The 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 cross talk between adjacent pixels. The same arrays have been characterized in the soft X-ray range ($E=270\text{--}1500\text{ eV}$). The base electrode response shows good energy resolving power ($E/\Delta E \approx 140$). Unwanted spectral features originating from other parts of the detector lay up can be largely eliminated by rise time filtering. Modifications in the lay up 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: $N(E)=E/\epsilon$ [2], [3], where $\epsilon \approx 1.7\Delta$ (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 led 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 ($E \approx 100\text{--}2000\text{ eV}$), 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].

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 $25 \times 25\text{ }\mu\text{m}^2$ 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 $1.5\text{ }\mu\text{m}$ 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 $1.5\text{ }\mu\text{m}$ via in the SiOx. The gaps between adjacent pixels is $4\text{ }\mu\text{m}$, 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 $3 \mu\Omega \text{ cm}^2$. 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 ^3He 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 cross talk 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 ($E=10\text{-}1900$ eV) at the radiometry laboratory of the Physikalisch-Technische Bundesanstalt (PTB). A dedicated ^3He 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 rise time 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 cross talk 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 $\langle n \rangle = 7$, and is uniform over all pixels to within 10%. Array #2 has responsivity corresponding to $\langle n \rangle = 4$.
- all pixels of array #1 show leakage currents $< 0.2 \text{ pA}/\mu\text{m}^2$, except for one which has $1.6 \text{ pA}/\mu\text{m}^2$. This means that all pixels can be operated with noise levels $\Delta E_{\text{NOISE}} < 0.3 \text{ eV}$ (FWHM)
- the bias voltage is not critical: only minor variations in responsivity between $V_{\text{bias}} = 100$ and $200 \mu\text{V}$ are found
- the Josephson current can be suppressed at the same magnetic field ($B \approx 105$ 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 cross talk between adjacent pixels by diffusion of QPs across the connecting bridge is of the order of 8% for array #1 (with $\langle n \rangle = 7$). 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 $\langle n \rangle = 4$), no measurable cross talk was observed. The residual cross talk 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-rise time scatter plot, middle: full spectrum, bottom: rise time 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 layup 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 *rise time-charge*

scatter plots (top row), showing that the contributions from the various layers can be discriminated by their rise time signature. The spectra in the bottom row contain mainly base electrode events, and are obtained after application of a single rise time 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 ($\Delta E_{\text{NOISE}} \approx 1.0$ eV). The solid line in Fig.4 represents the predicted statistically limited resolution for a symmetrical STJ [10],[11]:

$$\Delta E = 2.355 \sqrt{\epsilon E \left(1 + F + \frac{1}{\langle n \rangle} \right)} \quad (1)$$

Here, the mean energy to produce a QP $\epsilon = 1.7\Delta$ 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 $\langle n \rangle = 4$.

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 $\Delta E=35$ 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 $\Delta E=450$ 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 successfully 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. Cross talk between adjacent interconnected pixels is as

low as 8% due to the use of higher bandgap 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 rise time 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.

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Resolution Degradation in X-ray Detectors based on Superconducting Tunnel Junctions

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Resolution Degradation in X-ray Detectors based on Superconducting Tunnel Junctions

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Abstract—Despite considerable progress over the past years, the detection of medium-energy X-ray photons ($E > 1$ keV) with STJs near the energy-resolution limit, set by the Fano and tunnel noise, remains an elusive goal. There is presently little doubt that the spatially inhomogeneous response of the STJ is responsible for the degradation of the energy resolution. We review several proposed mechanisms against experimental data for Nb- and Ta-based STJs, of various sizes and in single or array-format. We argue against a single mechanism behind the resolution degradation. The experimental results presented here support a model in which quasi-particles are lost at the edges of the STJ, but also indicate that losses into the leads seriously degrade the energy resolution. Finally, an example is given of how fabrication details may play a role as well.

I. INTRODUCTION

Arrays of detectors based on Superconducting Tunnel Junctions (STJs) provide the possibility to perform non-dispersive, high-resolution imaging spectroscopy in a very broad range of wavelengths. Practical instruments for optical, UV and soft X-ray (< 1 keV) wavelengths are now feasible through the successful development of small-format STJ arrays, with up to 6×6 pixels (see Fig. 1) [1]. At soft X-ray wavelengths energy resolutions to within a factor ~ 2 above the statistical limit have been found for Ta-based STJs (i.e. $\Delta E = 3.4$ eV (FWHM) for 525 eV photons) [2, 3], but at higher X-ray energies the situation is less satisfactory.

The energy resolution of an STJ is usually approximated as the Gaussian sum of the following factors:

$$\Delta E = 2.355 [\sigma_{\text{Fano}}^2 + \sigma_{\text{tun}}^2 + \sigma_{\text{el}}^2 + \sigma_{\text{spat}}^2]^{1/2}. \quad (1)$$

Here σ_{Fano} is the Fano-limited resolution, the statistical fluctuation in the initial number of quasi-particles (QPs) created immediately after the photo-absorption [4, 5], and σ_{tun} is the fluctuation in the number of electrons that actually tunnel across the barrier [6, 7]. Both are proportional to $E^{1/2}$ and the Gaussian sum of these two factors forms the statistical limit on the energy resolution of STJs. σ_{el} is the noise contributed by the electronics and the surroundings, which is assumed to be independent of E . σ_{spat} represents the spatial non-uniformity in the charge response Q of the STJ, and is generally considered to be directly proportional to E .

The central question in the research presented here is the physical origin of the spatial variation of Q . The results presented here demonstrate that different mechanisms can lead to very similar spatial response functions. Detailed

Fig. 1. Top view microscope images of a 3×3 test array of Nb-based STJs (left) and a 6×6 Ta-based array (right). The (square) Nb-based STJs have a size of $40 \mu\text{m}$, the (also square) Ta-based STJs have a size of $25 \mu\text{m}$. Note that the top electrode of the central pixel (no. 9) of the Nb array is not connected. The base electrodes of adjacent STJs are connected via bridges. While in the Nb array the number of bridges is 2 or 3, depending on position, it is 2 for all pixels in the Ta array. The widths of the electrical connections to the top films are $1.5 \mu\text{m}$ in the Ta array, and in the Nb array resp. $1 \mu\text{m}$ for STJs 1, 6, 7 and 8 (top row), and $2 \mu\text{m}$ for STJs 2, 3, 4 and 5 (bottom row). In both arrays, the material of the bridges and leads is Nb.

knowledge of these physical mechanisms is essential in the selection of an effective strategy to improve the resolution.

II. EXPERIMENTAL RESULTS

A. Some experimental details

The results presented here are based on several types of measurements on a variety of different STJs, so space does not permit us to discuss all the experiments in detail. A more detailed description of the experiments is presented elsewhere [1, 2, 3, 8, 9]. Nevertheless, the lay-out of the STJs discussed here is quite uniform. The Nb-based STJs consist of a multi-layer of a 100 nm epitaxial Nb base film, sputtered on a super-polished sapphire substrate, a $\sim 10 \text{ nm}$ thick epi-Al / AlOx / poly-Al barrier layer and a 200 nm poly-crystalline Nb top film. The Ta-based STJs have instead a 100 nm poly-crystalline Ta top film. Each detector chip carries 8 to 10 single square STJs, with sizes L in the range $10 - 200 \mu\text{m}$, or a single array as shown in Fig. 1. The operating temperature is $0.3 - 0.4 \text{ K}$.

B. The magnitude of the spatial response inhomogeneity

Although we know from the analysis of spectral-line profiles that the Gaussian approximation breaks down for large contributions from σ_{spat} [10, 11], (1) provides an acceptable approximation. This is shown in Fig. 2, where ΔE is plotted as a function of E for STJs from the arrays shown in Fig. 1. The spatial non-uniformity of Q dominates the resolution above a few 100 eV , even though the magnitude of the variations is of the order of 1% of the charge output.

Fig. 2. The energy resolution as a function of photon energy, for both top film (▲) and base film (▼). Data points are presented for one pixel of the Nb 3x3 array (left) and as an average of 3 pixels for the Ta 6x6 array (right). The energy resolutions plotted here have been corrected for electronic noise. Solid lines indicate the statistical limit from Fano and tunnel noise, dashed lines correspond to a best fit model including the contribution from the spatial non-uniformity of the charge response. The size of these non-uniformities, σ_{spat} , defined as per cent RMS variations from the mean, is also indicated.

A 6 keV energy resolution to within a factor 2 from the statistical limit requires a spatial uniformity in the charge response better than $\sim 0.1\%$. We are approaching this goal for the Ta base film, but for the top films there is still an order of magnitude to be gained.

C. Energy resolution as a function of device size

From Fig. 3 it is apparent that the spatial inhomogeneity has a large geometrical component. The difference in the behaviour of ΔE between the epitaxial base film and the polycrystalline top film, in both Nb and Ta, is quite remarkable, particularly because Q increases with increasing device size for both electrodes. This is to be expected when the main QP losses take place at the edges.

The SRON group [10, 11] has developed a phenomenological diffusion model that represents the QP trapping at the edges by a reflectivity R slightly less than 1. Fig. 4 shows

Fig. 3. Charge output Q (top row) and energy resolution ΔE (bottom row) for both top film (▲) and base film (▼) as a function of STJ size, measured for series of single STJs based on Nb (left) and Ta (right). Data points are averages of several series of STJs.

Fig. 4. Illustrations of the response profiles predicted by the SRON model, for the base (solid line) and top film (dashed line) of a 10 μm (a) and a 100 μm (b) STJ. Q_0 is the charge response in the center of the STJ. On the right hand ΔE as a function of device size, based on this model. To be compared with Fig. 3c.

that this model can explain, at least qualitatively, the behaviour of ΔE for both films seen in Figs. 3c and d. The model parameters are edge reflectivity R , the QP mean free path ℓ , which is estimated from the low-temperature resistivity of the film, and the ratio Λ/L between the mean distance over which a QP diffuses during its lifetime τ_{life} and the size of the STJ. For Fig. 4 we took values typical for our Nb STJs in Fig. 3. In order to have ΔE_{top} decrease with size, Λ_{top} had to be taken a factor 30 smaller than its estimate $[2D\tau_{\text{life}}]^{1/2} \approx 30 \mu\text{m}$. While ℓ is equal to the diameter of the columnar grains in poly-Nb ($\sim 30 \text{ nm}$, determined with TEM), the actual diffusion of QPs appears much slower. Such an effect has been reported before, both for polycrystalline Nb and Ta [11, 12, 13]. Following [13], we speculate this is due to Andreev reflections of QPs at the grain boundaries, which make the QP trajectory less effective than a classical random walk with mfp ℓ .

The SRON model was originally motivated by a scenario in which NbO forms at the edges of the Nb-based STJs as the result of natural oxidation. Because NbO has a lower bandgap energy than Nb, the oxidized sites act as QP traps, thus providing the loss mechanism at the edges. However, the model applies equally well to Ta-based STJs, although none of the Ta-oxides are superconducting. In particular, the change from Nb to Ta as the main electrode material did not bring a large improvement in the STJ energy resolution [3, 10, 14, 15, and Fig. 3a, b]. It did, however, make a differences for the charge response, presumably because trapping losses from NbOx at the surface of the top electrode were eliminated. A similar improvement of Q could be obtained by covering the top electrode of a Nb STJ with a 5 nm layer of NbN, which has a higher bandgap than Nb and thus repels QPs [16]. So it seems that the QP trapping does have an effect, but not so much on the energy resolution.

D. Influence of leads

Fig. 5 presents a set of measurements on the individual STJs in the 3x3 Nb array. The charge output depends mainly on the number of base-film bridges; on average 7% of QPs

Fig. 5. Per cent deviations from the mean of charge output and energy resolution of the 8 connected pixels in the Nb 3×3 array shown in Fig. 1a. The top row panels demonstrate that the charge output of both the top and the base film varies with the number of bridges connecting to the base electrode (dark shading: 2; light shading: 3). Per bridge, on average 7% of the quasi-particles are lost to the adjacent STJ. The bottom row shows that the energy resolution is practically independent of the number of base-film bridges, but strongly depends on the width of the top lead. Here dark shading indicates a width of 1 μm, and light shading a width of 2 μm. The top-film resolution was measured at a range of energies for which all photons were absorbed in the top film.

diffuses across each bridge. This was confirmed by charge-output measurements with electronics that simultaneously read out adjacent pixels. However, the energy resolution hardly depends on number of base film bridges at all, but correlates strongly with the width of the top lead. Reduction of the width by 50% improves ΔE on average by 40%.

This result is not a complete surprise. An LTSEM measurement on one of our earlier Nb-based devices also shows a major impact of the contact lead on the homogeneity of the signal response of the STJ [12]. This effect was stronger than the influence from QP losses at the edges.

A potential remedy for the resolution reduction by the leads is to prevent QPs entering the leads by the application of materials with a higher bandgap energy Δ than the electrode. We found it possible to improve ΔE_{base} of the Nb-based 20 μm STJ described in [17] by 30% and ΔE_{top} by 50%, by inserting NbN plugs in the leads.

For Ta-based STJs the lead problem is not so easily solved. The 6×6 Ta array has Nb bridges, but still 7% of the QPs escapes across the 4 μm bridge, the same fraction as in the 3×3 Nb array which has unmodified bridges. *Somehow, QPs can escape into higher bandgap material.* This finding ties in with a comparison of two identical Ta-based STJs, one with Ta and one with Nb leads, which did not show an improvement of ΔE for the STJ with Nb leads, just like the number of base-film bridges did not influence ΔE in the 3×3 Nb array. It is a well-known fact that QPs can gain an energy of eV_{bias} ($\sim 0.25\Delta$ in our experiments) from the tunnel and back-tunnel processes [18]. In our Ta-based STJs, the number of tunnel processes per QP, $\langle n \rangle$, lies in the range of 4

to 7 for 25 μm STJs [3], so the bandgap difference between Nb and Ta (a factor of 2.3) can be easily bridged. A serious problem with this hypothesis is, however, that the scattering lifetime of QPs with energies above Δ is much shorter (< 1 ns) than the tunnel time (~ 1 μs) [19, see also 16]. QPs with an energy of 2Δ can travel ~ 7 μm in our epitaxial Ta films before being scattered into a lower energy state. Hence, a possible alternative explanation is that QPs created directly after the photo-absorption process, when the energy is still $\geq 2\Delta$, are able to escape from the electrode, provided the absorption takes place close enough to the base lead.

Work is currently in progress to incorporate diffusion into the leads and edge trapping of QPs in a numerical model based on the Rothwarf-Taylor equations. The situation may not be too different from QP trapping at the edges, except that instead of many small trapping sites we now have one big loss channel. Of course, the actual solution at the fabrication level requires an entirely different approach.

E. Spatial variations of the bandgap

Fig. 6a demonstrates that in our series of single Nb-based STJs there is a clear correlation between the bandgap Δ , as obtained from the I-V characteristics, and the size of the STJ. The observed 4% decrease in Δ over the range of sizes, implies that Δ increases towards the edge of a STJ. The Ta-based STJs do not show this variation of Δ with size, as is clear from Fig. 6b. The reason for this can be seen in the TEM cross-section photos of edge regions in Fig. 7. During the etch process, Al is etched away faster than Nb. As a result, the edge of the Nb-based STJs has a serration, typically 200 nm deep, centered at the Al layer. The 200 nm wide rim is not in direct contact with the Al, and therefore the local Δ_{Nb} above and below the rim is less influenced by the proximity effect. Clearly, the Ta-based STJs do not suffer from this problem. Fig. 8a illustrates several phenomenological models of the variation of Δ with distance to the edge d , where the variation is assumed to be independent of the size of the STJ. The variation in the charge response follows from $Q = E / (1.74 \Delta)$. The contribution to the resolution that

Fig. 6. The measured bandgap Δ as a function of device size for series of single Nb- and Ta-based STJs. Open symbols in the right panel indicate data points based on one measurement only. The various curves correspond to models detailed in Fig. 8.

Fig. 7. Cross-sectional TEM photographs of edge regions that are typical of our (a) Nb-based STJs, and (b) Ta-based STJs. In both photographs the central 10 nm thick sandwich of Al/AlOx/Al is visible as a bright line. The serration in the Nb edge at the position of the Al layer is ~ 200 nm deep.

results from this response inhomogeneity is given as a function of device size in Fig. 8b. Each of these models were fit to the data in Fig. 6a. Given the error bars, the data does not strongly distinguish between these models. Considering the correlation length in Nb, $\xi_0 \approx 40$ nm, the physically most plausible model is the one where Δ steps at 200 nm from the edge. However, the ΔE predicted by this model is much higher than we have measured, in particular for the smaller devices. A comparison between Figs. 3c and 8b suggests that all models are more suitable for the top film than for the base film. This would imply that the bandgap gradient is stronger in the top film than in the base film, which can be qualitatively understood in terms of the Golubov model of the proximity effect [20, 21]. In the presence of a resistive barrier, such as formed by the network of grain boundaries in the poly-crystalline top film, much larger bandgap gradients are possible than in a highly conductive medium, such as the epitaxial base film. Curiously, the best fitting model, $\Delta \propto d^{-1}$, predicts that Δ is affected by the rim over distances far greater than ξ_0 , the grain diameter or even the rim width. Since the Golubov model is one-dimensional, and this problem is clearly two dimensional, it is difficult to take this analysis much further. Moreover, the problem discussed here is probably typical of these STJs. It does, however, illustrate nicely how a completely different mechanism than QP loss at the edges, can give rise to the same spatial profile of response inhomogeneity.

Fig. 8. Illustrations of some phenomenological descriptions of the variation of bandgap Δ as a function of distance d from the edge of the STJ. Two models simply assume a step in Δ , one at 200 nm from the edge (short dash), consistent with Fig. 7a, and one at $4.9 \mu\text{m}$ (long dash), based on a best fit to the data in Fig. 6a. The other model assumes a more gradual decrease of Δ , based on a powerlaw: $\Delta \propto d^{-1}$ (solid). The left panel shows the resulting variation with position of the charge response in a $20 \mu\text{m}$ STJ, the right panel the relative variation of energy resolution with device size predicted by these models.

III. CONCLUSIONS

The strategy for improving the STJ X-ray energy resolution depends directly on the physical mechanism behind the resolution degradation. QP losses near the edges call for modifications of the fabrication process, while losses into the leads may be remedied by fabricating leads of higher bandgap materials. The analysis of the causes of energy resolution degradation, presented in this paper, has shown that it is not a question of choice between one of the described mechanisms, but that it is important to recognize that several factors are likely to play a role in the resolution degradation of STJs. This explains the persistence of the resolution problem over the past years. In order to solve it, all the key factors must be identified, and their impact on the resolution assessed.

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