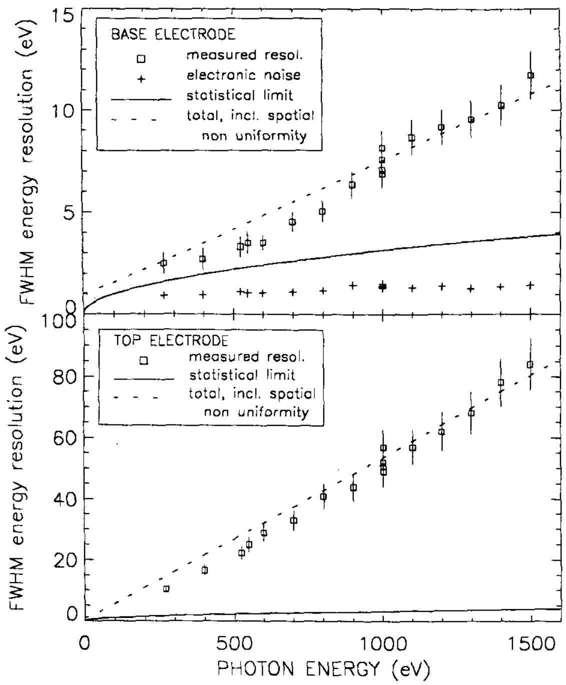

Fig.4: Measured energy resolution for the base (upper) and top (lower) electrodes of one array element.

The dashed line is the predicted resolution, if an additional contribution proportional to photon energy, arising from spatial nonuniformities in the response of the device, is included [12]. The measured energy resolution of ΔE=35 eV at E=5.9 keV (^{55}Fe source) for the base electrode is in good agreement with the dashed line. The top electrode clearly suffers far more from spatial non-uniformities in the response. Furthermore, the measured energy resolution of ΔE=450 eV at 5.9 keV is about 50% above the value predicted by the dashed line. This suggests that the energy resolution for the top electrode increases faster than linear with photon energy. The measured energy resolution for the base electrode at E=1000 eV for the nine pixels involved in the present experiment ranged from 6.2 to 7.9 eV, indicating a rather uniform performance over the array.

V. Discussion and Conclusion

Prototype arrays of 6x6 Ta-based STJs have been succesfully manufactured for application in ground based optical astronomy. The arrays are characterized by 100% yield of low leakage pixels, which can be simultaneously operated by virtue of a sufficient suppression of Josephson current for all pixels at the same magnetic field. They show a high uniformity in responsivity and energy resolution across the array. Crosstalk between adjacent interconnected pixels is as low as 8% due to the use of higher gap plugs in the interconnecting bridges.

The present arrays also show good soft X-ray (E=270-1500 eV) energy resolution (typically $E/\Delta E \approx 140$) for photons absorbed in the base electrode. Contaminating spectral features originating from the SiOx insulation, the top electrode and the substrate can be largely removed by risetime filtering. While the energy resolution in the soft X-ray range is almost sufficient for astrophysical applications, the detection efficiency of the base electrode (10-20%) needs to be improved and the number of array elements needs to be increased. Obvious changes to enhance detection efficiency are thicker base electrodes and thinner top electrodes and insulating SiOx layer. Larger format arrays will however suffer from reduced detection efficiency due to a larger number of top contact leads crossing the array.

Acknowledgment

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