A 10 cm × 10 cm CdTe Spectroscopic Imaging Detector based on the HEXITEC ASIC

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ABSTRACT: The 250 µm pitch 80x80 pixel HEXITEC detector systems have shown that spectroscopic imaging with an energy resolution of < 1 keV FWHM per pixel can be readily achieved in the range of 5–200 keV with Al-pixel CdTe biased to −500 V. This level of spectroscopic imaging has a variety of applications but the ability to produce large area detectors remains a barrier to the adoption of this technology. The limited size of ASICs and defect free CdTe wafers dictates that building large area monolithic detectors is not presently a viable option. A 3-side buttable detector module has been developed to cover large areas with arrays of smaller detectors. The detector modules are 20.35 × 20.45 mm with CdTe bump bonded to the HEXITEC ASIC with coverage up to the edge of the module on three sides. The fourth side has a space of 3 mm to allow I/O wire bonds to be made between the ASIC and the edge of a PCB that routes the signals to a connector underneath the active area of the module. The detector modules have been assembled in rows of five modules with a dead space of 170 µm between each module. Five rows of modules have been assembled in a staggered height array where the wire bonds of one row of modules are covered by the active detector area of a neighboring row. A data acquisition system has been developed to digitise, store and output the 24 Gbit/s data that is generated by the array. The maximum bias magnitude that could be applied to the CdTe detectors from the common voltage source was limited by the worst performing detector module. In this array of detectors a bias of −400 V was used and the detector modules had 93 % of pixels with better than 1.2 keV FWHM at 59.5 keV. An example of K-edge enhanced imaging for mammography was demonstrated. Subtracting images from the events directly above and below the K-edge of the Iodine contrast agent was able to extract the Iodine information from the image of a breast phantom and improve the contrast of the images. This

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is just one example where the energy spectrum per pixel can be used to develop new and improve existing X-ray imaging techniques.

**KEYWORDS**: X-ray detectors; Imaging spectroscopy; Pixelated detectors and associated VLSI electronics
1 Introduction

The increased availability and consistent quality of spectroscopic grade CdTe and CdZnTe detectors have enabled them to be considered for an increasing number of industrial and scientific applications. One of the major advantages of CdTe and CdZnTe based detectors over current scintillator and semiconductor X-ray and γ-ray detectors is the ability to conduct spectroscopic imaging at room temperature and high energies. The HEXITEC ASIC has demonstrated spectroscopic imaging with 1 mm thick CdTe Al-Schottky detectors with 80x80 pixels on a 250 µm pitch with an average pixel energy resolution of 800 eV FWHM at the 59.5 keV emission of $^{241}\text{Am}$ [1]. This level of spectroscopic imaging has a variety of potential applications such as SPECT where the spectroscopy allows multiple isotopes to be imaged simultaneously and separated from scattered events [2]; industrial inspection where the energy spectra can be used to identify elemental composition from absorption edges and fluorescence emissions [3]; in helio-astrophysics where the energy spectrum gives insight into the processes and impact of solar flares [4]; security scanning and material science where an energy dispersive diffraction image taken in a single exposure can identify the chemical composition of a sample [5]; and, as demonstrated here, the K-edge of contrast agents can be used to enhance images for mammography [6].

2 Tiled arrays

Many of these applications require large area detectors, ideally with completely active areas. The HEXITEC ASIC is approaching the maximum size area device that can be made with a CMOS process suitable for low noise analogue electronics. It has been demonstrated that multiple ASICs
can be bonded to a single monolithic piece of CdTe detector material [7] but the yield of spectroscopic grade CdTe or CdZnTe material and the bump bonding process currently restricts the adoption of this approach of building large area detectors. Manufacturing small detector modules and tiling them together for large area coverage has been successfully demonstrated with coplanar [8] and pixelated detectors [9, 10]. This tiling method has been adopted in the approach to build the $10 \times 10 \text{cm}^2$ HEXITEC detector. Each detector module has a $20.35 \times 20.45 \times 1 \text{ mm}$ CdTe Al-Schottky anode detector gold stud and silver epoxy bump bonded to an 80x80 pixel HEXITEC ASIC [11]. This is mounted on an aluminium block with the CdTe material forming the outer edge of the module on three sides. On the fourth side of the module the ASIC I/O pads extend 1 mm from the edge of the CdTe material and have wire bonds to a PCB that extends a further 2 mm. The PCB routes the signals underneath the active area of the CdTe, as shown in figure 1, and allows the modules to be plugged into the DAQ system. The detector modules can be arranged in completely flat panels of $2 \times N$ arrays [12]. In this case, the larger area is created by tiling the detector modules in a single row of five modules with a gap of $170 \mu \text{m}$ between each module, as shown in figure 2. The large dead-space along one edge of the modules with the wire bonds is covered by placing the edge of a neighbouring row of modules above the wire bonds. The neighbouring row is placed $2.5 \text{ mm}$ higher relative to the row it is covering to ensure that the HV on the bias wire bond to the cathode of the CdTe does not short to the neighboring row. As shown in figure 3, a total of 5 rows have been assembled in this imbricated geometry to give a total area of $5 \times 5$ modules, which gives $400 \times 400$ pixels on a $250 \mu \text{m}$ pitch with a 2 pixel dead-space between modules on the same row. The $250 \mu \text{m}$ pitch is maintained between modules on separate rows. The system is designed, and was operated in all experiments here, to face perpendicular to the incoming X-rays so that each row is square to the X-rays, but at different distances from the X-ray source. In applications where there is a point source, pin hole projection or cone beam of X-rays a correction can be applied to each row to correct for the different geometric magnification caused by the different positions of the rows. In the experiments presented here, no corrections were necessary as the difference in geometrical magnification between rows was negligible due to the large source to sample; and small sample to detector distances used.

![HEXITEC Detector Module](image)

**Figure 1.** HEXITEC Detector Module that can be tiled in an array.
3 Data acquisition system

The data acquisition (DAQ) system for the 5 × 5 array has been developed in a modular fashion so that the technology can be easily reproduced for any geometry of the detector modules. For this first demonstration test, all of the raw data from the detectors is readout and stored so that it can be analyzed in software. The data processing and suppression developed in software will be committed to firmware in the future to enable continuous operation of the detector.

The HEXITEC ASIC operates with a rolling row readout scheme where each ASIC reads out the energy measured on each of the 6400 pixels at a rate of 8.9 kHz. There are 4 parallel outputs where an analogue voltage proportional to the energy of the X-ray detected by a pixel is multiplexed out of the ASIC. Behind each detector module there is a multichannel 14bit ADC and an FPGA. The FPGA acts as a state machine for the ASIC, collates the data from the ADC and subtracts a dark level voltage offset value per pixel. The raw data rate is 600 Mbit/s per detector module.
The data from the 5 detector modules in a single row are combined and synchronized in another FPGA which subsequently stores the data in the 8 GByte of local RAM per row. This volume of RAM enables the detector to be operated continuously at the maximum rate for 13 s.

The five readout boards plug into a mother board which contains all of the power regulation and distribution from a single 24 V source and a further FPGA to collect and package the data from the 5 × 8 Gbyte RAM boards for transfer via a full CameraLink connection to a PC. The data is saved to hard disk in the PC at a rate of 5 GBit/s.

The raw data is calibrated on a pixel by pixel basis to account for the small variations in gain and offset of each pixel. This is due to variations in the CMOS process of the ASIC and the performance of the pixels of the CdTe detectors. Charge sharing corrections can be applied to the data to either remove events where the charge from a single photon has been shared over neighboring pixels or the sum of the charge can be allocated to the pixel with the highest fraction of the charge and the other pixels set to zero. The data is then sorted into energy spectra per pixel.

The detector contains a high voltage unit to provide a common bias level to all of the detector modules. This is user programmable with a maximum voltage magnitude of −700 V and programmable current limits. The bias voltage applied to the detectors is typically in the range of −300 to −600 V, depending on the operating temperature and subsequently the leakage current from the CdTe. For the experiments presented here the detector was biased to −400 V and held to an average detector module temperature of 20 ± 1°C. The voltage bias is set to 0 V at regular intervals to avoid polarization of the Schottky contact CdTe. In this arrangement the bias voltage is applied for 10 s which is sufficient time to fill the RAM with raw data. The bias voltage is then set to 0 V whilst the raw data is read out of RAM, which takes 45 s. The bias is allowed to settle for 2 s after it is reapplied following the clearing of the RAM and before more data can be collected. When data is not being collected the detector can still be biased but the bias is set to 0 V for 2 s once every 60 s to prevent the CdTe from polarizing.

The 25 detectors in the array had been characterised individually before being assembled into the array. I-V measurements showed that there was a variation in the maximum bias that could be applied to the detectors before they became unstable due to breakdown around the edges of the modules. As each detector is biased in parallel from a single high voltage source within the DAQ system the bias applied to all detectors was set to the lowest stable bias of −400 V for the experiments presented here. This is a lower magnitude than the −500 V or −600 V traditionally applied to 1 mm CdTe detectors to achieve the < 1 keV FWHM energy resolution measured with the single detector module system [1]. Additionally, the requirement to air cool the detector system meant that the detector could not be cooled to lower temperatures that would lower the leakage current and enable higher bias magnitudes to be applied.

There is an array of thermo-electric coolers (TECs) underneath each row of 5×1 detector modules to provide a constant detector temperature in the range of 15 to 20°C depending on the ambient conditions. The heat from the hot side of the TECs is dissipated by heat pipes and fan cooled heat sinks on the outside of the detector housing. The detectors are thermally isolated from the majority of the electronics which are air cooled with addition fans that blow ambient air through part of the housing. The detector system is shown in figure 4 with the detector array protected by a carbon fiber window.
4 Noise performance

The detector noise performance was evaluated by operating the detector with a bias of $-400\,\text{V}$ and at a temperature of $20^\circ\text{C}$ so that the ASIC was experiencing the same leakage current as when collecting X-rays. The raw data values per pixel were readout to provide a measure of the dark level noise limit. Then a voltage step was applied to the front end pre-amplifier in the ASICs. This test method provided a measure of the noise and linearity of the ASIC and DAQ system across the operating range separate from the energy resolution of the CdTe detectors.

A spectrum per pixel was collected from over 100,000 dark frames with the detector operating at 8.9 kHz. The FWHM of the dark level spectrum was used to estimate the dark level noise per pixel. This measurement showed that the average dark noise per pixel was 17 LSB which is equivalent to 500 eV. Figure 5 shows the distribution of the dark noise per pixel with 94% of pixels having less than 20 LSB (equivalent to 600 eV).

The test voltage input was provided from a digital to analogue converter (DAC) and had a magnitude of 0.05 V to 0.25 V in steps of 0.05 V. Figure 6(a) shows an example pixel spectrum for all of the voltage test pulse inputs. The linearity of the example pixel is shown in figure 6(b). All pixels in the detector demonstrate this typical test pulse performance. The linearity and FWHM of the ASIC response was as expected from the DAC analogue test input.

The FWHM of the pixel spectra from the 0.2 V test pulse input was measured for all pixels. The average FWHM was 26 LSB which is equivalent to 800 eV. Over 93% of pixels had a FWHM...
5 Imaging performance

The staggered rows of detectors that form the array of $5 \times 5$ detectors can create imaging artefacts if used in an application without a parallel beam of X-rays. In applications that have a geometric
magnification from pinhole collimation or from a cone beam X-ray source the 2.5 mm difference in distances between the rows of detectors relative to the sample and source may need to be corrected. When the source or sample distance is large relative to the separation between rows, as is the case in the tests presented here, the difference in geometric magnification is negligible.

A steel sheet with a regular pattern of 5 mm diameter circular holes on a 7.5 mm triangular pitch was imaged with a 100 kV Tungsten X-ray tube at 0.1 W. The sample was placed on the window of the detector 60 cm from the source. The total number of events above 15 keV was summed together on a pixel by pixel basis to provide an intensity image. Figure 8 (a) shows a raw image of a section of the detector where the red dashed line shows the edges of 4 detectors modules. The 150 µm inactive area on the edge of the detector modules and the 170 µm gap between modules cause a 2 pixel dead-space that distorted the shape of the circular holes between modules on the same row. The height and width of pixels of the circles in the middle of the detector modules was 20 pixels. The circles that over lapped the gap between modules on the same row had a width of 18 pixels and a height of 20 pixels. Figure 8 (b) shows that by adding 2 dummy columns and interpolating over the dummy columns the correct image can be presented. Additionally there is no distortion between the different rows of detectors as the 250 µm pixel pitch is maintained. The mechanics of the detector modules and the supporting framework ensured that the modules were parallel to each and there was no relative rotation of the images from individual detector modules.
Figure 8. (a) The raw intensity image at the position of 4 detector modules. (b) The same image with an additional 2 column spacing and interpolation added vertically to the central column of circles.

6 Spectroscopic performance

The spectroscopic performance of the detector was evaluated by exposing the detector to an 185 MBq $^{241}$Am source. The source was placed 10 cm from the detector and data was collected for a total of 1000 s, in 100 collections of 10 s, with the bias set to 0 V for 45 s whilst the raw data was readout of RAM. The detector was biased to $-400$ V and held to an average detector module temperature of $20 \pm 1$ °C.

The raw data was processed to remove charge sharing events and to individually calibrate each pixel based on a linear fit to the location (LSB) of the 59.54 keV, 13.98 keV and 20.98 keV peaks from $^{241}$Am and its daughter products. The calibrated spectra per pixel were interpolated and the FWHM of the 59.54 keV peak was automatically measured. An example single pixel spectrum with a FWHM of 1 keV is shown in figure 9.

Figure 9. The $^{241}$Am spectrum from an example pixel with calibration and charge sharing events removed.

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The median of the FWHM per pixel was 1.4 keV with 93% of pixels having a FWHM less than 2 keV (red dashed line in figure 10). The majority of pixels with a FWHM greater than 2 keV were on the edge of the detector modules and subjected to higher leakage currents than is ideal for the ASIC. The test pulse results in section 4 showed that it is possible to measure an energy resolution of 800 eV FWHM from the ASIC and DAQ system. However, the CdTe detectors, when biased to $-400 \, \text{V}$, can only achieve a median FWHM of 1.4 keV and are the limitation in the energy resolution.

Figure 10. The distribution of the pixel FWHM from the 59.5 keV peak.

Figure 10 shows the distribution of the FWHM of the 59.5 keV peak for all pixels. The spectrum from all pixels added together, after calibration and charge sharing corrections, is shown in figure 11. The FWHM of the peak at 59.5 keV for the summed spectrum was 1.6 keV. The pixels on the edges of modules with the higher leakage current increased the low energy noise edge in the spectrum which is visible below 10 keV.

Figure 11. The $^{241}$Am spectrum from the sum of all pixels after calibration and charge sharing correction.
7 K-edge enhanced imaging example

The detector was used to image a custom made plastic breast equivalent phantom that was 2.5 cm thick. A small area of the phantom had a porous detail, 0.5 cm in thickness, soaked in commercial Iodine contrast agent (Niopam® 150, Bracco) diluted to a concentration of 75 mg iodine/ml, inserted into the phantom. This is estimated to be 10 times more contrast agent than in a real mammogram. The phantom was placed on the front surface of the detector and imaged using a tungsten X-ray tube operated at 50 kV and 10 µA with a 3 mm Al filter. The X-ray tube was 70 cm from the detector. A flat field measurement with the same conditions, but with the phantom removed, was used to estimate the total energy incident on the phantom. It was possible to estimate the entrance dose on the phantom by integrating the energy spectrum per pixel, assuming all incident X-rays were detected by the 1 mm thick CdTe and estimating the mass of the CdTe from its dimensions and density of 6.2 g/cm³. The estimated entrance dose in air for the 100 s measurement of the phantom was 1 mGy. A typical mammogram would have an entrance dose in air around 5 mGy; and two scans would be required for a K-edge subtraction with conventional detectors. Therefore, this example experiment had a longer collection time with a relatively low dose due to the low power X-ray tube. However, the experiment used an order of magnitude more contrast agent and a thinner sample than would be expected in a real mammography scan. The experiment is designed to demonstrate an example application of the large area detector rather than to develop the mammography technique.

The detector was operated at 22°C and a bias voltage of −400 V. A higher temperature was used as the detector was enclosed in an X-ray cabinet which reaches a higher ambient temperature. Data was collect for 100 s, made up of 10 files of 10 s duration with a bias refresh, bias set to 0 V, between each collection. As in figure 8, 2 extra columns were added between modules on the same row and filled with data interpolated from neighboring pixels. An additional median filter was applied with a range of 2 × 2 pixels using a standard MATLAB® image processing tool to figures 12 and 14 to improve the image quality and suppress defective pixels. As a figure of merit, the “contrast” between the iodine to background was measured by taking the ratio of the average greyscale value of a 10 × 10 pixel area in the iodine and phantom only regions, as equation (7.1). The x and y scale are included in figure 12 to show the locations of the x and y values in equation (7.1).

$$\begin{align*}
\text{Iodine to Background} &= \frac{\left(\sum_{x=286}^{295} \sum_{y=126}^{135} I(x,y)\right)}{100} \div \frac{\left(\sum_{x=201}^{210} \sum_{y=201}^{210} I(x,y)\right)}{100}\end{align*}$$ (7.1)

Equation (7.1) shows the calculation of the Iodine to Background figure of merit where the image, I, has an area of typical background at pixel (201, 201) to pixel (210, 210). Similarly, I, has an area of iodine contrast agent at pixel (286, 126) to pixel (295, 135).

Figure 12 shows the image of the phantom with all events in the spectrum per pixel included. The area with the Iodine contrast agent is clearly seen as the dark area bottom-right of center. The iodine to background figure of merit of figure 12 was 1.9 ± 0.2.
Figure 12. Transmission X-ray image of the breast phantom containing events from all energies

The energy spectrum per pixel from the detector can be used to extract information from the images. For clarity, figure 13 shows the summed spectrum from an area of 10 × 10 pixels but the same spectral information is in every pixel. The blue line shows the spectrum transmitted through the phantom in an area with no contrast agent. The red line shows that the presence of the contrast

Figure 13. The energy spectrum from an area of 10 × 10 pixels where there is no contrast agent (blue) and with the contrast agent (red). The transmission of Iodine with the K-edge at 33.2 keV is also shown (black dashed line).
agent reduces the overall intensity of the spectrum and there is a very clear absorption edge at 33.2 keV due to the Iodine contrast agent. The ability to record the entire energy spectrum per pixel means that multiple contrast agents could be simultaneously imaged and discriminated using this detector.

A K-edge enhanced image was created by performing a logarithmic subtraction of the images obtained by integrating, pixel by pixel, 2 keV wide windows above and below the K-edge of iodine, respectively [6]. The resulting image is shown in figure 14. The same contrast analysis as figure 12 shows that the K-edge subtracted image had an improved contrast with an Iodine to background ratio of $4.2 \pm 0.3$. Additionally, the K-edge subtraction has removed all of the phantom features from the image and only displays the location of the Iodine.

8 Summary

A large area, fully spectroscopic CdTe detector with $10 \times 10 \text{ cm}^2$ active area and 160,000 pixels has been built and characterized. The modular detector and mechanical engineering has provided a robust method of covering large areas with minimal image distortions. The detector has demonstrated that the pixels can measure an energy spectrum with a FWHM resolution of 1.4 keV at 60 keV. The dark noise and voltage pulse tests showed that the spectral performance of the system is limited by the performance of the CdTe detector when operated at $20^\circ\text{C}$ and $-400 \text{ V}$ bias.

An example application of K-edge enhanced imaging for mammography showed how the energy spectrum per pixel can be used to improve contrast and extract specific information from the data.
The modular design of the detector modules, mechanics and the readout electronics demonstrate that CdTe detector technology is a viable option for large area, hard X-ray spectroscopic imaging with many potential applications including synchrotron science, astrophysics, medical, industrial and security imaging.

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