Edge effects in a small pixel CdTe for X-ray imaging

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ABSTRACT: Large area detectors capable of operating with high detection efficiency at energies above 30 keV are required in many contemporary X-ray imaging applications. The properties of high Z compound semiconductors, such as CdTe, make them ideally suitable to these applications. The STFC Rutherford Appleton Laboratory has developed a small pixel CdTe detector with $80 \times 80$ pixels on a $250 \mu m$ pitch. Historically, these detectors have included a $200 \mu m$ wide guard band around the pixelated anode to reduce the effect of defects in the crystal edge. The latest version of the detector ASIC is capable of four-side butting that allows the tiling of $N \times N$ flat panel arrays. To limit the dead space between modules to the width of one pixel, edgeless detector geometries have been developed where the active volume of the detector extends to the physical edge of the crystal. The spectroscopic performance of an edgeless CdTe detector bump bonded to the HEXITEC ASIC was tested with sealed radiation sources and compared with a monochromatic X-ray micro-beam mapping measurements made at the Diamond Light Source, U.K. The average energy resolution at 59.54 keV of bulk and edge pixels was 1.23 keV and 1.58 keV, respectively. 87% of the edge pixels present fully spectroscopic performance demonstrating that edgeless CdTe detectors are a promising technology for the production of large panel radiation detectors for X-ray imaging.

KEYWORDS: Solid state detectors; X-ray detectors; Detector design and construction technologies and materials; Pixelated detectors and associated VLSI electronics

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1 Introduction

The advantages of using cadmium telluride (CdTe) as a radiation detector for high energy X and γ ray applications are well known and documented [1, 2]. Many of these applications, for instance medical imaging [3], synchrotron imaging and explosive and drugs detection [4, 5], require large panel radiation detectors with significant active areas (> 4 cm²).

Recent progress in the growth of single crystal CdTe has produced high quality wafers of 100 mm in diameter [6]. The major limitation on detector size is the reticle size (slightly greater than 20×20 mm²) used by the foundry during the fabrication of the readout ASIC. In order to produce large active areas, multiple CdTe detectors have to be tiled in N×N arrays. To minimise the insensitive areas between modules, the use of four side “butt-able” detectors are required. The HEXITEC collaboration [2, 7] has developed a four side butt-able ASIC by redistributing the I/O interconnection on the fourth side to the back of the ASIC using through silicon via technology [8]. Novel edgeless detector designs, with minimum inactive areas, are required to be bonded to these ASICs.

During the production of detectors, the dicing of wafers into individual die introduces many crystalline defects and impurities in the crystal edges [9, 10]. These defects can have an adverse effect on the crystal properties, particularly near the edge, impeding charge transport and creating high surface leakage currents [9, 11]. For these reasons, it has been standard practise to employ guard bands in CdTe radiation detectors around the pixelated array. Guard bands are very effective in negating edge effects but create large dead areas between tiled modules, making them unsuitable
Figure 1. Illustration of a partial corner area of the traditional HEXITEC design (left) and that of the edgeless CdTe detector (right).

for the production of large area flat panel arrays. To maximise the active areas in a large flat panel CdTe detector, the STFC Rutherford Appleton Laboratory has developed an edgeless detector without a guard band and with edge pixels extended to the physical edge of the crystal.

In this paper, the spectroscopic performance of edge pixels in a small pixel edgeless CdTe detector is investigated and the design’s suitability for X-ray spectroscopic imaging assessed.

2 Methodology

2.1 Detector design

The HEXITEC ASIC was specifically developed for the HEXITEC collaboration by the STFC Rutherford Appleton Laboratory [7] for the readout of small pixel, fully spectroscopic Cd(Zn)Te detectors. The ASIC consists of $80 \times 80$ pixels on a $250 \, \mu m$ pitch. CdTe detectors bonded to HEXITEC are $20.55 \times 20.55 \times 1.0 \, mm^3$ Schottky detectors with a pixelated aluminium anode (AlN/Au/Ti/Al) and a platinum cathode.

To date, HEXITEC detector systems have been assembled using CdTe detectors with a $200 \, \mu m$ wide guard ring. However, this is unsuitable for the assembly of large area detectors where the insensitive area between tiled modules must be minimized. By removing the guard band it is possible to reduce the inter-module gap to the width of one pixel ($250 \, \mu m$). In order to cover the entire ASIC area, the dimensions of the outer pixels of the CdTe detector have been extended from $200 \, \mu m \times 200 \, \mu m$ to $200 \, \mu m \times 350 \, \mu m$, as shown in figure 1. The inter-pixel gap is $50 \, \mu m$.

This new design results in corner pixels with dimensions of $350 \, \mu m \times 350 \, \mu m$. The outer pixels are $50 \, \mu m$ from the physical edge of the CdTe crystal to comply with Acrorad’s detector design rules. The modified edge and corner pixels represent 5% of the total number of pixels in the detector. The notch observed on the corner pixel of the edgeless geometry was created for alignment precision during bonding.

An edgeless detector was fabricated by Acrorad Ltd with the design described above. The detector is a $20.35 \times 20.35 \times 1.0 \, mm^3$ Schottky CdTe detector, with a pixelated aluminium anode (AlN/Au/Ti/Al) and a platinum cathode. The detector was directly diced from a CdTe wafer and received no special edge treatment post-dicing.
2.2 Measurement of edge leakage currents

Three Schottky CdTe detectors with the standard electrode geometry, which includes a 200 µm wide guard ring on the pixelated anode, as seen on the left of figure 1, were used to measure edge leakage currents. As with the edgeless detector, the crystal edges received no special treatment post-dicing. Previous measurements with these Acrorad Schottky CdTe detectors bonded to the HEXITEC ASIC have achieved an average energy resolution (FWHM) of 0.75 keV at 59.54 keV [10].

The HEXITEC ASIC is capable of isolating the guard ring leakage current from the bulk leakage current which allows the properties of the edge surface to be investigated. The current-voltage characteristics of each detector were measured using two Keithley 2410 source meters. One acted as a high voltage supply to the cathode while the other read out the current drawn by the guard ring. Each detector was biased from −50 V to −600 V, in steps of −50 V. At each applied bias a measurement was performed for 180 s and the average leakage current over this period was calculated. All measurements were made with the detectors cooled to 14 °C.

The total leakage current drawn by each detector was measured at the cathode. The second Keithly measured the leakage current from the volume subtended by the guard ring and the crystal edges. The bulk leakage current was calculated as the difference between the two.

Using the leakage current measurements, a “stable operating voltage” was determined for the detectors. This was defined as the voltage over which the detector leakage current was stable within 5 nA, over a 180 s acquisition. This ensures that changes in the leakage current are small and do not affect the detector spectroscopy.

Using this definition, an ideal operating voltage of −400 V was determined for the edgeless CdTe detector with the detector cooled to 14 °C.

2.3 Edgeless detector characterization

The edgeless detector was uniformly irradiated with an Americium-241 (²⁴¹Am) sealed source. This source had a radiation flux of 60 photons s⁻¹ cm⁻² and the data were collected for 20 hours. Each individual pixel was calibrated with the known energy peaks of 13.95 keV, 17.70 keV and 59.54 keV of the ²⁴¹Am spectrum. To prevent polarisation of the CdTe detector, the bias voltage was refreshed and settled for 10 s every minute [12].

Two areas that were representative of the edge pixels performance based on the ²⁴¹Am data were selected to be characterized with an X-ray micro-beam. Firstly, a corner area consisting of 900 µm × 900 µm and secondly, a region of 600 µm × 1200 µm containing six edge pixels. A monochromatic 10 µm × 10 µm 20 keV X-ray beam produced on the B16 test beamline at the Diamond Light Source with a flux of 1 × 10¹¹ photons s⁻¹ cm⁻² was used to scan these areas in steps of 25 µm. The data were collected for 20 s at each position, followed by a 10 s bias refresh and settling time between steps to avoid polarisation. Each map required 10 h to 12 h to be completed. The spectrum at each position was calibrated with the mono-energetic 20 keV peak and the 3rd and 4th beam harmonics of 60 keV and 80 keV (the 2nd beam harmonic is forbidden).

Following collection of the data, the analysis was completed using a charge sharing discrimination algorithm implemented in Mathworks Matlab (R2012a, Massachusetts, U.S.A.). When two or more neighbouring pixels are found to have events above the low energy threshold of 3–4 keV...
in a single frame of data, they are considered to be charge shared events. The discrimination algorithm removes these events from the data set producing high resolution spectroscopy as described in [10]. The detector records the energy and pixel position of each individual event which allows the use of other charge sharing algorithms, for instance charge sharing addition [10], but these were not used in this work.

2.4 Bias voltage effect

The influence of the applied bias voltage to the CdTe detector on the spectroscopy of the edge pixels was studied with the X-ray micro-beam and a $^{241}$Am sealed source. Under the acquisition conditions described above for the micro-beam scan, a line scan was performed in four bulk pixels and one edge pixel, with the detector biased at $-200\,\text{V}$, $-300\,\text{V}$, $-350\,\text{V}$ and $-400\,\text{V}$ for each line scan. Sealed source measurements were made under the same conditions described above for the $^{241}$Am acquisition with the detector biased at $-200\,\text{V}$ and $-400\,\text{V}$.

3 Results and discussion

3.1 Leakage current measurements

All the detectors used in this study, both standard geometry and edgeless, were grown, processed and fabricated by Acrorad Ltd using identical techniques. CdTe wafers were cut into individual die using a diamond blade saw. The faces of the crystal were lapped, polished and etched with a bromide methanol solution but no additional processing was done to the crystal edges [13, 14]. A pixelated aluminium anode and a platinum cathode were deposited as contacts on the processed faces of the crystal.

The leakage current measured by the guard ring consists of the current drawn through the volume subtended by the $200\,\mu\text{m}$ guard band and an additional contribution from the crystal edges. The processing of the main crystal surfaces has been shown to reduce the leakage current in detectors [11, 15], and as the crystal edges have not received further processing after dicing, the leakage current measured from the guard ring is predominantly produced at the edge of the detector.

Figure 2 shows the total, edge and bulk leakage current density for one of the standard geometry Acrorad detectors (left). The bulk and edge leakage currents are shown as a proportion of the total measured leakage current (right).

The bulk leakage current was taken as the difference between the total current and the current drawn by the guard ring. To enable a comparison between the edge and bulk currents, each measurement was normalized to its respective area: $4.14\,\text{cm}^2$ for the total area, $4.06\,\text{cm}^2$ for the bulk array and $0.08\,\text{cm}^2$ for the guard area. Figure 2 (left) shows the result where the edge current density is an order of magnitude higher than the average current across the detector (total current).

The maximum operating voltage for this particular detector was established to be $-400\,\text{V}$. Between $-50\,\text{V}$ and $-400\,\text{V}$ the bulk current showed a small increase and represented up to 80% of the total detector leakage current, while the remaining 20% was contributed by the detector edges. Above the operating voltage the detector leakage current increased exponentially leading to a breakdown of the detector. By isolating and measuring the edge leakage current it was determined that this was the source of the detector breakdown at high voltages (figure 2, right).
Figure 2. Inversed current density in nA/cm$^2$ vs. applied bias (V) (left) and normalised bulk and guard leakage currents (right).

Figure 3. Current-voltage characteristics of the edgeless CdTe detector.

In edgeless detectors, where the guard band has been removed, additional leakage current generated at the crystal edges under high bias may have a negative effect on the detector performance. Figure 3 shows the current-voltage curve for the edgeless CdTe detector, in terms of its total leakage current.

The total leakage current of the edgeless CdTe detector follows the same trend as those with standard geometries (figure 2). This suggests that the edge leakage current is also a major contributor to the total leakage current of the detector at high bias voltages. If the operating bias is carefully selected, it may be possible to operate the edgeless detector with spectroscopic performance fabricated using existing techniques. In this case, the stable operating voltage for the edgeless CdTe was defined as –400 V, which was stable within 5 nA over a 180 s acquisition.
3.2 $^{241}$Am characterization results

The edgeless CdTe detector was flood illuminated with a $^{241}$Am sealed source to characterize the detector performance, particularly that of the edge pixels. The average FWHM of the bulk pixels at the operation bias of $-400$ V was 1.23 keV at 59.54 keV, and 1.58 keV for edge pixels. The standard deviation of the energy resolution with 95% coefficient bounds for the bulk and edge pixels was 0.36 keV and 0.38 keV, respectively. Figure 4 a) shows a typical $^{241}$Am spectra for a bulk pixel and figure 4 b) for an edge pixel, with a calibration pulse obtained for each pixel.

The energy resolution obtained for the bulk pixels of the CdTe detector was lower than that usually achieved with standard CdTe detectors bonded to the HEXITEC ASIC. The relatively high leakage current measured in the CdTe detector (35 nA) at the operating bias of $-400$ V resulted in a reduction of the spectroscopic performance of the detector compared to standard detectors [10]. The larger FWHM of the edge pixels compared to the bulk pixels was expected as a consequence of the larger pixel size that results in a reduction of the effectiveness of the small pixel effect [16].

Despite the reduction in energy resolution of the edge pixels, it should be noted that they are still capable of distinguishing closely-spaced energy peaks as those seen in the $^{241}$Am spectrum in figure 4. The calibration peaks in figure 4 give an upper limit for the detector electronics of approximately 800 eV demonstrating that the observed wider FWHM is due to material properties rather than the detector electronics.

The variation in the performance of the edge pixels was observed to be randomly distributed around the detector. Figure 5 shows spectra that are representative of some of the different types of edge pixel response.

The majority of the edge pixels (60%) have similar spectroscopic performance to the bulk pixels, with a photopeak FWHM below 2 keV and visible Np peaks (figure 5.a)). A further 27% of all edge pixels present good spectroscopic performance but show an increase in the number of counts below 10 keV (figure 5.b). The remaining edge pixels present severely degraded spectroscopic performance with the majority of the events shifted to lower energies, as shown in figure 5.c).

The $^{241}$Am characterization demonstrates that, without the use of a guard band, the CdTe detector still has excellent spectroscopic performance. The yield of the pixels with excellent characteristics for X-ray imaging was 87%. This demonstrates the feasibility of using edgeless CdTe
detectors with extended edge pixels to build large panel high Z detectors for X-ray imaging. In the following section, the differences between the high performance edge pixels and the remaining 13% with degraded performance will be investigated further using monochromatic micro-beam mapping measurements.

### 3.3 Micro-beam characterization

A 10 $\mu$m × 10 $\mu$m micro-beam of mono-energetic 20 keV X-rays was used to map a corner area of the detector in steps of 25 $\mu$m. This particular corner area was chosen for investigation as it contained edge pixels with different levels of spectroscopic performance. Figure 6 shows a map of the total number of counts for each scan position.

In figure 6, pixels a to f have similar dimensions to the physical pixel electrode size, with the bulk and edge pixels having widths of approximately 200 $\mu$m and 350 $\mu$m, respectively. Pixels g and h show large inactive areas with a significant drop in the total number of counts observed, indicating areas with poor charge collection efficiency. The active area of these pixels, defined as the area over which more than 9000 counts are detected, has been reduced from 200 $\mu$m × 350 $\mu$m to approximately 200 $\mu$m × 125 $\mu$m.

The non-uniformities observed in the micro-beam map of the corner area of the detector are reflected in the spectroscopic performance of each pixel, seen in figure 6. In pixels where the mapping measurements showed the expected pixel size relative to the electrode geometry, a well defined mono-energetic peak is observed (figures 6.b) and 6.f)). In pixels where a smaller active area was measured, an increase in counts at low channel numbers is seen (figure 6.h)). The corner pixel presents major non-uniformities, largely observed in the mapping of the centroid position of the 20 keV X-ray beam in figure 7. These non-uniformities in the corner pixel result in a broad spectrum (figure 6.i)) that is 2.7 times wider than a standard edge pixel.

A second area along one edge of the detector was mapped with the micro-beam. A map of the total number of counts detected is presented in figure 8. As with the first area mapped with the micro-beam, an area of reduced charge collection efficiency, with an average width of 100 $\mu$m was observed at the crystal edge.

Figure 9 shows how the spectroscopic performance varies across the width of a typical edge pixel. Position (16,20) is representative of the beam spectrum for all beam steps between steps 1 < X < 16 in the area of figure 8.
Figure 6. Mapping of a $3 \times 3$ pixel area of the edgeless detector with corresponding uncalibrated spectra.

Figure 7. Centroid (in channel numbers) of the mono-energetic 20 keV beam in the corner area.

As the beam moves towards the edge of the crystal the energy of the events is drastically and continuously reduced. After position (17,20) the majority of events have energies below 3–4 keV so they fall below the low energy threshold of the detector. The decrease in the energy of the events indicates charge losses during the drift of electrons across the CdTe detector, up to 100 $\mu$m of the physical edge of the pixel.

3.4 Comparison of the micro-beam results with the $^{241}$Am spectroscopy

To understand the extent of the inactive areas in the CdTe edgeless detector, the micro-beam data was correlated to that obtained with the $^{241}$Am flood illumination. The $^{241}$Am spectrum of the
pixels with larger inactive areas observed in the micro-beam map is comparable to that of the micro-beam as seen in figure 10, where in both spectra a large number of counts are shifted to lower energies. These pixels represent only 7% of all edge pixels and are a minority in the edgeless CdTe detector.

The edge pixels in figure 8 with an inactive region of up to 100 µm wide, display a spectrum similar to that in figure 5.b). This type of edge pixel spectra corresponds to 27% of all edge pixels. This suggests that pixels with inactive areas up to a third of their physical area are still able to produce good spectroscopy that allows calibration and spectroscopic X-ray imaging. Finally, fully active pixels (pixels c and f, figure 6) have a $^{241}$Am spectrum with excellent spectroscopic characteristics, as the one presented in figure 5.a). These represent the majority of the edge pixels in the edgeless CdTe detector.

This correspondence suggests major edge effects occur only in 13% of all edge pixels and 87% of all edge pixels present spectroscopic characteristics ideal for X-ray imaging.

**Figure 8.** Mapping of a typical edge area of the edgeless detector with corresponding uncalibrated spectra.

**Figure 9.** Sequential micro-beam positions.
3.5 Bias voltage effect

A micro-beam scan at several bias voltages was conducted across several bulk pixels and over an edge pixel which displayed a spectrum similar to that shown in figure 5.b. The total leakage current of the edgeless detector at $-200$ was measured to be 9 nA and 35 nA at $-400$ V. Figure 11 shows line scans at different voltages in terms of the number of counts in the 20 keV photopeak and the relationship between the inactive width of the pixel and the bias voltage.

The response of the bulk pixels was unchanged at different bias voltages while the number of counts detected in the edge pixel showed significant spatial variation. The active area of the edge pixel is larger at lower bias, both in terms of the total number of counts detected and the number of counts in the photopeak. The active width of the pixel is reduced in terms of total number of counts from 300 $\mu$m at $-200$ V to 150 $\mu$m at $-400$ V. In terms of photopeak counts, the active width of the edge pixel at $-200$ V and $-400$ V is 375 $\mu$m and 150 $\mu$m, respectively.

The reduction of the active area of the edge pixel at higher bias voltages is consistent with a collapse of the electric field at the detector edge. This collapse of the electric field is responsible for the poor spectroscopic performance of the 13% edge pixels identified with sealed source measurements (figures 5.b) and 5.c).

During fabrication, the area beneath the contacts was lapped, polished and chemically treated in order to minimise the surface leakage current. But, as the edgeless detector was directly diced from a CdTe wafer, it did not receive any special mechanical or chemical processing of the crystal edges [13]. Wafer dicing introduces crystalline defects and impurities in the crystal edge that result in a localised changes of the surface conductivity. This variation in conductivity creates leakage current paths [17] that affect the local uniformity of the electric field at the crystal edge leading to a degradation of the edge pixel charge collection efficiency [18]. The total leakage current in the edgeless CdTe has tripled from 9 nA to 35 nA between $-200$ V and $-400$ V. As shown in figure 2 and previously discussed, an increase of the total leakage current at higher bias was identified as an edge property. The inactive areas observed in 13% of all edge pixels at $-400$ V are related to this excess edge surface leakage currents that distort the local electric field.
The localised collapse of the electric field does not degrade the overall performance of edgeless CdTe detectors as 87% of edge pixels operate with excellent energy resolution. Mechanical and chemical treatment of the CdTe crystal edges might help increase the yield of edge pixels with excellent spectroscopy. These processes represent a significant technical challenge as the edge thicknesses are typically 1 mm or less and, as shown in this work, may not be needed to produce high quality devices.

4 Summary and conclusion

The performance of a small pixel CdTe bonded to HEXITEC was tested with sealed source measurements and micro-beam mapping at Diamond Light Source. The edge pixels of the detector were extended to the physical edge of the crystal to allow four-side-butting with minimum insensitive areas between modules. The edge and bulk pixels had an average energy resolution of 1.58 keV and 1.23 keV at the $^{241}$Am photopeak of 59.54 keV. The micro-beam measurements showed non-uniformities in the charge collection efficiency in 13% of the edge pixels, attributed to the localised collapse of the electric field. It was suggested that this collapse is due to localised large edge leakage currents on the crystal edges of the CdTe detector. At an operation voltage of $-400\,\text{V}$, 87% of all edge pixels present excellent spectroscopy and good charge collection in the majority of the pixel area. The results in this paper suggest that edgeless CdTe detectors with pixels extended up to the physical edge of the detector fabricated using existing techniques are suitable for the production of large panel radiation detectors.

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