Characterisation of the performance of p-type Si detectors for hard X-ray spectroscopy

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ABSTRACT: High-density compound semiconductors with sufficiently-high photon attenuations, such as CdZnTe, are required for the detection of the high-energy X-rays (>20 keV), typical to applications of the HEXITEC ASIC. However, in low-energy applications (2–20 keV), the lower electron-hole-pair generation energy of Si offers the potential of improved spectroscopic resolution. Si-based pixelated X-ray sensors are typically based on n-type material where holes are the carrier that form the signal measured on the pixels. However, the incorporation of p-type dopants into the material enables these sensors to be operated effectively in electron readout. This is similar to CdZnTe sensors, where electrons are measured by the pixels. Critically, this allows a single electron-sensitive chip to be utilised for low- and high-energy measurements. Presented in this paper are the results of the spectroscopic characterisation of four p-type-Si sensors (two 300 μm and two 500 μm thick), manufactured by Micron Semiconductors Ltd., and flip-chip bonded to the HEXITEC ASIC. At 13.94 keV all tested devices displayed average FWHM of <540 eV and the average ASIC-limited FWHM of 489 ± 75 eV measured for a single 300 μm module represents the highest resolution measured with the HEXITEC ASIC. Results also show very low pixel-to-pixel variations in the measured FWHM demonstrating the excellent spatial uniformity of these devices, and a study into the temporal stability of a single detector over a ~30 h period demonstrated negligible changes in spectroscopic performance.

KEYWORDS: Materials for solid-state detectors; Hybrid detectors; Si microstrip and pad detectors; X-ray detectors

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1 Introduction

The High Energy X-ray Imaging Technology (HEXITEC) ASIC was developed by the UKRI Science and Technology Facilities Council (STFC) for the readout of high-Z sensors for hard X-ray (>20 keV) spectroscopic imaging applications [1]. HEXITEC is utilised across a diverse range of sectors, including academic research and medical imaging [2]. Although readout electronics are a key component of these systems, the choice of sensor material is critical, with high-density semiconductors such as CdZnTe (CZT), with sufficient photon attenuation, required for higher-energy operation. In many high-Z sensor materials, the poor charge transport properties of holes means that electrons form the detector signal; for this reason the HEXITEC ASIC was designed to be electron-sensitive.

Certain applications, however, focus on low-energy photons (2–20 keV); in such cases, the lower electron-hole-pair generation energy of Si (3.62 eV cf. 4.67 eV for CZT) offers the potential of improved lower-energy spectral resolution [3]. Additionally, the crystallographic properties of Si enable the manufacture of larger monolithic detectors (~6 inch wafers cf. 2–3 inch boules for CZT [4]), and is therefore suited to applications where larger active areas are required.

Unlike high-density compound semiconductors, n-type Si is a hole-readout material. However, the electron-transport properties offered by p-type dopants enables sensors to be operated effectively in electron readout. Historically, p-type-Si sensors have been limited to particle-physics applications, where their excellent radiation hardness is effectively utilised [5]. However, p-type-doped Si would allow a single electron-sensitive chip to be used in the measurement of both low- and high-energy X-rays. Previously, detector groups were required to design separate versions of an application-specific integrated circuit (ASIC) or operate at sub-optimal performance (a change in
both the polarity and gain in the induced signal would be required when switching between Si and CZT [6]–[7].

In this paper, the results of initial studies into the spectroscopic resolution and uniformity of p-type Si electron-readout devices are presented. These experimental results were obtained with a $^{241}$Am sealed source and the full width at half maximum (FWHM) of the $^{237}$Np $\text{L}_{\alpha}$ 13.94 keV photo-peak was used as a measure of spectroscopic resolution at lower energies (the resolution at two higher energies, 26.34 keV and 59.54 keV, is also presented). Additionally, the variation in this performance across a device was used as a basic metric for the spatial and crystallographic uniformity of the supplied material.

2 Materials and methods

2.1 P-type Si detectors

The 300 $\mu$m and 500 $\mu$m thick p-type-Si HEXITEC sensors tested were produced by Micron Semiconductors Ltd. (West Sussex, U.K.) on six-inch high-resistivity wafers. P-type properties were achieved using a proprietary method involving light boron doping and each sensor comprises two aluminium electrodes — a planar cathode and a pixelated anode. The latter is a symmetrical array of 80 $\times$ 80 pixels on a pitch of 250 $\mu$m (this comprises a 220 $\mu$m pad and 30 $\mu$m inter-pixel gap), which is surrounded by a proprietary guard ring structure. Due to the guard ring design, the hybridised device is offset by four pixel rows, resulting in an array of 80 $\times$ 76 pixels (as opposed to 80 $\times$ 80 pixels). Overall, this results in sensor dimensions of $\sim$ 21.8 mm $\times$ 21.8 mm $\times$ 0.3/0.5 mm. A basic schematic of a p-type-Si sensor is shown in figure 1, with key features labelled.

![Figure 1](image.png)

**Figure 1.** Schematic side profile of a p-type Si sensor, manufactured by Micron Semiconductor Ltd.

Two 300 $\mu$m and two 500 $\mu$m sensors were selected from the centres of a single wafer of each thickness and hybridised to the HEXITEC ASIC at STFC through a combination of processes [8]. Stencil printing was used to deposit silver-loaded epoxy bumps onto each sensor pixel, whilst each ASIC pixel was gold studded. These two layers were flip-chip bonded together in a SUSS MicroTec
FC150 and cured in-situ at 150°C. The ASIC I/O pads were then wedge-bonded to the PCB and the aluminium carried attached. The four resulting hybrid devices are referred to as 300A, 300B, 500A, and 500B for the remainder of the paper, with the number referring to the thickness (in μm) of the p-type material used.

![Image](a)

![Image](b)

![Image](c)

Figure 2. An optical micrograph of the 80 × 80, 250 μm-pitch, pixel array of a 500 μm p-type Si sensor (a), and images of a completed 300 μm device following hybridisation to the HEXITEC ASIC ((b), (c)).

2.2 The HEXITEC detector system

The HEXITEC ASIC [1], developed by STFC, is a spectroscopic X-ray imaging chip. It has been utilised across a diverse range of disciplines, including medical imaging and solar physics [9]–[10]. The ASIC consists of 6400 channels in an 80 × 80 array on a 250 μm pixel pitch, which is fabricated on a 0.35 μm complementary metal-oxide semiconductor (CMOS) process. Each pixel contains a charge amplifier, a CR-RC shaping amplifier and peak-track-and-hold circuit. The magnitude of the peak-hold output voltage is proportional to the energy of the original interaction, and the analogue voltages stored in each pixel are read out every frame using a rolling shutter with a maximum frame rate of 8.9 kHz.

For these studies, each hybridised HEXITEC module was mounted to a HEXITEC GigE data acquisition system (DAQ) [2]. The DAQ contains all the readout electronics required for the clocks, power, 14-bit digitisation of the ASIC analogue output by four ADCs (analogue-to-digital converters), and detector bias from a programmable high-voltage supply. Additionally, the DAQ control system helps stabilise the ASIC temperature to 28°C. For the purposes of this study, the DAQ was operated at a frame rate of 1.5 kHz and controlled using the Spectral X-ray Imaging Data Acquisition (SpeXIDAQ) framework [11].

For the measurements presented below, 300 μm and 500 μm devices were operated at a bias of −180 V and −300 V respectively (corresponding to an electric field magnitude of 600 V mm⁻¹). These values were chosen following an investigation into the performance of these devices with
respect to the applied bias. 20 min data sets were collected using a $^{241}$Am sealed source (further details in section 2.3), and results show that these devices become approximately fully depleted at $-180$ V and $-300$ V respectively. This is shown in figure 3 for device 500A, where the number of counts in each pixel’s spectra is seen to increase with the applied bias. This is indicative of an increase in the active depleted volume of the p-type Si.

Figure 3. The CSD spectrum (10 ADU bin width) for pixel (40, 40) of device 500A at three bias voltages (a), and the average number of counts in the 13.94 keV $^{237}$Np $L_\alpha$ photo-peak ($\pm 1\sigma$) as a function of bias voltage (b).

2.3 Data collection and calibration

For each device, data was collected for one hour using a 183 MBq $^{241}$Am sealed source, before both calibration and subsequent spectroscopic analysis was performed within bespoke scripts (MATLAB ver. R2021a). The source was positioned ∼6 cm from the detector’s front face. For a single 500 μm device, this resulted in $\sim 5 \times 10^4$ raw events above a determined threshold per pixel (equivalent to a flux of $\sim 220$ photons mm$^{-2}$ s$^{-1}$). The placement of the source ensured an approximately uniform event distribution was achieved across each device’s active pixelated area, and allowed a low global occupancy (<10% of pixels with an event per frame) to be maintained when the DAQ was operated at 1.5 kHz. This enabled the use of charge-sharing discrimination (CSD) during post-processing analysis.

Prior to analysis, each module is calibrated, using its respective dataset, allowing the conversion between raw- and energy-spectra whilst correcting small variations in the signal gain across the ASIC. This is achieved using a linear fit to four well-defined $^{241}$Am photo-peaks — the 13.94 keV ($^{237}$Np $L_\alpha$), 17.75 keV ($^{237}$Np $L_\beta$), 26.34 keV ($^{241}$Am $\gamma$) and 59.54 keV ($^{241}$Am $\gamma$) lines. These peaks are identified within the per-pixel CSD spectra using a peak-fitting algorithm and their centroids in ADU (analogue-to-digital units) are matched against the known energy values, producing a linear fit. This is shown for a typical pixel in figure 4. Therefore, each channel has an associated gradient and intercept, used to align individual spectra, producing a highly-resolved global energy spectrum.

CSD removes non-isolated events that are charge shared over neighbouring pixels (signal above the threshold in any neighbouring pixels within a $3 \times 3$ connectivity matrix). The effect is to remove
Figure 4. The CSD spectrum for device 500A pixel (40, 40) showing Gaussian fits to four known $^{241}$Am emission peaks (a), and the linear calibration resulting from these fits (b) – 10 ADU bin width.

Figure 5. Comparison between the global raw (blue) and CSD (red) spectra of 500 μm device 500A – 200 eV bin width.

A low-energy background continuum from the acquired dataset, improving the resolution of the known photo-peaks [12]–[13]. This is demonstrated in figure 5, where the raw and CSD-filtered global spectra of device 500A are compared. The aforementioned per-pixel low-energy threshold is calculated through identification of the location of the noise peak in ADUs. The threshold was chosen to be 8σ above this value ($\mu + 8\sigma$) to ensure negligible noise contributions to the resultant spectra. Values typically lie between 8–32 ADU (approximately equivalent to 1–2 keV).

3 Results

3.1 Calibration

The results of the energy calibration of a single 500 μm device, 500A, are shown in figure 6, alongside a summary of all calibrations performed in table 1. The average values of the gradients
and thresholds measured were 24 eV ADU$^{-1}$ and 1.37 keV respectively. Although a distinct structure of four 20 × 76 subarrays can be identified in the obtained gradient values (figure 6(a)), this is an ASIC, not material, effect. It is the result of small variations in the four off-chip ADCs, each of which readouts blocks of 20 × 76 pixels.

Table 1. A summary of the calibration results of 4 p-type Si HEXITEC devices obtained using a $^{241}$Am sealed source. Errors quoted are the standard deviation in values obtained across the 80 × 76 arrays.

| Thickness (µm) | Device | Gradient (eV ADU$^{-1}$) | Threshold (keV) |
|---------------|--------|--------------------------|-----------------|
| 500           | 500A   | 24.2 ± 2.9               | 1.35 ± 0.19     |
|               | 500B   | 24.3 ± 3.9               | 1.41 ± 0.20     |
| 300           | 300A   | 23.6 ± 2.7               | 1.38 ± 0.21     |
|               | 300B   | 23.6 ± 2.5               | 1.33 ± 0.22     |

Figure 6. Calibration results for 500 µm device, 500A. Shown are the distributions across the 80 × 76 array of the calculated gradients coefficients (a), and thresholds (b). The distinct substructure of four 20 × 76 subarrays is the result of small variations in the four off-chip ADCs.

3.2 Spectroscopic performance

As mentioned in section 1, the spectroscopic resolution of a radiation detector, at the intended energy of operation, is an important metric of detector performance. This resolution is dependent upon several factors, which include, but are not limited to, the charge transport properties of the sensor material (e.g. charge carrier mobility, μ, and lifetime, τ) and the detector electronics.

In this study, the resolution of the tested p-type Si devices was quantified through calculation of the full width at half maximum (FWHM) of the 13.94 keV ($^{237}$Np L$\alpha$), 26.34 keV ($^{241}$Am $\gamma$) and 59.54 keV ($^{241}$Am $\gamma$) photo-peaks, representative of the performance at ‘low’, ‘mid’ and ‘high’ energies. The FWHM were calculated using the same peak-fitting algorithm used for calibration (section 2.3), in which a Gaussian distribution is fit to each respective peak within the per-pixel CSD spectra. This is shown for pixel (38, 34) of device 500A in figure 7. A bin width of 200 eV was chosen for the CSD spectra to reflect the results of device calibration (section 3.1), where gradients of ~240 eV ADU$^{-1}$ were obtained (bin widths equivalent to ~10 ADU).
The calibrated CSD spectrum for device 500A pixel (38, 34) showing Gaussian fits to the three reference $^{241}$Am photo-peaks ~200 eV bin width.

The distribution of FWHM for the 13.94 keV photo-peak across a single 500 $\mu$m and 300 $\mu$m device is displayed in figure 8, whilst table 2 summarises the results obtained for all four devices. As seen in table 2, all devices display average FWHM of $<620$ eV across the investigated energy range at 298 K, and the $489 \pm 75$ eV average value measured at 13.94 keV across device 300B represents the highest resolution measured to date using the HEXITEC ASIC. For comparison, the FWHM of the 13.94 keV and 59.54 keV photo-peaks in high-performance, high-flux CZT HEXITEC devices have been previously reported to be $610 \pm 130$ eV and $790 \pm 150$ eV respectively [14]. These represent the highest-resolution measurements made using a HEXITEC device prior to this study. Only minor differences in average performance are seen between the 500 $\mu$m and 300 $\mu$m devices, and the lower average FWHM of both 300 $\mu$m modules is likely the consequence of the larger leakage current in the 500 $\mu$m thick material, resulting in increased ASIC electronic noise. In fact, the spectroscopic performance of the p-type-Si HEXITEC devices is limited by the noise performance of the HEXITEC ASIC, previously reported to be $\sim500$ eV in CZT [12]. The lower fundamental limit to the attainable resolution is given by the Fano-limited energy resolution [15]. This limit is the consequence of the statistical fluctuation in the number of electron-hole pairs that are produced for incident, interacting particles of identical energy. For Si, this is calculated to be $175$ eV at 13.94 keV (using a Fano factor of 0.11). The overall system noise can be approximated to a combination of the material (Fano-limited) and electronic-noise contributions. These noise sources are uncorrelated, and are therefore summed in quadrature. Hence, comparison of the Fano-limited and obtained energy resolutions at the three investigated energies allows the electronic noise to be estimated at $\sim480$ eV. Therefore, use of an ASIC with noise and dynamic range optimised for the proposed energy range of these p-type-Si devices would enable improved resolution to be obtained. An example of a spectroscopic Si detector with a more optimised noise performance is the hyperspectral SLcam, developed at the University Ghent Centre for X-ray Tomography (UGCT). With a sensor comprising 450 $\mu$m thick Si, it has a specified energy resolution of $<152$ eV at 20 keV [16].

Additionally, the small variations in FWHM values measured across each array demonstrates the high spatial uniformity of these devices. Standard deviations of $<90$ eV were measured for all attained resolutions; for comparison, values of $\sim150$ eV at 59.54 keV have been reported for
Figure 8. The 13.94 keV FWHM distributions across the 80 × 76 pixel array for 500 μm device 500A (a), and 300 μm device 300A (b). Two distinct types of artefacts are labelled in (b).

Table 2. A summary of the spectroscopic results of 4 p-type Si HEXITEC devices obtained using a $^{241}$Am sealed source. Errors quoted are the standard deviation in values obtained across the 80 × 76 arrays.

| Thickness (μm) | Device | 13.94 keV FWHM (eV) | 26.34 keV FWHM (eV) | 59.54 keV FWHM (eV) |
|---------------|--------|---------------------|---------------------|---------------------|
| 500           | 500A   | 514 ± 47            | 535 ± 52            | 603 ± 67            |
|               | 500B   | 530 ± 54            | 548 ± 68            | 614 ± 75            |
| 300           | 300A   | 501 ± 72            | 521 ± 70            | 600 ± 82            |
|               | 300B   | 489 ± 75            | 507 ± 64            | 587 ± 79            |

the aforementioned high-performance CZT HEXITEC devices [14]. Despite this uniformity, both FWHM distribution maps (figure 8) reveal a gradient in performance across each device, with the poorest-performing pixels found, on average, furthest away from the I/O wire-bond pads. This is an ASIC effect, and the consequence of the variation in power-supply distribution across each device. Additionally, several small defects, most clearly visible and labelled in the 300 μm distribution, can be identified. These defects comprise two types. The first (labelled A) are characterised by a single unresponsive pixel adjacent to four noisier pixels. These are the result of a missing bond between the sensor and ASIC — an imperfection of the hybridisation process. The additional noise present in the adjacent pixels is the consequence of the disturbed electric field surrounding this dead pixel. The remaining artefacts (labelled B), which comprise multiple unresponsive pixels and a ring of noisier pixels, are believed to be detector defects. Their origin is under investigation — preliminary investigations indicate their behaviour is independent of the applied bias voltage. The larger standard deviations in the 13.94 keV FWHM measured across the 300 μm devices, despite their marginally superior resolution, is the result of a higher concentration of such defects, when compared to the 500 μm modules.

3.3 Temporal stability

Particular X-ray spectroscopy applications, such as colour X-ray computed tomography (CT), require energy-resolving detectors to be operated for extended periods. Consequently, it is critical that these detectors display excellent temporal stability, with negligible changes in performance with
time. To assess this, a single 500 μm thick device, 500A, was exposed continuously to the same $^{241}$Am source for ~30 h (experimental setup described in section 2.3), over which period 20 min datasets were collected every 80 min. For each acquisition, the global CSD spectrum, the average number of counts in the 13.94 keV photo-peak (within ±1σ of the peak) and the average resolution of this photo-peak was calculated. These results are presented in figure 9.

All results indicate excellent temporal stability over the investigated period. Comparison of the global CSD spectra of the initial and final acquisitions reveals negligible changes in spectroscopic performance. This is further exemplified in figure 9, with the counts ($±1σ$) in, and resolution of the 13.94 keV photo-peak fluctuating by <0.24% and <0.34% respectively during this period. Whilst evidently satisfactory for typical HEXITEC operating conditions, further studies at higher fluxes could be performed.

Figure 9. The change in performance of device 500A following exposure to a $^{241}$Am sealed source for ~30 h (200 eV bin width) (a), the fluctuation in the number of counts ($±1σ$) in the 13.94 keV photo-peak (b), and the average FWHM of the 13.94 keV photo-peak (c). Error bars are given by the standard errors in the mean across the pixelated array.
4 Conclusion

Four p-type Si detectors (two 300 µm thick and two 500 µm thick), manufactured by Micron Semiconductors Ltd., were hybridised to the HEXITEC ASIC at the Rutherford Appleton Laboratory, UKRI STFC, and characterised using a $^{241}$Am sealed source. The results obtained, and presented here, indicate spectroscopic resolution of $<$540 eV FWHM at 13.94 keV, and high crystallographic uniformity. Although limited by the noise performance of the ASIC electronics, the $489 \pm 75$ eV average FWHM value measured across a single 300 µm device (300B) is the highest resolution measured to date using the HEXITEC ASIC.

The p-type Si material tested shows great promise for use in X-ray spectroscopy imaging. This will allow both low- (2–20 keV) and higher- (20–200 keV) energy measurements using the electron-readout HEXITEC ASIC through a combination of p-type Si and CZT (or other high-density material) sensors. However, to fully utilise the performance of this material, an ASIC with a noise performance optimised for low-energy measurements should be considered. These results also demonstrate the potential of novel detector structures for low-energy measurements, and similar studies could be conducted for other novel devices, including LGADs (low-gain avalanche diodes) [17].

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