Development of CdTe/CZT Drift Ring Detectors for X and γ ray Spectroscopy

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Submitted for the degree of Doctor of Philosophy

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November 2014

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In the name of ALLAH, the Most Gracious, the Most Merciful.

Dedication

To the soul of my father, who was always with me when I needed him and I was away of him when he needed me.

To my mother who has sacrificed in order to see this moment.

To my wife and my daughters, who have shared with me hard and happy moments.
Abstract

The applications of radiation detectors in astronomy and space science require such detectors that provide high quantum efficiency and good energy resolution. CdTe and CZT material is an excellent candidate for the fabrication of high energy X-ray spectroscopic detectors due to their good quantum efficiency and room temperature operation. The main material limitation is associated with the poor charge transport properties of holes. The motivation of this project is to develop new CdTe and CZT detectors fabricated with a drift ring geometry that is insensitive to the transport of holes. The performance of a prototype (8 x 8) mm$^2$ Ohmic CdTe drift ring detector fabricated by Acrorad Ltd and a CZT fabricated at University of Surrey with 3 drift rings are investigated in which their thicknesses are 1 mm of CdTe and 2.3 mm of CZT. For both detectors, the inner anode has a diameter of 0.5 mm as are the widths of all three rings which are separated by gaps of 0.5 mm which are quite large in comparison to drift ring geometries which are published in literature. The energy resolution was studied by using different biasing schemes in terms of biasing the cathode (bulk field) and the rings (lateral field) and the data shows that the energy resolution of the CdTe at room temperature is limited by leakage current which is a combination of bulk and surface leakage current which was improved significantly by cooling the detector due to reducing the leakage current. For example, the CdTe detector shows energy resolution of (5.1 ± 0.3) keV at 59.5 keV at room temperature which was improved to (3.6 ± 0.1) keV at -15 °C as a result of reducing the leakage current from 23 to 0.4 nA using the same bias scheme. The CZT detector shows low leakage current at room temperature. Under an optimised biasing scheme, the FWHM of a 59.5 keV photo-peak was found to be (2.8 ± 0.2) keV at -15 °C and (3.3 ± 0.1) keV at room temperature using CdTe and CZT respectively with a trade off between energy resolution and quantum efficiency. In addition, the performance was studied as a function of incident X-ray position with an X-ray microbeam at the Diamond Light Source and the results show that the lateral fields i.e. the bias gradient across the rings) has a significant effect on increasing the active area, evaluated by the detected count rate.
Acknowledgements

All the praises and thanks to be to ALLAH, the Lord of all exists, WHO guided and helped me to perform this work, peace and blessing be upon his prophet Mohammad who said “Whoever does not thank people, will not thank Allah”.

I would like to express my deep appreciation to Prof. Paul Sellin for his guidance, explanations and advice throughout the last four years. Although he was very busy with his duties as a head of physics department, he always gives me enough time and opportunity to ask and discuss the various parts of my project even outside our weekly regular meetings. Also I am grateful to Dr. Annika Lohstroh, my co-supervisor, for almost every day meeting and for her patience regarding my frequent questions. I am grateful to Dr. Veeramni, Dr. Sandeep and Dr. Shada for their assistance in the experimental part of this project. The design of the CdTe drift ring detector was made by Dr. Shada alkazemi. Also I would like to thank Dr. Abdullah Al-Khalili and Mr. John-William Brown for their technical assistance. Significant part of this work was carried out with the support of Diamond Light Source Ltd. UK. A Big thank you to all my friends Peter, Chris, Paola, Hussain and Dimitrios for all their kind support and help. I gratefully acknowledge Prof. Hassan Basurah, Astronomy department head - King Abdul-Aziz University, for his efforts to facilitate my scholarship and special thanks to my wife, daughters, brother, sisters, brothers in law for their support.
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Introduction

Studying the properties and interaction of radiation will help to understand its effect and uses in many applications such as medical applications whether in treatment or diagnosis purposes, in industrial field or in astronomy γ-ray spectroscopy. The latter is considered one of the most important fields of research as many interaction processes in space are responsible for γ-ray emission. By improving the ways of detection, significant information can be acquired about the universe [1]. Semiconductor detectors are considered as a preferable type of detector for precise measurements of energy resolution. They are considered as alternative to scintillation detectors [1]–[3] which have poor energy resolution compared to semiconductor detectors as the final signal undergoes many steps of multiplication before it can be measured. In addition, the needed deposited energy to create a scintillation photon in scintillation detectors is 30 eV in comparison to 3-5 eV for semiconductor detector materials [3]. On the other hand, although semiconductor detectors have better energy resolution, their band gap energy plays an important role because of thermal charge carrier generation which may degrade the energy resolution. Therefore, some of them need to be cooled to decrease this effect such as using liquid nitrogen for cooling Ge detectors[1]–[3]. Commonly, silicon (Si) and germanium (Ge) are the two crystals which are usually used as semiconductor detectors [2], [3]. Figure (1) [4] shows a comparison between two different types of radiation detectors in which the semiconductor detector types have superior energy resolution compared to a common scintillation detector at 364 keV $^{131}$I.
Introduction

When incident radiation deposits its energy on the crystal of a semiconductor detector, it creates electron-hole pairs in the conduction and valence band which eventually drift across these crystals towards the electrodes by applying suitable voltages. If this semiconductor detector is pure enough to prevent any recombination or trapping, these electrons and holes will create a current in which its magnitude is proportional to the energy deposited in the crystal. The drift velocities, $v_{\text{drift}}$, for both electrons and holes can be calculated by considering their mobility ($\mu$), applied voltage ($V$) and detector thickness ($t$) in which:

$$
  v_{\text{drift}} = \mu \frac{V}{t} \quad [3]
$$

One of the most important features of semiconductor detectors is their purity in the active area which helps to prevent trapping as holes and electrons are spread in the lattice [1]–[3]. Table (1) summarises the general properties of different types of semiconductor detectors.
Introduction

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Si</th>
<th>Ge</th>
<th>CdTe</th>
<th>CZT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic / mass number</td>
<td>14/28</td>
<td>32/72</td>
<td>48/52</td>
<td>48/30/52</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>2.33</td>
<td>5.33</td>
<td>6.20</td>
<td>5.78</td>
</tr>
<tr>
<td>Energy gap (eV)</td>
<td>1.17</td>
<td>0.75</td>
<td>1.44</td>
<td>1.57</td>
</tr>
<tr>
<td>Electron mobility life time product $\mu_e \tau_e$ (cm$^2$/V)</td>
<td>$&gt;1$</td>
<td>$&gt;1$</td>
<td>$10^3$</td>
<td>$10^3$-$10^4$</td>
</tr>
<tr>
<td>Hole mobility life time product $\mu_h \tau_h$ (cm$^2$/V)</td>
<td>~$1$</td>
<td>$&gt;1$</td>
<td>$10^4$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Energy per e-h pair (eV) at 300K (W factor)</td>
<td>3.62</td>
<td>2.96</td>
<td>4.4</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Table (1) Physical properties of different types of semiconductor detectors [3], [5]

Si and Ge detectors which provide better energy resolutions in comparison to CdTe and CZT due to their charge carrier transport properties are limited by two factors. In the case of Si detectors, their low atomic number (Z=14) decreases the probability of photoelectric interaction and therefore their quantum efficiencies [3]. On the other hand, the low band gap of Ge detectors, 0.75 eV, necessitates certain setup of cooling to decrease the effect of leakage current which makes this kind of detectors unsuitable for certain applications [3]. These limitations of Si and Ge detectors in addition to the growing applications in the imaging systems have directed the efforts to investigate compound semiconductor detectors [3], [5], [6]. CdTe and CZT have become preferable types of semiconductor detectors for X and $\gamma$-ray spectroscopy due to their superior properties [3]. These include high atomic number which increases the probability of photoelectric effect and wide band gap energy which allow room temperature operation [3]. However, these detectors suffer from poor charge transport especially for holes, see Table (1), causing low energy tailing in the spectrum degrading the detector energy resolution. Both mobility ($\mu$) and lifetime
Introduction

The motivation of this project is to develop suitable types of CdTe/CZT ring detectors for X and γ-ray spectroscopy based on the drift technique which is not yet commercially available. In this project, these detector performances in terms of their energy resolution and detection efficiency have been studied by optimizing their bulk and surface voltages at room and low temperatures. Interesting findings have been obtained in terms of the effect of bulk and lateral fields in addition to the effect of cooling on their performances which will be explained in this thesis. The general feature of each chapter is explained as follows:

Chapter 1
A background theory which includes the principle of radiation interaction, attenuation coefficient and semiconductor physics are discussed. Then a literature review which summarises the previous and current studies of semiconductor detectors in terms of their limitations which affect their charge collection efficiency and
Introduction

subsequently their energy resolution and what are the efforts to overcome these limitations are discussed. In addition, the applications of CdTe/CZT detectors in astronomy and space science will be highlighted.

Chapter 2

The experimental set up is discussed which includes the spectroscopic characteristics of different sets of planar and drift semiconductor detectors. This chapter includes, the design of the ceramic substrate on which the drift detectors are mounted, in addition to explaining the low temperature measurement set up and the irradiation techniques (geometries).

Chapter 3

The results of the performance of some different types of planar anode (pad) detectors are discussed in this chapter. These results show certain limitations which need to be overcome. Initial results were obtained about the CdTe drift ring detector at room temperature which explains the general features of the drift performance and requirements to improve them.

Chapter 4

Further studies are conducted on the drift detectors at room and low temperature using CdTe and CZT drift ring detectors. In this chapter, the energy resolution and the active area of these detectors were studied as a function of incident X-ray position with an X-ray micro-beam at Diamond Light Source and by using different γ energy emitting radioisotopes. In this chapter, the effect of choosing the biasing scheme, i.e. cathode and ring voltages are studied. Moreover, the effect of cooling on reducing the leakage current and subsequently improving the energy resolution of the CdTe drift ring detector at low temperature are discussed.

Chapter 5

The main conclusions of this work are discussed in this chapter which include the key findings and the possible suggested ideas to further improve the performance of these drift ring detectors.
Chapter 1 (Background Theory and Literature Review)

Background Theory

In this section, an introductory background theory which is related to semiconductor detector physics is covered. To understand how X and \( \gamma \) - ray interacts with detector material and subsequently how the formed charge is generated, it is important to understand the performance and properties of different semiconductor detectors which were used in this project. The topics which are covered in this section include: the interaction of radiation with matter, the Shockley-Ramo theorem which describes the signal formation in the detector, and the pulse processing units. The physics and electrical properties of CdTe/CZT detectors are discussed which include the band structure in addition to their resistivity and electrical contacts. Moreover, the noise in the electronics and detector will be discussed.

1.1 Interaction of X and \( \gamma \) - ray with Matter

The signal which is generated inside the detector material as a result of collecting the composed charge by applying external bias is formed by interactions of photons with the detector materials. These interactions are: Photoelectric absorption, Compton scattering and pair production.

1.1.1 Photoelectric Absorption

In this interaction, the entire energy of a photon is transferred usually to a K or L -shell electron which then will be ejected from the atom with energy equal to the difference between the photon energy and the electron binding energy according to:

\[
E_e = E_\gamma - B_e \quad [3]
\]

Where \( E_e \) is the kinetic energy of the ejected electron, \( E_\gamma \) is the energy of the incident photon and \( B_e \) is the electron binding energy. Therefore, in order for this interaction to occur the entire photon energy must be absorbed by the atom and \( E_\gamma \) must be \( \geq B_e \). Subsequently characteristic X - rays will be formed due to rearranging the electrons inside the atom as a results of the empty location of the ejected electron [1]–[3].
1.1.2 Compton Scattering

In this interaction, Figure (2), an incident photon interacts with a free outer shell electron which results in a scattered photon and recoil electron. The energy of the incident photon is divided between the scattered photon and the recoil electron according to:

\[
E'_\gamma = \frac{E\gamma}{1 + \frac{E\gamma}{m_e c^2} (1 - \cos \theta)}
\]

Where \( E\gamma \) is the incident photon energy, \( E'_\gamma \) is the scattered photon energy, \( m_e c^2 \) is the rest mass energy of an electron (0.511 MeV) [3] and \( \theta \) is the scattering angle. Therefore, the kinetic energy of the recoil electron is equal to the difference between the energy of the incident and scattered photon. The scattered angle, \( \theta \), can be in the range between 0 and 180°. The scattered photon has the same energy of the incident photon when \( \theta = 0 \) and therefore the recoil electron gains very little energy. On the other hand, the incident photon backscattered in its original direction and the electron recoils with the maximum energy that can be gained by the electron when \( \theta = 180° \). Therefore, the recoil electron can gain different energies according to the scatter angles which appears as a continuum of energy. Its maximum value represents the Compton edge at \( \theta = 180° \). The cross section of Compton scattering can be determined through the Klein-Nishina formula [3]. The scattered photon may undergo another Compton scattering until it may annihilates by producing a photoelectron via photoelectric effect or scattered outside the detector. In the former, the incident
Chapter 1 (Background Theory and Literature Review)

photon deposits all its energy inside the detector while in the later, part of its initial energy deposits inside the detector.

1.1.3 Pair Production

In this interaction, an electron-positron pair will be created as a result of absorbing a photon whose energy is at least equal to $2m_e c^2 = 1.02$ MeV in the electric field near the atom. The excess amount of this threshold energy will be divided by the electron-positron pair as kinetic energy; equation (4) describes this interaction

$$ E_e + E_\gamma = E\gamma - 2m_e c^2 \quad [3] $$

Where $E_e, E_\gamma$ are the electron and positron kinetic energy respectively, $E\gamma$ is the energy of the incident photon and $2m_e c^2$ is the energy required to create electron-positron pair. In this process, the positron after consuming its kinetic energy will be combined with another electron and two annihilation photons of energy $m_e c^2 = 0.511$ MeV will be formed.

1.1.4 Cross Sections of Photoelectric Absorption, Compton Scattering and Pair Production

Figure (3) Interaction of radiation with matter cross sections [1]

Figure (3) shows the probability of X and $\gamma$ - ray interaction with matter as a function of energy and $Z$, atomic number. Generally, at low $Z$ number, the Compton scattering is predominant for all energies. However, at high $Z$ number, the probability of
interaction depends on the energy of the photon in which photoelectric absorption is predominant at low photon energy and pair production is dominant at higher energies. As CdTe and CZT materials have atomic number around \( \sim 50 \), photoelectric effect dominates the most fraction of interaction for energies below \( \sim 300 \) keV, see Figure (3), in which the entire photon energy is absorbed by the detectors. However, for higher energies, Compton scattering becomes most probable and therefore the electron scatters in the detector material with a portion of the incident photon energy. Therefore, photoelectric absorption is the most important interaction for X-ray detectors. A rough approximation of the probability of photoelectric absorption is proportional to \( \frac{Z^n}{E^{3.5}} \) where \( n \) ranges between 4 and 5\(^3\).

### 1.2 Typical \( \gamma \)-ray Spectrum

A typical \( \gamma \)-ray spectrum includes the features that correspond to all the interaction processes that described in section 1.1 according to the energy of the incident photon and its cross sections. The energy of the radioisotope, the size of the detector and its surrounding material are important factors of determining some energy features in the spectrum such as escape and back scatter peaks.

![Figure (4) Features of \( \gamma \)-ray spectrum][3]

Figure (4) shows a schematic diagram of a \( \gamma \) – ray spectrum. The full energy photo-peak corresponds to the photoelectric effect in which the energy of the entire photon is absorbed by the detector whereas the Compton continuum corresponds to the electron recoil energies for different scattered angles. Three energy features may
appear in the spectrum which are single and double escape peaks in addition to the back scatter peak. The single and double escape peaks are related to pair production in which the annihilation photons escape from the detector. If one photon (0.511 keV) escapes from the detector, a small peak under the full energy peak will appear in the spectrum in which its energy represents $E_\gamma - 0.511$ MeV whereas it represents $E_\gamma - 1.022$ MeV if both photons escape from the detector. In some cases, the incident photon interact via Compton scattering with an electron of the surrounding material at an angle $= 180^\circ$ which leads to a back scattered photon of energy equal to $E_\gamma - \text{Compton edge}$ that appears in the spectrum [1], [3].

1.2.1 Hole Tailing

The energy spectrum of CdTe/CZT and Si detectors reflect the properties of theses detectors in terms of energy resolution and quantum efficiency. The short mobility life time product of holes due to the trapping centres inside CdTe/CZT leads to the hole tailing effect especially at high energies (cathode irradiation) in which the holes need to travel long distance to the cathode and with high probability be trapped inside the detector material. However, this effect is extremely reduced using Si detectors due their superior charge carrier’s mobility and lifetime. On the other hand, the low atomic number of Si in comparison to CdTe/CZT leads to low cross section of photoelectric absorption for the same energy range which therefore leads to poor quantum efficiency.

1.2.2 Escape and Characteristic X - ray Peaks

Characteristic X – rays are produced as a result of de-exciting electrons into the K- shell following the photoelectric absorption which ejects an electron from the K-shell orbit. $K_\alpha$ and $K_\beta$ are characteristic X -rays emitted when an electron de-excites from shell L and M respectively with energy equal to the binding energy differences of these shells. If these X -rays escape from the detector, photo-peaks will appear in the spectrum in which its energy equals the difference between the incident photon and the emitted characteristic X -rays. Escaping these X- rays from a detector depends mainly on their energies and the incident photon interaction position. For Si detectors,
$K_a$ and $K_b$ are 1.7 and 1.9 keV respectively which are very low energy which can only escape from a detector for interactions near the surface due to their low average penetrating depth. However, in CdTe the characteristic X-rays are 23.2, 26.1 keV for Cd $K_a$ and $K_b$ and 27.5, 31 keV for Te $K_a$ and $K_b$ respectively. These characteristic X-rays have long penetrating depths and therefore with high probability escape from a detector.

Figure (5) $^{241}$Am spectrum acquired using a 750 μm CdTe planar detector [15]

Figure (6) $^{60}$Co spectra acquired using a 500 μm Si PIN-Diode and 750 μm CdTe planar detectors[15]
Figure (5) and Figure (6) show spectra which are acquired using a 500\mu m thick Si PIN-Diode and 750 \mu m CdTe planar detectors which are both have 25 mm$^2$ active areas. The important energy features appear clearly. The hole tailing effect and the four X-ray escape peaks appear in the spectra which are acquired using a CdTe planar detector whereas these escape peaks are invisible in the spectrum which are acquired using Si PIN-Diode due to their low penetrating depths. On the other hand, the spectrum which are acquired using Si PIN-Diode does not show hole tail effect due to its superior charge carriers transport. The small energy features between 60 and 80 keV in the Si PIN-Diode spectrum are believed to be due to environmental interference and characteristics X-rays emitted by the materials in the vicinity of the detector [15].

Moreover, the $^{241}$Am spectrum which is acquired by the Si detector shows $\gamma$-rays at 26.35 and 59.5 keV in addition to L X-ray from $^{237}$Np decay at 13.9, 17.8 and 20.8 keV [3], [15], [16].

1.3 Attenuation Coefficient of X and $\gamma$–ray

The aim of this section is to study how photons can be absorbed inside the detector material quantitatively, i.e. what is the average length a photon reaches before it stops (i.e. interaction takes place). This is very important in terms of detection efficiency as photons which are absorbed near the surface can be detected more efficiently than photons which cross the detectors as a result of their long penetration depths.

An exponential law describes how photons are transmitted inside a detector material as indicated in equation (5):

$$\frac{I}{I_0} = e^{-\mu t}$$ [3]  

Where $I$ and $I_0$ are the incident and transmitted photons respectively, $t$ is the detector thickness and $\mu$ is the linear attenuation coefficient which can be defined as the sum of the cross sections of all types of photon interactions in matter, i.e. photo electric
absorption, Compton scattering and pair production. Each of these interactions contribute to the interaction of photons either by absorption; photoelectric and pair production; or by scattering; Compton effect. The reciprocal of $\mu$ is the mean free path; $\lambda$ which can be defined as the average length of the photons before it stops inside the detector material [3]. Taking into account the different types of detector materials, equation (5) can be further specified by considering the density of the detector material; $\rho$; in which the mass attenuation coefficient can be introduced which is a function of energy defined as:

$$\text{Mass attenuation coefficient} = \frac{\mu}{\rho} \quad [3]$$

(6)

Figure (7) shows the mass attenuation coefficients as a function of energy for all the interaction processes of photons with matter for CZT as an example. It is clear from the figure that photon energy is a significant factor of determining the type of interaction. In addition, the mass attenuation coefficient decreases, i.e. more penetration depth, as the photon energy increases. In contrast, Figure (8) shows the total mass attenuation coefficients for three different detectors which indicates clearly
that due its low atomic mass number, Si detector shows more penetrating depth in comparison to CdTe and CZT detectors at higher energies.

Figure (8) Total mass attenuation coefficients of three detector materials [17]

Another factor which plays a role in detection efficiency is the detector thickness. Figure (9) shows that, at the same detector thickness, photon energy determines how the CdTe can detect photons efficiently. At low photon energy, 1mm thick CdTe detector can assure good quantum efficiency however, at higher energies more thickness is needed to assure good efficiency [5], [18].
1.4 Quantum Efficiencies of Si and CdTe/CZT Detectors

One of the most important characteristics of a detector is its intrinsic efficiency which indicates the fraction of photons which were detected by a detector and thus the intrinsic efficiency $e_i$ can be expressed by:

$$e_i = 1 - \frac{I}{I_o} \quad [3]$$

Where $I$ and $I_o$ are the incident and transmitted photons respectively.

From equations (5) and (6),

$$e_i = 1 - e^{\rho \times \mu} \quad [3]$$

Where $\rho$ is the density of the detector material, $\mu$ is the linear attenuation coefficient and $t$ is the detector thickness. Equation (8) and Figure (8) show that, the intrinsic efficiency is decreased by increasing the energy for the same detector material. CdTe and CZT detectors have higher intrinsic efficiencies in comparison to Si detectors. Figure (10) and Figure (11) shows that intrinsic efficiencies which were calculated using two commercially 1 mm CdTe XR100T and different thicknesses of Si PIN-diode detectors respectively which show the superior efficiency of CdTe in comparison to Si detectors [16].
Chapter 1 (Background Theory and Literature Review)

1mm Thick CdTe Detection Efficiency

Figure (10) Intrinsic efficiency of 1mm CdTe detector using different thicknesses of Be windows to absorb low energy X-rays [16]

Figure (11) Intrinsic efficiency of Si detectors using different thicknesses of Be windows to absorb low energy X-rays [16]
On the other hand, detection efficiency can be expressed by taking into account the $\gamma$ source activity which is used. The absolute efficiency is defined as:

$$\mathcal{E}_{\text{abs}} = \frac{C_t}{\gamma_A} \times 100\% \quad [3]$$

Where $\mathcal{E}_{\text{abs}}$ is the absolute efficiency, $C_t$ is the total count rate recorded per unit time integrated over the whole recorded spectrum and $\gamma_A$ is the source activity in Bq (disintegration per sec.). Equation (9) can be specified by considering the counting geometry i.e. the distance between the detector and source ($d$) and the detector area ($A$) in which the solid angle ($\Omega$) can be introduced, see Figure (12).

$$\Omega = \frac{A}{d^2} = \frac{\pi a^2}{d^2} \quad [3]$$

Thus equation (9) can be expressed by intrinsic efficiency $\varepsilon_i$ which is:

$$\mathcal{E}_{\text{int}} = \frac{\mathcal{E}_{\text{abs}}}{\Omega/4\pi} \quad [3]$$

Moreover, the photo-peak efficiency can be calculated by considering the decay % which is the fraction number of gammas emitted by disintegration and thus $\gamma_A$ can be corrected for specific photo-peak efficiency, see Table (2).

<table>
<thead>
<tr>
<th>Gamma energy</th>
<th>% yield by disintegration</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{241}$Am 59.5 keV</td>
<td>36</td>
</tr>
<tr>
<td>$^{51}$Co 122 keV</td>
<td>87</td>
</tr>
<tr>
<td>$^{137}$Cs 662 keV</td>
<td>85</td>
</tr>
</tbody>
</table>

Table (2) % yield per disintegration of some gamma energies [19]
Equation (11) with the decay % correction of $\gamma$ isotope requires that each $\gamma$ deposits its full energy in the detector which is not necessarily the case for $\varepsilon_i$ defined in equation (8).

Table (3) summarises the mean attenuation coefficient, average penetrating depths and the calculated quantum efficiencies at different energies for all pad detectors which will be used in this project (more detail of these detectors in chapter 3).

<table>
<thead>
<tr>
<th>Detector/Dimensions</th>
<th>Mass attenuation coefficient $\mu/p$ (cm$^2$/g)</th>
<th>Mean penetrating depth $\lambda = 1/\mu$ (mm)</th>
<th>Quantum efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy (keV)</td>
<td>59.5 122 662</td>
<td>59.5 122 662</td>
<td>59.5 122 662</td>
</tr>
<tr>
<td>Si A (10x10x1)</td>
<td>0.29 0.15 0.07</td>
<td>14.8 28.6 61.3</td>
<td>6.6 3.4 2</td>
</tr>
<tr>
<td>Si B (2.4x2.4x0.3)</td>
<td>0.29 0.15 0.07</td>
<td>14.8 28.6 61.3</td>
<td>2 0.1 0.5</td>
</tr>
<tr>
<td>CdTe (4x4x1)</td>
<td>6.5 0.9 0.07</td>
<td>0.25 1.8 23</td>
<td>98.2 42.3 3.9</td>
</tr>
<tr>
<td>CZT (5x5x5)</td>
<td>5.8 0.8 0.05</td>
<td>0.30 2.2 34.5</td>
<td>100 90 13</td>
</tr>
</tbody>
</table>

Table (3) Summary of the $\mu/p$, $\lambda$ and quantum efficiencies % for all pad detectors used

Table (3) shows that as the photon energy increases for the same detector material, $(1/\mu)$ the average penetrating depth is increased. In addition, it has lower values for CdTe/CZT in comparison to Si, see Figure (8) and Figure (9). Subsequently, the calculated quantum efficiencies depend on the energy and therefore depend on the $(\mu/p)$. They decreased by increasing the photon energy which explains the low count rate of the 122 keV as most of its interaction is due to Compton scattering deeper in the detector material. In addition, CdTe/CZT have higher quantum efficiency than Si detectors which is matching with the results obtained by considering the count rate and intrinsic efficiency, see chapter 3 for more detailed results. The calculated quantum efficiencies using $(\mu/p)$ include all the type of interactions and thus are not comparable to the peak intrinsic efficiency which is due to only photoelectric effect.

The count rate and peak intrinsic efficiency of CZT A is expected to be higher than the CdTe pad detector. However, the slight increase in the count rate and in the intrinsic efficiency of CdTe pad detector in comparison to the CZT A is believed to be due the events of the low energy tail which was excluded in the CZT A and may be included in the CdTe due to its broaden peak.
1.5 Physics and Electrical Properties of Semiconductors

1.5.1 Band Structure

The band structure of solids can be represented by a lower valence band and higher conduction band which is separated by the band-gap. The classification of a material whether it is a conductor, insulator or semiconductor depends mainly on this band-gap energy. Figure (13) shows a schematic diagram of the band structure of different materials in which the material is classified as an insulator if this band gap-energy is greater than 6 eV whereas it is around 1 eV for semiconductor detectors and zero in metal.

The conduction band contains electrons that contribute to the conductivity of the material which are free to move through the crystal whereas the valence band contains electrons in the outer-shell inside the crystal. The electrons normally occupy the sites in the valence band and the conduction band is empty. Due to thermal excitations, electrons in the valence band can migrate to the conduction band and contribute to the electrical conductivity. Therefore, both semiconductors and insulator show poor conductivity at low temperature. On the other hand, due to the absence of band gap-energy in metals electrons can easily move thorough the crystal to the conduction band and shows high electrical conductivity. The excitation process due to thermal energy which causes electron to be elevated across the band gap into the conduction band leaves a vacancy which is called a hole in the valence band. This combination is called an electron-hole pair. Under an electric field, the electron in the conduction band and the hole in the valence band will move in opposite direction which therefore
contributes to the conductivity of the material. The probability per unit time that describes the thermal generation of electron-hole pairs is given by:

\[ P(T) = C T^\frac{3}{2} \exp\left(-\frac{E_g}{2 k T}\right) \]  

(12)

Where \( T \) is the absolute temperature, \( E_g \) is the band gap energy, \( k \) is the Boltzmann constant and \( C \) is a proportionality constant characteristic of the material. Equation (12) shows that the dependency of thermal excitation on the band gap energy. Therefore, materials with high band gap energy show low probability of thermal excitation and vice versa. If no electric field is applied, the electron-hole pairs will recombine again and equilibrium is established between its concentrations at any time and its rate of formation. This equilibrium is directly proportional to the temperature according to equation (12) which means if the material is cooled this equilibrium will decrease [3]. The electrons and holes will diffuse after their generation which leads to distribution of charges as function of time mathematically described by:

\[ D = \mu \frac{kT}{e} \]  

(13)

Where \( D \) is the diffusion coefficient and \( \mu \) is the mobility of the charge carrier and \( e \) is its charge [3].

The band gap of a semiconductor can be classified into a direct and indirect band gap according to the crystal momentum of the minimum and maximum energy state of the valence and conduction band respectively. The electron momentum can be given by

\[ P = hK \]  

(14)

Where \( P \) is the crystal momentum, \( K \) is the wave vector and \( h \) is Planck’s constant. If the crystal momentum of the minimum energy of the conduction band and the maximum energy of the valence band has the same value which means a direct alignment between them, this is referred to as a direct band gap. Whereas in indirect band gap, the crystal momentum of the minimum energy of the conduction band and the maximum energy of the valence band had different values and they are not in alignment line, see Figure (14).
In the case of an indirect band gap, an electron needs photon energy higher than the band gap in order to transit from valence to conduction band with a change in momentum. Phonon emission is involved in indirect transition to conserve momentum. However, in a direct band gap structure, the electrons elevate directly to the conduction band, leaving the holes in the valence band. CdTe and CZT detectors fall in direct band gap material while Si falls in indirect band gap materials.

1.5.2 Charge Carriers and Electric Field

There are many factors which explain the charge generations and its migration in an electric field inside a semiconductor material. These are the $W$ factor, mobility of the charge carrier $\mu$, the drift velocity $v$ as explained in introduction and equation (1). The $W$ factor can be defined as:

$$W = \frac{E}{n_{(e-h)}} \quad [1]$$

Where $E$ is the energy of the incident radiation, $n_{(e-h)}$ is the number of created electron hole pairs. A simple diagram of the generation of electron – hole pairs is shown in Figure (15). The $W$ factor is a characteristic of each detector material as shown in Table (1) on page 3. Applying an electric field, the electrons and holes will drift to each respective electrode as a combination of the thermal and the drift velocity parallel to the direction of the electric field as described in Equation (1) where the applied voltage over the detector thickness is the electrical field $\xi$ [3].

Figure (14) Direct and indirect band gap structure [22]
The charge which will be produced as a result of collecting both the electrons and holes will create a current in which its magnitude is proportional to the radiation incident on the detector material.

Generally, there are three important physical parameters that indicate the performance characteristics of a detector; its energy resolution, counting efficiency and the volume of the depletion active area. For the last two parameters, it depends on the volume of the available CZT which is small compared to HPGe. This disadvantage can be solved in order to achieve high efficiency and large volume of active area by special techniques which include stacking arrays of small CZT crystals to build large CZT detectors [7]. In terms of the detector’s energy resolution, this parameter depends on three important factors which are the statistical fluctuations in the number of electron-hole pairs that are created inside the semiconductor detector, the statistical fluctuations in the number of electron-hole pairs that are collected towards the electrodes without trapping and the detector electronic noise which has a great impact on its energy resolution. The first statistical factor depends completely on the $W$ factor. In addition, it depends on the fano factor in which

$$\sigma^2 = FE / W \ [7]$$

(16)
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Where $F$ is the fano factor which usually has a value of a 0.1\cite{7}; $\sigma^2$ is the variance of the total number of electron-hole pairs produced. Fano factor is introduced since the creation of electron-hole pairs is not an independent event which means it cannot be related to Poisson distribution. The second factor indicates the fluctuation in the trapping of carriers inside the detector. In the case of uniformly distributed traps, as in HPGe, the contribution due to fluctuations in the trapping of carriers can be calculated using the following equation

$$\sigma^2 = FE/W(t/r) \ [7]$$ (17)

Where $(t/r)$ is the ratio of drift to life time. If this ratio is less than 0.01 it can be neglected as in HPGe, However, in CZT the above equation is not valid and the trapped charges may be subject to additional fluctuations due to non uniformity of charge carrier trapping inside the detector\cite{7}. Finally, the third factor is associated with the leakage current and has a significant impact on the energy resolution if the leakage current is high.

A theorem which explains how the current is induced in the detector as a result of charge carrier generation and motion was developed by Shockley and Ramo\cite{23}-\cite{25}. They stated that the charge $Q$ and current $i$ induced on an electrode by a moving point charge $q$ is given by:

$$Q = -q \varphi_0(x) \quad \text{(18)}$$

$$i = q \nu \cdot E_o(x) \quad \text{(19)}$$

Where $\nu$ is the instantaneous velocity of $q$ and $\varphi_0$, $E_o$ are the weighting potential and field respectively that exist at position $x$ of the charge $q$ when the selected electrode at unit potential and all other electrode at zero potential. The variation of the induced charge $Q$ on the electrode of interest (Anode as example) while $q$ moves from one position to another position ($i$ to $f$), by choosing the potential on anode (A) 1 and all other electrodes are zeros, can be calculated by

$$\Delta Q_A = \int_{x_i}^{x_f} q E_o dx = -q[\varphi_0(x_f) - \varphi_0(x_i)] \quad \text{(20)}$$

And therefore the induced current $i_A$ at anode is given by:

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\[ i_A = \frac{d Q}{dt} = q E_o \frac{dx}{dt} = q \nu E_o \]  

(21)

Figure (16) shows a planar conventional detector, when incident radiation deposits its energy in the detector, the electrons and holes will drift to their respective electrodes and the change of the induced charge \( \Delta Q \) on one of the electrodes is converted to a voltage signal with the pulse amplitude is proportional to \( \Delta Q \).

\[ \Delta Q = -(n_e e_o) (0 - Z) + (n_h e_o) (1 - Z) = n e_o \]  

(22)

The weighting potential of the interest electrode (Anode) is calculated by setting its potential to 1 and the cathode to zero and therefore, the weighting potential is linear as a function of depth \( Z \) as illustrated in Figure (17) top. In the case of high pure material such as in a HPGe detector when no charge is trapped in the detector, the total change of the induced charge on the anode can be calculated from Equation (20) when the holes and electrons are drifting from the point of interaction to their respective electrodes (Anode=1 and cathode=0) therefore,

Where \( e_o \) is the electronic charge and \( Z \) is the interaction depth. The output signal amplitude is proportional to the number of generated electron-hole pairs from the deposited energy and is independent of interaction depth as illustrated in Figure (17) bottom.
However, when the holes travel only a short distance due to the high probability to be trapped in the detector material such as in the case of CdTe and CZT detector materials, the induced charge on the anode is:

$$\Delta Q_x = n_e (1 - Z)$$

And thus is depth dependent. If the incident gamma ray interacts at all depths randomly, the induced charge will vary from zero to $n_e$.  

1.5.3 Configuration and Resistivity of Semiconductors

In the pure semiconductor detector material which is called the intrinsic semiconductor, the concentration of electrons in the conduction band and the concentration of holes in the valence band (number of charge carriers per unit volume) are equal as the equilibrium established by the thermal excitation of electrons and its recombination leads to equal number of electrons and holes i.e. ($n_i = p_i$). These concentrations are very low in the materials that have large band gap or when they are cooled to low temperatures. The movement of electrons and holes contribute to the conductivity of an intrinsic semiconductor material, its value can be determined by
the concentration of the charge carriers and their mobilities \((\mu_e, \mu_h)\). The reciprocal of the detector conductivity is the resistivity \(\rho\) in which:

\[
\rho = \frac{AV}{It}, \quad I_c = \frac{AV}{\rho t} \tag{24}
\]

Where \(A\) is the semiconductor detector surface area, \(t\) its thickness, \(I_c\) is the current which flows when a voltage \(V\) is applied across this detector. The total current in this case will be the summation of the current flow due to the holes and the current flow due to the electrons according to:

\[
I_c = I_e + I_h = A n e (\nu_e + \nu_h) \tag{25}
\]

\[
\rho = \frac{1}{en (\mu_e + \mu_h)} \tag{26}
\]

However, in n-type and p-type semiconductor detector materials, the effect of dopant concentration has a significant effect and the resistivity can be calculated from the dopant concentration and the mobility of the majority carrier. Impurity atoms such as \(\text{B}\) and \(\text{P}\), which have a valence of 3 and 5 electrons respectively, are introduced into for example the Si lattice. As Si has four valence electrons, P atoms will represent donor sites with extra electrons which then are excited into to the conduction band. Since theses charge carriers hold negative charges, this type of detector is called \(n\)-type detector [1, 3]. However, B atoms, with three valence electrons, need an electron to form a covalent bond. As a result, they represent acceptor sites which will be filled by electrons from the valence band and therefore leave positive hole carriers and thus will be called \(p\)-type detector [1, 3].

For example, the resistivity for an n-type semiconductor detector:

\[
\rho = \frac{1}{en N_D \mu_e} \tag{27}
\]

Where \(N_D\) is the activated dopant density.

A diode then will be formed by a junction between these two types of semiconductors in which negative charge carries (electrons) from n-type move towards the boundary and recombine with holes in the p-type semiconductor creating a free charge depleted region which is sensitive to radiation [1]. This combination of electrons and holes will be finally stopped as an electric field will be formed as a
result of this movement which creates negative charges on the p-type material and positive charges on the n-type material. The depletion region may be increased (becomes wider) or decreased (becomes narrower) as an external bias voltage will be applied. By applying forward bias voltage, by applying a positive voltage on the p-type and negative voltage on the n-type materials, the depletion region becomes narrower as a result of repelling negative and positive carriers (electrons and holes) towards the junction which cause a flow of current. However, by applying a reverse bias voltage, by applying a positive voltage on the n-type material and negative voltage on the p-type material, the depletion region becomes wider as each carrier will be attracted to electrodes. A leakage current may be formed which has a significant effect on the energy resolution of the detector [1, 3]. The diode equation describes the current of a pn junction as a function of diode voltage:

\[ I_d = I_{s,e} \left( e^{\frac{v}{K_N T}} - 1 \right) \]  

(28)

Where \( v \) is the diode voltage and \( I_d \) is the current flowing through the diode and \( I_{s,e} \) is the dark saturation current which is directly related to the recombination rate and inversely related to the material quality see Figure (18).

When the diode is reverse biased it gains a capacitance which can be calculated by considering the depletion voltage \( v_d \):

\[ V_d = \frac{e N t^2}{2 \epsilon} \]  

(29)

Where \( N \) is the density of activated dopant (n or p type) and \( t \) is the depletion thickness which covers the detector thickness. In this case the capacitance decreases by increasing the reverse bias. It is calculated by:
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\[ C = \left( \frac{e \varepsilon N}{2V} \right)^{\frac{1}{2}} \]  \[ (30) \]

Therefore,

\[ C = \varepsilon A / \varepsilon \]  \[ (31) \]

Where \( C \) is the capacitance, \( A \) is the detector area and \( \varepsilon \) is the permittivity of free space = \( 8.854 \times 10^{-12} \) F/m [3].

Lithium ions can be drifted in Si or Ge crystals to form intrinsic region of high resistivity in the diode and thus is called PIN-diode configuration, see Figure (19).

By diffusion the lithium through the p-type surface, the lithium donors exceed the existing acceptors and therefore converting this surface into \( n^+ \) layer which acts as an electrical contact. The p region at the opposite side acts as Ohmic contact. Good charge collection can results as the lifetime of the charge carriers inside the intrinsic region is greater than the time required to collect them at either surfaces. The electric field is uniform across the intrinsic region and it is directly proportional to the applied voltage. However, it falls to zero at the \( n^+ \) and p surfaces, see Figure (20) [3].
1.5.4 Ohmic and Schottky Contacts

CdTe and CZT detectors are generally fabricated in the form of metal-semiconductor -metal structure. Ohmic contacts which have very small contact resistance are generally referred to metals with high work function such as gold and platinum while Schottky or blocking contacts are referred to metals with low work function such as Indium. Ohmic contacts have almost linear current-voltage characteristics while Schottky contacts have non linear current-voltage characteristics. Figure (21) shows the Schottky model of the metal –semiconductor barrier before and after contact in which (Φ) is the work function which defines as the energy difference between the vacuum level (Evac), in which an electron at rest in infinite distance from the metal surface, and Fermi level (EF). Ec and Ev is the energy level of the conduction and the valence band while χ (electron affinity of semiconductor) is the potential difference between the vacuum level and the bottom of the conduction band. The potential (φ) is related to the work function by:

\[ \phi = \frac{\Phi}{e} \tag{32} \]

Where e is the electron charge. The barrier height (φb) when the metal is in contact with the semiconductor is given by:

\[ \phi_b = \phi_m - \chi \tag{33} \]

Where \( \phi_m \) is the metal potential and in this case the potential barrier stops holes and electrons from passing through contact (equilibrium).
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The metal potential $\phi_m$ is less than the semiconductor potential $\phi_s$ in Figure (21) (a) while they are equal in (b) and is greater than semiconductor potential in (c). Equation (33) shows that the barrier height depends only on the work function of the metal and the electron affinity of the semiconductor detector and is independent of the semiconductor doping density. Therefore, by choosing metals of different work functions, the barrier heights can be changed and subsequently three different barrier type contacts can be obtained; accumulation, neutral and depletion, see Figure (21). These contacts are referred to the majority carriers in the neutral substrate. In the 1st diagram Figure (21) (a) top, $\phi_m > \chi$ and therefore electrons will flow from the semiconductor, low work function, to the metal, high work function and thus Schottky barrier of height $\phi_B$ will be formed as equilibrium is being established according the to the type of the semiconductor whether it is p or n type according to :

$$\phi_{bn} = \phi_m - \chi\quad[27]$$

$$\phi_{bp} = -\frac{E_F}{e} + \phi_m - \chi\quad[27]$$

Where $n$ and $p$ stand for n and p semiconductor types respectively.
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Figure (22) Band structure of metal – semiconductor junctions in thermodynamic equilibrium (a) n-type and (b) p-type [27]

Figure (22) shows the band structure of metal – semiconductor junctions for both n and p semiconductor types where \( w \) is the width of the depletion region in which the semiconductor is neutral out side this region, \( \varphi_{Bn} \) is the Schottky barrier height and \( V_B \) is the built-in voltage which is the difference between the metal and semiconductor work functions. Since electrons in the metal face the least barrier to their flow, the accumulation type is the preferred Ohmic contact while blocking contacts can be formed when the metal work function is higher than the semiconductor work function [26], [27].

1.6 Noise in the Electronics and Detectors

1.6.1 Detector Instrumentation

Figure (23) Schematic diagram of detector instrumentation showing the pulse processing [3]
Figure (23) shows a schematic diagram of detector instrumentation and the pulse signal at each stage. The 1st stage is converting the current which is created by incident photon from the detector to a voltage pulse via the preamplifier. The preamplifier can be voltage or charge sensitive type. In this project, a coolFet (Amptek 250 CF) [28] which is a charge sensitive preamplifier was used.

![Radiation detector](Figure (24) Schematic diagram of charge sensitive preamplifier configuration [29])

The difference between voltage and charge preamplifiers is the dependency of the output pulse amplitude on the input capacitance. In the case of voltage sensitive preamplifier, the input pulse ($V_{in}$) is:

$$V_{in} = \frac{Q}{C} \quad [3]$$

Where $Q$ is the charge created by incident photon and $C$ is the input capacitance and thus the output pulse is proportional to $Q$. Therefore, if $C$ has to change, the output pulse will change according to the new value of $Q$. However, in the case of charge sensitive preamplifier, the output pulse is

$$V_{out} = -\frac{Q}{C_f} \quad [3]$$

Where $C_f$ is the feedback capacitance and thus is independent of input capacitance provided that the duration of the input pulse is less than the time constant $R_f C_f$ which determines the output pulse decay rate, see Figure (24). The 2nd stage is to convert the output pulse from a preamplifier to a suitable pulse which can be analysed. Since the produced output pulse from a preamplifier is in the order of milli-volt amplitude, a shaping amplifier is used to convert this pulse to a few volt amplitude pulse by
different gains in addition to optimise its energy resolution by shaping it by changing the long decay time of the preamplifier pulse to a short decay time. One of the most important characteristics of the shaping amplifier is its linearity to keep the proportionality between the pulse of the incident radiation and the output pulse. Finally, the output pulses are digitised and displayed on a multi channel analyser (MCA) as histogram style which reflects the channel number and the amplitude of the input pulse and therefore, the pulse height spectrum represents the incident radiation on the detector. This was conducted using analog to digital converter (ADC) which has a 390 ns conversion time and a resolution of 8192 channels[1], [3].

1.6.2 Serial and Parallel Noise

One of the most important factors that contribute to the signal output i.e. the energy resolution of the output peak is the leakage current which is generated from the bulk and the surface of a detector. The bulk leakage current is generated by thermal excitation of charge carriers and thus depending on the band gap energy of a semiconductor detector as discussed previously. The surface leakage current takes place at the edges of the detector where a large voltage gradient is needed over small distances. Both bulk and surface leakage current are components of parallel noise that contribute to the electronic noise. The other type of noise is the series noise which is associated with series resistance and electrical contact of the detector. These noises combine in quadrature. The significant source of noise takes place at the 1st stage of pulse processing as the noise will undergo the same amplification process of the input signal. The amount of noise produced by the 1st stage and the 2nd stage, preamplifier then amplifier, is expressed in equivalent noise charge (ENC) which is the amount of charge that give output voltage equal to the (root mean square σ) RMS level of the output due to noise only [3] and it has the unit of (electron) by dividing its value by the unit charge of an electron. The contribution of electronic noise to the energy resolution of a detector can be calculated from ENC as:

\[ FWHM = 2.35 \sqrt{\frac{FW}{E}} \] [3]

Where \( E \) is the energy of the incident photon and the number of electron-hole pairs equal to \( E/W \) and thus the \( FWHM \) is equal to 2.35 times RMS or ENC. To convert this value to energy it multiplies by the \( W \) factor as:
1.6.3 Relation of Noise on Shaping Time and Capacitance

As the shaping time increases, the contribution of series noise becomes less significant and the sources of parallel noise become more important. However, the sources of noise denoted as $1/f$ which includes for example the effect of capture and release charge in the input (field-effect transistor) FET does not depend on the shaping time, see Figure (25).

The overall electronic noise decreases as the shaping time is increased and the optimum values of shaping time can be obtained when the series and parallel noises are equal. On the other hand, the series noise increases with the detector capacitance while the parallel noise is independent of detector capacitance and therefore, the optimum shaping time tends to increase for detectors with large capacitance [3].
1.7 Techniques to Improve the Performance of CdTe/CZT Detectors

Since electrons are characterized by their superior transport properties in comparison to holes, all techniques which have been investigated depend on the collection of electrons. These techniques are referred in literature to single charge carrier detectors. In this section, an overview on the important techniques to improve the performance of CdTe/CZT in the literature will be presented. These techniques can be classified into two categories; signal processing and novel electrode geometry.

1.7.1 Signal Processing

In this technique, a pulse shape discrimination (PSD) circuit is used to identify the hole transport dominated pulses since they have long rise time in comparison to electron dominated pulses and rejected them to eliminate their effect which appears as low energy tail in the spectra [30], [31]. This technique was first investigated in 1975 [32]. Kondrashov et al, reported in 2001 [33] PSD was applied in a planar geometry (5x5x3) mm³ CdTe detector and the energy resolution was improved from 17 keV to 3.2 keV using 662 keV \(^{137}\)Cs source. These spectra are shown in Figure (26).

![Figure (26) \(^{137}\)Cs spectra without PSD (Left) and with PSD (Right) technique [33]](image)

The energy resolution is improved significantly and the tail effect of holes is eliminated. However, the count rate is dropped significantly due to this rejection of holes collection as it appears clearly in Figure (26). The basic operation principal is shown in Figure (27) in which the charge corresponds to short rise time responsible for the detector current and can be estimated by differentiating the preamplifier signal.
(signal 1) in Figure (27) and thus the charge signal of the preamplifier at a certain time represents the total charge induced up to this time and can be estimated by integrating the detector current. The rise-time discrimination therefore works by comparing the delayed detector current (signal 3) in Figure (27) to a fraction of preamplifier signal and by changing the attenuation of the preamplifier signal (signal 2) in Figure (27), the rise-time discrimination threshold can be adjusted [34]. Where $T_d$, is the delay time of the detector current.

Diagrams (a) and (b) indicate that the detector current signal exceeds the rise-time threshold set by the attenuated signal 2 and therefore the events are accepted whereas in diagrams (c) and (d) they are rejected since the detector signal does not exceed the rise-time threshold set by attenuated signal [34].
1.7.2 Novel Electrode Geometry

There are many electrode geometries have been proposed to eliminate the effect of hole trapping and therefore improve the CdTe/CZT performance which depends on the collection of electrons (unipolar detectors) such as, coplanar grids, multiple electrode and pixel detectors.

1.7.2 (A) Coplanar Grids Detectors

This technique was first proposed in gas detectors to overcome the slow positive ions by Luke [35]-[37]. Figure (28) shows a schematic diagram of the electrode configuration in which the anode is designed in the coplanar grid on a surface of the detector. This design allows biasing each set of electrodes with different values which are small in comparison to overall the potential across the detector. When the electrons drift close to the anode, the signal of the higher potential grid rises significantly in comparison to low potential grids. A net signal which is obtained by subtracting the signals from two grids is influenced only by the electron signal and thus the hole effect in which its signal is subtracted from the induced signal on the anode is eliminated [38].

Figure (28) Electrode configuration of coplanar electrode [38]
Figure (29) shows a schematic diagram and the basic principal of the coplanar grid technique. The detector surface consists of two grid electrodes A and B in an alternate manner where \( P \) is the period of the grids, i.e. a distance between each two grids of A or B. If a potential is applied to electrode C, a uniform electric field will be established inside the detector and the signal induced at an electrode due to the movement of charge carriers can be calculated. This can be done using the weighting potential method described by Ramo in which

\[
\Delta q = Q \Delta V_w [35]
\]

Where \( \Delta q \) is a charge which induced at selected electrode, \( Q \) is the charge of the carrier and \( \Delta V_w \) is the change in the weighting potential as the charge drift across the
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detector [35]. The weighting potential is the potential that would exists in the detector with the selected electrode at "unit" and all other electrodes set at zero potential. The weighting potential distribution for the grids A and B electrodes are identical except for a small region near the grid electrodes in the depth between 1-P and 1, see Figure (29). When the interaction takes place near electrode C and charge drifts across the detector towards electrode A, it will induce equal signals at the two grid electrodes (A and B) in the depth between 0< Z < 1-P until it comes close to the grid electrodes between 1-P < Z < 1. After that, the signal collected at electrode A (selected electrode) rises steeply to the value of the charge carrier \( Q \) \( (V_W = 1) \) whereas the signal at non-collecting electrode (B) drops to zero \( (V_W = 0) \). Thus the differential output pulse is proportional to \( (q_A - q_B) \), the output of the preamplifier. Therefore the net signal will be dominated mainly by electrons moving in the region 1-P < Z < 1, i.e near anode area and subsequently the movement of holes is eliminated, see Figure (29). In order to gain most of this configuration, i.e. effective unipolar charge sensing, the distance between two adjacent strip electrodes should be less than the detector thickness since calculations showed that 99.7 % of the net signal will be formed within twice the distance from the grid electrode to two adjacent strips. The problem of this technique is associated with the contribution from the subtraction on the leakage current between the coplanar grids which leads to decrease the signal-to-noise ratio [9].

1.7.2 (B) Multiple Electrode Detectors

This technique is characterized by involving a number of electrodes surrounding the collecting electrode (anode) in which their electric field directs the electrons to the anode and shields the anode from trapped holes. This technique has many configurations such as multiple strips or rings [39]-[41], [8]. This technique is also characterized by a small anode area which leads to a small capacitance and low leakage current in addition to eliminate the effect of hole trapping without decreasing the detector efficiency. A significant improvement in energy resolution was achieved by applying the hole correction using micro-strip electrodes. This was first described by Pamelen and Budtz-Jorgensen in 1998 [9],[42]. Applying the strip readout technique was introduced by the Danish Space Research Institute (DSRI) which made a remarkable change in the improvement of energy resolution [43], [44]. Based on the advantage of high quantum efficiency of a CZT detector due to its high atomic weight.
in addition to its their moderate band gap which makes this kind of detector working at room temperature without cooling, CZT detectors have become of interest for space applications. In 1996, DSRI [43] has initiated a program to develop CZT detectors suitable for a hard X-ray telescope based on the drift strip technique illustrated in Figure (30).

![Diagram of a detector based on drift strip technique](image)

Figure (30) Cross-section of a detector based on drift strip technique (3 mm long with 40 μm width strips and a pitch of 100 μm on a 1.5 mm thick CZT) [43], [44]

The principal of the drift strip technique [45],[46] is to eliminate the effect of incomplete hole collection which degrades the energy resolution by causing tailing in the low energy side. This technique is considered the best choice for space application as it improves the energy resolution by eliminating the effect of holes trapping without rejecting any events. Moreover, these trapped residual holes may be corrected to further improve the energy resolution [9], [43]. In Figure (30), there are 14 drift strip electrodes surrounding one anode readout strip which is held at ground, while the 14 strip electrodes are connected to a voltage divider. In this detector, 3 mm long with 40 μm width strips and a pitch of 100 μm on a 1.5 mm thick CZT. These strips act as electrostatic shield which allows the holes to induce only a small signal at the anode strip while the signal on the planar electrode is affected mainly by the holes. It was reported that [43], the 59.5 keV $^{241}$Am has an energy resolution (FWHM) of 11 keV for the planar electrode signal while it was 3.2 keV by applying this technique to the
anode strip signal. Moreover, for high energy peaks which may be absorbed deep in the crystal such as from the $^{137}\text{Cs}$, the peak was not resolved by the planar electrode while the anode strip technique gave a FWHM of 6.9 keV [43]. The drift strip readout technique also gives information about the depth of interaction. This can be calculated by considering both signals on the planar and anode electrodes ($Q_{\text{planar}}$, $Q_{\text{strip}}$) in which the ratio of $Q_{\text{planar}} / Q_{\text{strip}}$ has a value of $\sim 1$ for interactions close to the surface of the detector (cathode) and $\sim 0$ for interactions close to the strip electrodes (anode). This ratio determines the depth information as well as it can differentiate between charged particles and $\gamma$-rays which is important for space applications. Figure (31) shows the differences between 662 keV $^{137}\text{Cs}$ $\gamma$-ray and 1 MeV $^{90}\text{Sr}$ beta rays. The former are absorbed near the anode strip while the latter are absorbed near the planar surface [43], [47].

In addition this technique can be applied to a large CZT detector for space applications. The results of a large CZT detector (20 $\times$ 10 $\times$ 2) mm$^3$ which has Ni strips on one side and an Au planar electrode on the other side have been reported.
The CZT contacts strips have a pitch of 200 μm and are 100 μm wide. The crystal was supported by a ceramic substrate. The electric field is uniform in the crystal since the thicknesses are larger than the strip spacing dimension.

![Figure (32) spectra obtained from $^{137}$Cs 662 keV from the planar electrode (Left) and strip anode (Right) at 25 Celsius using (20 x 10 x 2) mm$^3$ CZT strip drift detector [43]](image)

By applying this technique, the 662 keV $^{137}$Cs width is improved and became resolved with 32.3 keV at 25 Celsius. However, its width is limited by the leakage current. At -25 C° the energy resolution became much better with energy resolution of 13.7 keV. By cooling the detector, the inter strip resistance increased from 4 MΩ to 17 MΩ which has a significant effect on the energy resolution, see Figure (32) and Figure (33). Moreover, It is reported that for future space applications with large area CZT detectors, it is essential to increase the inter strip resistances to the order of GΩ to reduce further the leakage current [43].

![Figure (33) spectra obtained from $^{137}$Cs 662 keV from the planar electrode (Left) and strip anode (Right) at -25 Celsius using (20 x 10 x 2) mm$^3$ CZT strip drift detector [43]](image)
Chapter 1 (Background Theory and Literature Review)

It is also reported that a drift strip CZT detector of dimensions \((10 \times 10 \times 3)\, \text{mm}^3\) [14] has energy resolutions of 2.18 keV at 59.5 keV \(^{241}\text{Am}\), 2.45 and 2.86 keV at 80 keV and 356 keV \(^{133}\text{Ba}\), and 3.89 keV at 662 keV \(^{137}\text{Cs}\). Figure (34) and Figure (35) show the energy resolutions of the 59.5 keV \(^{241}\text{Am}\), 80 and 356 keV \(^{133}\text{Ba}\) respectively. The effect of hole trapping appears as a tailing in the low energy side of the planar electrode which becomes dominant at high energies. The energy resolution at 59.5 keV \(^{241}\text{Am}\) is limited by the electronic noise of the preamplifier. By applying the correction method which is reported by Pamelen and Budtz-Jørgensen (1998) [42] the energy resolution of the 80 keV and 356 keV \(^{133}\text{Ba}\) becomes better as illustrated in Figure (36).

![Figure (34) 59.5 keV \(^{241}\text{Am}\) spectra which is taken by the surface and anode strip electrode simultaneously using \((10 \times 10 \times 3)\, \text{mm}^3\) CZT strip drift detector [14]](image-url)
Chapter 1 (Background Theory and Literature Review)

Figure (35) 80 and 356 keV $^{133}$Ba spectra which is taken by the surface and anode strip electrode simultaneously using (10 x 10 x 3) mm$^3$ CZT strip drift detector [14]

Moreover, the irradiation configuration method to increase the quantum efficiency was studied by using the planar transverse field (PTF) configuration [46]. A CZT drift detector of dimensions (10 x 10 x 2.5) mm$^3$ developed by National Space
Institute in Denmark was used to evaluate photon parallel field (PPF) and (PTF) configuration as illustrated in Figure (37). This detector has the same principal of drift detectors which was explained in Figure (30). In this detector, 4 drift electrodes were surrounded the anode readout strip and a voltage divider was used to bias each strips with -30V, -60V, -90 and -120V. The planar electrode was biased with -150V.

![Figure (37) Drift strip detector irradiation configurations: (a) PPF, (b) PTF][46]

For both configurations, the energy resolution was evaluated using $^{57}$Co and it was found to be the same, 3 keV. Whereas, the quantum efficiency using PTF provides higher efficiency in comparison to PPF due to the large effective thickness of 10 mm in comparison to 2.5 mm for the PPF as illustrated in Figure (38) [46].

![Figure (38) $^{57}$Co spectra using CZT drift detector (10 x 10 x 2.5 mm$^3$ for both irradiation configurations PPF and PTF][46]
1.7.2 (C) Pixel Detectors

Another technique is the pixel detectors which is described by H. Barrett [48]. In this configuration, the anode is divided into small pixel arrays which are small in comparison to the detector thickness. This technique has the advantage also to reduce the hole trapping effect and therefore yields good quantum efficiency. Figure (39) shows the geometry design of pixels detector. The ratio of the width to the thickness of the pixel cell is decreased and the charge become more localised near the anode.

![Geometry design of pixel detector](image)

Based on the Shockley – Ramo theorem, the weighting potential is very high close to the pixels (Anode) and therefore, the charge which is induced in the anode is mainly dependant on the electrons which is drifted to the anode. On the other hand, holes which are collected at the cathode do not induce a significant effect. The main limitation of pixel detectors associates with charge sharing between pixels. This effect increase as the diffusion of cloud charge following the interaction is significant in comparison to the pixel size [50], [51].

1.8 Applications of CdTe/CZT Detectors in Space Science

CdTe/CZT detectors have many applications in industries, medicine and security due to their advantages which were discussed in section 1. In this section, an overview
of the most important applications of CdTe / CZT detectors in astronomy and space science will be discussed. Many space missions in the keV to MeV band need such detectors which can be mounted in telescopes that show high efficiency and good energy resolution in addition to imaging capabilities of X-ray imaging optics [5], [46]. These applications concern detecting γ and X-ray from space and usually are referred in literature to γ and X-ray astronomy. One of the most important phenomena in space which attracts the interest of their origin and mechanism is γ-ray bursts (GRBs). This phenomena is the most bright explosions in the universe which have been detected as γ-ray flashes from distant galaxies [52]. A mission to determine their origin and therefore study the origin of universe has been lunched by the National Aeronautics and Space Administration (NASA) in 2004 which is the swift mission which using Swift’s Burst Alert Telescope (BAT) to detect (GRBs) [53]. This telescope has CZT detector material which aims to detect energy in the range from 15-150 keV with 7 keV energy resolution. It has 256 modules of 128 element modules and the detector element size (4 × 4 × 2) mm³. Another mission is using The Imager on-board INTEGRAL (IBIS) telescope which was lunched form Kazakhstan in 2002. This is an European Space Agency (ESA) project which aims to detect the γ-rays in the sky in the energy range from 3 to 10 MeV [54]. The IBIS system is based on two detector arrays for low and high energy. The low energy detector array uses a (128×128) CdTe matrix while the high energy uses a (64×64) CsI matrix [54]. Atmospheric X-ray Observatory (AXO) is another mission which is proposed by the Danish Satellite Program that aims to study the X-rays generated in the Earth’s atmosphere by using The X-ray Imager (XRI). (AXO) was proposed to have (XRI) which contains two CZT arrays 40 × 30 pixels with total area 800 cm² and it is planned to observe X-rays in the range from 5 to 200 keV. [46], [47]. The Atmosphere Space Interactions Monitor (ASIM) is another mission accepted by (ESA) to study the giant electrical discharges above thunderstorms which are seen as optical γ and X-ray flashes in the stratosphere and mesosphere. In this mission AXO XRI was developed further for this mission [46]. Moreover, CZT detectors were proposed as focal plane detector for The Gamma Ray Imager (GRI), see Figure (40) which was proposed by (ESA) in the energy range 10 keV to 1.3 MeV by combining a Laue crystal lens with a single reflection multilayer coated mirror. This focal plane in (GRI) contains four stacked CZT detector consists of 62,208 individual CZT pixels layers operated in PTF configuration [46], [55].
1.9 Si Drift Detector (SDD)

In 1983 Gatti and Rehak described the technique of Si drift detectors for X-ray and energetic particle spectroscopy by deriving the principal of sideward depletion in which n-type Si is fully depleted by reverse p junctions which cover both surfaces [11], [56]. In these type of detectors, the charge carriers, which are always electrons, will drift under the effect of the electric field in a specific way across the detector to a collection electrode, anode. These movements are taking place with the physical properties of these charge carriers, i.e the electron life time product. They can also give information about the position of the interaction [57].

Figure (41), shows a cylindrical SDD for X-ray spectroscopy in which the anode, which has a very small capacitance, is located at the centre and is collecting the electrons produced in the active area since the electric field is symmetrical. The lower side of the detector which is exposed to the X-rays has a rectifying junction biased at constant potential. The drift field can be created by applying suitable potentials to the
rings in the other side [12], [57]. SSD detectors were proposed as position sensitive detectors on particle physics. By calculating the drift time of charge carriers, mainly electrons, one coordinates of the particle’s interaction point can be reconstructed while the other coordinate can be given by suitable segmentation of the anode. The anode segmentation and drift directions can be made in different arrangements such as two-dimensional position sensitive sensors (4.2 x 3.6) cm² active area and cylindrical with 10 cm diameter and 1° angular resolution as reported in [59], [60]. The SDD of (10 mm² sensitive area and 300 μm thick wafer) has a very small total capacitance of the detector/amplifier system of 200 fF which gives an energy resolution of 147 eV FWHM at 5.9 keV at -10 °C at a count rate of 10⁶ photons/sec. The new design is a (Si drift droplet detector) SDD³ in which the collecting anode and integrated FET are placed at the edge of the sensitive area where it can be shielded from direct irradiation by a circular collimator and the electric field is formed by bow-shaped drift electrodes. This configuration offers an energy resolution of 128 eV at 5.9 keV and -10°C [12].

A SDD can have two configurations, a linear Si drift detector and a cylindrical drift geometry detector. The former has parallel strips in order to form the needed potential gradient to collect electrons at the anode which is segmented to help the specification of the second position coordinate in the dimension parallel to the strips [3]. While the latter has a number of circular rings in which the central anode is connected to an integrated field effect transistor (JFET). This location of the collecting anode has the advantages of keeping its capacitance to its minimum level. The back surface of the detector can be used as a thin window for low penetrating radiations [3]. The fabricated anode for both types of drift detectors (linear and cylindrical) in addition to the minimum amount of the capacitance of these types compared to conventional semiconductor diodes can improve the energy resolution since the electrons can be drifted from far distances to an anode of small area [3].

The detector capacitance plays a significant role that controls the electronic noise in any spectroscopic device. Therefore, keeping this capacitance at low level will increase the performance characteristics of any detector. Since drift detectors have this advantage, they can be used efficiently in X-ray spectroscopy for different applications [3]. Since leakage current will contribute to the resulting measured charge and affect detector’s energy resolution, cooling drift detectors will improve their energy resolution. P. Lechner et al (1996) reported that the energy resolution has
been improved for the 5.9 keV from 225 eV to 170 and 140 eV when a drift detector was cooled from room temperature to 263 and 200 K respectively [13]. SDDs can be operated efficiently between -10 °C and -20 °C compared to -40 °C for Si diodes, (CdTe and CZT). This low temperature is needed to keep dark leakage current below $10^{13}$ A [61].

1.10 Performance of Commercially (XR-100T) CdTe Detector

The aim of this part is to conduct a comparison between the performance of the CdTe Ohmic detector and its coolfet readout system against a commercial (XR-100T) CdTe detector, see Figure (44) [16]. This CdTe detector has a Beryllium window and is directly connected to the input FET transistor and they are thermoelectrically cooled to -20 °C. In operation, the detector is connected to a combined amplifier and power supply and it has the options to reject the hole effect by selection rise time discrimination (RTD) to be ON see Figure (42).

![Figure (42) spectrum using a CdTe based detector (XR-100T) (5x5x1) mm³ (RTD ON)](image)

Figure (42) shows the energy resolution of the 59.5 keV energy peak (FWHM = 0.59 keV at -400 V) which is much better in comparison to the test planar CdTe detector (which will be discussed in chapter 2). This is may be due to, cooling the detector to －
20 °C in addition to biasing the detector with -400V without experiencing high leakage current in addition to using input FET. A coolFet preamplifier was used with the planar detectors and therefore they are limited by its noise. By selecting the RDT to be OFF, the spectrum will be affected by hole trapping which add a tail in the low energy side of the spectra although there is an improvement in the count rate, see Figure (43).

![Figure (43) 241Am spectrum using a CdTe based detector (XR-100T) (5x5x1) mm³ (RTD OFF)](image)

![Figure (44) CdTe based detector (XR-100T) CdTe [16]](image)
Chapter 2 (Experimental Method)

The aim of this chapter is to explain the experimental method of this project which includes the specifications of pad detectors and drift ring devices. Then, the detectors’ mounting are explained at room and low temperatures. This includes mounting the pad detectors on a simple PCB and box and mounting one drift ring detector on a custom PCB and plug in board system with tracks for separate HV drift ring supplies for room temperature measurements. In addition, the design and layout of a ceramic substrate on which the other drift detectors were mounted inside a box for low temperature measurements will be explained. After that, the leakage current measurements and development of a voltage divider network to bias the drift ring devices are explained. These include, measuring the current - voltage (IV) and resistivity of pad detectors in order to model the resistor networks which are needed to bias the drift ring detectors using a single HV at low temperature. Finally, the γ - ray spectroscopy is explained which includes description of the spectroscopic processing chain, noise performance of the set-up and effect of leakage current on the energy resolution.

2.1 Detector Devices

2.1.1 Pad Detectors

Different types of pad detectors were used to investigate their properties and limitations as a function of applied bias voltage for a range of γ energies. A CdTe Ohmic test pad detector was used to prepare the low temperature measurement system and investigate the cooling effect on the detector’s performance. Table (4) shows the specifications of the pad detectors.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Company manufacturer</th>
<th>Dimension mm³</th>
<th>Mounting</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdTe Ohmic pad</td>
<td>Acrorad AR 0905-1081-2-1</td>
<td>4x4x1</td>
<td>PCB</td>
</tr>
<tr>
<td>CdTe Schottky</td>
<td>Acrorad AR 0905-1081-1</td>
<td>5x5x1</td>
<td>PCB</td>
</tr>
<tr>
<td>CZT A</td>
<td>Redlen RD1353</td>
<td>5x5x5</td>
<td>PCB</td>
</tr>
<tr>
<td>Large Si PIN-diode (Si A)</td>
<td>Hamamatsu S3590-081-09</td>
<td>10x10x1</td>
<td>PCB</td>
</tr>
<tr>
<td>Small Si PIN-diode (Si B)</td>
<td>Hamamatsu S0010</td>
<td>2.4 × 2.4 x 0.3</td>
<td>PCB</td>
</tr>
<tr>
<td>CdTe Ohmic test detector</td>
<td>Acrorad</td>
<td>2x2 x1</td>
<td>Ceramic</td>
</tr>
</tbody>
</table>

Table (4) Pad detectors specifications
Chapter 2 (Experimental Method)

The CdTe Ohmic and Scottky detectors were fabricated in Acrorad Ltd, Japan. The Ohmic detectors have platinum contacts on both surfaces while the Schottky one has indium-titanium contact in one surface and a platinum contact on the other [62]. The CZT detector has gold contacts on both surfaces and was produced by Redlen technologies, Canada [63]. Si detectors are PIN-diodes produced at Hamamatsu [64].

2.1.2 Drift Ring Devices

Figure (45) shows a schematic diagram of a CdTe drift ring detector (CdTe A). This detector was fabricated by Acrorad Ltd, Japan with a three ring geometry. Ohmic contacts were chosen rather than Schottky to assure the stability of the detector and to avoid the phenomenon of polarization which is associated with time instability under bias. The anode diameter is 0.5 mm as are the widths of all three rings; individual rings are separated by gaps of 0.5 mm and the active area is \((8 \times 8) \text{mm}^2\).

Figure (45) CdTe drift ring detector (A) schematic diagram

CdTe B and CZT B have the same dimensions as CdTe A. However, CZT B was fabricated in-house using the photolithography process described in Appendix A. It has gold contacts in both surfaces while CdTe A and B have platinum contacts. These detectors have designed in ring geometry of 0.5 mm (500\(\mu\)m) width due to the
difficulty of using epoxy glue dots to bond the detectors which have a diameter of ~200 μm. Table (5) shows the specifications of the CdTe and CZT drift ring detectors.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Thickness</th>
<th>Rings and gaps diameter (mm)</th>
<th>Anode diameter (mm)</th>
<th>Manufacturer</th>
<th>symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdTe mounted on a PCB in Box 1</td>
<td>1 mm</td>
<td>3 rings 0.5 mm</td>
<td>0.5 mm</td>
<td>Acrorad Ltd</td>
<td>CdTe A</td>
</tr>
<tr>
<td>CdTe mounted on a ceramic substrate in Box 2</td>
<td>1 mm</td>
<td>3 rings 0.5 mm</td>
<td>0.5 mm</td>
<td>Acrorad Ltd</td>
<td>CdTe B</td>
</tr>
<tr>
<td>CZT mounted on a ceramic substrate in Box 1, 2</td>
<td>2.3 mm</td>
<td>3 rings 0.5 mm</td>
<td>0.5 mm</td>
<td>Redlen (fabrication process at University of Surrey)</td>
<td>CZT B</td>
</tr>
</tbody>
</table>

Table (5) Drift ring detectors specifications

The dimensions of our CdTe and CZT drift ring detector is larger than CZT drift ring detector which is published in literature which has two rings of 0.19, 0.39 mm radii and its anode diameter is 0.08 mm. This detector was biased with a fixed bulk and lateral field and connected to input FET preamplifier which was mounted close to the detector [65]. While our CdTe and CZT drift ring detectors were biased by different bias schemes and were connected to a coolFET preamplifier which was mounted outside the box which will be explained later in this chapter.

2.2 Device Mounting

2.2.1 Room Temperature Test System

Figure (46) shows an image of the Schottky CdTe pad detector as an example which was plugged into a small metal box and mounted on a simple PCB which is the same plugging and mounting system for all pad detectors except the CdTe test detector which will be discussed in the coming sections.
Figure (46) An image of the Schottky CdTe pad detector

Figure (47) shows an image of CdTe A which is mounted on a custom PCB face up i.e. the detector was irradiated through the anode contact and plugged in a board inside Box 1, see Figure (48). This box is designed for room temperature measurement only.

Figure (47) CdTe (A) face up (mounted on a PCB) designed by Dr. Shada Kazemi

Figure (48) Image of (Box 1) for drift detectors room temperature measurements
Chapter 2 (Experimental Method)

Box 1 has HV inputs in which the cathode (bottom contact) and the rings (top contact) are biased separately by a quad power supply. This system set-up (Box 1 with different HV input with the PCB and the plug in board) was found to produce a significant noise at zero volt which will be discussed later in this chapter.

2.2.2 Low Temperature Test System

In order to conduct spectroscopy measurements at low temperature, a different box and mounting technique were used. This box (Box 2) is larger than (Box 1) and was used for CdTe Drift detector (CdTe B) and CZT drift detector (CZT B) which are mounted faced down i.e. the detectors were irradiated through the cathode (rear) contact. Both CdTe B and CZT B have the electrode geometry as CdTe A. However, CdTe A and B is 1 mm thick while CZT B is 2.3 mm thick. Figure (49) and Figure (50) show an image of CZT B and Box 2 which has a single HV input to bias the cathode and the rings.

![Figure (49) CZT B face down (mounted on the ceramic substrate)](image1)

![Figure (50) Image of (Box2) for drift detectors at low temperature measurements](image2)

In order to perform low temperature measurement experiments, a set-up was used which allows cooling the detectors through a ceramic substrate and using resistor networks to bias the rings. This ceramic was designed to mount the detectors (CdTe B and CZT B) on it. Figure (51) and Figure (53) show an image and a schematic diagram of the ceramic substrate which was designed at the University of Surrey and fabricated at Advanced Interconnection Technology (AIT). It has a dimension of 2.5 cm × 1.8 cm onto which the CdTe B and CZT B were bump-bonded by Rutherford
Appleton Laboratory (RAL). The entire bump bonds are 0.5 mm in diameter while all the tracks, rings and gaps widths are 0.4 mm in diameter. The detector is bump-bonded to the ceramic so that the central anode and the drift rings are connected to their respective track on the ceramic. As the detector will be mounted face down, i.e. the anode and rings will face the metal ring pattern in the ceramic, the upper two square pads (A and B) are used to bias the planar cathode in which a wire is glued from the cathode planar contact to the square pad A and is biased through the square pad B. The guard ring which shapes the electric field at the edge of the detectors was floating in all cases.

![Diagram of the ceramic substrate and drift detector](image)

Figure (51) Image of the ceramic substrate and (left) back side (right) front side
Ideally, this connection should be as short as possible, but as long as needed to be sure to have a flat central section of at least 0.3 mm diameter in the centre of the ring structure.

Figure (52) Ceramic substrate layout (front side)

Figure (53) Ceramic substrate layout (back side)
2.2.3 The Cooling System (Box 2)

Inside Box 2, water circulates through copper pipes and through a small tunnel inside the copper block onto which the Peltier cooler is fixed with heat sink. The ceramic substrate is also fixed above the Peltier cooler by metal clips. The Peltier cooler is connected to a 6V DC power supply. The copper block, metal clips, one end of the Peltier cooler and the temperature sensor are grounded to decrease the electrical noise. A BC 10, type 003-6612, Fisher Scientific ET 100 cooling unit was used to pump the water through the copper pipes. Using a (PT 100) temperature sensor mounted on the ceramic substrate above the Peltier cooler, the temperature of the ceramic substrate can be read indirectly by measuring the sensor resistance. The resistance of the PT 100 depends on the temperature of the ceramic substrate as cooled by the Peltier cooler. The temperature of the water can be reduced using the ET 100 cooling unit to avoid using high power to the Peltier cooler which may generate significant noise. Generally the temperature of the water was set to 5°C and the power supply of the Peltier cooler is connected to a power supply (HEWLETT PACKARD E3630A) which was set to 1.01 V and 0.9 mA (0.9 Watt). Using this arrangement in addition to using a vacuum of $2 \times 10^2$ mbar to avoid condensation of the samples, a temperature of -15°C can be reached within approximately 15 minutes. This temperature can be kept for all the measurement time. See Figure (54) in which a CdTe test detector was used with different ceramic substrates compatible to the test detector to asses the temperature control. Note that the same arrangement was used for CdTe B and CZT B and the only difference is the ceramic substrate.
Since the lateral fields which are formed by the rings are limited to specific values and in order to bias the CZT B with very high lateral field values, Box 1 with a quad power supply was used for some measurements. A comparison was conducted among these types of drift detectors to investigate how rings’ bias will affect the energy resolution and peak rates in addition, to study the effect of cooling on their performances. Different bias schemes, i.e. different cathode and ring bias voltages were used to examine these detectors at different \( \gamma \) – ray energies. The rear electrode was negatively biased for all drift detectors and each ring was biased with a specific percentage of the cathode bias using separate channels from a quad power supply or resistor networks in which the inner most ring has always the lowest percentage bias compared to the outer rings.

2.3 Leakage Current Measurements and Development of a Voltage Divider Network to Bias Drift Ring Devices

2.3.1 IV Measurement System

IV measurements were done for all pad semiconductor detectors at room temperature in air. In addition they were done for the CdTe Ohmic test detector at different temperatures and for CdTe and CZT drift ring detectors at room temperature and \(-15 \, ^{\circ}C\) to investigate their leakage currents and subsequently their effects on the
detector performance using a KEITHLEY 487 picoAmmeter / Voltage source instrument interfaced to a PC acquisition system developed in house using LabView. For pad detectors, the IV measurements were conducted by scanning different voltages which were generated from the KEITHLEY system through the cathode and measuring the current through the anode. However, for the drift detectors, a quad power supply and resistor networks were used to bias the cathode and the rings independently while the current on the anode were measured with the same KEITHLEY system.

2.3.2 Resistivity Measurements of Pad Detectors

The objective of this section is to estimate the values of the bulk resistances through the three rings and the bulk resistance of the anode and using them to model the resistor networks. Since Box 2 has a single HV input, therefore resistor networks are needed to bias both the cathode and the rings for CdTe B and CZT B at low temperature. The resistor networks were modelled using resistivity values of different pad detectors which are expected to have similar material properties as the ring drift detectors. These resistor networks are needed to achieve certain percentage voltage differences across the rings which were used for CdTe A at room temperature and using them for CdTe B and CZT B detectors. IV measurements were taken of a CdTe Ohmic pad detector at room temperature in order to calculate the resistivity of the CdTe material and subsequently use it to estimate the bulk resistances of the CdTe drift detectors. Since at low temperature measurements, one voltage supply will be used to avoid using multiple feed-through compromising the vacuum seals, a set of resistors are needed to drop the voltages across the rings as a percentage of the cathode bias.
Figure (55) shows the IV measurements of the CdTe pad detector. To estimate the resistivity of the CdTe drift ring detector and therefore estimating its bulk resistance, the resistivity of the CdTe pad detector was calculated at room temperature at low bias from -3 to +3 V to assure a good linearity. Using equations (41) and (42)

\[ V = \frac{i}{R} \quad [3] \]  
\[ \rho = \frac{RA}{d} \quad [3] \]

Where \( V \) is the applied voltage, \( R \) is the resistance, \( A \) is the surface area of the detector, \( d \) is the detector thickness and \( \rho \) is the detector resistivity. The resistivity of the CdTe pad detector was found to equal \( (14.4 \pm 0.7) \times 10^{10} \Omega \cdot \text{mm} \) at room temperature which matches the values published in the literature which shows that it is of order of \( 10^{10} \Omega \cdot \text{mm} \) [5]. Moreover, the resistivity of the CdTe material was calculated by using a different detector, 2 × 2 mm CdTe Ohmic test detector. This
detector is compatible to mount in Box 2 (the cooling system) which therefore, can be cooled to low temperatures and subsequently IV measurements can be conducted to investigate the resistivity at low temperature. Figure (56) shows the IV measurements of the CdTe test detector (bulk leakage current). The bulk leakage current and therefore the resistivity were measured at low bias between -3 and +3 V to assure good linearity. Using equations (41) and (42), the resistivity of the CdTe test detector at room and -15 °C were found to equal \( (5.70 \pm 0.03) \times 10^{10} \, \Omega \cdot \text{mm} \) and \( (1.40 \pm 0.02) \times 10^{13} \, \Omega \cdot \text{mm} \) respectively. The resistivity at room temperature is of the order of \( 10^{10} \, \Omega \cdot \text{mm} \) which is matching with the values published in the literature [5] However, this value is almost half of the resistivity which was estimated using the CdTe pad detector. These differences in resistivity values will affect the calculated bulk resistances of the anode and through the three rings of the drift detectors according to the resistivity value which will consider.

![Figure (56) IV of the CdTe test structure at room and low temperatures](image)

Figure (56) IV of the CdTe test structure at room and low temperatures

Figure (57) shows IV measurements of the CZT A pad detector (5x5x5) mm\(^3\). Similarly, the resistivity was calculated at low bias voltage to assure good linearity. The room temperature resistivity was found to equal \( (2.89 \pm 0.08) \times 10^{11} \, \Omega \cdot \text{mm} \).
which is matching with values published in the literature [5] which shows the resistivity of CZT is around of $10^{11} \ \Omega \cdot \text{mm}$.

![Graph of IV characteristic](image)

**Figure (57) IV of the CZT A pad detector at room temperature**

### 2.3.3 Modelling of the Resistor Network

Using the calculated resistivity of the CdTe pad detector at room temperature and the surface areas of the rings and anode of the drift ring detector, see Figure (45), the bulk resistances of the rings and anode can be calculated at room temperature using equation (42). Table (6) summarises the surface area and bulk resistances calculated for all rings and anode.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Area mm$^2$</th>
<th>Bulk resistances $10^{10} \Omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 3 – outer ring</td>
<td>8.64</td>
<td>(1.67 ± 0.08)</td>
</tr>
<tr>
<td>Ring 2 – Middle ring</td>
<td>5.49</td>
<td>(2.62 ± 0.13)</td>
</tr>
<tr>
<td>Ring 1 – Inner ring</td>
<td>2.35</td>
<td>(6.12 ± 0.30)</td>
</tr>
<tr>
<td>Anode</td>
<td>0.19</td>
<td>(73.5 ± 3.7)</td>
</tr>
</tbody>
</table>

**Table (6) Surface areas and bulk resistances of the CdTe drift ring detector**
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The bulk resistances have been calculated based on an assumption that both top and bottom contact of the drift detector have the same ring geometry. However, the bottom contact of the drift detector is a planar.

Software (Crocodile Clips) [66] was used to estimate the needed external resistors which drop the cathode bias to specific values. This software can make a simulation by building a circuit and calculating the voltage across each ring by inserting specific resistance values. The bulk resistors in these simulated circuits are scaled by a factor of 1 MΩ to be accepted by the software. The external resistors were estimated based on the values of the bulk resistances which were calculated depending on the resistivity value of CdTe pad detector.

Figure (58) electrical circuit of the simulated drift detector which gives (10-20-30) % of the cathode bias, resistors in black circles are the bulk resistors

Figure (58) shows an example of a resistor network simulation of the first percentage scheme (10-20-30) % in which the external resistors drop the cathode voltage to give ring potential of (10-20-30) % of the cathode. This model gives the effective resistance \( R_{1,2} \) (resistance between each adjacent rings) in which:
Chapter 2 (Experimental Method)

\[
\frac{1}{R_{1,2}} = \frac{1}{R_S} + \frac{1}{R_E} \quad [3]
\]

Where \( R_S \) is the surface resistance and \( R_E \) is the external simulated resistance. An assumption was made that \( R_S \) is infinite, \( \infty \), and thus the simulated \( R_E \) is equal to the effective resistance between each adjacent rings, \( R_{1,2} \). Therefore, \( R_S \) is neglected in this simulation. However, if \( R_S < \infty \), \( R_{1,2} \) will be < \( R_E \) and therefore, the simulated potential difference across the rings is increased.

After considering all the percentage values needed for the ring voltages and using the software to estimate the resistors required to achieve these voltages at room temperature, resistors were bought from Farnell and mounted on three veroborads. These resistors boards can be mounted separately in Box 2 which was designed for low temperature measurements in which each resistor board represents one set of ring voltages, i.e. (10-20-30) %, (20-40-60) % and (30-60-90) % respectively. Figure (59) shows veroboard 1 (VB1) as an example. Note that 1st, 2nd ring and 3rd ring mean where each of these rings will be connected.

![Figure (59) external resistors mounted on VB1, (10-20-30) %](image)

Table (7) shows the specifications of each resistor board and the ring voltage % that gives based on the resistivity of CdTe bad detector.

66
### Table (7) Resistor boards specifications based on the resistivity of CdTe pad detector

<table>
<thead>
<tr>
<th>Resistor boards</th>
<th>Number of resistors</th>
<th>Values of resistors</th>
<th>Ring voltages% of the bulk field</th>
</tr>
</thead>
<tbody>
<tr>
<td>VB1</td>
<td>6</td>
<td>10 GΩ × 3, 1 GΩ × 2, 2 GΩ × 1</td>
<td>(10-20-30)%</td>
</tr>
<tr>
<td>VB2</td>
<td>8</td>
<td>5 GΩ × 1, 1 GΩ × 1, 2 GΩ × 3, 100 GΩ × 2, 0.5 GΩ × 1</td>
<td>(20-40-60)%</td>
</tr>
<tr>
<td>VB3</td>
<td>7</td>
<td>0.68 GΩ × 1, 1 GΩ × 3, 0.5 GΩ × 3</td>
<td>(30-60-90)%</td>
</tr>
</tbody>
</table>

2.3.4 Direct Application of Bias vs. Resistor Network

The drift detectors were biased by two different techniques; the first technique by direct connection of the detector to a quad power supply in which the cathode and each ring were biased separately for room temperature measurements. This was done using Box 1 and CdTe A at room temperature. However, the second technique was used for CdTe B and CZT B in Box 2 in which resistor networks were used to bias all the rings using a single HV input. For some high lateral field values which cannot be achieved by using resistor networks, Box 1 was used for some high lateral field measurements for CZT B at room temperature.

Table (8) shows the bias schemes which were used for CdTe A, B and CZT B drift detectors where VB is the resistor board which gives certain percentage of the cathode bias.
### Chapter 2 (Experimental Method)

#### Detector Biasing

**CdTe A**
- Quad power supply
- Cathode voltages (V):
  - -100V, -200V
  - -100V, -180V
  - -100V, -120V
  - -100V
- Ring voltages:
  - (10-20-30)%
  - (20-40-60)%
  - (30-60-90)%
  - (40-80-120)%
  - (60-120-180)%
  - (80-160-240)%
  - (80-200-300)%
  - (80-250-400)%

**CdTe B and CZT B**
- Resistor networks
- Cathode voltages (V):
  - (-100, -120, -180, -200, -500) V
- Ring voltages:
  - VB1
  - VB2
  - VB3

**CZT B**
- Quad power supply
- Cathode voltages (V):
  - -500V and -700V
- Ring voltages:
  - (10-20-30)%
  - (20-40-60)%
  - (30-60-90)%
  - (500-600-700)%

Table (8) Biasing schemes used for CdTe A,B and CZT B drift detectors at room temperature and -15°C

#### 2.3.5 Summary

Since the external resistors where bought depending on the calculated bulk resistances based on the resistivity of the CdTe pad detector, the resistor simulation was reassessed. This was done by considering the resistivity of a CdTe test detector at room temperature and -15 °C and the resistivity of CZT A, see Table (9) and subsequently the new calculated values of bulk resistances. Table (10) shows the ring voltages as percentages of cathode bias which can be obtained considering the resistivity of all pad and test detectors.

Table (9) Bulk resistivity of the semiconductor material which was used for the resistor simulation

<table>
<thead>
<tr>
<th>Detector</th>
<th>CdTe pad detector at RT</th>
<th>CdTe test detector at RT</th>
<th>CdTe test structure at -15°C</th>
<th>CZT at RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity (Ω. mm)</td>
<td>(14.4 ± 0.7) 10^{10}</td>
<td>(5.70 ± 0.03) 10^{10}</td>
<td>(1.40 ± 0.02) 10^{13}</td>
<td>(2.89 ± 0.08) 10^{11}</td>
</tr>
</tbody>
</table>
Table (10) Ring voltages which are obtained using the resistivity of different CdTe detectors and a CZT pad detector

<table>
<thead>
<tr>
<th>Resistor boards</th>
<th>Simulated ring potential based on the resistivity of different detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CdTe pad detector at RT</td>
</tr>
<tr>
<td>VB1</td>
<td>(10-20-30) %</td>
</tr>
<tr>
<td>VB2</td>
<td>(20-40-60) %</td>
</tr>
<tr>
<td>VB3</td>
<td>(30-60-90) %</td>
</tr>
</tbody>
</table>

Since this CdTe test detector is from the same wafer as the CdTe drift ring device, the simulation process based on its resistivity and subsequently the bias on the rings as a result of this simulation is believed to be the best guess to the real values compared to the resistivity of the CdTe pad detector.

2.4 γ – ray Spectroscopy

2.4.1 Electronic Chain

The aim of this section is to study the performance characteristics and spectroscopic measurements of different types of semiconductor pad detectors. This will help to understand the different properties, advantages and disadvantages, of different semiconductor detectors, see Table (4) such as their quantum efficiencies, energy resolutions, effect of leakage currents, effect of hole trapping and the phenomenon of polarization. For each detector, a spectrum was acquired using different γ – ray energies at 10 mm distance, with the chosen best energy resolution Amptek 250 charge sensitive preamplifier (CoolFet) along with pulser signals at the same bias voltage to examine the effect of leakage current on the FWHM as a function of bias. When the γ-ray deposits its energy in the detector, it will create electron-hole pairs and, by applying different voltages, the holes will drift across the detector towards the cathode while the electrons will drift to the anode. The holes will be collected at the cathode to which a CoolFet preamplifier is connected, followed by a shaping amplifier and a multichannel analyser (MCA). The shaping amplifier was set to 200 coarse gain, 0.9 fine gain and 3 μs shaping time. Table (11) shows the equipment specifications
Chapter 2 (Experimental Method)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quad bias supply</td>
<td>ORTEC 710</td>
</tr>
<tr>
<td>Shaping amplifier</td>
<td>ORTEC 570</td>
</tr>
<tr>
<td>Pulser</td>
<td>ORTEC 480</td>
</tr>
</tbody>
</table>

Table (11) Equipment specifications

The detector, which is grounded, was biased through the coolFet preamplifier in which a coupling capacitor is connecting between the detector and the preamplifier. This configuration is called AC-coupled [3]. The γ sources were placed above the top contact. Pulse height spectra were acquired using a Canberra Multi-Channel analyser (MCA). This geometry was used for all the pad detectors studied in this work as illustrated in Figure (60). The bias polarity was also changed for the CdTe Ohmic contact to investigate the effect of the movement of the positive hole on the signal output.

Figure (60) Schematic diagram of the spectroscopic measurement set up of pad detectors

Three different sources were used for the spectroscopic measurements for pad and drift detectors which emit different γ ray energies. Table (12) shows the specifications of these sources.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Energy (keV)</th>
<th>Half life</th>
<th>Activity (kBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{241}$Am</td>
<td>59.5</td>
<td>432 y</td>
<td>420</td>
</tr>
<tr>
<td>$^{57}$Co</td>
<td>122</td>
<td>271 d</td>
<td>304</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>662</td>
<td>30 y</td>
<td>230</td>
</tr>
</tbody>
</table>

Table (12) Specifications of the γ sources which were used [67]
Chapter 2 (Experimental Method)

The aim of using three different sources is to investigate the average penetrating depth by calculating the mean attenuation coefficients of different energies and its effect on the performance of the detectors. The spectroscopic measurements for pad detectors were conducted at room temperature. Whereas they were conducted at room temperature and -15 °C for drift detectors.

2.4.2 Preamplifier Noise Measurements

The electronic noise for three different preamplifiers was studied in order to determine which preamplifier is most suitable for the spectroscopic measurements, i.e. produce the best pulser FWHM signal. Table (13) shows the specifications of these preamplifiers.

<table>
<thead>
<tr>
<th>Preamplifier</th>
<th>Model</th>
<th>Serial number</th>
</tr>
</thead>
<tbody>
<tr>
<td>eV 550</td>
<td>eV products</td>
<td>A 1261</td>
</tr>
<tr>
<td>eV 550</td>
<td>eV products</td>
<td>A 2535</td>
</tr>
<tr>
<td>Coolfet 550</td>
<td>AMP TEK</td>
<td>Amptek250CF</td>
</tr>
</tbody>
</table>

Table (13) Preamplifier specifications

A charge terminator of capacitance $C = 2.31 \, \text{pF}$ was used with these preamplifiers to determine the energy resolution of each pulser signal. In addition, a calibration curve was plot by correlating different pulser amplitudes ($V_{\text{pulser}}$) to different channel number values and calculating their corresponding energies ($E_{\text{keV}}$) by using the $W$ factors [3], average energy which is needed to create one electron-hole pair, to calibrate the system. By applying voltage pulses to the charge terminator, an output pulse was measured using an oscilloscope to determine the pulse amplitude of each signal. The centroid channel was determined for each signal amplitude and the energy of each pulse amplitude was calculated using:

$$E(\text{pulser})(\text{keV}) = \text{Pulseramplitude}(\text{mV}) \times C(\text{pF}) \times W(\text{eV/ehp}) \times 6.25 \ [68]$$

Equation (44)

Where $C$ is the capacitance of the charge terminator, $W$ is the average energy to create one electron-hole pair [2] and 6.25 is a conversion factor. Equation (44) describes when the charge, which was created by the $\gamma$ - ray, $E \gamma / W \times 1.6 \times 10^{19} \, C$, and the
charge which was created by pulser, \( Q = C \times V \), appears in the same channel number of the MCA. Then, a calibration graph was plotted between each channel number and its energy. The slope gives the keV for each channel. This calibration graph was used to determine the pulser resolution (width in keV) for each detector and preamplifier. Figure (61) shows the pulser resolutions measured using the three different preamplifiers. The intrinsic energy resolution of the CoolFet preamplifier was measured to be in the range between approximately 1.2 and 1.75 keV. This is caused by the differences in W factors for the three materials in equation (44).

For comparison, the pulser widths (considering the W factor of CZT) are 1.75, 2.8 and 2.3 keV for the CoolFet, eV A1261 and eV A2535 respectively. Whereas they are 1.66, 2.6 and 2.1 by considering the W factor of CdTe. As the CoolFet has the best energy resolution among the other preamplifiers, it was chosen for the spectroscopic measurements for all subsequent measurements.
2.4.3 Noise Performance of the Test Set-up

The objective of this section is to investigate the performance of the Peltier cooler that was installed in Box 2 by measuring the temperatures of the ceramic substrate which is mounted on the Peltier cooler. These measurements will help to investigate the temperature range obtained by the Peltier cooler, and this calibration will be used for the X and γ-ray spectroscopy of the drift detectors at low temperatures. In addition, by measuring the FWHM of the preamplifier signal when connected only to the ceramic substrate at low temperatures, this will help to investigate the electrical noise generated due to the Peltier cooler and the ceramic substrate at low temperatures. Therefore, the electrical noise induced in the ceramic substrate must be optimised and identified before starting the real measurements (i.e. when the drift detectors are mounted on the ceramic substrate).

Table (14) shows the specifications of the Peltier cooler which was used.

<table>
<thead>
<tr>
<th>Model type</th>
<th>Dimension</th>
<th>Maximum current</th>
<th>Maximum power</th>
<th>Maximum Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermoelectric</td>
<td>15x15 x3.2mm</td>
<td>3.9 A</td>
<td>8.2W</td>
<td>3.75V</td>
</tr>
<tr>
<td>module CP1.0-31-05L</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.2W</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table (14) Specifications of the Peltier cooler

Figure (62) [69] shows the relationship between the resistance and the temperatures of the PT 100 sensor. The performance of the Peltier cooler was assessed using a range of different voltages and currents which produce different temperatures of the ceramic substrate. The temperature of the water can be reduced using the ET 100 cooling unit to avoid using high power to the Peltier cooler which may generate significant noise. Generally the temperature of the water was set to 5 °C and the power supply of the Peltier cooler was set to 1.01 V and 0.9 mA (0.9 Watt). Using this arrangement in addition to using a vacuum of $2 \times 10^{-2}$ mbar to avoid condensation of the samples, a temperature of -15 °C can be reached within approximately 15 minutes. This temperature can be kept for all the measurement time.
Chapter 2 (Experimental Method)

Figure (62) Resistance-temperature characterisation plot of the PT100 temperature sensor [69]

The output of the ceramic substrate (the centre pad) is connected to the CoolFet preamplifier using a screened cable and therefore should not introduce additional electronic noise. The noise is expected to be due to metal tracks on the ceramic substrate, the vibration due to water pump and the power supply of the Peltier cooler. Condensation at low temperatures is eliminated by using a rotary pump which evacuates Box 2 to $2 \times 10^{-2}$ mbar. Using these arrangements, the pulser width was found to equal $2.00 \pm 0.01$ keV taking into account it is $1.66 \pm 0.01$ keV when the CoolFet preamplifier is in isolation. Whereas the pulser width was found to equal $3.7 \pm 0.01$ keV using Box 1. The difference in pulser widths could be due to the PCB board and the unscreened cable which was connected the central pad to the CoolFet preamplifier. These values were calculated by considering the W factor of CdTe, $4.4$ eV/ e-h at 300 K, and subsequently its calibration curve. No significant change was noticed by considering the W factor of CZT.
2.4.4 CdTe Test Detector Energy Resolution at Room Temperature

A CdTe Ohmic test pad detector (2×2×1) mm$^3$ was first used to study the spectroscopy and energy resolution as a function of voltages at room temperature. This detector was mounted in a different ceramic substrate which has different design from the one which was designed for drift detector. The detector was irradiated from its top contact (Cathode) by placing a $^{241}$Am source (59.5 keV $\gamma$-ray) outside Box 2 in which the detector is mounted in. The detector was positively biased at the bottom contact (Anode). Figure (54) shows an image of the experimental setup. The objective of this section is to investigate the spectroscopic performance of the CdTe test detector using different voltages at room temperature to see how the leakage current affect the energy resolution.

Figure (63) shows the trends of the FWHM of the 59.5 keV $\gamma$-ray full energy peak at different voltages at room temperature. The effect of leakage current on the detector performance is clearly shown in this figure as the energy resolution of the 59.5 keV $\gamma$-ray full energy peak as well as the energy resolution of pulser peak became very broad by increasing the bias voltage which dominates any potential improvement in energy resolution due to more complete charge collection. The FWHM of the 59.5 keV $\gamma$-ray full energy peak increased (become worse) from (5.6 ± 0.2) keV to (8.6 ± 0.2) keV when the bias is increased from 15 to 60 V as a result of increasing the leakage current from 0.9 to 11.3 nA and subsequently the pulser width increased from (2.80 ± 0.01) to (4.90 ± 0.01) keV. Taking into account the preamplifier noise in isolation was (1.63 ± 0.01) keV and on connecting the preamplifier to the detector at 0 V, the pulser FWHM was equal to (2.10 ± 0.01) keV. The additional noise which causes broadening in the FWHM despite the lack of leakage current is believed to be due to the additional capacitance of the connecting circuits and cables, ceramic substrate and the Peltier cooler. This value was increased slightly to 2.3 keV by operating the cooling system as results of the additional noise which was generated by the power supply of the Peltier cooler and the vacuum system. This slight increasing in the pulser width was not observed by using the ceramic substrate which was designed for the drift detectors.
2.4.5 CdTe Test Detector Energy Resolution at Low Temperature

In this section, the effect of cooling on the spectroscopic performance of CdTe test detector is investigated to see how the leakage current decreases with temperature and subsequently its effect on the trends of the FWHM of the $^{241}\text{Am}$ 59.5 keV line. This study will help to understand how the trends of the FWHM of the $^{241}\text{Am}$ 59.5 keV line will be improved for the CdTe Ohmic drift ring detector as a result of cooling it to decrease the leakage current.

Figure (64) shows the IV measurements for the CdTe test detector at different temperatures. The leakage current reduced significantly as the detector is cooled. It decreased by 78.1 %, 94.6 % and 99 % when the detector is cooled to 10 °C, -5 °C and -15 °C respectively at 60V as an example.
The effect of leakage current and subsequently the improving energy resolution can be seen by comparing the Am$^{241}$ spectrum at room temperature when the detector was biased to 60 V to the Am$^{241}$ spectrum at -15 °C at the same voltage (60 V), see Figure (65) and Figure (66). The pulser width at -15 °C at 60V was found to equal 2.3 keV which is the same width at 0 V when the cooling system starts working; in this instance the leakage current reduced from 11.3 nA at 60 V at room temperature to 0.11 nA at 60V at -15 °C. However, due to incomplete hole collection, a tailing effect appeared in the low energy side of the spectra.
59.5 keV peak
(8.6 ± 0.2) keV

Pulser
(4.90 ± 0.01) keV

Figure (65) Am$^{241}$ spectrum at room temperature (+ 60V)

59.5 keV peak
(3.8 ± 0.2) keV

Pulser
(2.30 ± 0.01) keV

Figure (66) Am$^{241}$ spectrum at -15 °C (+ 60V)
Figure (67) shows the trends of the FWHM of the 59.5 keV γ-ray full energy peak at different temperatures at 60V. The effect of lowering the leakage current on the widths of 59.5 keV and pulser peaks appears clearly.

2.5 Conclusion

By cooling the CdTe ohmic test structure to low temperatures, its performance characteristics improved as a result of decreasing the leakage current which has a great effect on the detector energy resolution. The width of the pulser peak improved from 4.9 keV at 60 V at room temperature to 2.3 keV at 60 V at -15 Celsius which is equal to the energy resolution of the pulser peak at 0 V. This has a great influence on the energy resolution of the $^{241}$Am 59.5 keV γ-ray peak. The behaviour of the CdTe ohmic drift ring detector can be predicted qualitatively as its performance can be improved by cooling it to low temperatures.
Chapter 3 (Baseline Measurements of Room Temperature Detectors)

In this chapter, the performance characteristics of a Si PIN-diode, different types of CdTe and a CZT A pad detectors were investigated by conducting IV and spectroscopy measurements using different γ-ray energies. The aim of this study is to understand the basic properties and limitations of these pad detectors in terms of their energy resolution and quantum efficiencies and how these limitations could be overcome by using the drift technique.

3.1 Characterization of Pad Detector Performance

3.1.1 Performance of Si PIN-diode Detectors

Si detectors have low atomic number, 14 [70] which make these detectors suitable for spectroscopy for low energies, below 30 keV, see Figure (11). However, for higher energies and due to the low probability of photoelectric effect, these detectors suffer from poor quantum efficiency. Si detectors show significantly better energy resolution than compound semiconductor detectors due to their configurations (diode) [2], [3]. In addition due to the fact there is no charge trapping inside the detector material due to its superior charge mobility which show almost complete Charge Collection Efficiency (CCE), which is defined as the ratio of measured charge to the total generated charge in the detector, even at low voltages in comparison to compound semiconductor detectors, see Table (1). Moreover, Si drift detectors [11] show even much better energy resolution in comparison to PIN-diode detectors, see chapter 1 for principle operation of PIN-diode and Si drift detectors. Their moderate band gap which is around 1.12 eV [3], allows Si detectors to operate at room temperature without cooling. In this section the spectroscopic performance of two different sizes of commercial Si PIN-diode detectors are studied. Table (4) shows the specifications of these two PIN-diode detectors. The small Hamamatsu Si PIN-diode detector (Si B) has an active area of (2.4 x 2.4) mm² and is fully depleted (0.3 mm) at -30 V whereas the large one (Si A) has an active area of (10 x 10) mm² and is fully depleted (1mm) at -100 V. Si B shows better energy resolution which is below 3 keV (2.6 ± 0.2) keV at its depletion voltage in comparison to Si A which is (3.2 ± 0.2) keV at its depletion voltage using 59.5 keV lines ^241Am source. There are no significant differences by using higher energies, 122 keV ^57Co, at their depletion voltages in terms of energy resolution which shows (2.9 ± 0.2) keV and (3.3 ± 0.1) keV for Si B.
and A respectively due to almost 100 % CCE. Figure (68) and Figure (69) show the trends of the FWHM for both detectors.

![Graph showing the trends of FWHM for Si B](image)

**Figure (68) The trends of FWHM of Si B**

![Graph showing the trends of FWHM for Si A](image)

**Figure (69) The trends of FWHM of Si A**
Figure (70) and Figure (71) show the IV measurements for both detectors which indicate that Si B has low leakage current in comparison to Si A. Si B has a leakage current around 0.1 nA at its depleted voltage in comparison to 0.5 nA for Si A due to its bigger size and higher voltage. These leakage currents have a significant effect on the energy resolution for both detectors as Si B shows better energy resolutions with low leakage currents. Both detectors show high leakage currents at positive voltages (orders of μAmp) which indicates good diode configuration. Si B pulser peak shows a better energy resolution which is $(2.40 \pm 0.01)$ keV in comparison Si A pulser peak which shows a resolution of $(3.20 \pm 0.04)$ keV at their depleted voltages respectively.

The difference in pulser peak widths could be due to the increase in the leakage current as it clear from Figure (70) and Figure (71) or due to the increase in the detector capacitance. Using equation (31), Si A has a capacitance of 0.9 pF while Si B has a capacitance of 0.17 pF when both are depleted. As the noise depends strongly on the capacitance, the difference in pulser peak widths can be explained as due to the increased in detector capacitance.

At low voltage (-10V), both Si detectors are under-depleted (small depletion thickness) and therefore, their capacitances are high which have the effect of increasing the noise ($C$ is proportion to $1/d$) according to equation (31). This effect is particularly noticeable in Si A, as shown in Figure (69).
Chapter 3 (Baseline Measurements of Room Temperature Detectors)

Figure (70) IV of Si B

Figure (71) IV of Si A
Moreover, due to its bigger size (area and thickness), Si A shows better detection efficiency which is expressed as count / s / mm\(^2\) in comparison Si B which needs a very long time to acquire good spectra. The large active area of Si A (10 \(\times\)10 mm\(^2\)) increases the probability of interaction of the photons inside the detector in comparison to Si B (2.4 \(\times\)2.4 mm\(^2\)) see Figure (72) and Figure (73). The count rates are 0.03 and 0.7 count / s / mm\(^2\) for the 59.5 keV for Si B and A at their depleted voltages respectively. On the other hand, they are 0.002 and 0.09 count / s / mm\(^2\) for the 122 keV for Si B and A at their depleted voltages respectively.

![Figure (72) Count rate of Si B](image)

Figure (72) Count rate of Si B
The 122 keV $^{57}$Co shows less efficiency in comparison to the 59.5 keV $^{241}$Am for both Si detectors due to the low probability of photoelectric absorption as its most fraction of interaction is due to Compton scattering, see Figure (3), although its activity is almost similar to the 59.5 keV $^{241}$Am source. See chapter 1 for the quantum efficiency discussion and a comparison between 300 \( \mu \)m Si and 1 mm CdTe in terms of their quantum efficiencies as a function of energy. By considering the intrinsic efficiency see chapter 1, Si A shows also better efficiency in comparison to Si B by correcting the detection geometry and this can be explained by their thicknesses of 1 mm and 0.3 mm for Si A and B respectively which match qualitatively with Figure (11) as the intrinsic efficiency increased by increasing the detector thickness and thus at the same photon energy, 0.5 mm thickness Si PIN-Diode is better than 0.3 and 0.2 mm. At their depleted voltages, the 59.5 keV peak intrinsic efficiencies are 1.5 % and 0.8 % for Si A and B respectively and they are 0.1 % and 0.02 % for the 122 keV peak, Figure (74).
Figure (74) Intrinsic efficiency of Si A and B using different gamma energies

Figure (75), Figure (76), and Figure (77) show examples of spectra which were taken by Si A and B using 59.5 and 122 keV γ-ray Sources. As explained in chapter 1 section 1.2.2, the most important features appear clearly in these figures. The 59.5 and 26.3 keV appear clearly in Figure (75) Figure (76) in both spectra which are taken by Si A and B and due to the high noise edge of Si A, 26.3 keV is not visible in the spectrum when the detector is under-depleted at -10 V. In addition, the L X-ray form 237Np decay at 17.8 keV appear clearly in both spectra when these detectors are depleted due to improving in the noise as a result of decreasing the detector capacitance. However, the 13.6 keV does not appear because it exists under the threshold level. The small peak at 48 keV in Figure (75) is believed to be due to the interaction of the incident photon via Compton scattering with an electron of the surrounding material see chapter 1 section 1.2. This interaction leads to a back scattered photon of energy equal to (Eγ- Compton edge) which appears in the spectrum as it is absorbed inside the detector and it does not appear in Si B due to its small area see Figure (76).
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Figure (75) $^{241}$Am (59.5 keV) spectrum using Si A

Figure (76) $^{241}$Am (59.5 keV) spectrum using the small Si B
On the other hand, the 122 keV peaks appear clearly in Figure (77) and Figure (78). The features of Compton effect; Compton edge and back scatter; are clearly visible in these figures for spectrum taken by Si B. The calculated Compton edge using equation (3) equal to 39.4 keV and the back scatter peak 82 keV (see section 1.1.5) match with the features appear in the spectra. This is also true for spectrum taken by Si A.

![Figure (77) $^{57}$Co (122 keV) spectrum at -30V using Si B](image1)

![Figure (78) $^{57}$Co (122 keV) spectrum at -30V using Si B](image2)
3.1.2 γ-ray Spectroscopy using CdTe Pad Detectors, Influence of Leakage Current and Effect of Polarization

The CdTe Ohmic pad detector is limited by bulk leakage current which adds more noise to the spectra and subsequently degrade the energy resolution especially at higher voltages. However, Schottky contact CdTe detectors have been introduced to overcome the problem of the high leakage currents which are shown in Ohmic CdTe detectors and therefore show better energy resolution. This is clearly indicated in their IV measurements and corresponding FWHM in Figure (79), Figure (84) and Figure (87).

Figure (79) IV measurements of the CdTe Ohmic and Schottky pad detectors at negative voltages

Figure (79) compares the reverse-bias leakage current measured from the Schottky CdTe detector with that of the Ohmic device over the same voltage range. It shows that even with very high voltages, the Schottky contacts produce low leakage current in comparison to the Ohmic detector. At -100V, the CdTe Ohmic pad detector shows -88 nA while it is only -0.45 nA for the Schottky detector.
Figure (80) and Figure (81) show examples of the 59.5 keV lines with the pulser taken by CdTe Ohmic at -15 V and -50 V respectively. From the figures the effect of leakage current (-3 nA) and (-28 nA) on the 59.5 and the pulser signals are clear, which are (6.7 ± 0.4), (3.8 ± 0.1) keV and (10.0 ± 0.3) and (8.6 ± 0.1) keV widths at -15V and -50V respectively. Due to low leakage current at -15V, Cd and Te escape peaks appear in the spectrum and because the high noise edge due to high leakage current, they are not visible at -50V.
Although the CCE has improved from 92% at -15V to 98% at -50 V for the 59.5 keV lines, yet the effect of leakage current predominates on this improvement. This also true for the 122 keV lines, however, due to its interaction position deeper in the crystal which therefore shows less CCE in comparison to the 59.5 keV lines due incomplete charge collection, 122 keV shows worse energy resolution in comparison to 59.5 keV lines, see Figure (82). At the same voltage -50 V, the FWHM of 59.5 keV is $(10.0 \pm 0.3)$ keV in comparison to $(14.7 \pm 0.1)$ keV for the 122 keV.

![Figure (82) $^{57}$Co (122 keV) at -50 V using the CdTe Ohmic pad detector](image)

Figure (84) shows the trends of FWHM of all bias voltages for both the 59.5 keV and the 122 keV using the CdTe pad detector along with the pulser peak. The spectrum was acquired at each voltage with a pulser peak. The pulser peak widths are a combination of leakage current as a result of biasing the detector and the coolFet preamplifier noise. Figure (83) shows how pulser width degraded with voltages as a result of increasing leakage current. The pulser width when the coolFet disconnected
from the detector is \((2.20 \pm 0.01)\) keV and this value is increased to \((11.0 \pm 0.1)\) keV at -75V due to increasing in leakage current from zero to 55 nA.

The trends of the FWHM of the 59.5 keV and 122 keV match with the pulser peaks. However, the 122 keV shows worse energy resolution than 59.5 keV as it is absorbed deeper in the crystal. Therefore, the CCE of the 59.5 keV is higher than the 122 keV, see Figure (84).
Chapter 3 (Baseline Measurements of Room Temperature Detectors)

Figure (84) The trends of the 59.5 and 122 keV FWHM for different voltages using the CdTe Ohmic pad detector

In contrast, Schottky detectors show better energy resolution in comparison to CdTe Ohmic pad detectors due to the improvement in leakage current. Higher CCE can be achieved and therefore better energy resolution by increasing the bias to higher values without experiencing high leakage current especially for the 122 keV. Figure (85) and Figure (86) show examples of the 59.5 keV and 122 keV spectra taken by a CdTe Schottky contact device at -500V. The FWHM are (4.1 ± 0.2) keV and (6.3 ± 0.2) keV for the 59.5 keV and 122 keV respectively at -500V which are much better than spectra taken by the CdTe Ohmic detector. Moreover, due improving in the leakage current the pulser width is (3.30 ± 0.01) keV corresponds to 2.5 nA only, see Figure (85) and Figure (86).
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59.5 keV
FWHM = (4.1 ± 0.2) keV

Cd and Te
Fluorescence and escape peaks

Pulser
FWHM = (3.30 ± 0.01) keV

Figure (85) $^{241}$Am (59.5 keV) spectrum at -500V using CdTe Schottky detector

122 keV
FWHM = (6.3 ± 0.2) keV

Figure (86) $^{57}$Co (122 keV) spectrum at -500V using CdTe Schottky detector
Moreover, due reducing in the leakage current and subsequently due to the lower noise edge, the Cd and Te escape peaks are visible in the 59.5 keV line spectrum between 28.5 and 36.3 keV. However, in contrast to CdTe Ohmic, these peaks are visible only at low voltages.

Figure (87) shows the trends of the FWHM of the 59.5 and 122 keV line along with the pulser peaks. From the figure the improvement in the leakage current and therefore in the FWHM for both peaks in comparison to CdTe Ohmic detector is clear. The FWHM of the 59.5 keV are almost constant until -500V and after that the leakage current starts to affect its width. This is matching with the pulser width. However, for the 122 keV peak, due to low leakage current, there is an improvement in the FWHM until -500V which gives the best energy resolution and after that the leakage current starts to affect the 122 keV peak widths.

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**Figure (87) The trends of the 59.5 and 122 keV FWHM for different voltages using the CdTe Schottky detector**

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95
However, spectroscopy using CdTe Schottky detectors should be conducted within short time, 90 seconds for above measurements, to avoid the phenomenon of polarization which is associated with shifting the centroid channel dramatically within several minutes. This may make the detector unsuitable for spectroscopic measurements, especially if this phenomenon continues and does not reach stability. This phenomenon may correspond to electrons being captured by specific acceptors in the material which therefore leads to a decrease in its depletion region which affects the space-charge distribution and the electric field in the detector. A deep acceptors level present as a reason of Cd vacancy can cross the Fermi level when the Schottky junction is made which therefore cause ionization of deep acceptors level and subsequently the electric field provide is changed inside the detector material. This phenomenon can be decreased by using a high bias voltage and low temperature and subsequently improves the energy resolution by cooling the detector with compact Peltier cells [72]. Figure (88) shows the effect of polarization within several minutes at -250V using a 59.5 keV $^{241}$Am source. In this figure, after 15 minutes the 59.5 keV peak starts to shift to lower energy and worse energy resolution.

![Figure (88) Effect of polarization on the CdTe Shottky detector at -250V using the 59.5 keV $^{241}$Am source](image-url)
This effect becomes critical if higher energy $\gamma$ rays are used, for example 662 keV $^{137}$Cs source, in which most of its fraction of interaction is due to Compton scattering and therefore low count rate are expected which needs to run the experiment for long time to acquire good spectrum.

The quantum efficiency, expressed as count / s / mm$^2$, has improved significantly by using CdTe detectors in comparison to Si detectors due to higher atomic number, 48 for Cd and 52 for Te [3], [5], which increases the probability of the photoelectric effect. For contrast, at the same field strength 25V/mm, the Si diode (10x10x1) mm$^3$ shows a quantum efficiency of 0.55 count / s / mm$^2$ (1 %) while for CdTe Ohmic detector it shows 15.5 count / s / mm$^2$ (29 %) using the same 59.5 keV $^{241}$Am source. This improvement is also seen for the 122 keV $^{57}$Co but with lower count rates.

3.1.3 Investigation the Poor Spectroscopy when the Irradiation Contact is the Anode

By inverting the bias, biasing the detector with positive voltage, see Figure (60) i.e. the irradiation contact is the anode, the effect of drifting the holes towards the cathode is investigated using the CdTe Ohmic detector. The 59.5 keV $^{241}$Am interacts near the surface and the holes need to drift a long distance to the anode and with high probability be trapped in the detector as its mobility is less than the electrons by a factor of 1000 for a similar life time, see Table (1). The 59.5 keV signal suffered from very low CCE and bad energy resolution (58.6 ± 1.3) % and (15.6 ± 0.4) keV respectively at +15 V. While the CCE and FWHM using -15 V were (91.3 ± 0.7) % and (9.70 ± 0.04) keV respectively. Figure (89) shows that using positive bias on the top electrode, due to the incomplete charge collection, the CCE is very low at low bias considering the 59.5 keV peak. Increasing the bias and therefore increase the CCE will improve the FWHM until + 50V, see Figure (90). After that, the detector again becomes limited by high leakage current which further degrades the energy resolution. These data confirm that, even for the Ohmic detector, the preferred mode of operation is the top electrode at negative bias.
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Figure (89) CCE of the 59.5 keV $^{241}$Am using the CdTe Ohmic pad detector

Figure (90) The trends of the FWHM of 59.5 keV $^{241}$Am source using positive and negative bias polarity (CdTe Ohmic pad detector)
Chapter 3 (Baseline Measurements of Room Temperature Detectors)

No significant effect was noticed by inversing the bias on the performance by using 122 keV $^{57}$Co in terms of energy resolution and CCE. This is can be explained by the distribution of the 122 keV $\gamma$ interactions inside the detector which has different values across the detector thickness unlike the 59.5 keV $\gamma$ which stopped near the surface. This is illustrated in Figure (91) where the photons attenuation was calculated using equations (5) and (6) by considering the mass attenuation coefficient, see section 1.3. Thus the photons fraction transmitted % as a function of thickness was calculated for different energies. Figure (91) shows that most of the 59.5 keV photons are stopped near the surface of the irradiation contact while 122 and 662 keV photons have different ranges across the detector thickness.

![Figure (91) Photons fraction transmitted % as a function of detector thickness](image)

3.1.4 Hole Tailing in CZT Pad Detector

CZT detectors have a higher band gap energy ($\sim 1.64$ eV) [3] compared to CdTe due the blending composition of ZnTe in CdTe. The increase in band gap leads to a decrease in the intrinsic free carrier concentration and leakage current [3]. A CZT pad
detector shows better energy resolution at low $\gamma$-ray energy with a low energy skewing tail due to hole losses which can be improved by decreasing the detector thicknesses, however, CZT shows poor energy resolution at high $\gamma$-ray energies with severe tailing effects [3]. This is due to the large distance for the holes to be drifted to the cathode and with high probability be trapped in the detector material. In comparison with the CdTe Ohmic type detector, CZT A shows low leakage current, see Figure (92) due to its higher bulk resistivity and high band gap energy which therefore, play an important role on the energy resolution of the 59.5 and 122 keV peaks at high voltages, see Figure (95).

Figure (92) IV measurements of the CdTe Ohmic and CZT A pad

Figure (92) shows that at the same field strength (-50V/mm) CZT A shows -0.74 nA in comparison to 28 nA for the CdTe Ohmic detector. Figure (93) and Figure (94) show examples of the 59.5 keV and 122 keV spectra. At the same field strength (50V/mm), CZT A detector shows (4.70 ± 0.2) and (2.40 ± 0.01) keV for the 59.5 keV line and pulser width respectively whereas they are (10.0 ± 0.3) and (8.6 ± 0.1) keV for the CdTe Ohmic detector. This is mainly due to improving in the leakage current. Moreover, the Cd and Te escape peaks are visible in the spectrum taken by CZT A at all voltages whereas they appear in CdTe Ohmic detector at low voltages.
only. On the other hand, due to the higher penetrating depth of the 122 keV, its spectrum suffers from severe tailing effect due to incomplete holes collection which trapped inside the detector material as illustrated in Figure (94). The FWHM of 122 keV line and the pulser width are (14.7 ± 0.1) and (2.40 ± 0.01) keV at -50V (10V/mm) which are improved significantly to (8.1 ± 0.1) and (2.90 ± 0.01) keV at -250V (50V/mm) as a result of improving the CCE from 86% to 99%. In contrast with the CdTe Ohmic detector, the FWHM of the 122 keV line and the pulser width are (16.2 ± 0.1) and (7.70 ± 0.01) keV respectively due to the high leakage current.

![Diagram of 59.5 keV peak with FWHM (4.7 ± 0.2) keV and Cd and Te Escape peaks between 28.5 and 36.3 keV](image)

**Figure (93)** $^{241}$Am (59.5 keV) at (-250 V) -50 V/mm using the CZT A pad detector
Figure (94) $^{57}$Co (122 keV) using the CZT A pad detector at different voltages

Figure (95) and Figure (96) show the trends of the 59.5 and 122 keV lines FWHM at different voltages and the CCE respectively. It is clear from Figure (95) that the improvement of the FWHM of the 59.5 and 122 keV is a result of improving the leakage current in comparison to the CdTe Ohmic pad detector. As the 122 keV $^{57}$Co shows less CCE in comparison to the 59.5 keV $^{241}$Am, their energy resolution is worse than the 59.5 keV $^{241}$Am. Increasing the bias to high values to increase the CCE of 122 keV, results in improving the energy resolution without experiencing high leakage current. However, this CZT A pad detector shows low energy tailing in agreement with incomplete hole collection as the $\mu_\tau$ for holes is expected to be much smaller than for electrons [3], [5]. The 59.5 and 122 keV energy resolution of CZT A is now mainly limited by the 5 mm thickness of the detector due to poor charge transport across this thickness, in comparison to the leakage current limitation seen in the 1 mm thick CdTe Ohmic contact pad detector.
Chapter 3 (Baseline Measurements of Room Temperature Detectors)

<table>
<thead>
<tr>
<th>Am-241 (59.5 keV)</th>
<th>Co-57 (122 keV)</th>
<th>Pulser</th>
</tr>
</thead>
</table>

Bias (−ve)

Figure (95) The trends of the FWHM of 59.5 and 122 keV peaks using CZT A pad detector.

Figure (96) CCE of the 59.5 and 122 keV using CZT A pad detector.
Chapter 3 (Baseline Measurements of Room Temperature Detectors)

3.1.5 Summary of Energy resolution and Peak efficiencies at the Same Field Strength using Different Pad Detectors.

Table (15) summarises the performance of all pad detectors at the same field strength -50V/mm using 59.5 keV $^{241}$Am.

<table>
<thead>
<tr>
<th>Detector/dimension(mm$^3$)</th>
<th>59.5 keV width (keV)</th>
<th>Detector only resolution keV</th>
<th>Intrinsic efficiency %</th>
<th>59.5 keV count rate / mm$^2$/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si A (10x10x1)</td>
<td>3.2 ± 0.1</td>
<td>0.8</td>
<td>1.4</td>
<td>0.80 ± 0.01</td>
</tr>
<tr>
<td>CdTe Ohmic(4x4x1)</td>
<td>10.0 ± 0.3</td>
<td>4.9</td>
<td>31.2</td>
<td>16.7 ± 0.1</td>
</tr>
<tr>
<td>CZT A (5x5x5)</td>
<td>4.7 ± 0.2</td>
<td>3.7</td>
<td>24.4</td>
<td>13.0 ± 0.1</td>
</tr>
</tbody>
</table>

Table (15) Spectroscopic performance of all pad detectors at the same field strength -50V/mm

Where the detector only resolution can be defined as:

\[ \text{FWHM}_{\text{detector}}^2 = \text{FWHM}_{\text{photo-peak}}^2 - \text{FWHM}_{\text{pulsed}}^2 \]  \( ^{(45)} \)

And thus it represents the detector resolution after eliminating the effect of preamplifier noise and the noise due to leakage current.

Although the Si detector shows the best energy resolution 3.2 keV, its quantum efficiency is extremely below the CdTe and CZT A pad detectors. On the other hand, the CdTe Ohmic type detector has better quantum efficiency but its 59.5 keV $^{241}$Am peak width is limited by the leakage current which adds more noise to the spectrum. CZT A pad detector shows better energy resolution than CdTe even after eliminating the effect of leakage current (detector only resolution) with good quantum efficiency with the effect of hole tailing.

3.1.6 Conclusion and Summary of Required Improvement

From the last measurements, a conclusion can be drawn that; in order to achieve the good energy resolution of Si detectors and good quantum efficiency of CdTe and CZT detectors; an effort has to be made to eliminate the effect of leakage current and
hole tailing of the CdTe Ohmic and CZT detectors. This can be done by investigating
the spectroscopic performance of CdTe and CZT drift detectors. These detectors have
the advantages of having small anode area which may decrease the effect of leakage
current, small input capacitance and the advantages of eliminating the effect of hole
trapping as described in chapter 1.

3.2 Initial Characterization of CdTe A Drift Ring Detector at Room
Temperature

The aim of this section is to investigate the performance characteristics of CdTe
drift ring detector (CdTe A) which is mounted on a PCB at room temperature using
Box 1 see chapter 2. This detector has two advantages; a small anode diameter to
decrease the bulk leakage current and its geometry which was discussed in Chapter 1
which has the advantage of eliminating the effect of hole trapping and therefore
improving the energy resolution. In this part, the spectroscopic performance was
studied using a 59.5 keV $^{241}$Am source.

3.2.1 Spectral Response at Room Temperature

Figure (97) Cross section of the CdTe A used in this study [73]

Figure (97) shows a cross section of the 1 mm thick prototype CdTe A drift ring
detector studied at room temperature. The detector was fabricated by Acrorad Ltd
with a three ring geometry. Ohmic contacts were chosen rather than Schottky to
assure the stability of the detector and to avoid the phenomenon of polarization which is associated with time instability under bias [72]. The anode diameter is 0.5 mm as are the widths of all three rings; individual rings are separated by gaps of 0.5 mm.

The detector was mounted on a PCB positioned face up inside Box 1. The pad electrode and the three rings were negatively biased by directly connecting them to the 4 channel bias supply and the guard ring was not connected (floating). All the pulse height spectra recorded were collected from the central anode which was connected to the charge sensitive preamplifier (coolFet).

The spectroscopic performance of the detector was conducted by irradiating the detector with 59.5 keV γ rays of a 420 kBq $^{241}$Am source. The source was positioned at 50 mm distance above the centre of the detector and pulse height spectra collected with the MCA. Different electrode bias combinations were used to assess the detector performance at room temperature in terms of energy resolution and counting efficiency.

The spectroscopic performance of the detector was conducted by irradiating the detector with 59.5 keV γ rays of a 420 kBq $^{241}$Am source. The source was positioned at 50 mm distance above the centre of the detector and pulse height spectra collected with the MCA. Different electrode bias combinations were used to assess the detector performance at room temperature in terms of energy resolution and counting efficiency.

Figure (98) $^{241}$Am (59.5 keV) spectrum at -100V (10-20-30) %
Figure (98) shows an example of a 59.5 keV spectrum at its optimum electrode combination for energy resolution -100V bulk field and (-10,-20, -30) V on the 1st, 2nd and 3rd ring respectively. The 59.5 keV peak is clearly visible as well as two smaller features below it which are believed to be due to Cd and Te escape peaks. The pulser width at this combination is nearly equal to the 59.5 keV photo-peak width indicating good energy resolution i.e. detector only resolution is 0.9 keV see equation (45). The CCE at this combination is (97.6 ± 1.3) % and the 59.5 keV energy resolution is (4.5 ± 0.3) keV which is in comparison better than the energy resolution which was obtained by CdTe Ohmic pad detector at the same CCE (97 %) which was (12.2 ± 0.3) keV at -75 V. This is due to the leakage current (large anode) which was 55.2 nA in comparison to 1.2 nA for CdTe A (small anode). However, the efficiency evaluated by the count rate was very low in comparison to the pad detector because the active area of CdTe A is small. An effort was done to increase the active area of the detector by choosing different bias schemes which include increasing the bulk fields for the same lateral field and increasing the lateral fields for the same bulk field.

3.2.2 Leakage Currents and Energy Resolution

Initial measurements were made to investigate the effect of the anode leakage current on the spectroscopic performance of CdTe A. The FWHM of the pulser peak at different electrode bias combinations was used to assess the detector resolution. Figure (99) shows the IV measurements of the CdTe A at room temperature using the optimum bias scheme, -100V (10, 20, 30) % and different cathode bias for the same ring voltage ratio (10,20,30) %. IV measurements were done for all voltage combinations for a fixed time interval (10 minutes each). The leakage current on the anode starts with a certain value then it decreases with time as the leakage current on the cathode and rings reach stability. This stabilization can be reached within 10 minutes and the leakage current decreases by ~ 50 % from its original value. Subsequently all spectroscopic measurements using 59.5 keV $^{241}$Am source were conducted after 10 minutes from setting the cathode and ring voltages.
As the bulk (cathode) and lateral (ring) fields are increased, the leakage current on the anode is increased and subsequently the energy resolution of the 59.5 keV photo-peak is degraded. For example, at the same ring voltage ratio (10, 20, 30) % increasing the bulk field from -100V to -200V increases the leakage current on the anode from -1.3 to 3.5 nA. On the other hand, at the same bulk field -100V, increasing the lateral field from (10, 20, 30) % to (80,160,240) % as a percentage of the cathode bias increases the leakage current also from -1.3 nA to 3.9 nA. Figure (100) shows the pulser widths as a function of anode leakage currents for all voltage combinations studied which indicates that there is a linear increase in pulser width with leakage current. Therefore, the spectroscopy performance of CdTe A is significantly degraded by leakage current which is a combination of surface and bulk leakage currents formed by the rings and the cathode respectively.
The measured pulser peak width is a product of the intrinsic noise in the electronic read-out chain and the detector leakage current. The CoolFet noise in isolation was measured by generating a pulse through the test input, with the detector input left unconnected; in this arrangement the FWHM was $(1.66 \pm 0.01)$ keV. On connecting the preamplifier to the detector system with the detector at 0V, the pulser FWHM was found to be equal to $(3.70 \pm 0.01)$ keV. The broadening of the FWHM despite the lack of a leakage current is due to the additional capacitance of the connecting circuit and cables in addition to the PCB board.

Figure (101) shows the trends of the FWHM of 59.5 keV at -100V bulk field and different lateral fields. The figure shows the effect of the surface leakage currents on the energy resolution as they were degraded by increasing the lateral fields. The 59.5 keV peak width was increased from $(4.5 \pm 0.3)$ keV at -100V (10,20,30) % to $(7.5 \pm 0.2)$ keV at -100V (80,160,240) %. No significant effects were noticed by increasing the bulk field either on the CCE or the count rate, despite the fact that the energy resolution degraded due to an increase in the leakage current. However, by increasing
the lateral fields for the same bulk field, the count rates were increased significantly which end up with a trade off between the energy resolution and the detection efficiency.

![Graph showing FWHM vs Lateral field (ring voltage) % of cathode bias](image)

**Figure (101)** The trends of the FWHM of the 59.5 keV $^{241}$Am at -100V bulk field and different lateral fields using CdTe A

It was found that by fixing the 1$^\text{st}$ ring voltage to -80 V and increasing the bias voltages of the 2$^\text{nd}$ and 3$^\text{rd}$ rings did not increase the anode leakage current. It is thought that in this instance the 1$^\text{st}$ ring acts as a guard ring and subsequently the 59.5 keV width starts to improve.
Figure (102) The trends of the leakage current at -100V bulk field and different lateral fields using CdTe A

Figure (102) confirms improvements in the FWHM of the 59.5 keV and pulser peaks as a result of decreasing the leakage current when the 1st ring bias was fixed at -80 V and increasing the bias to the 2nd and 3rd ring.

3.2.3 Summary of CdTe A Drift Ring Performance

Table (16) summarises CdTe A performance in terms of energy resolution and count rates for different bias schemes. Increasing the bulk field for the same lateral field did not improve the counting efficiency; however, it degrades the energy resolution due to the increased leakage current. Although increasing both the bulk and lateral fields
increase the leakage currents on the anode, the dominant part of the total leakage current is due to the current flow between the cathode and the anode driven by the bulk field. On the other hand, Figure (103) shows the improvement of counting efficiency by increasing the lateral fields for the same bulk field, -100V. The count rates continue to increase until large surface current limits the performance of the detector at -80V for the first ring. An attempt to further increase the count rate by increasing the potential to ring 2 and 3 led to a reduction in efficiency due to reduced bulk field strength as illustrated in Figure (103).

![Graph showing count rate vs. lateral field](image)

**Figure (103)** The trends of the count rate of 59.5 keV $^{241}$Am at -100V bulk field and different lateral fields using CdTe A

Figure (104) shows the 59.5 keV line $^{241}$Am spectra at different bias schemes. At the same bulk field -100V, increasing the lateral field fields from (20, 40, 60) % to (80,160,240) % improves the detection efficiency of the 59.5 keV from (2.70 ± 0.03) c/s to (20.6 ± 0.2) c/s as a result of increasing the active area. However, it degrades the energy resolution of the 59.5 keV peak from (5.50 ± 0.02) keV to (7.5 ± 0.2) keV due to the increased leakage current from 1.25 nA to 3.89 nA. However, increasing the bulk field from -100V to -200V for the same lateral field (-20,-40,-60) V has no
significant effect on the detection efficiency and it deteriorates the energy resolution from \((5.50 \pm 0.02)\) keV to \((6.50 \pm 0.03)\) keV as a result of increasing the leakage current from \(-1.25\) nA to \(3.49\) nA see Figure (104) and Table (16).

![Figure (104) 59.5 keV $^{241}$Am spectra at different voltage combination schemes](image)

3.3 Conclusion and Summary of Required Improvement

The performance of CdTe A drift detector shows that in order to increase the active area of this detector, high lateral field at \(-100\)V cathode bias has to be used to improve the detection efficiency. However, this degrades the energy resolution due to increase in the leakage current which ends up with a trade off between detection efficiency and energy resolutions. From the above initial measurements, although the small anode area of the drift ring detector decreases the leakage currents in comparison to the CdTe pad detector and therefore a reasonable CCE can be achieved with low leakage current. However, CdTe A is still limited by leakage current which
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is a combination of bulk and surface leakage current. Different bias schemes were investigated to improve the detector efficiency and increase further the CCE to improve the energy resolutions. No significant effects were noticed by increasing the bulk fields on detection efficiency despite the fact the detector energy resolution degraded by leakage current. The critical issue is that the active area of the CdTe A remains very small. So that studying the active area with a focused synchrotron beam is very important to determine the active area of this detector and how it could be improved by using different bias schemes. Moreover, based on the former results which show improvement in the energy resolution of the CdTe test detector at low temperatures which were discussed in chapter 2. It is expected that the energy resolution will be improved by cooling CdTe A to lower temperatures to reduce the leakage current which helps to increase the counting efficiency with reasonable energy resolution. Using Box 2 which was designed for low temperature measurements and CdTe B mounted on a ceramic substrate will reduce the electronic noise as discussed in chapter 2. Moreover, due to its high resistivity, CZT A drift detector could provide lower leakage current and good energy resolution at room temperature.
Chapter 4 (Line - Scan Studies at Diamond Light Source)

The aim of this chapter is to study the performance characteristics of CdTe and CZT drift ring detectors at room and low temperatures (CdTe A, B and CZT B). This was done by measuring the response uniformity and active area of these detectors as a function of incident X-ray position with an X-ray micro-beam which was carried out on the beam line B 16 at the Diamond Light source Synchrotron [74]; in addition to study their performances using different γ ray energies. Based on the conclusions which were achieved in the last chapter in which CdTe A performance was limited by leakage current, a comparison will be made between CdTe A and CdTe B to investigate the effect of low temperatures and the irradiation techniques (geometries), i.e. irradiating cathode and anode contact, on the detector performance. Moreover, due to the low leakage current of CZT B, high bulk and lateral fields will be tested to investigate its active area at high voltages.

4.1 Introduction to Diamond Line Scan Studies

![Figure (105) Photographs of the mounted devices at the Diamond Light Source set-up (Left) CdTe A (Right) CdTe B](image)

As explained before, see Figure (105), CdTe A was mounted on a PCB inside Box 1 and measured only at room temperature. It was connected to an Amptek 250 CoolFet charge sensitive preamplifier, to a 4 channel power supply (ORTEC 710), a shaping amplifier (ORTEC 570) and a pulse generator (ORTEC 480). Pulse height spectra were acquired using a Canberra Multi-Channel analyser (MCA). The rear cathode and the three rings were negatively biased by connecting them to the 4 channel bias supply, and the guard ring was floating. All the pulse height spectra
recorded were collected from the central anode and all the measurements were conducted at room temperature. Device CdTe B was mounted on a ceramic substrate inside Box 2 connected to the same electronic modules. The temperature of this device could be controlled in the range of room temperature down to -15 °C. However, the rings were biased through different resistor networks. The line scans were conducted with the photon beam incident on the anode/ring contacts for CdTe A and on the cathode contact for CdTe B as illustrated in Figure (106).

The storage ring was operated at 3 GeV with a current of 250 mA. The X-ray energy was tuned to 25 keV by a Si (1 1 1) double crystal monochromator; a small amount of flux is also produced at the 3rd harmonic which has an energy of 75 keV. The beam spot size was collimated to 20 μm × 20 μm using a set of tungsten slits and scanned across the detector in a number of line scans. 7.5 and 12.5 mm thick aluminium (Al) absorbers were used for CdTe A and CdTe B respectively to reduce

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**Figure (106) Cross sections of the CdTe A (top) and CdTe B (bottom) shows the irradiation techniques (geometries)**
the beam intensity to $\sim 1 \times 10^9$ photons s$^{-1}$ cm$^{-2}$; this hardened the X-ray beam, changing the ratio of the first harmonic (25 keV) and third harmonic (75 keV) X-ray lines and reducing the pile up effects at 50 and 100 keV. Table (17) summarises the beam specifications which were used for the line scan measurements.

<table>
<thead>
<tr>
<th>X-ray Beam size</th>
<th>20 μm × 20 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>X/Y step size</td>
<td>100 μm</td>
</tr>
<tr>
<td>Time per scan</td>
<td>120 s for CdTe A and 30 s for CdTe B</td>
</tr>
<tr>
<td>1$^{\text{st}}$ harmonic</td>
<td>25 keV</td>
</tr>
<tr>
<td>3$^{\text{rd}}$ harmonic</td>
<td>75 keV</td>
</tr>
</tbody>
</table>

Table (17) The specifications of the X-ray microbeam measurements

A coarse positioning of the central anode of the drift detectors was made using a computer controlled X/Y stage and a laser beam which had been pre-aligned to the X-ray beam. A 2D scan was conducted from this as the initial starting point in 0.1 mm steps, 60 s and 20 s for CdTe A and CdTe B respectively. Acquisition was made at each position with the pad electrode voltage at -100 V and the ring voltages to -20V, -40V and -60V for the 1$^{\text{st}}$, 2$^{\text{nd}}$ and 3$^{\text{rd}}$ ring respectively for CdTe A and -100 V with VB1 for CdTe B at room temperature. A 2D scan of count rate vs. position showed a plateau region which drops significantly when the scan position exceeded the anode area. Based on these measurements, the centre of the anode was determined to be the middle of the plateau within ± 100 μm. Once the beam position relative to the anode was aligned, line scan measurements were made for a number of different bias schemes using a 4 channel power supply and resistor networks for CdTe A and CdTe B respectively at room temperature and -15 °C. Since the drift ring geometry of the detector has rotational symmetry, line scans were only made in the + Y vertical direction. The 2D scan was repeated for the CdTe B at -15 °C to assure the centre of the anode had not shifted by cooling the detector.

Figure (107) shows the 2D calibration scan for the CdTe A at room temperature as an example which shows the counts under the 25 keV peak. The scan trend is also true for 75 keV peak.
Microbeam measurements were used to investigate the spatial variation of the detector efficiency. The efficiency was evaluated from the count rates detected as a function of radial distance from the centre of the anode in a series of line scan measurements. The integrated photo-peak count rates were calculated for each scan position, i.e. from the centre of the anode until the position where the peak count rate is at the level of the noise; this indicates the active area of the detector.

### 4.2 Comparison of CdTe (A & B) at Room and Low Temperatures

#### 4.2.1 Line Scans of CdTe A at Room Temperature

Figure (108) shows examples of the X-ray spectra using CdTe A at room temperature measured for three different positions using -100V bulk field and (-10,-20,-30) V for rings 1, 2 and 3 respectively. The 25 keV peak count rate is at maximum at the centre of the anode and starts to decrease as the scan moves outward from the anode. The peak position moves to low energy at high radial position. The same trend is also observed for the 75 keV photo-peak but with reduced count rates. This
behavior is true for all bias schemes. However, as this detector is limited by leakage currents as indicated in Figure (99) and Figure (100), the 25 keV peak suffers from a high noise edge at some higher bulk and lateral fields which tend to merge with the 25 keV peak at high radial position.

Moreover, the FWHM of the 25 keV peak at the centre of the anode have been measured for different bias scheme combinations and show degraded energy resolution with increasing bulk and lateral fields. This result matches the results obtained by using the 59.5 keV $^{241}$Am source, see Figure (101) and Table (16). The FWHM of the 25 keV at -100V (10-20-30) % at the centre of the anode is $(8.20 \pm 0.01)$ keV which is mainly dominated by noise due to high leakage current of this device.

Increasing the lateral fields plays an important role in terms of detection efficiency. It was found that the active radius of the detector was increased significantly by increasing the lateral fields which were formed by the rings while no effect was observed by increasing the bulk fields for fixed lateral fields. However, increasing the bulk fields for fixed relative ring biases (as percentage of the cathode
bias) improved also the active radius of the detector. Figure (109) shows a histogram of the total count rate under the 25 keV peak for different bias schemes. For each bias scheme, the count rates were added up for each position, i.e. from the centre of the anode until the position where the peak collapse to the level of the noise. The total count rate integrated over the entire energy range was found to have a large contribution from the low energy noise edge at ~ 18 keV. For this reason only counts in the photo-peak were taken into account for all scans.

It clearly appears in Figure (109) that the total count rate of the 25 keV peak increased significantly by increasing the lateral fields for fixed bulk field and also by increasing the bulk field for fixed-ratio lateral fields. However, at the same lateral field (-20,-40,-60) V, increasing the bulk field from -100V to -200V did not affect the total count rate significantly. The same behaviour was noticed also by increasing the bulk field from -120V to -180V for the same lateral field (-36,-72,-108) V. As CdTe A is limited by leakage current as discussed in chapter 3 and due to the high noise edge, the 25 keV peak cannot be resolved by the detector at higher bulk and lateral fields, -200V.
However, the trend of increase in total count rate is expected to be observable if the high noise edge is decreased by lowering the temperature, as the same trend was already confirmed by studying the 75 keV peak signal for the three lateral field schemes, with overall lower count rate, see Figure (110).

Figure (110) Histogram shows the total count rates for the 75 keV peak summed across a complete radial line scan for different bulk and lateral fields using CdTe A at room temperature.

Figure (111) Active radius of the CdTe A for different bias schemes at room temperature.
Figure (111) shows that the active radius of the CdTe A extends to 0.4 mm which corresponds to the edge of the 1st gap at -100V (-20,-40,-60) V and increasing the bulk field to -200V within this lateral field has no effect. In contrast, it was increased slightly to 0.5 mm by increasing the lateral field to (-36,-72,-108) V with also no effect by increasing the bulk field from -120V to -180V within this lateral field. This also true for 75 keV but with lower count rates. Therefore, the lateral field formed by the rings has the significant effect of increasing the active area of this detector.

Since the significant factor of increasing the active radius is related to the lateral fields, line scan measurements were conducted for several lateral fields for fixed bulk field at -100V as illustrated in Figure (112).

![Figure (112) Active radius of the CdTe A as a function of lateral field at -100V bulk field considering the 25 keV peak](image)

It is clear from Figure (112) that the active radius of the CdTe A is increased a small distance as the lateral voltages are increased up to 100% of the bulk field (3rd ring). In addition, there is a significant increase in the active radius for lateral voltages greater than bulk voltages (2nd and 3rd rings). A maximum active radius at 1.9 mm was
achieved at (-80, -160, -240) V lateral field. When using this bias scheme, X-rays are
detected in high numbers up to 0.8 mm from the centre of the anode; beyond this
point the number of X-rays detected decreases to ~ 20 % of the maximum between
rings 1 and 2 before they were increasing again to 40 % of the maximum when
interacting under ring 2. It was found that the 1st ring bias voltage could not be
increased beyond -80 V due to an increased contribution of surface leakage currents.
An attempt to further improve the active radius of the CdTe A was made by fixing the
voltage on the 1st ring to -80 V and increasing the voltages on the 2nd and 3rd rings.
Despite the increase in the bias voltages of the outer rings, the active radius was found
to decrease slightly and this is believed to be due to reduced effective bulk field
strength. When the lateral field becomes significantly larger than the bulk field, a drop
in count rate was observed due to the high field of 2nd and 3rd rings which forces
electrons away from the anode. These phenomena were also observed for the 75 keV
3rd harmonic but with a small reduction in the efficiency compared to the 25 keV
photo-peak. Using (-80, -160, -240) V lateral field, the count rate under the 2nd ring
was reduced to 17% for the 75 keV peak compared to 40 % at 25 keV. It appears that
the interaction depth plays an important role in terms of detection efficiency. At 75
keV, the X-rays interact deeper in the crystal in comparison to 25 keV and this
corresponds to a reduced efficiency. The behaviour of reducing count rates at higher
lateral field schemes matches with the reduction in the 59.5 keV count rate seen in
Figure (103).

4.2.2 Line Scans of CdTe B at Room and Low Temperatures

The aim of this section is to investigate the effect of cooling and irradiating the
detector through the cathode contact on the detector spectroscopic performance (IV
and energy resolution). This has been performed using the CdTe B and resistor
networks. Figure (113) shows that the performance of CdTe B is limited by leakage
current which is a combination of bulk and surface leakage current which are formed
by the cathode and ring biases. Although the leakage current reduced significantly by
cooling CdTe B to -15° C, for example it falls from 1.8 nA at room temperature to
0.15 nA at 15° C using -100V (VB1) bias scheme. However, the FWHM of the 25
keV and the pulser width at the centre of the anode were increased by increasing the
bulk fields for each resistor boards. This increase became significant above -200V which also true for the 75 keV peak (Figure (114)).

![Figure (113) IV measurements of the CdTe B for different bulk and lateral field schemes](image)

Figure (113) IV measurements of the CdTe B for different bulk and lateral field schemes
Chapter 4 (Line - Scan Studies at Diamond Light Source)

Figure (114) 25 keV widths at the centre of the anode using different bulk and lateral field schemes using CdTe B at -15°C.

Figure (115) X ray spectra at the centre of the anode using the CdTe B, -100V(VB3) at room temperature and -15°C.
On the other hand, cooling CdTe B has a significant effect of reducing the leakage current and subsequently improving the energy resolution. It is clear from Figure (115) that both the 25 and 75 keV becomes more resolved as a result of cooling the detector which has a great effect on decreasing the leakage current. The FWHM of the 25 keV and 75 keV at this bias scheme at -15 °C are (2.50 ± 0.01) and (2.54 ± 0.01) keV respectively in comparison to (5.50 ± 0.01) keV and (4.30 ± 0.01) keV at room temperature for the same bias scheme (-100V (VB3)) due to the reduced leakage current from 23 to 0.4 nA. The count rates have not changed as in both cases they show almost similar count rates.

In comparison to CdTe A at room temperature, CdTe B at -15 °C shows both low leakage current and better energy resolution. The leakage currents at -100V using all resistor boards are less than 0.5 nA using CdTe B at -15 °C in comparison to 1.2 nA at -100V and the lowest lateral field (10-20-30)% using CdTe A at room temperature. The 25 keV width at the centre of the anode using CdTe B at -15 °C using the highest bias scheme -250V (VB3) is around 4 keV in comparison to 8 keV for the CdTe A at room temperature at the lowest bias scheme -100V(10-20-30)%.
4.2.3 Effect of Cooling on the CdTe B Device

Figure (116) shows that by using VB3 which gives almost similar lateral fields (35-65-90) % in comparison to (30-60-90) % which was obtained using a quad power supply, see Table (10), the active radius of CdTe B at room temperature was extended to 1 mm from the centre of the anode which corresponds to the 1st ring using -100V bulk field. In contrast, the active radius was extended to only 0.4 mm (1st gap) using CdTe A at room temperature, see Figure (112), using -100V (30-60-90) % bias scheme. Therefore, at the same bias scheme, by irradiating the detector through the cathode contact, the active radius of the detector was increased significantly. The FWHM of the 25 keV at this bias scheme is (5.50 ± 0.01) keV at room temperature which is much less than the FWHM of the 25 keV using CdTe A (8.50 ± 0.01) keV at the same bias scheme. Although the leakage current using CdTe B at room temperature is larger than CdTe A, yet the 25 keV peaks are more resolved by using CdTe B taking into account that the electronic noise of all components inside Box 2 is less than Box 1. The same behaviour of CdTe A could be expected for CdTe B in terms of increasing the active radius by increasing the lateral fields to high values.
greater than VB3 which is the highest lateral field which can be obtained by the resistor networks.

In contrast to Figure (116), Figure (117) shows spectra at the same bias scheme -100V (VB3) at -15 °C. Both the 25 and 75 keV peaks become more resolved as a result of decreasing the leakage current. Moreover, no significant effect has been noticed in terms of the active radius of the CdTe B by cooling it to -15 °C as in both cases it was extended to 1 mm away from the centre of the anode which corresponds to the 1st ring.

![Figure (117) X ray spectra using CdTe B at different positions at -15 °C using bias scheme -100V (VB3)](image)

A general feature, as the line scans move away from the centre of the anode, both the 25 and 75 keV peaks shift to lower energies. This shifting becomes significant at greater radii due to reduced bulk electric field. However, an increase in the drift field (lateral field) due to high ring potential can reduce this effect as well as increase the active radius of the detector. Due to the noise edge, the 25 keV peak can not be resolved at higher bulk fields. It seems that by increasing the lateral field initially, from VB1 to VB2 at low temperature i.e. from (3-6-12) % to (5-12-21) %, there is a
significant increase in the active radius of the detector as well as reducing in the peak shift. However by increasing the lateral fields using VB3 to (35-65-90) %, the improvement becomes more significant in terms of reducing the peak shift (uniformity of the peak) rather than in increasing the active radius. No significant effect on the active radius of the CdTe B was noticed by increasing the bulk field nor on the peaks shift. Figure (116) and Figure (117) show that both the 25 and 75 keV peaks shift to lower energies as the line scans moved away from the centre of the anode, until the peaks become invisible at distance greater than 1 mm using bias scheme -100V(VB3). However, the effect of shifting the 25 keV peaks to lower energies is more obvious than the 75 keV for the same positions. This is could be due to the mean interaction depth of the 75 keV photons which are absorbed deeper in the crystal, close to the anode, which makes the probability of its charge to recombine less than the 25 keV photons at the same position at the same bulk and lateral fields. Moreover, as the 25 keV peak is close to the noise edge, shifting this peak to lower energy ends up with interference with the noise edge and therefore disappears in comparison to the 75 keV at the same positions. This is true for all bias schemes using all resistor boards. Table (4) summarises the active radius of the CdTe B at -15°C using different bias schemes.

<table>
<thead>
<tr>
<th>Bulk field (V)</th>
<th>VB1 (1st gap)</th>
<th>VB2 (1st ring)</th>
<th>VB3 (1st ring)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-100</td>
<td>0.6 - 0.7</td>
<td>0.9 - 1 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>-120</td>
<td>0.6 - 0.7</td>
<td>0.9 - 1 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>-160</td>
<td>0.5 - 0.7</td>
<td>0.9 - 1 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>-180</td>
<td>0.5 - 0.7</td>
<td>0.9 - 1 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>-200</td>
<td>0.5 - 0.7</td>
<td>0.9 - 1 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>-250</td>
<td>0.5 - 0.7</td>
<td>0.9 - 1 mm</td>
<td>1 mm</td>
</tr>
</tbody>
</table>

Table (18) Active radius for all bias schemes using CdTe B at -15°C

Overall we conclude that the lateral fields have a significant effect on increasing the active radius of the detector whereas an increase in the bulk field has no significant effect on the active radius. Although by using VB2 and VB3 the active radius of the detector extends to the same radius considering the 75 keV peak, however, the total number of counts was increased and the effect of peaks shift to lower energies were reduced by using VB3, i.e. higher lateral field. Figure (118) shows that the effect of
reduced peak shift at increased lateral field strength. The position of the 25 keV is reduced significantly at low ring voltages (using bias scheme VB1) whereas there is only a very small shift in the peak position when higher lateral fields are used (bias scheme VB2 and VB3). This is also true for 75 keV peaks.

In contrast, increasing the bulk field using the same relative (percentage) lateral fields does not improve the active radius and does not cause the peak position to move up in energy. Figure (119) shows an example of increasing the bulk field from -100V to -250V using VB1 at the same position 0.6 mm from the centre of the anode using CdTe B at -15°C.
4.2.4 Uniformity of the 25 and 75 keV Peaks using CdTe B at -15°C

In terms of the active radius of the detector, increasing the bulk field does not improve the active radius of the detector as illustrated in Figure (120). This shows that the active radius of the detector is limited to 0.6 and 0.7 mm from the centre of the anode for 25 and 75 keV peaks respectively which corresponds to the 1st gap. However, due to the effect of the noise edge on the 25 keV, the 75 keV can be visible at 0.7 mm from the centre of the anode. This behaviour is true for all bias schemes using all resistor boards.
On the other hand, by increasing the lateral fields, i.e. using resistor boards VB1 and VB2, the active radius of CdTe B was increased significantly as illustrated in Figure (121). In this case the active radius of the detector extends to 0.9 and 1 mm away from the centre of the anode which corresponds to the 1st ring using VB2 and VB3 respectively at -100V bulk field by considering 25 keV peak. Although by using VB2 and VB3, the active radius extends to 1 mm from the centre of the anode at -100V bulk field considering 75 keV peak, yet the peak shift was reduced significantly at this position by using VB3. Moreover, the count rates were increased significantly as shown in Figure (121).
Figure (121) Line scans which show the active radius of CdTe B using -100V bulk field and different lateral fields at -15 °C.

Figure (122) and Figure (123) show how the 25 keV peak centroid varies at different positions for different bulk and lateral fields. This indicates the significant effect of the lateral field on the active radius as well as on reducing peaks shift whereas no significant effect was noticed by increasing the bulk fields. Moreover, Figure (123) shows the effect of the lateral field on the uniformity of the 25 keV peak. The 25 keV peak was uniform until 0.4 mm distance from the centre of the anode using VB1 then it starts to shift to lower energy. However, by using VB2 and VB3 the uniformity of the 25 keV peak increases to 0.5 and 0.7 mm from the centre of the anode respectively. This is also true for the 75 keV, however, due to the mean interaction depth of the 75 keV peak, the peak shift is more obvious in the 25 keV than in the 75 keV peak.
Figure (122) 25 keV peak centroid at different bulk and lateral fields

Figure (123) 25 keV peak centroid at different lateral fields at -100V bulk field
4.2.5 Studying CdTe B Performance when Rings are Floating

By disconnecting the bias on the rings (rings become floating), bias on the rings is floated to specific values which can be estimated by investigating the active radius of the detector and compare it to the active radius of the detector when different resistor boards were used. At -200V bulk field at room temperature, CdTe B is affected by high noise edge which interferes with the 25 keV peak especially at positions away from the centre of the anode in which both the 25 and 75 keV peaks were shifted to lower energy values. As the lateral field which is formed by the rings when they are floating is slightly higher at room temperature due to its lower resistivity in comparison to the resistivity of the detector at -15°C, the active radius at -100V bulk field extends to 0.9 mm away from the centre of the anode in comparison to 0.8 mm at -15°C considering the 25 keV peak. Although the active radius extends to 0.9 mm considering the 75 keV peak at room temperature and -15°C, however, the 75 keV peak shift reduced at room temperature at 0.9 mm to 42 % in comparison to 74 % at -15°C. Taking into account the total count rates and the active radius, therefore, the lateral field of the floating rings is approximately similar to VB2. However, at room temperature, the floating rings have a potential greater than VB2 and at -15 °C they have potential less than VB2. Table (7) summarises the active radius of the detector when the rings are floating at room temperature and -15°C. Figure (124) shows the 25 and 75 keV peaks at 0.9 mm from the centre of the anode when the rings were floating and when VB2 was used at room temperature and -15 °C. The 25 and 75 keV peaks shift were reduced by using VB2 at -15 °C and floating rings at room temperature respectively in comparison to floating rings at room temperature which indicates that the potential which were formed by the rings was floated to a specific value less than VB2 at -15°C and greater than VB2 at room temperature.
4.3 Spectroscopic Performance of CdTe B using Different γ ray Emitters

In this section, the spectroscopic performance of CdTe B at room temperature and -15 °C was studied using 59.5 keV $^{241}$Am and 122 keV $^{57}$Co γ ray sources. Unlike the line scans in which the interaction position takes place in specific regions in the CdTe B crystal, these sources emit photons uniformly in all direction (isotropic) which gives us information about the average performance of the detector across the whole surface area.
4.3.1 Effect of Cooling on the CdTe B Performance

Figure (125) shows clearly the effect of cooling on the energy resolution of the 59.5 keV and pulser peaks. As VB3 provides almost similar ring potentials at room temperature and -15 °C according to the previous simulation, see Table (10), however, at room temperature the potential in rings 2 and 3 is slightly higher (by 5%) than at -15 °C. This may explains the slightly higher CCE at room temperature (98%) than at -15 °C (96%).

As the leakage current was reduced significantly from 23 to 0.4 nA when the CdTe B was cooled to -15 °C, the energy resolution was improved from (5.1 ± 0.3) keV to (3.6 ± 0.1) keV. Moreover, the pulser width improved from (4.40 ± 0.01) keV to (2.70 ± 0.02) keV due to improving in the leakage current. This result matches qualitatively with the CdTe test detector at -15 °C.

4.3.2 Spectroscope Performance of CdTe B at -15 °C using Different bias Schemes

Unlike the line scan measurements, which show that the width of both 25 and 75 keV peaks at the centre of the anode were degraded by increasing the bulk and lateral
fields, CdTe B performance behaved differently using the 59.5 keV and 122 keV $\gamma$ ray sources. These sources emit energy uniformly in all direction in which some interaction position takes place near the anode and others at large radius.

![59.5 keV spectra at different bulk fields using VBl at -15 °C](image)

Figure (126) 59.5 keV $^{241}$Am spectra at different bulk fields using VBl at -15 °C

Figure (126) shows that by using VBl which gives the lowest lateral field at -15 °C (3-6-12) %, increasing the bulk field from -100V to -250V improves CCE from 94 to 98 % which subsequently improves the energy resolution of the 59.5 keV peak from (4.00 ± 0.03) keV to (2.8 ± 0.2) keV. No significant effect was observed on the pulser peak widths at these bias schemes which are almost constant around (2.2 ± 0.2) keV. However, when increasing the bulk field further more to obtain a much higher CCE, an increased leakage current was observed which degrades the energy resolution. No significant effect was observed in terms of improving the detection efficiency evaluated by the count rates when increasing the bulk field for the same lateral field ratio which matches the results which were obtained using the line scans. The count rate of the 59.5 keV peak at -100, -200 and -250 V using (VBl) is around 0.3 c/s. On the other hand, increasing the lateral field has increased the count rates significantly which also matches with the line scan measurements which shows the
active area increased significantly by increasing the lateral field. The count rate of the 59 keV peak increased from 0.3 c/s to 1.8 c/s by increasing the lateral field using the same bulk field -250V i.e. using VB1 and VB3 respectively (Figure (127). However, the energy resolution slightly worsened from (2.8 ± 0.2) keV to (3.40 ± 0.11) keV by using VB1 and VB3 at -250V respectively due to increasing in the leakage current which starts to be a significant issue at this bias scheme and onward (Figure (113). The pulser peak width increased from (2.2 ± 0.2) keV to (2.8 ± 0.2) keV due to increasing in leakage current from 0.9 nA to 2.9 nA.

![Graph showing 59.5 keV spectra using CdTe B at -250V bulk field at -15 °C](image)

Figure (127) 59.5 keV $^{241}$Am spectra using CdTe B at -250V bulk field at -15 °C

It seems that, the energy resolution was improved by increasing either the bulk field with fixed ratio lateral fields, or by increasing the lateral fields with a fixed bulk field which tended to initially improve the CCE. After that, the detector becomes limited by leakage current. Overall, to obtain good quantum efficiency with reasonable energy resolution, this detector works efficiently at low temperature using low bulk field and very high lateral fields.

Table (20) summarises the key points of the performance CdTe B at -15 C° in which a much better energy resolution can be predicted at -100V bulk field with higher lateral
field greater than VB3. At the lowest lateral field i.e. VB1, the active area of the detector is very small which explains the very low count rate (0.09 c/s).

<table>
<thead>
<tr>
<th>Bias scheme</th>
<th>59.5 keV width (keV)</th>
<th>59.5 keV CCE %</th>
<th>59.5 keV count rate (c/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-100V(VB3)</td>
<td>3.6 ± 0.1</td>
<td>96%</td>
<td>2.6</td>
</tr>
<tr>
<td>-250V (VB3)</td>
<td>3.3 ± 0.1</td>
<td>98%</td>
<td>2.5</td>
</tr>
<tr>
<td>-250V(VB1)</td>
<td>2.8 ± 0.2</td>
<td>98%</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Table (20) Summary of the energy resolution and CCE% for a selection of bias scheme using CdTe B at °C

Similarly the 122 keV $^{57}$Co spectra show the same behaviour. However, the count rates are very low in comparison to the 59.5 keV $^{241}$Am as most of the interaction in the photo-peak is due to Compton scattering. Figure (128) shows the 122 keV $^{57}$Co spectra at different bias schemes. The energy resolution and CCE of the 59.5 keV $^{241}$Am peak are better than that of the 122 keV $^{57}$Co, (4.7 ± 0.1) keV at -100V (VB3) for the 122 keV in comparison to (3.6 ± 0.1) keV for the 59.5 keV. Moreover, at energies higher than -100 keV which may be absorbed deeper in the crystal, holes may still contribute to the anode signal than that absorbed near the surface taking into account 122 keV $^{57}$Co cannot be resolved at very low electric field i.e., using VB1 at -15°C.

Figure (128) 122 keV $^{57}$Co spectra at different bias schemes at -15°C
4.4 Line Scan Studies of CZT B at Room Temperature

The aim of this section is to investigate the performance characteristics of the CZT drift ring detector at room temperature, CZT B. This detector has a similar geometry and specifications to CdTe A and B in terms of number and width of rings and gaps. The only difference is its thickness is 2.3 mm in comparison to 1 mm for CdTe A and B, see Table (5). This study includes line scan measurements at room temperature using Box 1, see Figure (48) and subsequently using a quad power supply to bias the rings separately rather than using resistor networks. The aim of using Box 1 and a quad power supply for the CZT B is to bias the rings with high values independently from the cathode taking into account the previous conclusion from the results of CdTe A and B in which the lateral fields have the significant effect of increasing the active radius and total count rates. Therefore, this conclusion can be tested in the case of CZT B without experiencing high leakage currents due to its high resistivity, see Table (9) and chapter 2. The same X ray micro-beam specifications which were used for CdTe B, have been used for CZT B, see Table (17). Moreover, the spectroscopic performance of CZT B was also studied using different radioisotopes which emit different energies, see Table (12). This study was conducted at room temperature and at -15 C° using two different techniques of biasing, i.e. resistor networks and a quad power supply. Different voltage bias schemes were used to investigate the detector performance. This includes increasing the bulk field; cathode bias; and the lateral field; rings bias; as a percentage of cathode bias, increasing the bulk fields for the same lateral field, and increasing the lateral fields for the same bulk field, see Table (8). The detector was mounted on the same ceramic substrate in which the X ray and photons were incident on the planar cathode, whereas the anode and ring structures were connected to the ceramic board.

4.4.1 Spectroscopic Performance and IV Measurements

Figure (129) shows that the IV measurements of the CZT B at room temperature using the resistor networks VB1-VB3. Although the line scans of the CZT B were conducted using the quad power supply, however, the trends of the leakage current by using different bulk and lateral fields are expected to be similar qualitatively if the IV measurements were conducted using the quad power supply. CZT B shows low leakage currents in comparison to CdTe B at -15 C° although the resistivity of the
CdTe B at -15°C is higher than that of the CZT at room temperature, see Table (9). In the case of the CdTe B at -15°C, both the 25 keV and 75 keV peaks were limited by the leakage current see Figure (113) and Figure (114). They hardly changed by using different bias schemes in the case of the CZT B at room temperature. Figure (130) show that, both the 25 and 75 keV signals and the pulser peaks have not changed significantly with leakage current at -700V bulk field and different lateral fields i.e (10-20-30)% - (30-60-90)%. However, at -700V and very high lateral field, (-500,-600,-700) V, these peaks started to be affected by high leakage current. Although Figure (129) shows a trend of increasing leakage currents by increasing the bulk and lateral fields however, this increase is very low, less than 0.2 nA, to be a significant effect to deteriorate the energy resolution. However, increasing in leakage current significantly is expected to start at the bulk field greater than -700V and lateral field greater than (-500,-600,-700) V. The FWHM of the 25 keV and 75 keV 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. Theses widths are increased at -700V bulk field and (-500,-600,-700) V lateral field to (5.8 ± 0.1) and (6.3 ± 0.1) keV for the 25 keV and 75 keV peak with a pulser width of (5.0 ± 0.1) keV due to increasing in leakage current.

Figure (129) IV measurements of the CZT B at room temperature

![Graph showing leakage current on the anode (nA) vs. Bulk field](image_url)
Figure (130) The FWHM of the 25 and 75 keV at the centre of the anode using different lateral fields at -700V bulk field.

Figure (131) shows X ray spectra at two different bias schemes which represent minimum and maximum leakage current tested in this work at the centre of the anode. The energy resolution of both the 25 and 75 keV starts to be affected by the leakage current at high bulk and lateral fields. The FWHM of the 25 keV and 75 keV at -100V bulk field and (-10,-20,-30) V lateral field are (4.7 ± 0.1) keV (4.9 ± 0.1) keV respectively which increased to (5.8 ± 0.1) and (6.3 ± 0.1) keV at -700V bulk field and (-500,-600,-700) V lateral field.
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Cooling the CZT B detector to -15°C decrease the leakage current significantly, see Figure (132). Improvement in the detector performance in terms of the energy resolution is expected to be seen at high bulk and lateral fields at low temperatures.

Figure (131) X ray spectra at two different bias schemes using CZT B at room temperature

Figure (132) IV measurements of CZT B at -15°C
However, it seems that cooling the CZT B detector from room temperature to -15 °C has no significant effect on the detector performance in terms of improving the energy resolution at low bulk and lateral fields. Figure (133) shows the 59.5 keV peaks at the same bias scheme, -500V (VB3), at room temperature and -15 °C. Although the leakage current has reduced from 0.2 nA to 0.01 nA, yet these values are too low to provide significant effect on the energy resolution for the CZT B because this detector is now limited by the preamplifier noise only. The 59.5 keV at -500V (VB3) at room temperature is (3.3 ± 0.1) keV whereas it is (3.1 ± 0.2) keV at -15 °C which are almost equal the pulser width at this bias scheme (2.8 ± 0.1) keV. This behaviour is also true at -300V (VB3) bias scheme at room temperature and -15 °C.

On the other hand, as the leakage current is expected to be high at -700V (-500,-600,700) V and above, cooling the CZT B at this bias scheme may provide better energy resolution as a result of reducing the leakage current.
4.4.2 Uniformity of 25 and 75 keV Peaks at Different Bias Schemes

Similar to the performance of CdTe at -15°C, both the 25 and 75 keV peaks start to shift to lower energies as the line scans move away from the centre of the anode. However, in the case of CZT B the distance from the anode that shows full charge collection can be extended by increasing both the bulk and lateral fields, while in the case of CdTe B at -15°C, the improvements can only be seen by increasing the lateral fields, as increasing the bulk field did not increase the active area. This difference is attributed to the larger thickness of 2.3 mm for the CZT B device compared to only 1 mm in CdTe B. Figure (134) and Figure (135) show the effect of increasing the bulk field of the CZT B detector from -100V to -700V for the same lateral field percentage ratios, (30, 60, 90)% of this bulk field, on the active radius of the detector. The active radius improved from 0.6 to 0.8 mm by increasing the bulk fields from -100V to -700V. Moreover, the effect of peak shift reduced in the positions where 25 keV signal is sufficiently resolved. This is also true for the 75 keV but with lower count rate.
Initially at low bulk and lateral field of the CZT B detector, -100V (30,60,90) %, the 25 keV peak position is uniform until 0.4 mm distance from the centre of the anode. After that, the 25 keV starts to shift to low energy until it become invisible at 0.7 mm and thus reflect the active area of the detector, Figure (134). However, by increasing the bulk field to -700V within the lateral field ratio (30-60-90) %, the uniformity of the peak is increased and it extends to 0.6 mm distance from the centre of the anode. Again after that, it starts to shift to low energy until it become invisible at 0.9 mm distance from the centre of the anode, Figure (135). Figure (136) shows 25 keV and 75 keV peaks at 0.7 mm (~ edge of the 1st ring) distance from the centre of the anode using different bias schemes. It is clearly appear the effect of increasing both bulk and lateral fields on the uniformity of the peaks. At -300 V (30-60-90) % bias scheme, the 25 keV peak position shifts to 9 keV position at 0.7 mm distance from the centre of the anode. However, by increasing this bias scheme to -500V and -700V for the same lateral field ratio (30-60-90) %, the effect of shifting reduce to 15 and 20 keV position. Further increasing the lateral field to (500,-600,-700) V, keeps the peak position uniform at 25 keV position due to the increase in the active area of the detector.
Figure (136) X Ray spectra at 0.7 mm distance from the centre of the anode using CZT B at room temperature

Figure (137) shows a summary plot of the active radius for different bias schemes for both 25 and 75 keV peaks which show clearly the effect of both bulk and lateral fields on the active radius of the detector. Theses active radii are within uncertainty of line step size, i.e. 0.1 mm.

Figure (137) Active radius of CZT B for different bias schemes at room temperature
Although lateral fields have the most significant effect in improving the active radius, however, increasing bulk fields show also an improvement which includes increasing in the active radius and reducing the peaks shift (peak uniformity). For example, the active radius extends to 0.4 mm considering the 25 keV peak at the lateral field (10-20-30) % as a percentage of the bulk fields. However, the 25 keV peak shift was reduced significantly by increasing the bulk field from -300V to -700V within this percentage lateral field ratio, i.e. (10-20-30) %.

Figure (138) shows a summary plot of the effect of increasing the lateral fields at the same bulk field, -700V.

By increasing the lateral field from (10-20-30) % to (30-60-90) % at the same bulk field -700V of the CZT B detector, the uniformity of the 25 keV peak is extended to
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0.6 mm distance from the anode. However, due to its low leakage current, the lateral fields on the rings of CZT B can be increased significantly without experiencing high leakage current. Therefore, large active radius can be achieved with a uniform peak. At -700V bulk field and (-500,-600,-700) lateral field, the active radius extends to 2.5 mm distance from the centre of the anode which corresponds to the gap between 2\textsuperscript{nd} and 3\textsuperscript{rd} ring. Moreover, the 25 keV peak position is uniform until 2.3 mm distance from the centre of the anode, see Figure (139). Therefore, the uniformity of the peak is increased significantly by increasing both the bulk and lateral field to very high values using the CZT B detector without experiencing high leakage current.

![Image](image.png)

Figure (139) X-ray spectra at -700V (-500,-600,-700) V bias scheme using CZT B at room temperature

4.4.3 Performance Characteristics of CZT B using Different $\gamma$ ray Energies

The aim of this section is to study the performance of CZT B using different $\gamma$ radioisotopes which have different penetrating depths. This was done by using $^{241}$Am (emits $\gamma$ at 59.9 keV), $^{57}$Co (emits $\gamma$ at 122 keV) and $^{137}$Cs (emits $\gamma$ at 662 keV). Different bias schemes were used to investigate the detector performance. These $\gamma$
isotopes emit photons uniformly in all direction which has different effect than that of line scans. As the highest lateral field is limited to (30-60-90) % using VB3, a quad power supply was used for some high lateral field i.e. > VB3 to investigate the trends of the energy resolution of different photo-peaks. As a general trend and like the CdTe B at -15°C, at low bulk and lateral fields, CZT B had low CCE which ends up with broad FWHM. Increasing both the bulk and lateral fields improve the energy resolution as a result of improving the CCE. Figure (140) shows that at -100V (VB1), the active area of the detector is very small which shows large events at low energy. This is believed to be due to photons which were absorbed at large distance from the anode. The FWHM of the 59.5 keV at this voltage scheme is (6.4 ± 0.1) keV. By increasing the bulk field within this lateral field ratio, the active area is increased which decreases the large events at low energy and subsequently the energy resolution is improved to (5.0 ± 0.1) keV and (4.0 ± 0.1) keV at -300V and -500V respectively. Due to low leakage current, the pulser widths did not change and therefore the energy resolution is now mainly limited by the geometry of the detector and the preamplifier electronic noise which is (2.6 ± 0.1) keV. Further increasing the bulk and lateral field improves the energy resolution as a result of increasing the active area and CCE as shown in Figure (141). The FWHM of the 59.5 keV at -500V (VB3) is (3.3 ± 0.1) keV and the pulser width is (2.8 ± 0.1) which indicates very good energy resolution.
Figure (140) $^{241}$Am spectra (59.5 keV) at different bulk fields using resistor network VB1 (10-20-30) % and CZT B

Figure (141) $^{241}$Am spectra (59.5 keV) at different bulk fields using resistor network VB3 (30-60-90) % and CZT B
Figure (142) shows the trends of the FWHM of the 59.5 keV for different bias schemes using CZT B detector and the resistor networks. A quad power supply was used to bias the rings with very high values i.e. (-500,-600,-700) V. At this lateral field and using -700 Bulk field, the active area is increased significantly but the detector becomes limited by leakage current as illustrated in Figure (143).

![Figure (142) The FWHM trends of 59.5 keV using CZT B at room temperature using different bias schemes (Box 2)](image1)

![Figure (143) The FWHM trends of 59.5 keV using CZT B at room temperature using different bias schemes (Box 1)](image2)
Figure (144) shows the 59.5 keV line at -700 V (-500,-600,-700) V bias scheme which shows the best active area achieved according to the line scan studies. Most of events at large distance from the centre of the anode has eliminated and subsequently Cd and Te escape peaks are visible. However, due to high leakage current, the FWHM of the 59.5 keV is limited by leakage current. The FWHM of the 59.5 keV is $(6.2 \pm 0.1)\text{ keV}$ and the pulser width is $(5.1 \pm 0.1)\text{ keV}$ using the quad power supply.

These results match with IV measurements in which at high bulk and lateral fields, the leakage current starts to be a significant effect in terms of deteriorating the energy resolution. On the other hand, increasing the lateral fields has a significant effect of increasing the detector efficiency expressed as count rates. Recalling the main conclusion of the performance of CdTe B at -15°C and CZT B at room temperature using the line scans in which the 25 and 75 keV peaks shift to lower energies as the line scans move away from the centre of the anode. This behaviour can be decreased either by increasing the lateral fields for the CdTe B at -15 °C or increasing both the bulk and lateral fields for the CZT B at room temperature. By Increasing the lateral
fields from (-70,-140,-210) V to (-500,-600,-700) V at the bulk field -700V, the features of the spectrum become clearer and this depends on the interaction depth in the CZT B crystal. Figure (145) shows the 59.5 keV $^{241}$Am spectra at two different bias schemes. At (-70,-140,-210)V the events at low energies represent the interactions which occurred at radius far from the anode which was improved by increasing the lateral fields further to (-140,-280,-420) V. By reaching lateral fields (-500,-600,-700) V, the escape peaks due to Cd and Te k X ray can be distinguished as discussed in Figure (144).

Similarly, Figure (146) shows the same effect for the 122 keV $^{57}$Co, however, the features of the spectrum can be identified clearly at higher lateral fields in comparison to the 59.5 keV $^{241}$Am which is in this case at (-500V,-600,-700)V in comparison to -(140,-280,-420)V in the case of the 59.5 keV $^{241}$Am.
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Figure (146) The 122 keV $^{57}$Co spectrum at different lateral field at -700 V bulk field using CZT B

However, in the case of $^{137}$Cs where the interaction position takes place deeper in the crystal the 662 keV $^{137}$Cs cannot be resolved at lower lateral fields while by reaching the lateral fields (-500, -600, -700) V the 662 keV can be identified with very low count rates and poor energy resolution as illustrated in Figure (147).

Figure (147) The 662 keV $^{137}$Cs spectrum at -700 V (-500, -600, -700) V using CZT B
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Table (21) summarises the detector performance at -700V bulk field and different lateral fields along with different radioisotopes. As the depth of the interaction takes place near the cathode surface, the better energy resolution is obtained. If the interaction takes place deeper in the crystal, much higher lateral field are needed to obtain good spectrum and energy resolution.

<table>
<thead>
<tr>
<th>Lateral field (V)</th>
<th>FWHM (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>59.5 keV</td>
</tr>
<tr>
<td>(-70,-140,-210)</td>
<td>5.4 ± 0.2</td>
</tr>
<tr>
<td>(-140,-280,-420)</td>
<td>5.0 ± 0.2</td>
</tr>
<tr>
<td>(-210,-420,-630)</td>
<td>5.5 ± 0.1</td>
</tr>
<tr>
<td>(-500,-600,-700)</td>
<td>6.2 ± 0.1</td>
</tr>
</tbody>
</table>

Table (21) Performance of CZT B using different isotopes at -700V bulk field

Figure (148) shows the calculated photons fraction transmitted across the CZT detector material. At 2.3 mm, the 59.5 keV transmitted photons reduced to 0.5 % whereas for the 122 keV and 662 keV are 35 % and 94 % respectively. Therefore, the 662 keV $^{137}$Cs photons are distributed much deeper in the crystal than 122 keV $^{57}$Co and 59.5 keV $^{241}$Am.

![Figure (148) Photons transmitted % for different isotopes using CZT detector](image-url)
It seems that at low lateral field, the events at low energy is believed to be due to interaction positions at large radius from the anode in which peaks shift to lower energies. By increasing the lateral field these events are reduced, reduced peak shift, which ends up with clear spectra without high edge which represents events at low energies. These low energy events depend on the interaction positions in the crystal in which higher energy isotope which absorbs deeper in the crystal needs higher lateral field than isotopes absorb in the surface as illustrated in Table (21), Figure (145) and Figure (146). This effect was proven by using the line scan measurements and correction of the radius. By adding up the number of counts for each position at the bias schemes -700V (-500,-600,-700) V, similar plot was obtained to the spectrum by using the 59.5 keV $^{241}$Am as illustrated in Figure (149). This simulation was conducted by assuming the line scans at the centre of the anode covers the area between the centre and 0.05 mm away from the centre of the anode and the line scans at 0.1 mm covers the area between 0.05 and 0.15 mm and in each scan this assumption was conducted then the number of counts were added up for all areas.

The small feature under 25 keV is believed to be due to low energy event at positions faraway from the centre of the anode.
Chapter 5 Conclusion and future work

In this project, the performance of CdTe and CZT drift ring detectors shows promising results that may direct the efforts to produce these kind of detectors commercially. Due to its potential applications in many fields especially for astronomy and space science, which were explained in chapter 1, CdTe and CZT drift ring detectors may overcome the limitations of current planar detectors. These limitations are associated with low quantum efficiency and poor energy resolution. The key elements which are achieved in this project can be summarised in many points. The drift technique which has the advantage of eliminating the limitations of hole trapping and compromise the effect of leakage current due to its low input capacitance, can provide good quantum efficiency by controlling the lateral fields. The effect of high leakage current which was observed using CdTe A at room temperature which deteriorates the energy resolution while attempt to increase the active radius was strongly eliminated by cooling the detector. CdTe B at -15 °C shows reasonable energy resolution with good quantum efficiency. As the lateral field was limited to (35-65-90) % of the bulk field using VB3 and Box 2, CdTe B at -15 °C was not tested at lateral field greater than (35-65-90) %. However, as a general trend and based on the performance of CdTe A at room temperature, it is expected that the active radius of CdTe B at -15° C extends further more to large radius from the centre of the anode with reasonable energy resolution in comparison to CdTe A at room temperature. Both irradiation geometries, irradiation the cathode and anode/ring side, and reducing the leakage current by cooling the detector provide large active radius at low bulk and higher lateral fields, taking into account that increasing the bulk field and lateral field as a ratio of bulk field did not improve CdTe B performance. On the other hand, as the CZT B provides better active radius at -700V (-500,-600,-700) V, 2.5 mm from the centre of the anode which represents the gap between ring 2 and 3. The energy resolution could be improved more by cooling this detector at this high bias scheme. Due to it thickness, 2.3 mm, CZT B in comparison to 1 mm thick CdTe B demonstrates better quantum efficiency. This appears as increase in the active radius, increase in total count rate and reduced peak shift by either increasing the bulk and lateral fields as a ratio of bulk field or increasing the lateral field for fixed bulk field. However, CdTe B demonstrates these improvements by increasing the lateral field only. Moreover, as higher penetrating isotopes have not been resolved using
Chapter 5 Conclusion and future work

CdTe B at low bulk and lateral fields and show low count rate using CZT B, the thickness of CZT could be compromised. A thicker crystal could be fabricated to this ring geometry without suffering significantly from hole trapping in order to detect much higher energy radioisotopes efficiently and subsequently higher bulk and lateral fields can be optimized to increase the active radius of the detector. Moreover, as the leakage current can be reduced significantly by cooling the detector, CZT B could provide much better energy resolution while attempt to increase the active radius by increasing the bulk and lateral fields. Although, the 3rd ring area is dead by using both CdTe and CZT B, the active radius could extend to ring 3 by increasing the bulk and lateral fields to high values of CZT B with cooling it to low temperatures and optimising its thickness to detect more penetrating isotopes.

For future work, the current geometry can be optimized by decreasing the ring widths and therefore achieve a large active radius. In addition, Schottky contact of the same geometry which is charcaterized by its low leakage current could be tested at low temperature and high bias voltage to reduce the effect of polarization and reach stability. Both increasing the bias and lowering the temperature have effects on increasing the effective depletion layer and the ionization time of the deep acceptors in the detector respectively and subsequently decrease the effect of polarization. Therefore, the stability can be maintained by keeping the electric field distribution stable in the detector, see section 3.1.2 page 85 [71].

Optimizing the resistor networks to yield much higher lateral fields could increase the active radius without using an independent power supply. Finally, improving the readout system by using input FET similar to the commercially pad CdTe detector and the small CZT drift ring detector [65] could improve the energy resolution significantly.

To conclude this project, CZT based on the drift technique of ring geometry with high lateral field is definitely better than CdTe and this is attributed to its large resistivity which decreases the leakage current and assures room temperature operation.
Appendix A

Fabrication process of the CZT drift ring detector

The aim of this part is to describe the process of the Photolithiography which was made at the University of Surrey by Dr. Veeramani Perumal. Generally, in this process the three ring pattern, see Figure (150), is transferred from a mask onto the CZT crystal covered by a chemical material (Negative photo-resist). Then a chemical treatment which includes using a developer and remover is used. In the following subsections, the steps of this process are explained.

![Glass plate which contains different ring patterns](image)

1. Spin coating (photo-resist)

After cleaning the CZT crystal from any possible contaminating materials by using isopropanol, methanol and acetone solutions, one drop of negative photo-resist (ma-N1410) is used to cover the crystal using a spin coater. Since photo-resist is a UV sensitive material, this process should be done under yellow room light to avoid any reaction of photo-resist with the normal light. The spin coater was programmed to run the spin header for 3500 rpm for 2 minutes in order for ~100 nm thickness of the photo-resist to spread uniformly onto the CZT crystal. Figure (151) shows a schematic diagram of the CZT crystal after coating with the photo-resist.
2. Mask aligner

The aim of this process is to transfer the three rings pattern from the mask to the CZT crystal by exposing it to the Ultraviolet light (UV) using the mask aligner. The CZT crystal will contain finally the photo-resist that exposed to the UV light and the three rings which are the chemical photo-resist only.

Figure (152) and Figure (153) show a schematic diagram of the CZT crystal during and after the process of UV exposure.
3. Developing the CZT Crystal

A ma-D533s developer is used to develop the ultraviolet exposed photo-resist in the CZT crystal and give the three rings device pattern. Therefore, the photo-resist which exposed to the UV light will be removed from the CZT crystal by the developer while the photo-resist which did not react with UV light will remain in the CZT crystal giving the three rings pattern. The CZT crystal now has the three rings with photo-resist and the three gaps. Figure (154) shows a schematic diagram of the CZT crystal after the process of developing.

4. Sputtering

In this process, the developed crystal is moved to a sputterer for metal deposition to evaporate a 100 nm gold contact on the CZT crystal for both top and bottom contacts. After that, the CZT crystal is placed in mr-Rem 660 photo-resist removal solution. The photo-resist with gold metal on the crystal will be removed from the crystal as it reacts with the photo-resist removal leaving behind the crystal with the final three rings pattern (gold metal), the three gaps (CZT crystal). Figure (155) and Figure (156) show the CZT crystal after using the sputter and using the removal solution respectively.
Passivation

In this process, a photo-resist is spread out the crystal again using spin coating. After that, the mask aligner is used with the reverse pattern to expose UV light onto the crystal but in the process the UV light will expose to the non-metal contact. Using the same procedure, the developer will react with photo-resist that exposed to the ultraviolet light. Then, the crystal was placed into hydrogen peroxide for the passivation process in which the Te part oxidised into TeO$_2$ layer and become highly resistive to reduce the surface leakage current while the back contact will be protected by the photo-resist layer. Finally, a removal is used to remove the photo-resist layer above the gold and in the back contact. This process is called (positive photo-resist).
Appendix D

List of publications
MATERIAL REDACTED AT REQUEST OF UNIVERSITY