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D.H. Lumb, A. van Dordrecht, A. Peacock,
N. Rando, P. Verhoeve, J. Verveer,
*Astrophysics Division, Space Science Department of the European Space Agency,
P.O.Box 299, NL-2200 AG Noordwijk*

D.J. Goldie, J. Lumley,
*Oxford Instruments Scientific Research Division,
Newton House, Cambridge Business Park, Cowley Rd., Cambridge CB4 4WZ, U.K.*

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D. H. Lumb, A. van Dordrecht, A. Peacock, N. Rando, P. Verhoeve, J. Verveer,
*Astrophysics Division., Space Science Dept. of European Space Agency, ESTEC, PO Box 299,
2200AG Noordwijk, The Netherlands*

D. J. Goldie, J Lumley
*Oxford Instruments Scientific Research Division, Newton House, Cambridge Business Park, Cowley Rd.,
Cambridge CB4 4WZ, U.K.*

ABSTRACT

Measurements are presented on the X-ray response of superconducting tunnel junction (STJ) detectors, over the energy range of 50 - 1800 eV. This includes the measurement of the lowest X-ray energies published to date. Energy resolution and response linearity is measured as a function of device geometry. It is shown that self-recombination of quasi-particles leads to an energy non-linearity which depends on junction volume. The effect of count rate limitations on energy resolution is established for rates up to 10kHz.

Keywords: Superconducting Tunnel Junctions, X-ray astronomy, X-ray energy resolution

1. INTRODUCTION

1.1 Comparison with present generation detectors

At the time of writing, the two world class X-ray Observatory facilities, AXAF and XMM, are undergoing detailed definition of their calibration activities. During the next two years these projects will finish their hardware fabrication phases and undergo extensive calibration prior to launch. Both missions will extend the pioneering work of the ASCA satellite, by further exploiting the use of CCDs for imaging spectroscopy. Apart from the advances in technology which will enhance angular resolutions and/or collecting area, these future missions will be able to build upon the scientific insight gained from ASCA with respect to the requirements for calibration. The enhanced energy resolution of CCDs, compared with previous gas counter instruments, has revealed a necessity to produce detailed energy response matrices including such second order effects as EXAFS signatures near absorption edges due to mirror gold coatings or in the detector materials, and also new evidence about small scale non-linearity in the silicon energy response^{1,2}.

For the next generation of astronomy missions, after AXAF and XMM, Superconducting Tunnel Junction (STJ) X-ray detectors, have the potential to offer non-dispersive spectroscopy with an order of magnitude higher spectral resolution. While the currently achieved performance of STJ's is only slowly approaching this goal, it is not too early to examine such second order effects, present in any spectrum as a result of the detectors' inherently complex response. For example the implications of the existence of these spectral response matrix artifacts would include a requirement for a corresponding order of magnitude increase in calibration details. Of course, a more pressing motivation to examine such physical processes includes the potential for further improving our understanding of the basic physics of the devices, hopefully leading to measures to improve significantly the implementation of the device technology.

The physical size of the detectors is important for future missions, both directly in determining the angular resolution and field of view coverage of a practical astronomical system, and indirectly through effects such as counting rate capability. For the measurements described here, the size of detectors is also explored with respect to X-ray performance, so that geometric effects may probe yet further the device physics. For example, the junction volume partially determines the magnitude of charge signal and energy linearity.³

1.2 Energy range and linearity

Recent work published elsewhere³ described in some detail experiments performed at the Berlin Electron Synchrotron facilities (BESSY), into energy linearity effects in STJs. We present here a brief description of similar experiments at lower energies, facilitated by improvements in detectors, the cryogenic system and associated electronics.

A wide energy bandpass is important in a X-ray spectrometer to ensure that source temperature measurement is not biased by selection within the temperature sensitivity range of the detector system. To date, the lowest energies measured with STJs are of order 150eV³. With the lower noise performance we report here, we examine the parameters which limit the attainment of the lowest energy limit, down to energies of ~50eV.

1.3 Count rate performance

For current CCD detectors to be used as X-ray spectrometers, photon counting requires that the typical rate be $<10^{-2}$ per pixel per image frame. In order to obtain high count rate capability for the special limited cases of point sources, special readout modes must be invoked. (In the case of the XMM EPIC MOS camera, for example⁴ this provides a count rate capability of hundreds of counts per second at a temporal resolution of milliseconds, which effectively gives up imaging capability of the detector for the field of view coverage, in order to ensure a certain time resolution for the brightest field source.) Meanwhile, for the competing technology to STJ's in the domain of high non-dispersive resolution (i.e. the bolometer/microcalorimeter developments⁵) the count rate capability is limited by the thermal time-constants necessary to establish the high energy resolution. To date the demonstrated performance has been limited by system decay times of order 1msec, so that for accurate settling a count rate limit of order 10's Hz is imposed⁶.

Such count rate limits already represent a compromised performance, because the over-riding concept for high spectral resolution missions is to ensure a large collecting area to enable an adequate number of photons per spectral bin. This in turn implies that for the bright X-ray sources already well-characterised by previous missions, the count rates will be necessarily very high.

For the STJ, signals are intrinsically fast, limited in practice by the analogue electronics. Although fast rise-times of the order microseconds are typical in our devices, we are presently limiting the count rate capability by a signal processing time of 160µsecs. We will establish that this is indeed the limit to count rate capability by confirming resolution properties as a function of controlled count rate.

2. THE STJ DETECTOR SYSTEMS

2.1 The STJ devices

The STJs have been fabricated for the European Space Agency as part of a long-term superconducting technology development programme, by the Oxford Instruments Thin Films Group, from Cambridge (U.K.). These devices comprise a multi-layer structure of Nb/Al/AlOx/Al/Nb which is deposited on a polished sapphire substrate. A range of junctions have been produced. The typical features include an epitaxial base Nb layer of 100nm thickness and a polycrystalline top Nb layer of 200nm. The aluminium and oxide layers comprise typically a total of 10nm

A previous version of devices was fabricated with a mask producing four each of two junction sizes ($20 \times 20 \mu\text{m}^2$ and $50 \times 50 \mu\text{m}^2$) with $3 \mu\text{m}$ leads. We have previously reported⁷ X-ray energy resolution measurements of 53eV FWHM with such devices, in a collimated beam of 6keV, and they were also the subject of previous energy linearity measurements³. For these most recent experiments, a new mask set allowed production of experimental junctions with a range of sizes from $10 \times 10 \mu\text{m}^2$ to $200 \times 200 \mu\text{m}^2$ and with lead sizes of 1 or 3 μm . The film thicknesses were comparable with the former devices. For reference the designation of the device under test was KJL44.1.1.

2.2 Cryostat

To enable the illumination of the STJs with an external radiation source, a small pumped He⁴ cryostat was fabricated. The detector chip was mounted on a cold finger connected to the bottom plate of the dewar. In close proximity were a pair of superconducting magnets which supplied a field of up to 0.1T to suppress the Josephson current in the junctions. An isolation vacuum was provided by the synchrotron beam line and radiation shields with $\sim 1\text{mm}^2$ beam aperture completed the thermal isolation. For reference and calibration purposes, there was an internal Fe⁵⁵ source located several mm from the devices, providing Mn K α and K β calibration lines of 5.895 and 6.490 keV. A lower temperature of ~ 1.22 K was achievable at the cold finger in this new set of measurements, an important factor in enabling the measurements at the lower energy regime we have been able to report here.

2.3 Electronics

The detected current pulses were routed to a set of room temperature read-out electronics comprising a charge sensitive pre-amplifier and shaping stages. The output was fibre-optically coupled to a PC which stored the total charge and rise-time of the signal pulses. A 16-bit digitisation was employed, and to maximise dynamic range capability over the wide energy range, and with different signal outputs from the different detector geometries, a range of post-amp gains were made available. The signal sampling was performed in parallel channels with different risetimes to allow a more sophisticated selection of events on the basis of risetime, which was an aid to establishing the origin of events from different portions of the junctions.

3. BESSY EXPERIMENT DETAILS

The measurements were performed at the electron storage ring, BESSY in Berlin. The SX700 plane grating monochromator of the radiometry lab of the Physikalisch-Technische-Bundesanstalt was used⁸. The following beam performance was obtained: an energy selection of $E/\Delta E$ in the range 500-2000, absolute energy scale accuracy of order 0.1% , and a small false light contamination through the SX700 of some 2% at 1.5keV, reducing with energy to $\ll 1\%$ below 1keV.

To monitor potential drifts in detector response, and to confirm the reproducibility of our measurements, a procedure was adopted for frequent monitoring at a reference energy of 1200 eV. This was found adequately to allow for any changes from one thermal cycle of the dewar to the next, and was found to be a very important procedure based on the previous experience³. As a further precaution, signals from an electronic pulser at a rate of 10Hz were continually monitored for noise performance checks, while pulses from the Fe⁵⁵ source were also recorded. Indeed it was found that the change in response within one day ($\ll 0.1\%$), was comparable with the measurement accuracy, with the largest gain change for one junction between successive days being $< 1\%$. The cold stage temperature was monitored in parallel. It was found that the temperature marginally changed during each day ($\sim 20\text{mK}$), but this temperature variation had no significant effect on junction gain.

The energy response of the detectors was measured by scanning across the energy range with a step interval of 100eV to 10 eV (depending on energy). By measuring the response of the different junction sizes for these common energy ranges, the effects of junction volume were investigated (e.g. self-recombination non-linearity). By discriminating between signals from the base and top layers the diffusion properties have been investigated as a function of the structure of the two niobium films

For most measurements, the beam intensity was adjusted to allow about 400 cts/sec in the junction, and then measurement times adjusted to ensure sufficient events were accumulated in spectral peaks from both films so that the peak centroids could be determined to better than 0.3%. At those energies where essentially all radiation was absorbed in the top film, the criterion was relaxed to the precision required for measurements of the top film peaks alone.

Additionally a series of measurements were taken at a range of count rates in one junction. This was performed using a dedicated event grabber which collected all events in a 1 second frame before processing in the computer. In this case the maximum rate was limited by the processing time of the pulse height analyser (160 μ s).

4. RESULTS

4.1 General observations

Figure 1 shows a typical data-space representation of the pulse height and rise-time characteristics. Typically these plots comprise (in order of descending energy) separately resolved peaks from the base and top films, and a large region of events with anomalously low pulse heights, resulting from the absorption of events in the sapphire substrate. The relative separations and ratios of included events vary with energy due to effects of non-linearity in response, and to the changing fractions of events absorbed in the layers according to the mass attenuation coefficients. At the time of writing, more detailed analysis is proceeding with attention to the fitting of multiple Gaussian peaks, extraction of second-order monochromator light and Fe⁵⁵ substrate events etc., so the data presented here are only preliminary. Nevertheless, due to the high spectral purity of the synchrotron beam, and intrinsic high energy resolving power of the STJ, it is possible already to make useful deductions.

Figure 1 - Rise time/Energy phase space representation of the signal detected from 1200eV X-rays in an STJ. The key signal components are identified

4.2 Charge output

The charge output varies with junction size, detector bias and between top and base films. Similarly the noise depends critically on the junction bias, dynamic resistance of the junction etc.. For the reference energy of 1200eV, Table 1 lists the mean charge outputs and the measured pulser noise at the nominal operating points.

Junction size (mm)	Junction lead (mm)	Base film output (elct)	Top film output (elect)	Pulser noise (r.m.s elect)
100	1	1.36×10^6	9.43×10^5	41200
50	3	1.15×10^6	8.25×10^5	16500
20	3	6.52×10^5	5.40×10^5	5150
20	1	7.50×10^5	5.92×10^5	6500
10	3	2.43×10^5	1.97×10^5	1860

Table 1 Summary performance data at 1.2keV of the junctions tested

The theoretically predicted signal expected from a 1200eV X-ray is of order 4×10^5 electrons. These higher measured values indicate there is some limited level of carrier multiplication through multiple tunneling effected by a small amount of quasi-particle trapping. The higher quality base films produce higher charge outputs than the top films. However, there is a charge deficit with lower junction size, which we attribute to effects of trapping at the junction edges, out-diffusion at the contact leads and of self recombination of quasi-particles, which must have higher density in the smaller junction volumes. This leads to expectations that there will be commensurate non-linearity in energy. Comparison of the two 20 μ m junctions allows some insight into the effects of the lead size. The output of the base film is more than 15% higher with the smaller lead. The top film the difference is only 10%. This would imply that while lead size is important, the degradation by diffusion to the top contact is partly obscured by other effects due to the polycrystalline nature of the top film. The noise on pulser signals does not scale directly with junction area, suggesting that leakage current is not the sole source of internal noise. This is expected because the noise is a function of sub-gap current, dynamic resistance and capacitance, all of which depend on junction size. Figure 2 highlights the variation of charge output with junction size.

Figure 2 Variation of charge output with junction size at 1.2keV - note that one of the 20 micron devices and the 100 micron devices have 1 micron lead widths- the remaining devices have 3 micron widths

4.2 Lowest measurable energy

Figure 3 shows the pulse height distribution which was obtained in the 20 μ m junction with 1 μ m lead as a result of illumination by 50eV X-rays. At the time of writing, this is the lowest measured X-ray energy with an STJ device to be published. The energy resolution is about 50% FWHM at this point. The absorption length is so short at this energy, that essentially all signal is generated in the top film, with a mean signal of $\sim 22,000$ electrons. [Note: subsequent devices containing aluminum trapping layers to amplify the intrinsic charge have reduced this limit to 500 nm (~ 2.5 eV) ⁹]

Figure 3 Pulse height distribution for 50 eV stimulation . The bulk of X-rays are absorbed in the polycrystalline top film

4.3 Energy linearity

The typical linearity is shown in Figure 4, for the base and top films of the 20 μ m junction with 1 μ m leads. The plot is displayed as a *normalised* linearity, i.e. it is based on the 1200eV reference energy as unity. The deviations from linearity at the lowest energies are probably dominated by statistical limitations in determining the peak centroids, due to the overlapping contributions from substrate, top and base films. More significant is the steadily increasing charge deficit to higher energies. This is attributed to the effects of the self-recombination of quasi-particles, which is greater for the higher densities of particles generated by the higher X-ray energies. Comparison with other junctions shows that the charge deficit at higher energies progressively decreases with increasing junction size.

These data have already accounted for the calibration in offsets in the amplifier/ADC chain. One systematic error in assessing the linearity of both films (especially the top film), is that at the higher energies (>500 eV) it is possible to establish a clear peak value, manually, of the film response which is non-Gaussian in energy distribution. At lower energies, the top film response becomes confused with substrate events, and the base and top films also become co-located in energy and rise-time domain. Then the most suitable data processing is with a multi-Gaussian fitting approach. However this actually calculates the *mean* of the response rather than the *peak* and hence the data analysis procedures themselves may be responsible in part for the discrepancy in the linearity of response. Only a small representative set of error bars are shown in the figure, in order to maintain the clarity of the plot. However a similar spread in data results if individual data points are repeatedly analysed with small variations in the energy range over which the Gaussian fitting is performed.

Figure 4 Linearity in energy response in top (Δ) and base (*) films of the 20 μm junction with 1 μm leads
a selection of points have representative error bars overplotted

It is clear that in the top film, one may expect surface layers of Nb₂O₅ which might cause such response variations in the range 200 - 500 eV, but further work is proceeding to confirm if this is a likely explanation. XPS analysis of a similar device showed an oxide layer of some 5 - 6 nm on the film surface. Figure 4 displays the Nb M and O K absorption edge energies. Across the oxygen K absorption edge, for example, this would cause a change in oxide layer transmissivity to the X-ray photons of from 94% to 91%. For a 1% change in mean signal across an absorption edge, it would not require a large redistribution of photon absorption depth in different device volumes with slightly different response. However it is difficult to posit a physical model which allows for signal *reduction* in being preferentially absorbed deeper in the top film.

4.4 Energy resolution

Figures 5a and 5b display the typical variation of energy resolution with energy, in this case for junctions with two different lead widths. By performing a quadrature subtraction of electronic noise, it is possible to calculate the intrinsic component of the STJ itself. However the raw measured resolution is dominated by the junction component, which varies linearly with energy, indicating it is dominated by spatial variations in its response.

Within the experimental errors there is only a marginal difference between the measured resolution in the two base films, but there is a significantly worse resolution in the top film of the 3 micron lead junction. This corresponds with greater spatial response variations such as trapping at the junction perimeter and diffusion to the contact. Due to the carrier multiplication fluctuations¹⁰ and the phonon coupling between the polycrystalline top film and the high quality base epitaxial films, the base film resolution may be affected by the top film, but it cannot be distinguished in this data from effects of the lead size.

Figure 5a Energy resolution of a 20 micron junction with 1 micron leads

Figure 5b Energy resolution of a 20 micron device with 3 micron leads

4.5 Count rate dependence

The influence of count rate on spectroscopic performance needs to be evaluated so that the application to astrophysics instruments can be ascertained clearly. Figure 6 shows the variation with count rate of the FWHM energy resolution for an X-ray photon energy of 1200eV. Also shown for comparison is the FWHM of the electronics and device itself, as measured on the pulser signal. As the count rate increases, the interval between events becomes comparable with the electronics settling time (160 μ s), so that the baseline is not properly restored. For 10% degradation in energy resolution, a count rate of $\sim$ 1000 per second is clearly maintained.

Quadrature subtraction of the pulser noise from the measured X-ray FWHM, leaves an intrinsic STJ resolution which is constant at 18eV FWHM for all rates. This is expected, as the typical timescale for quasi-particle loss and tunneling processes is of order 1 μ s. These key measurements indicate that fundamentally the STJ is a practical high speed astronomical sensor.

Figure 6 Variation of energy resolution with count rate for 20 micron junction with 1 micron leads

5. DISCUSSION

The measurement of different device geometries on the same chip has allowed an evaluation into some of the important features of the X-ray energy response of STJ's. Based on the non-linearity due to a charge deficit with increasing energy and also the lower junction area, we have further evidence that self-recombination of the quasi-particles is an important effect. Trapping at the junction perimeter, diffusion to the contacts further affect the energy resolution.

The resolution of the base film may be compromised by the top film, as multiple tunneling and/or phonon coupling is important in the charge generation process. If this is so then for this device design, further attention to film quality issues must be paid, such that the degradation of resolution due to spatial response variations are eliminated.

Then the performance would be limited by system noise, which for this room temperature electronics located 1m from the device, is only 20eV FWHM. Reduction of noise would require further cooling to reduce the sub-gap current, and employing cooled electronics in close proximity to the junctions.

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