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ABSTRACT

We present an experimental study of the performance of Distributed Read-Out Imaging Devices (DROIDs), 1- and 2-dimensional photon-counting imaging spectrometers, based on Ta/Al-based STJs placed on a Ta absorber. Results obtained with highly collimated illumination with 10 keV X-ray photons clearly demonstrate the imaging capabilities of 2-dimensional DROIDs. The derived spatial FWHM resolution is 7 μm for a $200 \times 200 \mu\text{m}^2$ absorber. With a 1-D DROID we have measured an intrinsic energy resolution of 15 eV FWHM for 6 keV photons. At high energies ($E > 6$ keV) the resolution is limited by spatial fluctuations in the qp recombination rate.

Keywords: Superconducting tunnel junctions, X-ray detectors, X-ray imaging, X-ray spectroscopy, DROID, XEUS

1. INTRODUCTION

With the successful launches of XMM and Chandra behind us, the time has come to focus on the next generation of astronomical X-ray missions. The demands on the instrumentation for these missions are challenging. Taking ESA's proposal XEUS as an example [1, 2], the requirements on the X-ray imaging spectroscopy detector include a pixel size of 100 μm with a total detector area of $7 \times 7 \text{ mm}^2$, an energy resolution of 0.1% of the photon energy in energy ranges from 0.1 – 2 keV and/or 0.5 – 10 keV, and a time resolution $\leq 5 \mu\text{s}$.

Compared to Si-based CCDs, cryogenic detectors such as microcalorimeters and superconducting tunnel junctions (STJs) offer a superior energy resolution, a broad energy range, and the possibility of single photon counting with high rates (up to several tens of kHz). For the specific case of STJs, which is the focus of this paper, the requirement to individually bias and read-out each device implies at least one electrical connection per pixel. Such a requirement seriously impedes the development of the equivalent of a large-format imaging array [3, 4]. A possible solution is offered by distributed read-out devices (DROIDs), in which photons are absorbed in a single crystal of large dimensions [5] or a smaller poly-crystalline layer [6–8], and subsequently detected by STJs located at the corners or the edges of the absorber. Compared to an array of STJs, such a detector geometry provides a large sensitive area with a considerable reduction in the number of read-out connections. By time-coincident event measurement it is possible to reconstruct both the absorption position and the energy of the incoming photons. Disadvantages of this approach are the relatively low sustainable count rate and the possible degradation of the energy resolution.

In this study we investigate 1- and 2-dimensional DROIDs as prototypical astronomical X-ray detectors. The emphasis of this study is on spatial and energy resolution. Although the sizes of these detectors do not yet meet the requirements of the next generation X-ray telescopes, DROIDs do hold the promise of providing a large-format array of (virtual) imaging elements. While the energy resolutions of the present 1-D DROIDs are reasonable, they are still at least a factor of three away from the requirements. We investigate the factors that degrade the energy resolution. Using a finite-difference model, which is initially fitted to sets of sampled pulses, we describe how the energy resolution is affected when the size of the DROIDs is scaled up to dimensions compatible with XEUS instrument requirements.

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Fig. 1 *a.* Sketch of the cross-section of a DROID. Not indicated are the top-lead connections and the ~ 1.5 nm thick AlOx between the two Al layers. The SiOx layer is ~ 480 nm thick, the Al layers are each 55 nm thick. The grayscale gradient in the absorber illustrates the change in energy gap from absorber to junction, due to the proximization of the absorber by the first Al layer in the junctions. *b.* A top view Nomarski microscope image of a 1-D DROID (type 1D-100). *c.* Nomarski image of a 2-D DROID (type 2D-200).

2. EXPERIMENTAL SET-UP

Fig.1 shows images of the 1- and 2-dimensional DROIDS. These detectors consist of an epitaxial Ta absorber with a thickness of 100 nm and a RRR of ~ 48 , deposited on a sapphire substrate. The STJs are symmetrical, with 100 nm thick Ta layers and 55 nm thick Al trapping layers. The base electrode is common with the absorber (see Fig. 1a). The whole detector is covered with a 480 nm thick SiOx layer to protect it from oxidation. The STJs have individual Nb connections to their top electrodes and a common Nb return contact via the absorber (see Figs. 1b, c), intended to avoid quasi-particle (qp) losses through out-diffusion into the electrical connections. The junctions have a normal resistance of $\sim 4.2 \mu\Omega \text{ cm}^{-2}$ and the gap energy Δ in the junctions is 0.42 meV. For the study presented here, we have tested three 1-dimensional DROIDS and two 2-dimensional DROIDS. The 1-D DROIDS have absorber sizes of respectively 100×20 and $200 \times 20 \mu\text{m}^2$ (hence with $20 \times 20 \mu\text{m}^2$ STJs) and $400 \times 50 \mu\text{m}^2$ (with $50 \times 50 \mu\text{m}^2$) STJs. These devices are identified below as 1D-100, 1D-200 and 1D-400. The two 2-D DROIDS have a $100 \times 100 \mu\text{m}^2$ absorber with four $20 \times 20 \mu\text{m}^2$ STJs and a $200 \times 200 \mu\text{m}^2$ absorber with $50 \times 50 \mu\text{m}^2$ STJs respectively, and are identified as 2D-100 and 2D-200.

The first series of experiments comprised uniform illumination of the DROIDS with a ^{55}Fe source ($E_{K\alpha} = 5895$ eV and $E_{K\beta} = 6490$ eV) in a ^3He cryostat ($T_{\text{base}} = 320$ mK). In this well-controlled environment, the IV-curves of the 4 STJs of the 2D-200 device showed subgap currents of ~ 15 nA at a bias voltage of 0.2 mV, implying a junction quality parameter $R_{\text{SG}} / R_N = 1.3 \cdot 10^5$. The expected thermal current at 320 mK for these devices is 23 pA. From the shapes of the IV-curves we conclude that the subgap current is due to leakage, and not magnetic flux trapping.

The second and third series of experiments were performed in collaboration with the Physikalisch-Technische Bundesanstalt (PTB) in Berlin, at the PTB SX-700 beamline at the BESSY I synchrotron facility which offers a range in photon energies from ~ 40 eV to 1950 eV, and at the PTB FCM beamline at Bessy II, offering energies from ~ 1700 eV to 11 keV [9]. Here the same 2D-200 detector was operated in a portable ^3He cryostat ($T_{\text{base}} = 470$ mK). The IV-curves showed subgap currents of the order of 100 nA. However, the expected thermal current is 36 nA, which, together with a leakage current of 15 nA, implies that half of the subgap current was due to magnetic flux trapping. Therefore, flux trapping was a problem throughout these measurements.

The electronic read-out of the STJs is done in two modes. In the first mode, the pulses are processed on-line by reading out the STJs through a charge-sensitive pre-amplifier with JFET input stages, followed by electronic shaping with a bipolar semi-gaussian filter. This can be done in coincidence for up to four channels. For each photon detected by a 2-D DROID, four coincident pulse heights S_1 , S_2 , S_3 and S_4 are registered. In the second mode, the pulses are read out by a quasi current-sensitive pre-amplifier (actually a charge-sensitive pre-amplifier with a very short, 0.5 μs , characteristic time) and then sampled with a digital oscilloscope. In this case, we are limited to two coincident channels, so only the 1-D DROIDS can be read out in this mode.

3. IMAGE RECONSTRUCTION AND SPATIAL RESOLUTION

In order to properly convert four coincident charge signals (S_1 , S_2 , S_3 and S_4) into an event position (x , y), we first need to define a model that predicts (S_1 , S_2 , S_3 , S_4) as a function of (x , y), and then invert this model to derive the event positions for

Fig. 2. Steps in the image reconstruction process. See the text for details.

our list of measured coincident charge signals. A realistic model must, of course, take into account qp diffusion, losses and tunneling, as well as the characteristics of the pulse-processing electronics. It is relatively easy to construct a model based on numerical finite-difference techniques [10]. However, in order to obtain enough spatial resolution to allow useful image reconstruction, we found such models require exceedingly large computational resources. At present we are investigating analytical techniques to compute a set of charge signals for a grid of event positions (x, y) . For the moment, however, a simpler approach was adopted, which is illustrated in Fig. 2. First, a set of intermediate positions are constructed from the list of measured coincident charge signals S_1, S_2, S_3 and S_4 :

$$\begin{aligned} x^m &= \frac{1}{2} \ell (S_1 - S_2 - S_3 + S_4) / (S_1 + S_2 + S_3 + S_4) \\ y^m &= \frac{1}{2} \ell (S_1 + S_2 - S_3 - S_4) / (S_1 + S_2 + S_3 + S_4), \end{aligned} \quad (1)$$

where ℓ is the size of the absorber (200 μm). Such a set is shown in Fig. 2c. These positions are to be compared with a set of positions (x^p, y^p) , that is obtained from a uniform grid of initial event positions (x^i, y^i) , using Eq. (1) and a simple assumption about the relation between the individual charge signals S_i , the positions of the STJs (x_i, y_i) , and the event position (x, y) :

$$S_i(x, y) = [(x - x_i)^2 + (y - y_i)^2]^{-p}, \quad (2)$$

where p is some positive number in the range from 0.1 to 1.0. The choice for this relation is one of convenience; it does not have a physical, but a purely mathematical motivation. By a suitable choice of p (plus a linear scaling in the x and y direction), the uniform grid of initial event positions (x^i, y^i) , as shown in Fig. 2a, can be projected into a cushion-shaped distribution (x^p, y^p) , like Fig. 2b, that very closely overlaps the actual measured distribution (x^m, y^m) , as shown in Fig 2c. Since the transformation between (x^i, y^i) and (x^p, y^p) is a simple bijection, the image can be reconstructed by finding for each point (x^m, y^m) the nearest (x^p, y^p) , which then automatically gives the corresponding position (x^i, y^i) in the image plane. The result of this procedure is shown in Fig. 2d. This search process is a computational bottleneck: the time needed scales with the product of the numbers of points (x^p, y^p) and (x^m, y^m) , although it can be made very efficient by subdividing the problem into small cells. The advantages of this approach are obvious: the final result is always a square map of event positions, and it is fail safe. But is it accurate?

The reconstructed image Fig. 2d, which was obtained by a uniform illumination of the 2D-200 device with photons from a Fe^{55} source, shows that there are no large-scale distortions of the image. The selected events were all 5895 eV photons captured in the absorber layer. The $50 \times 50 \mu\text{m}$ STJs clearly stand out, as they received less events due to the presence of 100 nm Ta film on top of the absorber. To investigate the imaging resolution of the 2-D DROIDS, the largest device, 2D-200, was illuminated at the FCM beamline with 10 keV X-rays through a 5 μm pinhole, located at ~ 65 cm from the detector. In this configuration the spot size on the detector is completely dominated by the Fraunhofer diffraction from the pinhole and the first minimum of the diffraction pattern is expected to be at a radius of $\sim 25 \mu\text{m}$ from the center of the pattern. A photon energy of 10 keV (close to the end of the energy range of the FCM beamline) was selected to make the diffraction pattern as sharp as possible, and, since it is just beyond the Ta L_{III} edge (9881 eV), to ensure a detection efficiency of still 4% in the thin absorber. The imaging resolution can be assessed from Fig. 3a and b, which show the 2-dimensional and radially averaged Fraunhofer pattern that was obtained in this experiment and reconstructed with the above algorithm. In Fig. 3b the measured radial pattern is compared to the theoretical pattern based on the photon energy, pinhole size, and distance between pinhole and detector (dotted line). Clearly the difference between the first minimum and second maximum is over estimated. Also shown are two patterns resulting from a convolution of the theoretical Fraunhofer pattern with a Gaussian point-spread function (PSF), which represent the cases in which the imaging resolution is limited.

Fig. 3a. A Fraunhofer diffraction pattern created with 10 keV photons through a 5 μm pinhole at a distance of 650 mm in the FCM beamline of the Bessy II synchrotron facility [9]. b. Radial average of the Fraunhofer pattern, compared with the theoretical pattern for the above parameters (dotted line), and the theoretical Fraunhofer pattern after convolution with a Gaussian point-spread function (PSF) of width of 12 μm (dashed line) and 7 μm (solid line).

In the case of convolution with a PSF of 7 μm FWHM (solid curve) the contrast between the first minimum and second maximum is exactly reproduced, while in the case of convolution with a PSF of 12 μm FWHM (dashed curve), the contrast is washed out. This strongly suggests that the actual imaging resolution during this measurement was 7 μm . Provided this resolution is maintainable over the entire surface and scalable to larger formats, this 2-D DROID is the equivalent of a 28 $\times$ 28 pixel array.

4. ENERGY RESOLUTION

4.1. Two-dimensional DROIDS

Using the reconstructed positions found with the above procedure, it is possible to construct maps of the charge output and the energy resolution as a function of photon-absorption position. Figs 4 show the result of such an exercise for uniform illumination by radiation from a Fe^{55} source detected in the absorber of two DROIDS of different size. The displayed events were selected in a narrow band around the Mn-K α peak. The charge-output maps show two striking features. The first is the decrease of the charge output towards the Nb ground contact (cf. Fig. 1c), and the second is the increase in charge output towards the STJs, followed by a steep decrease towards the corners of the absorber. The Nb ground contact was initially intended to prevent qp losses through diffusion into the electrical contacts. Nb has a higher energy gap than Ta, so the qps in the Ta absorber should be Andreev reflected from the Nb contact. What presumably happens instead is that qps are trapped in regions with a low energy gap in or near the contact. Such traps may be the result of damage to the Ta lattice during the removal of the SiO_x layer at the position where the contact is to be made. Another possibility is that Nb-oxides are formed close to the absorber, which are either superconducting with a lower energy gap than Ta (NbO, with $\Delta=0.21$ meV) or have the properties of normal metals when the layers are thin enough. This problem with Nb contacts on Ta has been reported also by other groups [7]. The increase of the charge output towards the edges of the STJs is related to the decrease of the energy gap in the absorber material, due to the proximity of the Al layers in the STJs [11]. Finally, the losses towards the corners are most likely due to the presence of the Nb top contacts.

The average values for the FWHM energy resolution in the area that excludes these large gradients in charge output (i.e. STJs and near the ground contact) are 94 eV for 2D-200 and 57 eV for 2D-100. These values still have to be corrected for the electronic noise (51 eV and 42 eV, respectively). The energy resolution in these devices appears to be dominated by the

Fig. 4. Reconstructed maps of charge output and FWHM energy resolution as a function of the absorption position of 5895 eV photons, for two different 2-dimensional DROIDs. The energy resolutions have not been corrected for electronic noise and are expressed as a percentage of the peak position. The impact from the Nb ground contact is clearly visible at the left-hand side of the charge output maps.

charge-output gradients across the absorber surface. We therefore refrain from further attempts to analyse the intrinsic energy resolution of DROIDs using these devices, but concentrate instead on the 1-D DROIDs.

4.2. One-dimensional DROIDs

Although the analysis of the data from 1-D DROIDs is simpler than the data from 2-D DROIDs, there are still several complications. As is clear from Fig. 5a, our DROIDs do not show the ‘classical’ behaviour of the device discussed by Kraus et al. [6]. In particular, when the signal of the one STJ is maximum, the signal from the other STJ is still ~60% of its maximum value. This means that qps are hardly trapped at all in our STJs, despite the fact that there is a considerable gradient in energy gap between the part of the absorber that is covered with Al and the rest. Therefore, the *sinh*-relation between charge output and event absorption position, derived by Kraus et al., no longer holds for our devices. Another factor is that the shape of the current pulses generated in the STJs depends on absorption position. In particular the rise-time of the pulses depends on the diffusion of qps towards the STJs and becomes slower for events absorbed closer to the center of the absorber. A single shaping filter cannot be optimized for all the different pulse shapes emerging from the DROIDs. We deal with this problem by correcting for the differences in charge output. Fig. 5b and c illustrate our data-reduction procedure for a measurement of 5895 eV photons in the 1D-100 DROID with on-line pulse shaping, made at the FCM beamline. After the initial selection of all absorber events in the signal 1 vs. signal 2 plane, the selected events are transformed to a plane in which the horizontal corresponds roughly with event position in the absorber and along the vertical the total charge is measured. This selection is then corrected for variations in the total charge output due to the processes discussed above, by fitting a high-order polynomial and correcting the charge output to the median value of the selection. In this way the signal-to-noise ratio (the ratio of vertical position of the band of events to its width) is, at least on average, preserved. Fig. 5d and e show histograms for a selection of charge-corrected events, illustrated in Fig. 5c, at two different energies. Such an additional selection is necessary to exclude the remaining effects of the presence of the Nb contact in the middle of the absorber and the variation of energy gap close to the STJ. An intrinsic energy resolution of 15.3 eV for 6 keV photons was obtained for a selection that comprises ~20% of the total number of events. So far, such good resolutions have only been obtained in Ta STJs with a highly collimated beam [12] or in STJs made from materials with a lower energy gap (Al) [13]. Nevertheless, as we will discuss below, there is considerable room for improvement.

Fig. 5. Data reduction steps in the computation of the energy resolution of 1D-100. The data were obtained at the PTB FCM beamline. *a.* Scatter plot of the charge signals from the two STJs against each other. The border indicates the selected absorber events. *b.* Transformation to a plane in which the x-axis corresponds roughly with position in the absorber, and the y-axis with the total charge of the event. The fit is a high-order polynomial, which is used to correct for the variations in charge output with position. *c.* Plot of the corrected charge output as a function of the equivalent of position in the absorber. The dashed vertical lines indicate the selection of events for the determination of the energy resolution. *d.* Histograms of the selected 5895 eV events and the electronic pulser. The histogram was oversampled to improve the accuracy of the FWHM determination. The dashed line indicates a Gaussian fit to the high energy flank of the histogram. *e.* Idem, but for the lower energy of 1820 eV.

4.3. Factors affecting the energy resolution

4.3.1. The various components

The statistical limit on the energy resolution consists of three contributions. All these processes are essentially Poissonian in nature and their contribution to the energy resolution scales with the square root of the photon energy:

$$\Delta E_{\text{stat}} = 2.355 \sqrt{\varepsilon E (F + G + H)}, \quad (3)$$

where $\varepsilon = 1.74\Delta$ is the energy needed to create one qp and E is the photon energy.

Fano limit. This fundamental limit to the energy resolution is set by the statistical noise on the number of qps created after the absorption of a photon. This Fano limit is independent of the design of the superconducting detector, as long as it is based on the detection of charge. It is characterized by the Fano factor F , which was calculated as 0.22 for photons of a few eV in Nb [14, 15]. For the moment we assume it is valid for other materials and higher photon energies as well.

Tunnel limit. In STJs, which are based on the tunneling of qps, additional statistical fluctuations occur in the number of tunneled qps [16, 17], characterized by a factor G , which is given by [17] as

$$G = \frac{1 - P_1 + 3P_2 + P_1P_2}{P_1(1 + P_2)^2}, \quad (4)$$

where P_1 is the probability for qps to tunnel from the base electrode (absorber) into the top electrode, and P_2 is the probability for tunneling from top to base film.

Cancellation noise. Quasi-particles with energies in excess of $\Delta + eV_{\text{bias}}$ may tunnel in a way that reduces the tunnel current. These are tunnel events that correspond to the two terms in the tunneling Hamiltonian that are usually ignored [18]. The two other terms give rise to the usual forward and back tunneling. Statistical fluctuations on this process gives rise to cancellation noise [19, 20], which is characterized by a factor H . It may give significant contributions for very low bias voltages or in the case of incomplete relaxation of the qp population. H is given by [19, 20]:

Fig.6. Charge output as a function of bias voltage, measured in 1D-200 for uniform Fe⁵⁵ illumination. Plotted as well are two fits of theoretical IV curves, for two different assumptions about the effective qp temperature. The curve for $T=0.9$ K was split into a forward and counter current.

Fig. 7. Analysis of sampled, coincident pulses. The results of the best fit of the finite-difference model to these pulses are also indicated.

$$H = \frac{4\gamma(1-\gamma)}{(1-2\gamma)^2}, \quad (5)$$

where γ is the ratio between counter and forward current. Clearly, γ is a function of the bias voltage V_{bias} .

Several other statistical contributions that were discussed by Segall [20] are only applicable to DROIDS that are in the strong-trapping regime. Our DROIDS are obviously in the weak-trapping limit. Although the energy gap difference of ~ 0.3 meV between the bulk and the proximized absorber would in principle give rise to some qp trapping, in practice qps can easily escape from the STJ region. Even when their energies have scattered down to 0.42 meV, qps may eventually escape the region of the STJ because after tunneling forward- and back again to the base film, they have gained an energy of $2eV_{\text{bias}}$ [21, 22]. Since $V_{\text{bias}} \geq 0.15$ mV in these experiments and each qp tunnels on average between 20 to 100 times, the fluctuations on the number of tunneling qps in both STJs are not independent. Therefore we ignore here the statistical fluctuations in the numbers of trapped qps and we incorporate the fluctuations due to qp losses in the absorber into the tunnel noise, by a redefinition of the tunnel probability P_1 as the probability for a qp in the absorber to tunnel across either one of the two barriers. Essentially, we treat the DROID as a single pixel STJ in which the barrier area is smaller than the base film area.

Besides these statistical contributions there are several contributions that do not scale as $E^{1/2}$, but show another dependence on the photon energy:

Electronic noise. The contribution from the read-out electronics is of course independent of photon energy, and can be easily monitored with a pulser. It is orthogonal to all other contributions and can be easily subtracted from the total noise. The pulser signal is also a good monitor for noise due to pile-up, microphonics and the IR background.

Bias instability. There may also be a contribution from fluctuations of the bias voltage. The effect of these fluctuations depends on the slope dI/dV of the IV curve at V_{bias} [7, 20], and it generally scales with photon energy E , because the generated current I is proportional to E . Because the pulser signal does not depend on V_{bias} , bias fluctuations are not corrected for when the pulser width is subtracted from the noise.

Finally there are contributions from variations of qp losses with photon-absorption position. As we have information on the event position, the fluctuations in charge output along the length of the absorber can be removed effectively in the data-reduction procedure outlined in the previous section. There are, however, also two mechanisms for qp loss that cause fluctuations along the width of the absorber, and will therefore result in a low energy tail on the spectral distribution.

Traps. The presence of a Nb contact or any other strong trap at the edge of the absorber will, as in the 2-dimensional case (see Figs. 4a and c), create a strong gradient in charge output. Because of the geometry of the 1-D DROID its influence is limited to the direct vicinity of the contact only, and can be avoided by making a judicious selection of events, as in Fig. 5c.

Recombination. There is another mechanism that causes fluctuations in the detected charge through positional variations in the rate of qp recombination. Le Grand [23] already noticed that for events absorbed close to the edge, half of the qps are reflected back from the edge, and the qp cloud will initially expand with twice the qp density, compared to qp clouds emerging from events absorbed far away from the edge. Since the recombination rate scales with the square of the local qp density, one would expect that initially the losses due to qp self-recombination are four times higher close to the edge of the absorber than in the center, and increase quadratically with photon energy. In reality, the situation is more complicated, and depends also on the rate at which the phonons generated by the qp recombination can escape from the absorber.

4.3.2. Energy resolution modelling

The cancellation noise can be estimated by fitting the I-V characteristics to a plot of charge output against bias voltage. In Fig. 6, we have assumed BCS densities of state and Fermi distributions of energies. Both assumptions are only approximately valid a proximized superconductor with a dynamically evolving qp population. Still, it is clear from Fig. 6 that the assumption that the qp population has a temperature equal to the lattice temperature of 0.3 K is not tenable, and that a qp temperature of ~ 0.9 K is in much better agreement with the data. Such a high qp temperature is in good agreement with previous findings [7, 22] and is, in our case, a consequence of the energy boost the qps receive when they tunnel. Separating the forward and counter current, we can readily compute current partition ratio γ for each bias voltage. Most of our measurements were made at $V_{\text{bias}} = 0.2$ mV, for which $\gamma \approx 0.07$.

Fig. 6 also contains information about the impact of bias instability. At a bias voltage of 0.2 mV, a 1% rms fluctuation of V_{bias} , 2 μV , results in an increase of the fwhm of the spectral peak by 0.2% of the central energy.

The computation of the tunnel limit is complicated by the diffusion of qps through the absorber. By simply measuring the charge output of the two STJs we cannot tell whether the qps diffuse very fast but tunnel only a few times, or diffuse very slowly, with the limited number of qps which eventually reaches the STJ undergoing many tunnels. A proper distinction between these two regimes is essential for an accurate calculation of the tunnel noise. Moreover, since we start with a finite number of qps, which are distributed between the two STJs by means of diffusion, the tunneling processes in both STJs are not independent. A larger number of qps in one STJ automatically implies a smaller number in the other STJ. Basically, this requires us to model the qp diffusion through the absorber. Therefore we have developed a finite-difference code that solves the qp diffusion equation on a 1-dimensional grid, taking into account qp tunneling and losses in the absorber and the STJs. The effects due to the presence of the Nb contact in the center of the absorber and the possible trapping of qps underneath the Al layers have not (yet) been included. This model is very suitable for an estimate of the tunnel probabilities P_1 and P_2 in Eq. (4). It reproduces the two pulses as they would be recorded after detection by a quasi current-sensitive amplifier, allowing a direct comparison with data. The shapes of the pulses that are measured with a digital oscilloscope contain in fact a wealth of information about the diffusion process. We have therefore fitted the results of our model to pairs of measured pulse shapes. Fig. 7 shows an example of the results of this code, fitted to a typical pair of measured pulses. To date we have studied two positions on 1D-200 and two on 1D-400, processing about 100 pulses per position. The main outcomes are that the diffusion constant is about $15 \text{ cm}^2 \text{ s}^{-1}$ in 1D-200, and $20 \text{ cm}^2 \text{ s}^{-1}$ in 1D-400, and the qp lifetime in the absorber is on average 12 μs in 1D-200 and 34 μs in 1D-400. The qp lifetime depends on photon-absorption position ($\pm 10\%$ variations), and becomes larger with distance from the Nb contact, while the diffusion constant is more or less independent of position. This indicates that the Nb contact should be a factor in the model. Nevertheless, considering the magnitude of the variations in the derived parameters, we are confident that this model provides a reasonable account of the processes going on in these DROIDS.

The dependence of qp recombination on photon-absorption position is essentially a 2-dimensional problem, that requires a separate treatment of qp recombination and other qp loss processes. We have studied this problem using an analytical method in which the response of both STJs is calculated by the decomposition of the solution of the balance equations for the qps into a series of eigenfunctions. The effects of the STJs on the qp diffusion in the absorber are taken explicitly into account. Unfortunately, space does not permit us here to go into the details of this method and we must refer to future publications for a detailed description. The advantages of this method over a 2-dimensional finite-difference computation are speed and resolution, both spatial and temporal, which is essential to accurately follow the initial stages of the expansion of the qp cloud, when the qp density is highest. Fig. 8a demonstrates that this model is capable of giving an accurate account of the non-linearity in charge output, observed in 1D-200 for photon energies beyond 1 keV. The main free parameter in this model is the effective recombination coefficient $R^* = 2.9 \mu\text{m}^3 \text{ s}^{-1}$ [24, 25]. This value depends only on the rates of phonon escape to the sapphire substrate and the SiOx cover layer, which are dominated by conditions at the interfaces [26].

Fig. 8. Charge output and energy resolution as a function of photon energy. *a.* Open symbols indicate measurements on 1D-100 at the SX-700 beamline, closed symbols correspond to measurements at the FCM beamline. The short-dashed line indicates the case of perfect linearity, the dot-dashed line is based on calculations of the charge output including the effects of qp recombination. *b.* Open diamonds indicate SX-700 measurements, scaled to the same energy resolution at 1820 eV as the FCM measurement. Energy resolutions are corrected for the electronic noise, which is indicated by open circles. The solid curve assumes only statistical contributions to the energy resolution with a sum $F+G+H$ of 5.9, the dashed curve is based on the theoretical value of 1.3. Note it is not a fit to the electronic noise. The dashed-dotted line is a combination of the theoretical statistical limit and the effect of qp recombination, and the dotted line is a combination of the theoretical limit plus 0.1% gain variations due to bias instability.

4.3.3. Discussion

In Table 1 we compare the best measured energy resolutions at several energies to the contributions from the mechanisms listed above. Some discrepancies between measurement and theory still exist. Because the contributions from the various mechanisms depend in different ways on photon energy, the relation between the measured energy resolution and photon energy is an important diagnostic tool. In Fig. 8b we attempt to exploit the relation between ΔE and E to identify the additional mechanisms responsible for the resolution degradation. The best results were obtained for a run at the FCM beamline, which has a lowest energy of ~ 1.7 keV. The points between 1.7 and 6 keV suggest a square-root relation between resolution and photon energy, implying a Poissonian nature for the dominant components. To substantiate these findings we combine these results with measurements made at the SX-700 beamline (solid diamonds), in order to cover the lower energies as well. These measurements have obviously a worse energy resolution, but scaled down to the same resolution as the FCM results, using the overlap in energy range of the two beamlines around 1.8 keV as a reference, these low-energy results (indicated by open diamonds in Fig. 8b) confirm this square-root law.

Photon energy:	FWHM resolution [eV]			
	1000 eV	3500 eV	5895 eV	10 keV
measured:	-	13.3	16.9	30.0
pulser:	-	5.8	7.1	12.0
intrinsic:	6.3*	12.0	15.3	27.5
Fano limit	1.2	2.3	2.9	3.8
tunnel limit	2.7	5.1	6.6	8.6
cancellation noise	0.3	0.6	0.8	1.0
recombination	0.9	4.6	9.0	28.8
total expected:	3.0	7.3	11.6	30.3

Table 1. Comparison between measured energy resolution and estimated contributions from various mechanisms.

* Extrapolated from higher energy measurements: see Fig. 8b

This square-root law is consistent with the sum factor $F+G+H$ being 5.9 (solid line), although the 10 keV point is clearly above this line. This fitted sum factor is 4.5 times higher than the sum of 1.3 (dashed line), which we derive from our numerical model. It must be stressed here that although this computed statistical limit is well below the derived value at X-ray energies, it actually agrees with the intrinsic resolution measured at optical energies [27]. Therefore we are confident that we are not underestimating the statistical limit with our model.

Figs. 5d and e show that the asymmetry of the peak does not change much between 1.8 and 6 keV, and the tail of low energy events seems to hardly affect the FWHM value at all. This is consistent with a statistical contribution. Enhanced qp recombination at the edges can explain why the 10 keV point lies so much above the fitted curve (note the model even seems to overestimate the contribution at 10 keV), but is obviously not an explanation for the discrepancy between theory and measurement at lower energies. It would explain only part of the discrepancy at 6 keV and it would not explain a symmetrical broadening of the peak. Fluctuations in the bias voltage do not provide a satisfactory explanation either, although they would result in a symmetric broadening of the peak. The dotted line is a combination of the theoretical statistical limit, plus a contribution from $\sim 1 \mu\text{V}$ rms fluctuations in V_{bias} , and result in 0.1% gain variations (fwhm). Although such variations would not be implausible for our electronics, it is impossible to explain the resolution near 1.8 keV without overestimating the resolution at 6 and 10 keV by a large factor.

Our current hypothesis for the excessive line-broadening is based on the fact that the two runs displayed in Fig. 8b, which were made with the same device, using the same cryostat and electronics (though different beamlines) show a factor of 2 difference in energy resolution at the overlap energy of 1.8 keV. This clearly points to different experimental circumstances. The most likely candidate is the trapping of magnetic flux, as this was a continuous concern during these runs. We find also some evidence for flux trapping in the IV characteristics of the STJs (see Section 2). Magnetic flux lines penetrating the absorber locally suppress the energy gap, and are thus likely to trap qps. Fluctuations on the number of trapped qps could, at least in principle, give rise to a contribution to the energy resolution that scales as $E^{1/2}$. This would therefore imply that up to energies of 6 keV the computed statistical limit could be reached, if the magnetic environment were improved.

4.3.4. Requirements for large-format detectors

The calculation of the statistical limit can be easily extended to DROIDS with formats of the scale required by the optics of future X-ray missions, i.e. absorber sizes of several mm. Fig. 9a shows the dependence of the statistical limit on absorber size, taking the above model for 1D-400 as a starting point. The tunnel noise is the main limitation. Increasing the length of the absorber while keeping the STJs at the same size is equivalent to a reduction of the barrier area. Hence the tunnel probability P_1 decreases, thus raising the tunnel noise (Eq. 4). Scaling up the width of the absorber as well would diminish the adverse effect of position-dependent qp recombination rates that is found at higher energies. The width of the STJs then has to be scaled as well so as to avoid an increase of the tunnel noise, although this will increase the capacitive noise of the STJs, which scales with the area of the barriers.

Figs. 9b and c show that the improvement of the qp statistics by application of lower energy-gap materials is the most important step. The requirement of an energy resolution of 1 eV for 1 keV photons for the XEUS cryogenic instrument [2], is only met by DROIDS based on Hf. Nevertheless, an improvement of the qp diffusion does help and is even essential in the case of Hf [28]. Although a large (~ 4 mm) absorber length does not exclude the possibility of an energy resolution below 1 eV, it places strong demands on the diffusion speed of the qps in the absorber, in particular if one considers the current situation, summarized in Table 2. Here T_{qp} is the temperature of the qps in the absorber, which is taken equal to the operating temperature, usually set at $\sim 0.1T_C$. The energy gap Δ and the Fermi velocity v_F were taken from the literature, but the values of the residual resistance ratio (RRR) for 100 nm thick films and mean-free path at room temperature λ_{300} (except for Hf) were measured in our group. Note that the measured RRR in the Ta and Mo films is constrained by the film thickness. The theoretical diffusion constants in Table 2 are based on the following expression [29, 30]:

	T_{qp} [K]	Δ [meV]	v_F [10^6 ms^{-1}]	λ_{300} [nm]	RRR	D_{theor} [cm^2s^{-1}]	D_{meas} [cm^2s^{-1}]
Ta	0.3 K	0.67	0.38	7	45	63	15 – 20
Mo	0.1 K	0.14	0.47	16.6	21	108	-
Hf	0.01 K	0.019	1.6	2.1	1.5	2.8	-

Table 2. Summary of the diffusion constants in Ta, Mo and Hf.

Fig. 9. *a.* Statistical limit on the energy resolution for 1 keV photons for increasing absorber size, based on Fano limit (dotted line), cancellation noise (short-dashed curve) and tunnel noise (long-dashed curve). The computation was made for a 1D-400 with parameters as obtained from fits to the pulse-shapes. *b.* Statistical limit as a function of diffusion constant D and absorber material. Taking the 1D-400 parameter set as a starting point, the length of the absorber was set at 2 mm. The squares indicate optimal diffusion constants, based on Eq. 6 and measured RRR values in 100 nm thick films. The dotted line indicates the XEUS NFII requirement on energy resolution. *c.* Idem, but now assuming an absorber length of 4 mm.

$$D \equiv \frac{1}{3} \sqrt{\frac{2kT_{qp}}{\pi\Delta}} v_F \lambda_{300} RRR. \quad (6)$$

Fig. 9b indicates that a $D = 20 \text{ cm}^2\text{s}^{-1}$ is already adequate for a 2 mm long bar, so a 1 eV energy resolution does not necessarily require high values for the diffusion constant. Unfortunately, the additional demands on time resolution are not compatible with such slow diffusion speeds. With this D value, and the qp loss times equal to those in 1D-400, the pulses emerging from the STJs take already 50 μs to reach their maximum, which is at odds with future X-ray missions such as XEUS, which require a time resolution of $< 5 \mu\text{s}$. The easiest way to improve D is to increase the film thickness, since the RRR scales proportional with it. This will improve the quantum efficiency of the absorber, but decrease the tunnel probability P_1 , thus increasing the tunnel noise. The measured value of D in the Ta absorbers is a factor of 3 lower than the value based on Eq. 6. Such a discrepancy has been reported by other groups as well [5, 7]. It has been linked by van den Berg [30] to metallic impurities with a local magnetic moment. Young et al. [31] have demonstrated that the energy gap of W films could be suppressed by the implantation of magnetic impurities at a level of a few 10 ppm. This implies that magnetic impurities could again act as qp traps and the diffusion of qps may therefore be impeded. The qps might actually hop between such local traps. Thus, an important improvement of D may be obtained by decreasing the impurity content of the sputtering targets. Our Hf film was poly-crystalline and only 97% pure, with Zr as the main contaminant, which suggests ample room for improvement of the RRR value.

5. CONCLUSIONS

In this study we have explored the performance of 1- and 2-dimensional DROIDs as X-ray photon-counting imaging spectrometers for application in future space-based X-ray telescopes. The DROIDs that have been tested were based on high-quality Ta absorbers read out by two or four STJs.

We obtained a FWHM spatial resolution of 7 μm for a 2-dimensional DROID based on a $200 \times 200 \mu\text{m}^2$ absorber with four $50 \times 50 \mu\text{m}^2$ STJs.

Maps of the charge output as a function of photon-absorption position reveal that the Nb contacts, intended to prevent qp out-diffusion, act as strong qp traps. This problem with Nb contacts may also be one of the reasons for the degradation of the energy resolutions of our single-pixel STJs.

The energy resolution was investigated with 1-dimensional DROIDs, in which the qp trapping associated with the Nb contacts is less prominent. A measured intrinsic energy resolution of 15.3 eV for 6 keV photons, based on a subset of 20% of the total number of events.

An extensive study of the principal factors contributing to the energy resolution was made. The main component is the tunnel noise, which is related to the ratio between the absorber area and the barrier area. A new contribution was identified,

which is due to position-dependent qp recombination, and is responsible for the non-linearity in the charge output and the degradation of energy resolution for photon energies above a few keV. While this effect can not be avoided in the vicinity of the edges, its influence can be diminished by increasing the ratio between area and perimeter of the absorber.

Finally, it was investigated how the energy resolution of 1-dimensional DROIDS will degrade when the length of the absorber is increased. This degradation may be compensated by the application of materials with a lower energy gap than Ta. For absorber lengths above 2 mm, Hf appears the only material that is still compatible with the resolution requirements of future X-ray missions.

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