Development of a CZT drift ring detector for X and γ ray spectroscopy

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ABSTRACT: CdTe and CZT detectors are considered better choices for high energy γ and X-ray spectroscopy in comparison to Si and HPGe detectors due to their good quantum efficiency and room temperature operation. The performance limitations in CdTe and CZT detectors are mainly associated with poor hole transport and trapping phenomena. Among many techniques that can be used to eliminate the effect of the poor charge transport properties of holes in CdTe and CZT material, the drift ring technique shows promising results. In this work, the performance of a 2.3 mm thick CZT drift ring detector is investigated. Spatially resolved measurements were carried out with an X-ray microbeam (25 and 75 KeV) at the Diamond Light Source synchrotron to study the response uniformity and extent of the active area. Higher energy photon irradiation was also carried out at up to 662 keV using different radioisotopes to complement the microbeam data. Different biasing schemes were investigated in terms of biasing the cathode rear electrode (bulk field) and the ring electrodes (lateral fields). The results show that increasing the bulk field with fixed-ratio ring biases and lateral fields with fixed bulk fields increase the active area of the device significantly, which contrasts with previous studies in CdTe, where only an increasing lateral field resulted in an improvement of device performance. This difference is attributed to the larger thickness of the CZT device reported here.

KEYWORDS: CdTe; CZT; Drift Detector; X-Ray; Synchrotron.

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1. Introduction

The growing applications of radiation detectors in many fields especially in astronomy and space science require detectors with certain properties, like high quantum efficiency, good energy resolution and room temperature operation [1], [2]. Although Si PIN-Diodes [3]–[6] and Si drift detectors [7]–[9] provide good energy resolution, these detectors suffer from poor quantum efficiency at higher photon energies which limits their effectiveness to below 30 keV due to their low atomic number ($Z=14$). On the other hand, due to the narrow band gap energy (0.75 eV) of HPGe detectors, these detectors need significant cooling to decrease the adverse effect of leakage current [3]. These limitations of Si and HPGe detectors have directed efforts to investigate compound semiconductor based detectors, such as CdTe and CZT, which are considered an excellent choice for room temperature gamma- ray spectroscopy due to their good quantum efficiencies at high energies [1], [10]. However, the effect of poor hole transport in CdTe and CZT detectors (hole mobility life time product, $\mu\tau$, are 10^{-4} and 10^{-5} cm²/V in CdTe and CZT respectively, in comparison to 1 cm²/V in Si and Ge detectors [1]) in some cases represents a critical limitation causing low energy tailing in the spectrum degrading the detector energy resolution especially at high energies [3], [6], [11], [12]. Many techniques have been proposed to overcome the problem of poor hole transport. These include, signal processing and novel electrode geometries. In signal processing, a pulse shape discrimination circuit is used to reject pulses which are predominantly due to hole transport since they have a long rise time. However, in this technique a large number of events are rejected reducing the overall detection efficiency [13]–[15]. Novel electrode geometries, such as the Co-planar grid technique [16]–[18] are associated with increased electronic noise due to the leakage currents between the grid electrodes [11], whereas pixel detectors [19] are limited by charge sharing effects between pixels [20], [21]. The drift ring technique is an alternative detector geometry that reduces the sensitivity to hole transport, improves the detector energy resolution, and further corrects for

residual holes [11], [22]. This drift ring technique was first proposed by Gatti and Rehak in 1983 [23] for Si detectors. In 1998, Pamelén and Budtz-Jørgensen of the Danish Space Research Institute demonstrated the potential of CZT drift strip detectors for X-ray astronomy applications [11], [12]. We have previously presented results from a 1 mm thick CdTe drift ring detector with Ohmic contacts at room temperature [24], which suffered from relatively high leakage current limiting the bias that could be applied. This results in reduced active area and a trade-off between energy resolution and quantum efficiency. In this work we present data from a CZT drift ring device which shows significantly lower leakage currents than CdTe due to the higher material resistivity. The CZT devices are significantly thicker than the CdTe and can be operated at significantly higher bias voltages, resulting in a larger active area and higher quantum efficiency for the same ring geometry.

2. Experimental Method

2.1 Specifications of the CZT drift ring detector

The CZT drift ring detector which was used in this work has the same dimensions as the CdTe drift ring detector reported in [24] with the exception of its 2.3 mm thickness (compared to 1 mm for the previously reported CdTe). The CZT material was sourced from Redlen and the detector fabricated in-house using photolithography. Gold contacts were sputtered on both sides of the crystal. The anode diameter is 0.5 mm as are the widths of all three rings; individual rings are separated by electrode gaps of 0.5 mm and the overall area is $(8 \times 8) \text{ mm}^2$, see [Error! Reference source not found. Figure \(4\)](#) top.

2.2 Device mounting, electronic chain and detector calibration

The CZT drift ring detector was mounted face down on a ceramic substrate i.e. the detector was irradiated through the rear planar cathode contact. [Error! Reference source not found. Figure \(4\)](#) bottom shows the mounting of the detector onto the custom ceramic substrate. The CZT detector was bump-bonded to the ceramic using conductive adhesive by the STFC Rutherford Appleton Laboratory (RAL).

The CZT detector was connected to an Amptek CoolFET A250 charge sensitive preamplifier, a shaping amplifier (ORTEC 570) and a pulse generator (ORTEC 480). Pulse height spectra were acquired using a Canberra Multi-Channel analyser (MCA). The planar rear electrode and the three drift rings were negatively biased by using a 4 channel power supply, whilst the collecting anode was held at zero potential. The energy calibration of the detector system was carried out as described in [24] using an average energy to create one electron hole pair, W factor of 4.6 eV/ehp in CZT [1].

IV measurements were done at room temperature in air and -15°C under vacuum using a KEITHLEY 487 picoAmmeter / Voltage source instrument interfaced to a PC acquisition system. Different bias schemes were used to bias the cathode and the rings with the 4 channel quad power supply, while the current was measured directly from the KEITHLEY system. The detector ceramic was mounted on a peltier cooling system that allowed the detector to be cooled to -15°C .

2.3 Microbeam Measurements and γ – ray spectroscopy

Microbeam measurements were carried out at the beam line B16 at the Diamond Light Source Synchrotron [25] to study the response uniformity and active area of the CZT detector as a function

Figure (1) (Top) Schematic diagram of the CZT drift ring detector showing the ring pattern.

(Bottom) Cross section of the CZT drift ring detector geometry and its bonding on a ceramic substrate with metal track electrical connections.

Table (1) The specifications of the X-ray microbeam measurements

X-ray Beam size	20 μm $\times$ 20 μm
X/Y step size	100 μm
Time per scan	30 s
1 st harmonic	25 keV
3 rd harmonic	75 keV

of incident X-ray position with an X-ray microbeam. The main objective of these measurements was to measure the radial variation in performance in the CZT drift ring detector, and the effect of various lateral and bulk biasing schemes to extend the active area of the device.

[Error! Reference source not found.](#) Table (1) summarises the beam specifications which were used for the line scan measurements for CZT detector, with the microbeam incident on the rear planar contact of the detector.

The storage ring was operated in top-up mode with a current of 300 mA. The X-ray energy was tuned to 25 keV by double crystal monochromator (DCM) with a beam flux of 2×10^5 photons/sec. In addition a beam flux of 100 photons/sec was also produced at 3rd harmonic (75 keV). A total of 12.5 mm thick aluminium absorbers were used in order to reduce the event rate, pile up effect and change the ratio of the 25 and 75 keV signals by reducing the beam flux to 400 and 50 photons/sec at 25 and 75 keV respectively. Under the optimized bias scheme in terms of detection efficiency, additional γ - ray spectroscopy was performed using different γ - ray energy radioisotope sources (59.5 keV of a 420 kBq ^{241}Am source, 122 keV of a 304 kBq ^{57}Co source and 662 keV of a 230 kBq ^{137}Cs source which were positioned at 50 mm distance above the centre of the detector) providing information about the average performance of the detector across the whole surface area.

3. Results and discussions

3.1 Spectroscopic performance of the CZT drift ring detector using different bias schemes

The CZT drift ring detector shows low leakage current due to its high resistivity at room temperature ($10^{11} \Omega \cdot \text{mm}$ for CZT in comparison to $10^{10} \Omega \cdot \text{mm}$ for CdTe). The leakage current on the anode was found to equal 0.05 nA at -100V bulk field and (-30,-60,-90) V on the 1st, 2nd and 3rd ring respectively at room temperature. Figure (2) shows the anode leakage current for increasing bulk field (cathode bias) with different fixed ratio lateral fields, i.e. different percentages of bulk field to bias the rings. Although the room temperature anode leakage current increases with applied voltage, it remains below 0.2 nA at -500V, which is not expected to significantly deteriorate the energy resolution. Moreover, by cooling the detector from room temperature to -15 °C the anode leakage current at -500V reduced significantly to below 0.01nA.

Error! Reference source not found.Figure (3) shows a pulse height spectrum acquired with the optimum bias scheme in terms of detection efficiency, with -700V applied to the cathode and drift voltages of -500V,-600V,-700V applied to the 1st, 2nd and 3rd ring electrodes respectively. The X-ray microbeam was incident on the centre of the anode, with the detector at room temperature. The spectrum clearly shows the primary 25 keV photopeak, and also shows significantly smaller peaks at 50 keV and 75 keV due to additional harmonics from the synchrotron beam. The intensity of the 25 keV peak has been

Figure (2) IV measurements of the CZT drift ring detector at different bulk (controlled by the cathode bias) and lateral fields (percentage of cathode bias applied to ring 1, 2 and 3 respectively)

significantly reduced by hardening the incident beam with aluminium attenuators. The FWHM of the 25 keV and 75 keV signals at the centre of the anode at this bias scheme are (5.8 ± 0.1) and (6.3 ± 0.1) keV respectively with a pulser width of (5.1 ± 0.1) keV. The 5.1 keV width of the pulser peak represents the intrinsic noise in the electronic read-out chain primarily due to the leakage current, and this electronic noise in the readout system dominates the overall peak resolutions observed in this work. The preamplifier noise in isolation was measured as (1.63 ± 0.01) keV by generating a pulse through the preamplifier's test input. However, by connecting

the preamplifier to the detector system at 0 V, the pulser width increased to (3.8 ± 0.1) keV due to the additional capacitance of the connecting circuits, cables and metal tracks in the ceramic substrate. The remaining “detector only” energy resolutions at 25 and 75 keV are 2.9 keV and 3.8 keV respectively.

Error! Reference source not found. Figure (4) shows the FWHM of the 25 and 75 keV signals at different lateral fields and fixed -700V bulk field under anode irradiation. In this figure, both the 25 and 75 keV signals in addition to the pulser peaks do not change significantly by increasing the lateral field from (-70,-140,-210) V to (-210,-420,-630) V. At these bias schemes, the leakage current is sufficiently low to not cause any deterioration in the energy resolution. The FWHM of the 25 keV and 75 keV signals at the centre of the anode are (5.1 ± 0.1) and (5.4 ± 0.1) keV respectively with a pulser width of (4.2 ± 0.1) keV at -700V bulk field and (-70,-140,-210) V lateral field which continue to be approximately around these values by further increasing the lateral fields

Figure (3) An X- ray spectrum at -700V (-500,-600,-700) V bias scheme using CZT at the centre of the anode at room temperature.

to (-140,-280,-420) V and (-210,-420,-630) V. The fluctuations in pulser widths are within the limits of reproducibility for measuring the pulser. However, a significant change in energy resolution has been noticed at (-500,-600,-700) V lateral field due to increasing leakage current.

3.2 Effect of using different bias schemes on the active area of the CZT drift ring detector

To optimize the energy resolution and the quantum efficiency of the drift detector it is necessary that the charge collection remains constant over as great a radial distance from the anode as possible. This is shown by the radial line scans in Figure (5). However the energy of both the 25 and 75 keV peaks in the spectra start to shift to lower energies which correspond to a reduction in the count rate as the line scans move sufficiently far away from the centre of the anode. The region of full charge collection, represented by the radial distance from the anode where the response is uniform, can be extended by increasing both the bulk and lateral fields

[Error! Reference source not found.](#) Figure (5) shows that increasing the lateral field from (10-20-30) % to (30-60-90) % as a ratio of the bulk field i.e. increasing the ring voltages from (-70,-140,-210) V to (-210,-420,-630) V, the uniformity of the 25 keV peak is extended to 0.6 mm distance from the centre of the anode. However, due to the low leakage current, the lateral fields on the rings of CZT can be increased significantly without experiencing high leakage current. At -700V bulk field and (-500,-600,-700) V lateral field, the active radius extends to 2.4 mm distance from the centre of the anode which corresponds to the gap between 2nd and 3rd ring. Note that the voltage difference

Figure (4) The FWHM of the 25 and 75 keV signals at the centre of the anode using different lateral fields at -700V bulk field using CZT detector

between ring 3 and the cathode is zero at this bias scheme. The uniformity of the detector response as a function of position increases significantly by increasing both bulk and lateral fields. This is also true for the response of the 75 keV photopeak as illustrated in Figure (6) in terms of the uniformity of the peak and active radius of the detector. However, due to different average penetrating depths in the CZT material; $\sim 100\ \mu\text{m}$ and $500\ \mu\text{m}$ for 25 and 75 keV respectively [26]; there is a slight difference in peak shifting to lower energies at some distances from the centre of the anode between 25 and 75 photopeaks which is eliminated at (-500,-600,-700) V lateral field, see Figure (6). Note that a similar trend can be obtained if the count rate under the peaks is considered in Figures (5) and (6).

3.3 Performance characteristics using different γ - ray energies

The γ - ray detection performance of the detector was investigated using broad beam irradiations with γ emitting radioisotopes with main emission energies at 59.5 keV (^{241}Am), 122 keV (^{57}Co) and 662 keV (^{137}Cs), corresponding to increasing average penetration depths.

Figure (7) shows the 59.5 keV line at the -700 V (-500,-600,-700) V bias scheme which results in the best active area achieved according to the line scan studies. For comparison, the -700V (-70,-140,-210) V data is also shown, which exhibits significantly more low energy events below the photopeak caused by photons which are absorbed at large distance from the anode in which the detector does not show full charge collection, see [Error! Reference source not found. Figures \(5\) and \(6\)](#). Increasing the lateral field to (-500,-600,-700) V, minimizes these events due to the extended active area of the

Figure (5) 25 keV peak centroids at -700V bulk field and different lateral fields using CZT at room temperature.

device and subsequently the Cd and Te escape peaks are visible as small features between 28.5 and 36.3 keV. By increasing the lateral field from (-70,-140,-210) V to (-500,-600,-700) V, the FWHM in the pulser signal and in the 59.5 keV peak increased by the same amount within uncertainty.

Similarly Figure (8) shows the ^{57}Co 122 keV spectra at the optimized -700V (-500,-600,-700) V and -700V (-210,-420,-630) V bias schemes. The 122 keV energy peak at the optimum bias scheme is symmetric and no strong tailing effect on the low energy side which is reported to appear in CZT detectors due to hole trapping at high energies [3], [6] is seen. However, at reduced lateral field (-70,-140,-210) V, the 122 keV photopeak cannot be resolved and at (-210,-420,-630) V a large number of events occurs at low energy side of the peak causing the tail effect that appears in the 122 keV ^{57}Co spectrum, see Figure (8). In contrast, the same improvement could be expected for the ^{137}Cs 662 keV spectrum by increasing the lateral field however due to its higher average penetration depth, the peak cannot be resolved except for the highest lateral field value (-500,-600,-700) V see Figure (9). Therefore, as the interaction takes place deeper in the CZT material, higher lateral fields are needed in order for the device to work effectively and subsequently large active area can be achieved.

Figure (6) 25 and 75 keV photopeak centroids normalized to the anode maximum energy at -700V bulk field and different lateral fields using CZT at room temperature.

4. Conclusions

The performance of a 2.3 mm thick CZT drift ring detector has been studied, which demonstrates good spectroscopic performance with well-defined photopeaks observed from ^{57}Co at 122 and 136 keV and no significant evidence of hole tailing. High resolution lines scans with a 20 μm diameter X-ray beam have demonstrated the excellent uniformity of this device to radial distances beyond 2.3 mm for X-ray energies up to 75 keV, equivalent to the 2nd ring electrode. The optimum operating conditions for the detector were found using -700V applied to the rear cathode and ring voltages of -500V, -600V and -700V respectively. These conditions corresponded to an active area of 17 mm^2 . This device overcomes the energy resolution limitations caused by excessive leakage current that was observed in a previous CdTe drift detector [24], and the higher resistivity of CZT resistivity allows the use of significantly higher applied potentials. A systematic improvement in quantum efficiency was found for increasing bulk and lateral fields independently. In general the spectroscopic performance of this device was limited by the electronic noise present in our system, and future work is needed to implement a low noise preamplifier that is optimized for CZT drift detectors.

Figure (7) The 59.5 keV ^{241}Am spectra at -700V bulk voltage and using two different lateral fields

Figure (8) The 122 keV ^{57}Co spectra at -700V bulk voltage and using two different lateral fields

Figure (9) The 662 keV ^{137}Cs spectrum at -700 V (-500,-600,-700)V using CZT detector

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