Fabrication and Optimisation of Room-Temperature CdZnTe Radiation Detectors

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By

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ABSTRACT

The ternary compound Cadmium Zinc Telluride (CdZnTe) is one of the most promising room-temperature semiconductor detectors. It possesses the necessary material properties that are required to exhibit optimal detection performance. But unfortunately it does not display that expected level of performance because it has some shortcomings at various stages from crystal growth to contact fabrication. Investigations in each area have been pursued individually over the last decades and it is a goal in the field to integrate the optimal properties from each area into a fully optimised detector.

In this work, the metal contacts to CdZnTe detectors have been investigated since these are believed to be one of the most vital areas among the possible detrimental aspects. In order to evaluate the contact features, different configurations of contact were fabricated on the supplied CdZnTe detector crystals using the available laboratory facilities. A great deal of effort was put into contact design and fabrication as well as the characterisation of the fabricated devices.

Endeavour was made to correlate the characterisation results of different configurations with their physical structure as well as drawing comparison with commercial devices. Work was concluded by focussing on optimum detector designs including the factors that limit their performance.
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Experimental work is much harder than theoretical work for me....

but still I like it..

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List of Publications:

The following papers, based on work presented in this thesis have been published or received to be published in scientific journals:


CONTENTS

Abstract .......................................................................................................i
Acknowledgements ....................................................................................ii
Personal Word ..........................................................................................iii
List of Publications ...................................................................................iv

CHAPTER ONE: Introduction ..................................................................1

CHAPTER TWO: Background - Radiation Physics ..............................6

2.1 Interaction of ionizing radiation with matters ..............................6
  2.1.1 Alpha particle interaction .......................................................7
  2.1.2 Beta ray interaction ...............................................................8
  2.1.3 Neutron interaction ..............................................................9
  2.1.4 Gamma and X-ray interaction .............................................9
    2.1.4.1 Photo-electric effect .....................................................9
    2.1.4.2 Compton effects ..........................................................10
    2.1.4.3 Pair production ..........................................................12
  2.2 Biological effects of radiation .................................................13
    2.2.1 Deterministic effects .......................................................14
    2.2.2 Stochastic effects ............................................................14
    2.2.3 Reasons for being exposed ............................................14
  2.3 Route of radiation hazard .......................................................15
    2.3.1 External radiation hazard ..............................................15
    2.3.2 Internal radiation hazard ..............................................16
  2.4 Radiation Dosimetry ...............................................................16
  2.5 Conclusion ..................................................................................18

References ............................................................................................19

CHAPTER THREE: Radiation Detection Systems .............................20

3.1 Introduction ..................................................................................20
3.2 Brief description of various detection systems ............................20
  3.2.1 Guiger-Mueller (G-M) detector ..........................................20
3.2.2 Scintillation detector ............................................. 22
3.2.3 Semiconductor detector ........................................... 23
3.3 Gamma and X-Ray spectroscopy ..................................... 25
  3.3.1 Detector characterisation ....................................... 28
    3.3.1.1 Energy calibration ..................................... 28
    3.3.1.2 Energy resolution ..................................... 28
    3.3.1.3 Detection efficiency ................................... 31
3.4 Compound Semiconductor detectors ................................ 33
3.5 Semiconductor properties ........................................... 34
  3.5.1 Energy band of semiconductor and metal ....................... 34
  3.5.2 Charge carriers ............................................... 35
  3.5.3 Charge transport ............................................. 36
  3.5.4 Carrier Mobility ............................................. 37
  3.5.5 Carrier lifetime .............................................. 38
3.6 CdZnTe as Room-Temperature Semiconductor Detector ............... 40
  3.6.1 CZT crystal structure ......................................... 41
  3.6.2 Metal-semiconductor contacts ................................ 42
    3.6.2.1 Ohmic contact ......................................... 43
    3.6.2.2 Rectifying contact ................................... 44
3.7 Electro-optic effects in CZT ....................................... 46
  3.7.1 The Kerr effect ............................................. 47
  3.7.2 The Pockels effect ........................................... 47
    3.7.2.1 E-field measurement .................................. 48
3.8 Conclusion ..................................................................... 50
References .......................................................................... 51

CHAPTER FOUR: Overview of Experiments and Equipment .............. 55

  4.1 Introduction ............................................................ 55
  4.2 Brief description of overall experiments .......................... 55
  4.3 Optical instruments and their properties ......................... 57
    4.3.1 Laser Diode ..................................................... 57
    4.3.2 Silicon photodiode detector .................................. 59
    4.3.2.1 Spectral response ....................................... 60
4.3.2.2 Photodiode responsivity ........................................... 60
4.3.2.3 Quantum efficiency (Q.E.) ........................................ 61
4.3.2.4 Dark current ....................................................... 61
4.3.2.5 Temperature effects ............................................. 62
4.3.3 Polarizing components ............................................. 62
        4.3.3.1 Extinction ratio ............................................ 64
4.3.4 Neutral density filter ............................................. 64
4.4 Optical beam waist measurement .................................... 64
4.5 Optical calibration .................................................... 67
        4.5.1 Laser beam power calibration ................................. 67
        4.5.2 Reflected beam measurement ................................. 68
        4.5.3 Attenuation uniformity of neutral density filter .......... 69
4.6 Cryostat ........................................................................... 70
4.7 Noise in the system ....................................................... 72
4.8 Conclusion ......... 74
References ........................................................................... 75

CHAPTER FIVE: Band Structure and Optical characterisation
of CZT detector ................................................................. 76

5.1 Introduction .................................................................... 76
5.2 Theory ............................................................................. 78
        5.2.1 Barrier formation ..................................................... 78
5.3 Experiments .................................................................... 79
        5.3.1 I-V characteristics ................................................... 80
        5.2.2 Bulk Resistivity ....................................................... 81
5.4 Investigation of Schottky barrier ..................................... 82
        5.4.1 Barrier height measurement ....................................... 82
        5.4.2 Photovoltaic measurement ....................................... 82
        5.4.2.1 Experimental set-up ............................................ 83
        5.4.2.2 Results and discussions ....................................... 84
        5.4.3 Study of the source of proposed barrier ..................... 86
5.5 Discussion ....................................................................... 88
5.6 Photo-Electronic Investigation of CZT spectral detector ...... 88
CHAPTER ONE

INTRODUCTION

The extensive popularity of silicon and germanium materials for detector fabrication is attributable to their excellent energy resolution. However, the need to operate at liquid nitrogen temperature to keep the leakage current to a minimum level limits their widespread use in practice. A wider band-gap semiconductor material could reduce the bulk generated leakage current so that use at room temperature would be possible. Moreover, gamma-ray spectroscopy detectors with a high atomic number result in higher x- and gamma ray detection efficiency than detectors with lower atomic number. The compound semiconductors like CdTe, HgI₂, GaAs etc. have received a great deal of attention as potential room temperature radiation detectors.

Among the compound semiconductor detectors CdTe [1-5] was the first material to have been developed as a room temperature radiation detector. It has good stopping power for energetic photons, produces reliable spectra, and is fairly rugged in field applications. However, a problem of CdTe during crystal growth is the high vapour pressure of Cd which can cause serious stoichiometry problems that impairs the detector performance. To reduce the stoichiometry problem during crystal growth, it has been suggested that the lower vapour pressure material Zn should be added to replace Cd so forming the ternary compound Cdₙ₁₋ₓZnxTe. The yield of spectrometer type crystals demonstrates dramatically improved performance as a radiation detector [6]. A Zn concentration of a few percent increases the energy band gap and resistivity of the detector, which are the pioneer characteristics of semiconductor detectors.

There are still a lot of problems associated with both CdTe and CZT detector that must be solved in order to offer a reasonably excellent detection performance. Problems are mainly due to defects in crystal material and detector fabrication. The defects may be of intrinsic origin like vacancies, dislocations or of extrinsic origin like all the impurities and their associated complexes. In CZT, another problem is the concentration distribution of Zn alloying which leads to stoichiometric defects.
Chapter one: Introduction

Unintentionally introduced impurities are mostly responsible for acting as trapping sites at various levels within the bandgap and it is very difficult to attain an impurity free crystal. In fact, the source materials of Cd, Zn and Te contain impurities. Apart from this, some impurity materials are unintentionally introduced into the crystal boule during crystal growth. The influence of these defects can not be eliminated but the concentrations of defects should be reduced or at least kept under control.

However, CZT crystal grown by the high pressure Bridgman method allows one to obtain spectrometric quality crystals but some extrinsic problems restrain the detector performance away from the satisfactory goal. The common problem observed with CZT detector materials is the low mobility and short lifetime of holes, and the tendency of the carriers to get trapped in deep levels within the forbidden band which substantially influence the electrical properties of the detector. Moreover, leakage current arises from the bulk as well as the surface of the detector. There are both sources of noise in the detection system that also degrade the performance of the detector. The mechanism of radiation detection is that charge carriers generated by the incident radiation inside the detector move toward their respective electrodes under the influence of an electric field. If the carriers mean free path is long enough to reach the electrode then one can expect 100% charge collection. Unfortunately this does not always happen in reality. The charge carrier mean free path depends on mobility (μ), carrier lifetime (τ) and the applied electric field. The carrier mobilities cannot be further increased by improving the material while the lifetimes can increase by decreasing the concentration of active defects located in the band gap. The mobility-lifetime product of CZT for both electrons and holes, but especially holes, are not good enough for excellent charge collection. The electric field depends on the metal-semiconductor nature of the contacts. In order to create enough electric field in CZT to achieve efficient charge collection, voltage of typically 1kV/cm should be applied across the active volume. This causes some degree of electrical conductivity even in absence of external ionization.

The metal-semiconductor interface is an important area of study where the understanding of the chemical species formed at the interface, the inter-diffusion of the metal and the semiconductor, the defect formation and the interaction of e-h pairs with the latter are concerned with detector performance [7]. There are several contact-
Chapter one: Introduction

related problems that remain to be solved in the development of low noise and high efficiency CZT detectors.

One of the problems that has been frequently reported is that of the active volume not being equal to the geometric volume of the detector. This results in non-uniform electric field throughout the detector volume. In fact, a large fraction of the total electric field is dropped over the 400 μm adjacent to the negative contact [8] and there exists little field in the bulk of the material. This field distribution can be explained by the presence of injecting contacts and space-charge effects. This problem exists in the commercial CZT and CdTe with Au and Pt contacts.

Metal deposited on a semiconductor will result in a gradual transition in concentration through the semiconductor due to interdiffusion effects. Charge carriers can be emitted over the barrier into the metal through the depletion region of the semiconductor. So the motion of carriers is determined by the usual mechanisms of diffusion and drift. Charge carrier injection into the semiconductor from the metal will cause bulk leakage current. So besides bulk material, the electrical contact determines, to a large degree, the performance of a detector. Even if the detector is fabricated in high quality material, nonoptimized contacts will result in an inferior performance. Therefore, proper contact designs as well as choice of the electrical contact material, method of contact deposition, interface control, surface treatment and passivation are extremely important in the fabrication of CdZnTe nuclear detectors [9]. Moreover, the choice of contact metal and deposition method also plays an important role in lowering surface leakage current and increasing the charge collection to enhance detector performance.

In this work, commercial electroless Au-Au back to back contact CZT detectors have been studied to look into the nature of the bulk as well as the contact of the detector and to see how they behave. Chapter five has been compiled from our published information. In the light of this work, a number of CZT detectors have been fabricated with high purity gold (Au), Indium (In) and Aluminium (Al) metal contacts.
Chapter one: Introduction

Chapter six describes details about the contact fabrication process using various techniques and chapter seven elucidates the characteristics of fabricated devices and associates these with a proposed model of band structure. Finally chapter eight concludes the work describing the comparison studies of all the devices and how optimised detectors can lead to a reasonable and promising device.
Chapter one: Introduction

References


CHAPTER TWO

BACKGROUND - Radiation Physics

It is over 100 years since the discovery of ionizing radiation. The use of radiation and nuclear energy has brought a great deal of benefits to us, but at the same time radiation protection has to be considered as being of pioneer importance for the safety of professional workers, members of the public and the environment from the detrimental effects of ionizing radiation. Ionizing radiation is essentially invisible to the human senses and so it may easily cause biological damage depending on its intensity and energy. It is understood that radioactive materials should only be used where the benefits significantly outweigh the risks.

In order to understand the necessity of radiation safety and dosimetry, it is essential to know the mechanisms by which the various ionizing radiations interact with matter and how much they affect the human body. To quantify the nature and the degree of impairment caused by exposure to radiation, it is a requirement to detect and analyze any radioactive elements that may be concerned with the interaction events. Radiation spectroscopy is a technique that gives the required information about the energy of a particular radiation emitted from a radioactive source.

This chapter will briefly focus on the energy transfer that occurs from radiation to the matter with which it interacts and on the consequences of radiation exposure in the human body.

2.1 Interaction of Ionizing Radiation with Matters

Ionizing radiation lies in such a place in the photon energy spectrum that the photon energy is high enough to excite and eject electrons out from atoms or molecules in the matter. Although the precise ionization energy differs with the atom or molecule involved, a general statement is that any radiation with quantum energy above a few electron volts is considered to be ionizing radiation. Fig. 2.1 shows the consequences of the interaction of wide a range of radiation energy with matter [1]. The threshold for ionization lies somewhere in the ultraviolet region of the electro-magnetic
spectrum, so all x- and gamma-rays are ionizing radiation. The nature of interaction and energy transfer to target electrons depends on the energy of the photon.

![Diagram of radiations](image)

*Fig. 2.1. The interaction of various radiations with matter.*

Following the initial interaction with matter, a photon may undergo further interactions in which it loses more energy until it eventually loses all its energy at some distance away from the first interaction. Energy loss by a photon in matter happens through many processes including the photoelectric effect, Compton scattering and pair production which we will discuss later in this chapter.

### 2.1.1 Alpha Particle Interaction

The alpha particle follows a straight, short path in the material it penetrates, causing very dense ionization and excitation events along the track, in orders of millions per cm. The most typical alpha particle range is less than 5-6 cm in air. The alpha range can be calculated using the following empirical rule [2]

\[
R_\alpha = 0.56E \quad (E<4)
\]

\[
R_\alpha = 1.24E - 2.62 \quad (4<E<8)
\]

Where \( R_\alpha \) is the range in cm of air at ambient temperature. \( E \) is energy in Mev.
An alpha particle is composed of two protons and two neutrons as a nucleus of helium. Because of its very large mass and its +2 charge, the alpha particle has a very short range and can even be stopped by a sheet of paper.

### 2.1.2 Beta Ray Interaction

The range of a beta particle is considerably greater than an alpha particle and it scatters at large angle frequently. The density of ionization and excitation events along the path are much less than that due to alpha particles. However, interaction of high energy beta particles in dense material can generate bremsstrahlung x-rays which can be much more penetrating than the beta particle itself. The production of bremsstrahlung x-rays increases with the atomic number of the target material and beta energy. Therefore, low Z materials are used as a beta shielding. Fig. 2.2. gives an idea about the penetrating power of various radiations.

![Schematic diagram of various radiation absorption](image)

*Fig. 2.2. Schematic diagram of various radiation absorption*
2.1.3 Neutron Interaction

The way neutrons interact with matter depends on their energy and the type of absorbing material. Absorption of neutrons is one type of interaction. A neutron is absorbed by the nucleus of an atom and a secondary radiation, gamma or beta, is produced. Another type of reaction is the absorption of neutron followed by emission of one of the target atom's nuclear components. Neutrons can collide with the nucleus elastically or inelastically depending on the mass of the target. Some nuclei like uranium and plutonium can fission as a result of neutron absorption.

2.1.4 Gamma and X-ray Interaction

The predominant interactions that occur between gamma or x-rays and atoms depend on the photon energy and the atomic number of the material. The photon energy during interactions can be transferred either partially or completely to orbital electrons in the matter through three dominant mechanisms. The photon can be absorbed fully by what is called the photoelectric effect; it can be scattered by Compton scattering; and it can be converted to particles of mass by pair production. The photoelectric effect has the highest probability with a low energy photon and a high atomic number absorber. For intermediate energy photons Compton scattering is the most frequent interaction. Pair production is the predominant interaction at higher photon energies with a threshold energy of 1.022 MeV.

2.1.4.1 Photoelectric Effect

The incoming photon is absorbed by the target atom and imparts all of its energy to an orbital electron that will eventually eject from the bound system. The energy of the escaped photoelectron depends on the initial photon energy where the majority of the photon energy will be carried away by the photoelectron as kinetic energy. We can mathematically express the photoelectron energy as \( E_{ph} = h\nu - E_b \); where \( h\nu \) is the initial photon energy and \( E_b \) is the binding energy of the photoelectron in the atom.
Chapter two : Background - Radiation Physics

Fig. 2.3 Photoelectric Effect

It is most likely that in this process an electron from the innermost shell will be ejected followed by one from the L-shell and so on. Depending on the binding energy of the target atom only a few eV of photon energy is enough to raise the electron from its own shell. Photons with energy less than the binding energy of the inner shell electron in the target atom cannot interact with that particular atom at that energy level, although it might interact with other atomic electrons whose binding energy is smaller than the photon energy. However, subsequent to the ejection of an inner shell electron, a series of characteristic x-rays are emitted when the vacancies in the excited atom are filled through capture of an electron from higher shells. The energy of the x-ray emitted is the difference between the energy levels involved in the electron transition. Finally we can make a comment that the photoelectric effect is not dependent on photon intensity but only on its energy. In addition, the probability of photoelectric interactions is proportional to $Z^{4.5}$ [3]. This means that photoelectric interactions mainly occur in high atomic number materials. The mechanism of this effect is shown in fig. 2.3.

2.1.4.2 Compton Effect

The interaction process of Compton scattering occurs between a gamma or x-ray and an electron in the atom. The incoming photon changes direction transferring part of its energy to the electron (known as a recoil electron) and the electron is kicked out from the atom. Fig. 2.4 represents the Compton effect mechanism. Obviously, the photon energy must be well above the binding energy of the electron which is being knocked out. Compton scattering dominates at lower to intermediate energy such as up to 1
MeV which is much higher than the usual binding energy on electron in the atom. However, the actual energy change depends on the incident energy and the angle at which the photon is scattered. The electron and the scattered photon may experience further ionization through a photoelectric absorption or another Compton scattering if enough energy remains.

The Compton effect describes the interaction of a photon with a free electron. Consider a photon with energy $E_\gamma$ that interacts with a stationary electron. After the interaction, the electron will possess some recoil energy $E_e$ and the photon energy will be reduced to $E'_\gamma$. Hence we can write

$$E_\gamma = E'_\gamma + E_e. \quad (2.3)$$

As we mentioned above, the energy change depends on the angle of scattered photon. Assume the photon scattered at an angle $\theta$ with respect to the incident photon direction, while the electron recoils at angle $\phi$.

![Fig. 2.4. Compton Effect](image)

Then the amount of energy transferred to the electron is given by well-known Compton scattering equation;

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2} (1 - \cos \theta)} \quad (2.4)$$
Where \( m_0c^2 \) is the rest-mass energy of the electron. As we can see from the above equation, with a smaller scattering angle of the photon, the energy transfer to the recoil electron is less. As the scattering angle tends to zero, the recoil electron energy also tends to zero while the scattered gamma ray energy tends to the incident gamma ray energy. As the photon scattering angle increases, the energy transferred to the electron increases. Maximum energy will transfer to the recoil electron at a scattering angle of \( \theta = \pi \) where the incident photon and the recoil electron will be scattered in opposite directions to each other along the direction of incident photon. At high incident photon energy, the maximum energy of the back scattered photon is limited to \( m_0c^2/2 = 0.256 \text{ MeV} \) and rest of the energy of the incident photon will be carried by the electron.

2.1.4.3 Pair Production

Pair production is the mechanism by which a photon is transformed into an electron-positron pair that shown in fig. 2.5. The energy of the photon goes partly to the rest masses of the two particles and partly to their kinetic energies \( E_p \) and \( E_e \).

![Fig. 2.5.Pair Production](image)

The sum of the two kinetic energies must be equal to the energy in excess of the total rest energy:

\[
E_p + E_e = h\nu - 2m_0c^2
\]  

(2.5)
Chapter two: Background - Radiation Physics

Obviously the process can not occur for photon energies less than $2mc^2=1.022$ MeV. The available kinetic energy can be shared in any proportion between the two particles. For momentum conservation, pair production can only occur in the Coulomb field of a nucleus [4]. Subsequently, the electron simply dissipates its kinetic energy and stops; but the positron loses most of its kinetic energy at which point it can annihilate with a nearby electron. Following annihilation, two photons are produced which travel in (almost) opposite directions with energies of 0.511 MeV each. In this process, mass is converted into energy and energy is converted into mass. The total cross-section for pair production is zero at less than 1.022 MeV energy. The probability of pair production occurring is nearly proportional to $Z^2$ so the effect is much more important in heavy materials.

2.2 Biological Effects of Radiation

It has been recognized that exposure to high levels of radiation can cause clinical damage to the tissues of the human body and is also a potential cause for the delayed induction of malignancies. The interaction of ionizing radiation either externally or internally with living tissues transfers energy and ionizes atoms in cellular molecules that are biologically important for the functioning of cells. The free electrons and the ions or free radicals which are generated by ionization are most likely to recombine and those that remain after recombination may cause chemical reactions with other molecules in a number of ways. This may cause inactivation of cellular mechanisms or may lead to interaction with genetic molecules that control the structures and functions of the cells, resulting in clinical symptoms at the end. Most commonly, the human body has defense mechanisms against damage induced by radiation as well as by chemical carcinogens, and is able to overcome this cellular disorder or damage.

At low doses, cells can repair the damage rapidly. However at higher doses (e.g. around 1 Sv), the cells might not be able to repair the damage, and the cells may either be changed permanently or die. In the right circumstances, these cells may become cancerous. This is the origin of our increased risk of cancer as a result of radiation exposure. At even higher doses, the cells cannot be replaced fast enough and tissues fail to function. At high acute doses to the whole body (>2 Gy), the body's immune system is damaged and cannot fight off infection and disease.
However, the nature and severity of these symptoms, and the period over which they appear, depend on biological factors as well as radiation quality factors like age, sex, state of health, body size, body weight, the amount of radiation absorbed, type of radiation, dose rate and which organs of the body were exposed. If cellular damage does occur and is not adequately repaired then the outcomes have profound implications for the organism as a whole, leading to so-called deterministic and stochastic effects.

2.2.1 Deterministic Effects

Deterministic effects (or non-stochastic effects) have a certain threshold limit of exposure. A single accidental exposure to a high dose of radiation during a short period of time may produce biological effects within a short time. These effects are not necessarily life threatening to the human organism, unless a tissue or an organ absorbs an above threshold dose that is high enough to kill or to impair the reproduction of a significant fraction of that organ. However, the pattern of exposure response or disease syndrome depends on the magnitude of dose and affected organs of the body since all organs or systems are not equally sensitive to radiation.

2.2.2 Stochastic Effects

Unlike a deterministic effect, stochastic effects have no such threshold value of exposure. A single overexposure or continuing low-level overexposure may cause delayed effects. In fact, any dose of radiation, no matter how small, is assumed to involve a possibility of risk to human health. The appearance of the disease may be delayed by many years after a person's exposure to a potential cause of cancer.

2.2.3 Reasons for Being Exposed

Radiation has always been present in the environment and in our bodies, and this is called background radiation. Levels of background radiation can vary greatly. People living in granite areas or on mineralised sands receive more terrestrial radiation than others, while people who live or work at high altitudes receive more cosmic radiation.
A lot of our natural exposure is due to radon gas which seeps from the earth’s crust and is present in the air we breathe.

In addition to the natural radiation, there are various other sources of radiation to which humans can be exposed. Humans are exposed to artificial sources of ionizing radiation from nuclear power plants, atomic bomb test fallout, medical x-rays, and radioactive sources used for diagnostic and therapeutic purposes etc.

A question may arise, should we avoid using radiation entirely because radiation exposure carries a risk? The answer is that even if we want to, this will be impossible as we are apparently living in a natural sea of radiation. In fact, many of us owe our lives and health to artificially generated ionizing radiation for diagnostic and therapeutic purposes. We get benefit from a multitude of products and services made possible by the careful use of radioactive materials. However we should avoid undue radiation exposure and this is one of the key objectives of radiation protection.

2.3 Route of Radiation Hazard

We are all aware of the hazardous effect of radiation and we are being perpetually exposed by radiation from naturally occurring as well as artificially generated radiation. However, in order to minimise the radiation related risk from any undue exposure it is important to know how exposures are generated from various radioactive sources and radiation producing equipment.

Radiation exposures involved in human health can result from natural and artificial radiation sources with either external or internal exposure.

2.3.1 External Radiation Exposure

External hazards arise mainly from natural sources and radiation producing equipment like cosmic rays, X-ray machines, LINACs, radiotherapy machines etc. These exposures can be from gamma or x-rays, neutrons, alpha particles or beta particles; they are dependent upon both the type and energy of the radiation. Most beta particles can not penetrate through the skin, but when sufficiently intense, can cause skin
and/or eye damage. Therefore, alpha particles typically are not an external radiation hazard. X- and gamma rays, along with neutron radiation, are very penetrating, which can ionize the cells within the body. Exposure to external radiation can be controlled by optimised handling of radiation sources.

### 2.3.2 Internal Radiation Exposure

Internal exposures arise when radiation is emitted from radioactive materials present within the body. Questions may arise as to where and how the radiation comes into the body. As we know, natural radioactive materials are already contained in the body. We are concerned here about the artificial radiation which can enter into the body by three routes of entry: *inhalation, ingestion and skin contact* through breathing, consuming contaminated food and drink or by spillage into open wounds in the skin. Once they get into the body by any way, the radionuclides concentrate into particular organs of the body (where local chemical environment suits the radioactive elements) and they continue to irradiate the surrounding cells until either they either decay or are excreted from the body.

Although x-rays, gamma rays, high energy betas and neutrons cause external hazards, they can also cause internal exposures. In addition, Alpha particles produce a high concentration of ions along their path, and can cause severe damage to internal organs and tissues when they are inhaled, ingested or are present on the skin because of their higher mass, slower velocity, and greater electrical charge. Internal exposures are not limited to the intake of large amounts at one time. Chronic exposure may arise from an accumulation of small amounts of radioactive materials over a long period of time.

### 2.4 Radiation Dosimetry

Although we are having huge benefit directly or indirectly from ionizing radiation in our real life, we should not ignore the health risk involved in using ionizing radiation. We therefore should reflect upon our views to minimize the harm rather to refrain from using it. So, in order to minimize the harm, it is imperative to monitor every single aspect involved in the use of ionizing radiation on regular basis like radiation sources, radiation producing equipment, occupational workers and even the
environment. It is also important to know the dose by which the radiation workers are being exposed while working with ionizing radiation. In that sense, dosimetry is an essential part of radiation science. Radiation dosimetry is just the measurement of radiation dose by means of dosimeters. Radiation dose is the energy imparted to matter by ionizing radiation per unit mass.

Among the units used to define the radiation doses, the Roentgen (R) was the first unit define to measure radiation exposure. The roentgen is defined by the number of ions produced by x-rays and gamma-rays in a certain quantity of air under specified conditions. This unit is difficult to measure and not often used today. Fluence (F) is a unit of exposure dose defined as the number of particles or amount of energy incident per unit area. "Flux" is often used in neutron physics in lieu of fluence rate. The rad was the original unit of absorbed dose. One rad corresponds to the absorption of $6.242 \times 10^{13}$ eV by one gram of material for any type of ionizing radiation. The current unit of absorbed dose is the gray (Gy); $1 \text{ Gy} = 100 \text{ rad} = 1 \text{ J per kg}$. Other units of absorbed dose have been employed to express the biological effectiveness of a given radiation. The rem (roentgen–equivalent-man) is the dose in rads multiplied by the radiation quality factor (Q) factor e.g. x- and gamma ray Q=1. An alternative unit is the sievert (Sv) which equals 100 rem. Thus, the dose in Sv and Gy are the same for x- and gamma rays.

To restrict exposure to below the limits set by the ICRP [5] for occupational workers, members of the public and the environment, routine monitoring and measurements have to be practiced in all areas occupied by radiation sources and radiation producing equipment. In order to adopt this practice, the following methods have to be followed where there is risk of radiation exposure.

(1) No practice should be authorized unless the practice produces sufficient benefit to the exposed individuals or to society to offset the radiation harm that it might cause.

(2) To follow, there are three basic principles - time-distance-shielding – that should be considered to reduce the exposure. In this regard, one needs to plan all activities carefully in order to minimize the time-spent in handling or in the vicinity of radiation sources. Increasing the distance from a radiation source by
the use of handling devices will reduce the dose received, since exposure rate decreases as the square of the distance. For example: if the dose rate is 100mR/hr at 1 meter; then at 2 meters away it will only be 25mR/hr. Shielding is the one of the three methods to reduce the exposure dose. X- and gamma-rays can be attenuated by appropriate shielding materials. Attenuation depends on the energy of the radiation, the density of the absorber medium, and the thickness of the absorber. This can be expressed approximately as

\[ I = I_0 \exp(-\mu x) \]  

(2.6)

Where \( I_0 \) is the intensity of the initial radiation, \( I \) is the radiation intensity after it has passed through the absorber, \( \mu \) is a factor called the linear absorption coefficient and \( x \) is the thickness of the absorber.

(3) A personal monitoring badge should to be worn by all occupational workers during all practices. Either a film badge or a thermoluminescent dosimeter (TLD) is used to measure whole body cumulative dose for a certain period of time due to exposure from external sources.

(4) Workers who use unsealed radionuclides need to be monitored for internal dose by a bioassay program.

### 2.5 Conclusion

This chapter has described the basic properties of radiation and the effect of this radiation on people. Further, the principles of radiation protection have been discussed together with an evaluation of dosimetry measurements and units.

In the next chapter, we will describe the basic properties of radiation detectors and semiconductor detectors in particular.
Chapter two : Background - Radiation Physics

References

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CHAPTER THREE

RADIATION DETECTION SYSTEMS

3.1 Introduction

As a part of a radiation monitoring and measurement program, it is necessary to determine the properties of the ionizing radiation especially the amount of a particular type of radiation present and the energy distribution of the radiation beam. In order to measure these things, the radiation detector is an essential instrument. Generally radiation detectors are optimised to record either intensity or the energy distribution of a radiation beam. Detectors designed to measure intensity of a beam (such as a dose rate meter) generally operate in integrating mode where the number of radiation interactions in the detector are recorded over a period of time and display as the sum in appropriated units. For those detectors which operate in energy spectral mode, event-by-event information is stored and displayed at regular intervals by a computer program. The incident radiation in the detectors mainly converts into electrical charge which is collected at electrodes as an electrical current. Eventually signals may be amplified or further processed to form the basic signal. Generally detectors may be operated either in current mode or in pulse mode. In this chapter, the basic properties of radiation detection systems will be discussed together with a description of various specific types of detection system.

3.2 Brief Description of Various Detection Systems

There are various types of detection system like gas detectors, scintillation detectors, semiconductor detectors etc., that are used to measure different kinds of ionizing radiation. Here we will concentrate on the G-M counter, scintillation and semiconductor types which have been widely used for radiation detection purposes.

3.2.1 Guiger-Mueller (G-M) Detector

The GM detector is a widely used gas filled detector for γ-ray and β-particle detection besides other gas-filled detector like the ion chamber and proportional counter. G-M tube are manufactured in a wide variety of geometries and are suitable for counting
solid, liquid or gaseous radioactive materials. They are usually constructed with a cylindrical cathode surrounding a very fine co-axial anode wire. The cathode is either metallic or it may be formed from a glass envelope coated on the inside with a graphite conductor. The tube is filled with a mixture comprising a noble gas like helium, neon or argon together with a small quantity of a quench gas (typically a halogen based compound) at about 1 atmosphere pressure. The basic mechanism of a gas-filled detector is shown in fig. 3.1.

![Fig. 3.1. The G-M detector](image)

Radiation causes ionization inside the detector volume and the liberated electrons are collected at the anode in the center of the detector. High electric potential is applied between the anode and the cathode in which the primary ions begin to move toward their respective electrodes. While moving toward the anode, the accelerating electrons cause a succession of ionization to form avalanches. This process is called gas multiplication and it produces a large numbers of charges. The gas multiplication factor for a GM tube is in the range of $10^6$-$10^8$. The charges collected at the anode generate electrical pulses which are processed by suitable electronics.

The GM detector is a simple, inexpensive, easy to operate and reliable instrument that is sensitive to low activities. The three major types of radiation (alpha, beta, and gamma) can be detected by the GM detector. The thin window GM is sensitive to low level radiation and well suited to checking for contamination on one’s clothing and body as well as in work areas. Portable survey meters with GM’s are usually equipped with a speaker or other audible indicator to allow surveys without watching the meter. GM detectors come in many different sizes. A cylinder type with a beta shield is one type, and a cylinder with thin end window is another type. For example, the
"Pancake" GM detector might have a 2 inch diameter thin mica window so forming a relatively large active detector area. It is capable of detecting alpha, beta, and gamma radiation. GM detectors with thin end windows can detect almost all commonly used radionuclides in research laboratories except tritium.

3.2.2 Scintillation Detector

Scintillation detectors are used for detection of high energy x- and gamma-rays as well as charged particles. Mainly it is in-organic materials like Thallium activated Sodium Iodide NaI(Tl) and Thallium activated Caesium Iodide CsI(Tl) that are used as scintillation detector materials. Inorganic scintillators possess a semiconductor-like band structure with a characteristic band gap. The incident radiation interacts with the scintillation material and transfers energy to electrons in the valence band to allow them to excite into the conduction band. The electrons will then tend to de-excite into the valence band by either loosing energy to the lattice through transfer of vibrational energy or emission of excess energy in the form of optical photons (light). The intensity of the light is directly proportional to the amount of radiation energy deposited into the detector. If the electron de-excites and returns across the full energy gap, then it is likely that the photon will be quickly reabsorbed by exciting another electron into the conduction band. Therefore, impurity materials are introduced into the lattice to act as activators. The addition of acceptor impurities greatly improves the scintillation efficiency of the detector. An electron in the conduction band may fall into an activator site and back to the valence band via an acceptor state which is sited just above the valence band. So the energy released will be less than the full bandgap energy so making the lattice transparent to the photon. For an example, the scintillation efficiency of NaI is enhanced by the presence of activator sites of Tl. The detection mechanism of inorganic scintillation materials is shown in fig. 3.2.
Once scintillation light has been generated in the detector, it is essential to collect as much of the light as possible. The greater the efficiency of light collection, the lower the effective W-value and hence the better the performance of the detector. In order to record these photons, an optical sensor called a photomultiplier tube (PMT) is used which converts the optical pulse to electrical charge. Here we will not describe the detailed mechanism of the PM tube as most radiation detector related textbooks describe this in detail [1-4].

3.2.3 Semiconductor Detector

Semiconductor devices, as the basic detection medium for ionising radiation became practically available in the early 1960s. Early versions were called crystal counters, but modern detectors are referred to as semiconductor detectors.

Semiconductor detectors act as a solid state ionisation chamber. The use of a solid detector medium is of great advantage compared to gas detectors. For the measurement of high-energy electrons or gamma rays, detector dimensions can be kept much smaller than the equivalent gas-filled detector because solid densities are some 1000 times greater than that for a gas [5]. At the same time their greater density and stopping power make it feasible for them to achieve complete absorption of long-range particles. An average energy needed to produce a detected ion-pair by impact
ionisation in a semiconductor is much lower (approx. 3.6 eV) when compared with an average figure of about 30 eV for gases or 300 eV for scintillators [6]. Consequently, the number of carriers created in a typical radiation interaction is usually much higher in semiconductors than other detectors.

When ionizing radiation is incident on a semiconductor detector, a number of e-h pairs are formed along the track. Charge carriers are then drifted towards their respective electrodes by the influence of applied electric field and are eventually observed at the electrodes as an electrical current. Signals may be amplified or further processed to form the basic signal by providing suitable electronics that record the detector output.

Basically, a semiconductor detector acts as a p-n junction. At reverse bias the p-n junction is considered as good semiconductor detector because the charge carriers generated within the depleted region can be collected quickly and efficiently. The depletion region of p-n junction, which represents the active volume of the detector, is as almost as wide as the detector length at reverse bias. The electric field in the detector is associated with the width of the depletion region as the field extends through the depletion region. So as charge carriers are created within the depletion region, the corresponding conduction band electrons will be swept out quickly to the contact, resulting in a measurable current pulse. This is the basic mode of operation of all semiconductor detectors.

By absorbing energy from the incident photon, the valence electrons jump to the conduction band and drift toward the cathode. So if the band gap is small, less energy will be required to produce conduction electrons and even thermally excited electrons will conduct which causes leakage current associated noise in the detector. Therefore, narrow band gap materials such as Ge (bandgap=0.6eV) or Si (bandgap=1.1eV) must always be operated at liquid nitrogen temperature to reduce thermally generated leakage current. In that sense, wider band gap semiconductors are promising for use as a room-temperature detector.

In considering detector operation we must be concerned with the nature of the interaction between the incident radiation and the volume of the detector material
where the charge is created, the efficiency of the excitation process, the efficiency of
the charge collection process, and finally the background noise of the device.
Semiconductor detectors however, present the best performance when compared to
the gas detector and scintillation detectors. Semiconductor detectors can be fabricated
in various ways, for example using diffused junctions, surface barriers, ion
implantation etc. We will not go in to a detailed description of such detectors, but
information can be found in most of the radiation detector textbooks [1-4]. The basic
properties of various detectors are shown in table-3.1.

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Gas detector</th>
<th>Scintillation detector</th>
<th>Semiconductor detector (Ge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector size</td>
<td>29-30mm dia [7]</td>
<td>7.5x7.5x cm²</td>
<td></td>
</tr>
<tr>
<td>Density (gm/cm³)</td>
<td>3.67</td>
<td>5.32</td>
<td></td>
</tr>
<tr>
<td>Operating bias (V)</td>
<td>400-1600</td>
<td>350-1000</td>
<td>~2500</td>
</tr>
<tr>
<td>Fano factor</td>
<td>0.2</td>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

3.3 Gamma and X-Ray Spectroscopy

An X- and gamma-ray spectrometer is an instrument that provides information on
both the energy and intensity of radiation that is emitted from a source of x- and/or
gamma-rays [10]. Several types of detection principle are used in these instruments,
with the two most popular types being based on scintillation and semiconductor
crystals. In both cases, detection of a gamma photon is only achieved if part or all of
the incident photon energy is initially transferred to one or more electrons in the
detector material. Interpretation of the response of such detectors is therefore greatly
facilitated by an understanding of the basic mechanisms by which photons interact
with matter. Once the gamma ray photons are incident on the detector material, as we
described earlier, three major processes are most important in the attenuation of those
gamma-rays. The way in which energetic recoil electrons produced by these three
processes subsequently interact in the detector material characterises the detection
mechanism and thus the mode of operation of the detector. The desirable feature of any good spectrometry system is that the magnitude of the output pulse should be directly proportional to the energy deposited in the detector by the incident ionizing radiation, i.e. there should be a linear relationship between photon energy and output pulse height.

The most widely used gamma-ray detector is the thallium activated sodium iodide scintillation detector NaI(Tl). The energetic recoil electrons that result from gamma interactions inside the NaI(Tl) crystal undergo inelastic collisions with the crystal and elevate secondary electrons to the conduction band. Some of these conduction electrons subsequently de-excite via an activator site with the emission of photons in the visible region. NaI(Tl) is particularly efficient scintillator with 13% of the absorbed energy appearing as scintillation light and its iodine content (Z=53) gives it a high gamma-ray detection efficiency [11]. The scintillation light is measured by a photomultiplier tube (PMT) that is placed in good optical contact with the exit face of the NaI(Tl) crystal. The photoelectrons are accelerated by the applied voltage and multiplied through secondary emission from a number of dynodes in the PMT. A charge sensitive preamplifier is generally employed to collect and amplify the current pulse from the PMT. The output of the preamplifier is fed to a shaping amplifier and then to a multi-channel analyser (MCA).

The spectrum for a $^{152}$Eu source in Fig. 3.3 is recorded from an MCA by probing the source with a NaI(Tl) detector. The $^{152}$Eu radionuclide emits radiation at single gamma-ray energy of 662 keV that appears in the spectrum as a full-energy peak. However, apart from this full energy peak, there are many features that occur from low energy to high energy. To illustrate this, the first thing we can say is that the response of the detection system is not a simple function of the input radiation spectrum but also there are certain characteristic features involved. The Compton continuum, Compton edge and back scattering peak appear besides the full energy peak due to Compton scattering events which result in partial energy deposition in the detector. Characteristic X-ray peaks also arise when the detector is closely surrounded by shielding materials in which incident photons may interact via the photoelectric effect.
Lithium drifted germanium Ge(Li) and hyper-pure germanium HPGe detectors contain a germanium crystal diode which behaves as a solid-state ionization chamber at high voltage reverse bias. Energetic electrons produced by incident photons excite secondary electrons to the conduction band. These electrons are rapidly swept from the active volume of the detector by the intense applied electric field and appear as a charge pulses at the output. The detected signal is passed to a low noise charge sensitive preamplifier after which the systems are treated by comparable electronics to those outlined above.

The spectrum for a $^{152}\text{Eu}$ source as shown in fig 3.4 is recorded from an MCA by probing with a Ge(Li) detector. The general features of this spectrum are comparable with those from scintillation detectors. However if we compare the peaks from both spectra it can be seen the germanium detectors have considerably better energy resolution, which makes them extremely desirable for many applications where complex gamma-ray spectra are studied.

![Fig.3.3 Typical Eu-152 photopeak from NaI(Tl) detector.](image-url)
3.3.1 Detector Characterisation

The performance of a gamma-ray spectroscopy system is generally characterised by three properties; energy calibration, energy resolution and detection efficiency.

3.3.1.1 Energy Calibration

Energy calibration is essential to trace out and quantify unknown radiation sources. Energy calibration can be obtained by plotting known incident photon energy versus the centroid channel number of the MCA for the corresponding full energy peak.

3.3.1.2 Energy Resolution

If we compare the spectra in fig 3.3 & fig 3.4 it can be seen that the energy peaks in figure 3.3 are significantly broader than those in figure 3.4. This difference occurs because the NaI(Tl) detector can not resolve individual energy peaks with only small energy differences so the neighbouring full energy peaks have been merged into a large broadened region. It can be illustrated as poor resolution of the detector. So the energy resolution of a detector can be defined as a measure of its ability to resolve
small differences in the energy of incident gamma-rays. Hence, energy resolution, $R$ is defined as:

$$R = \frac{\text{FWHM}}{H_0} \times 100\%$$

(3.1)

Where FWHM = Full Width of the full energy peak at half of maximum height, expressed as either channel or energy, $H_0$= Centroid channel or corresponding energy. FWHM of a pulse height spectrum and resolution concept whether good or poor are shown in fig. 3.5.

Fig. 3.5. Illustration of FWHM of a pulse height spectrum. Resolution concept in inset.

Peak broadening can result from several sources but the most important cause is due to statistical fluctuations in the number of charge carriers produced in the detector for events with identical energy deposition. An estimation can be made of the statistical fluctuations. If the number of charge carriers is $N$ then the standard deviation would be expected to be approximately $\sqrt{N}$. Assuming Gaussian probabilities, the FWHM can be related to the standard deviation by

$\text{FWHM}=2.35\sigma$ where $\sigma=K\sqrt{N}$ where $K$ is the proportionality constant.
Therefore the energy resolution can also be defined in terms of the number of charge carriers:

\[
R = \frac{FWHM}{H_0} = \frac{2.35 K \sqrt{N}}{KN} = \frac{2.35}{\sqrt{N}} \tag{3.2}
\]

So the energy resolution will improve as the number of charge carriers increase. In the above explanation, the generation and transport of charge carriers through the detection system is assumed to be uncorrelated, but this case is not always true. The observed variance is less than that predicted directly by Poisson statistics where there is correlation between charge carriers. So a correction factor can be introduced, the Fano factor, F which typically has a value in the range of 0.1 to 1. The Fano factor helps to improve the spectral resolution so the equivalent expression can be written as

\[
R = 2.35 \sqrt{\frac{F}{N}} \tag{3.3}
\]

We can rewrite this expression in terms of W-value,

\[
R = 2.35 \sqrt{\frac{F \cdot W}{E}} \tag{3.4}
\]

as \( N = \frac{E}{W} \); E is the photon energy and W is the minimum energy required to generate an e-h pair.

It can be seen in equation 3.4 that the smaller the W-value, the better the spectral resolution of the detector. The W-value and Fano factor for some common detectors are displayed in table 3.2.

<table>
<thead>
<tr>
<th>Detector type</th>
<th>W-value (eV)</th>
<th>Fano factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semiconductor (CZT)</td>
<td>5</td>
<td>0.1</td>
</tr>
<tr>
<td>Gas detector</td>
<td>20</td>
<td>0.2</td>
</tr>
<tr>
<td>Scintillation detector</td>
<td>50</td>
<td>1</td>
</tr>
</tbody>
</table>
Chapter three: Radiation detection systems

It can be said from the values shown in table-3.1 that the semiconductor detectors should provide superior energy resolution when compared to gas and scintillation detectors.

As we mentioned about the peak broadening due to statistical fluctuation, electronics noise also one of the noise components which affect the FWHM. Therefore the actual FWHM can be derived from the sum in quadrature of the individual noise terms in the system:

$$\text{FWHM}_{(\text{stat})} = \sqrt{\text{FWHM}^2_{(\text{total})} - \text{FWHM}^2_{(\text{electronics})}}$$  \hspace{1cm} (3.5)

3.3.1.3 Detection Efficiency

Efficiency is one the major characteristics of a detection system. A radiation detector can be called 100% efficient if it can sense every single photon that passes through the active volume of the detector, producing as many output pulses as the number of interactions that take place. However, in practice, it is difficult to reach this situation with any detector. In fact, for photons and other uncharged particles, no signal will be produced by the detector until a significant interaction occurs. However, heavy charged particles like alpha particles can generate significant charge carriers immediately after they enter into the detector. So a typical detection system will show a higher efficiency for detection of heavy charged particles than uncharged particles. It should be mentioned here that the detection efficiency could also be defined in other ways depending on what quantities are measured.

In order to have a precise figure for the detector efficiency, it is convenient to classify efficiency into three categories namely absolute total efficiency, intrinsic total efficiency and intrinsic full-energy peak efficiency.
Chapter three: Radiation detection systems

(1) Absolute total efficiency

The ratio between the total number of counts recorded per unit time and the number of gamma quanta emitted per unit time by the given radionuclide:

\[ \varepsilon_t = \frac{C_t}{N_\gamma} \times 100\% \] (3.6)

where \( C_t \) = Total number of counts per unit time and \( N_\gamma \) = number of gamma quanta emitted by the radionuclide per unit time. \( N_\gamma \) is obtained from \( N_\gamma = D_s I_\gamma \) where \( D_s \) is the disintegration rate of the source and \( I_\gamma \) is the total number of gamma quanta emitted per disintegration.

(2) Intrinsic total efficiency

Intrinsic total efficiency can be defined as the total number of counts recorded per unit time divided by the total number of gamma quanta incident on the detector. Therefore, \( \varepsilon_i \) is independent of the counting geometry. The intrinsic efficiency of a detector depends on the detector material, the radiation energy and the physical thickness of the detector and also source to detector distance. So we can express it as

\[ \varepsilon_i = \frac{C_t}{N'_\gamma} \] (3.7)

Where \( N'_\gamma \) = total number of gamma quanta which are incident on the detector. So

\[ N'_\gamma = \frac{\Omega}{4\pi} D_s I_\gamma = \frac{\Omega}{4\pi} N_\gamma \] (3.8)

Where \( \Omega \) is the solid angle subtended by the detector crystal at the source point.
Intrinsic peak efficiency can be expressed as

\[ \epsilon_p = \frac{C_p}{N'_\gamma} \times 100\% \]  \hspace{1cm} (3.9)

where \( C_p \) is the net number of counts in a photopeak corresponding to energy \( E_\gamma \) and \( N'_\gamma \) is the total number of gamma quanta of energy \( E_\gamma \) incident on the detector crystal, and is given by

\[ N'_\gamma = \frac{\Omega}{4\pi} D_s I_{\gamma E_\gamma} \]  \hspace{1cm} (3.10)

where \( I_{\gamma E_\gamma} \) is the fractional number of photons of energy \( E_\gamma \) emitted per disintegration.

### 3.4 Compound Semiconductor Detectors

The widespread popularity of silicon and germanium materials is attributable to their excellent energy resolution due to low ionisation energy and good charge transport properties. However, both detectors have some sorts of disadvantages. Since the bandgap of both materials are very narrow (i.e., 0.6eV and 1.1eV respectively), then at any nonzero temperature valence electrons thermally excite out of the conduction band and cause detectable leakage current. Therefore, detectors must always be operated at liquid nitrogen temperature to reduce thermally generated leakage current. But cooling is not practicable in the widespread use of any device. In principle, a wider band-gap semiconductor material could reduce the bulk generated leakage current so that use at room temperature would be possible. Moreover, in gamma-ray spectroscopy, detectors with a high atomic number give a higher x- and gamma radiation detection efficiency. A great deal of attention has therefore been focused on seeking some suitable semiconductor materials of high atomic number as well as wider energy bandgap. So, the compound semiconductors have received the most attention as potential room temperature radiation detectors such as CdTe, HgI2, GaAs, etc. The materials of these detectors have high atomic number with large enough band gap energy to permit room temperature operation with low leakage current.
Chapter three: Radiation detection systems

probability of interaction with detector materials is proportional to $Z^{4.5}$ for photoelectric effect, $Z$ for Compton effect and $Z^2$ for pair production [12]. Hence, high $Z$ gives the highest detection efficiency.

3.5 Semiconductor Properties

3.5.1 Energy Band of Semiconductor and Metal

In a semiconductor, the conduction band is almost empty and the valence band is almost full and both are separated by a very narrow energy gap (of the order of 1 eV). In the absence of thermal excitation, there are no electrons in the conduction band and the valence band is completely filled. In that circumstance, semiconductors do not electrically conduct. However, the energy bandgap varies with temperature because the electronic energy levels depend on the spacing between the atoms. With increasing temperature from 0K, the bandgap tends to decrease quadratically from its initial value while finally at room temperature it continues to decrease linearly. The bandgaps of Si are 1.165 eV and 1.115 eV and of Ge are 0.746 eV and 0.665 eV at 0K and 300K respectively. The bandgap of Ge and Si vary by about $3.9 \times 10^{-4}$ eV/°C and $2.4 \times 10^{-4}$ eV/°C respectively [13]. Therefore, thermally excited electrons in the valence band surmount the comparatively lower forbidden energy gap into the conduction band leaving behind the same number of positive holes in the valence band. Those conduction electrons then take part in electrical conductivity. The band diagram for both cases is shown in fig 3.6(a)(b).
In a metal, the valence band is either just touching or overlapping the empty conduction band. The highest occupied energy band is not completely full. Therefore electrons can easily migrate throughout the materials with a very small amount of thermal energy. Unlike the semiconductor and insulator, a metal does not have any energy gap due to absence of forbidden energy gap. Another point worth noting is that in the absence of forbidden energy gap in good conductors, there is no structure to establish holes. The total current in such conductors is simply a flow of electrons.

### 3.5.2 Charge Carriers

At any nonzero temperature, thermal energy is shared by the electrons in the crystal. It is possible for a valence electron to gain sufficient thermal energy to be elevated across the bandgap into the conduction band. An electron in the conduction band can
jump to an adjacent location in the conduction band more readily than it can jump back to the valence band from where it had come earlier. When an electron is ejected from the valence band, a covalent bond is broken and a positively charged hole is left behind. The combination of the two is called an electron-hole pair.

The probability per unit time that an electron-hole pair is thermally generated is given by

\[ p(T) = CT^{3/2} \exp \left( -\frac{E_g}{2kT} \right) \]  

(3.11)

where \( T \) = absolute temperature, \( E_g \) = bandgap energy, \( k \) = Boltzmann constant, \( C \) = proportionality constant characteristic of the material.

From the above equation, the probability of thermal excitation is critically dependent on the ratio of the bandgap energy to the absolute temperature. Material with a large bandgap will have a low probability of thermal excitation and consequently will show the very low electrical conductivity characteristic of insulators. If the bandgap is as low as several electron volts, sufficient thermal excitation will cause conductivity high enough for the material to be classified as a semiconductor. In the absence of an electric field, the thermally created electron-hole pairs ultimately recombine and an equilibrium is established in which the concentration of electron-hole pairs observed at any given time is proportional to the rate of their formation. The equilibrium concentration in the above equation is a strong function of temperature and will decrease drastically if the material is cooled.

### 3.5.3 Charge Transport

When an electric field is applied, both the electrons and holes will undergo a net migration. The motion will be the combination of a random thermal velocity and a net drift velocity parallel to the direction of the applied field. At low-to-moderate values of the electric field intensity, the drift velocity \( v \) is proportional to the applied field. This can be written as

\[ v_{e,h} = \mu_{e,h} E \]  

(3.12)
where $E$ is the electric field magnitude and $\mu$ is the mobility for electrons and holes.

![Graph showing saturation drift velocity in silicon](image)

**Fig. 3.7. Saturation drift velocity in silicon [14].**

At high electric field values, the drift velocity increases more slowly with the field and eventually, it saturates. Further increases in the electric field, the energy will increase which help to heat up the lattice rather than enhance the carrier's kinetic energy. Fig. 3.7 shows how the drift velocity saturates at high electric fields. Many semiconductor detectors are operated with electric field values sufficiently high to result in saturated drift velocity for the charge carriers. Because these saturated velocities in Si and Ge are of the order of $10^7 \text{cm/s}$, the time required to collect the carriers over typical dimensions of 0.1cm or less will be under 10ns.

### 3.5.4 Carrier Mobility

As we saw, at low electric field the drift velocity is proportional to the electric field strength and the proportionality constant is defined as the mobility $\mu$ in $\text{cm}^2/\text{V-s}$. The field causes the generated electrons and holes to move towards the respective electrodes as the field will exert a force of $qE$ on the carrier, not with constant acceleration, as would happen for carriers in a vacuum. The carrier velocity is limited by various scattering events in the material. If the carriers were moving through a
perfect crystal with lattice atoms stationary, then nothing would impede the carrier progress and the crystal would appear to have zero resistance to current flow. However crystals are not perfect in practice, there are many parameters in it to alter the carriers free movement Among them, the crystal contains impurity atoms in the lattice, vacancies where the actual atom is missing or interstitials (extra atoms sitting off lattice sites). They all will upset the perfect periodicity in the lattice which enhances the probability of interaction with the carriers resulting in lowering of the carrier mobility. So it raises the question of how long will the carrier be free from collision or how far can the carrier go before a collision? The average time between collisions is called the relaxation time or the mean free time between collisions. The average distance the carrier travels between collisions is known as the mean free path. The drift velocity will be given by the product of carrier acceleration and the time for which the acceleration is acting [15]. So the equation 3.12 can be rewritten as

\[ v_d = \frac{F \tau}{m} = \frac{qE \tau}{m} = \mu E \]  

(3.13)

or

\[ \mu = \frac{q \tau}{m} \]  

(3.14)

where F is the force due to electric field and \( \tau \) is the relaxation time.

### 3.5.5 Carrier Lifetime

The carrier lifetime is determined by the rate of recombination of electrons and holes. Carriers will tend to migrate either spontaneously through thermal diffusion or under the influence of an applied electric field until they are either collected at an electrode or recombined within the bandgap. There are theoretical predictions that the average lifetime of charge carriers in pure semiconductors could be as large as a second but in practice, lifetimes are measured to be at least three to four orders of magnitude smaller than a second. The carrier lifetime in Ge detectors is about \( 10^4 \) sec. Carrier lifetime is material parameter that depends very much on the density of carrier traps and recombination centres within the semiconductor. The properties of various semiconductor detectors are displayed in table 3.3.
Table 3.3 Properties of various semiconductor detectors

<table>
<thead>
<tr>
<th>Properties</th>
<th>CdTe</th>
<th>CdZnTe</th>
<th>HgI₂</th>
<th>Ge</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal structure</td>
<td>Cubic</td>
<td>Cubic</td>
<td>Tetragonal</td>
<td>Cubic</td>
<td>Cubic</td>
</tr>
<tr>
<td></td>
<td>(Zinc Blend)</td>
<td>(Zinc Blend)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atomic number Z</td>
<td>48/52</td>
<td>48/30/52</td>
<td>80/53</td>
<td>32</td>
<td>14</td>
</tr>
<tr>
<td>Density (gm/cm³)</td>
<td>6.06[16, 6.2[17]</td>
<td>=6 [16]</td>
<td>6.4[16,18]</td>
<td>5.33</td>
<td>2.33</td>
</tr>
<tr>
<td>Band gap (E₉) eV</td>
<td>1.52[16], 1.44[18], 1.47[19,20], 1.6[21]</td>
<td>1.6[16], 1.7[20]</td>
<td>2.13 [16,19]</td>
<td>0.72[16], 0.67[18]</td>
<td>1.12[16,18]</td>
</tr>
<tr>
<td>Resistivity(ρ) Ωcm</td>
<td>3.0x10⁹[22] 10⁸-10⁶[23]</td>
<td>(Zn:04.-2 2.5x10¹⁰-- 2.5x10¹¹[23], 1.5x10¹¹[24]</td>
<td>1x10¹³[28]</td>
<td>=10²</td>
<td>=10³</td>
</tr>
<tr>
<td>Lifetime τ/τ₀ (μs)</td>
<td>1/1[16], 2.3/1.7[28]</td>
<td>1/0.2[16]</td>
<td>7/3[16] 100/10 [19]</td>
<td>&gt;100</td>
<td>&gt;100</td>
</tr>
<tr>
<td>µτ/µ₀τ₀ (cm³V⁻¹)</td>
<td>2x10⁻⁷/4x10⁻⁴ [18], 10⁻⁴-10⁻⁵ 10⁻⁷-10⁻⁴[29]</td>
<td>2.3x10⁻⁷/1.8x10⁵[30], 2x10⁻⁵/10⁵[31] 8x10⁻⁷/ 3x10⁻⁵-3x10⁻⁵ [20]</td>
<td>10⁻⁷/10⁻⁵ [32]</td>
<td>3.6/4.2 [16], 0.72/0.84 [18]</td>
<td>0.15/0.05 [16], 0.42/0.22 [18]</td>
</tr>
<tr>
<td>Permittivity (ε₀)</td>
<td>10[19]</td>
<td>10.5 - 11[33]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W-value (eV)</td>
<td>4.43[16], 4.46[34]</td>
<td>5.0[16,35,36]</td>
<td>4.3[16], 2.98[16], 2.9[37]</td>
<td>3.6[16,38]</td>
<td></td>
</tr>
</tbody>
</table>
3.6 CdZnTe as Room Temperature Semiconductor Detector

CdTe is the one of the first materials to have been developed as a room temperature radiation detector. It has good stopping power for energetic photons, produces reliable spectra and is fairly rugged in field applications. The probability of photoelectric absorption per unit path-length is roughly a factor of 4-5 times larger in CdTe than in Ge and 100 times larger than in Si for typical gamma-ray energies. Although CdTe has shown great promise as a room temperature detector for use with x- and gamma rays, it does have some drawbacks that limit the widespread use of these devices. In particular, CdTe detectors have relatively poor energy resolution (resulting from poor charge collection efficiency) while the leakage currents are too large for many x-ray applications [39]. The charge collection problems of CdTe are mostly due to losses of the hole component. Another problem during crystal growth is the high vapour pressure of Cd which can cause serious stoichiometry problems. One of the methods to overcome this problem is to use chlorine doping at the $\sim 10^{18}$ cm$^{-3}$ level. Although some high quality radiation spectra were published, the yield of spectrometer type crystals is not apparently satisfactory. However, adding 5 to 20% Zn to replace Cd in CdTe, forming the ternary compound Cd$_{1-x}$Zn$_x$Te, improves dramatically the performance of the material as a radiation detector [40]. In addition, Zn, which has lower vapour pressure than Cd, helps to reduce the dislocation density during crystal growth [41]. Apart from this, the highest atomic number of the elements in a CZT detector is 52 (gamma-ray absorption efficiency depends on the highest Z number element, not the average atomic number of the materials [42]) while a density of the order of 5.8 gm/cc provides an excellent stopping power for energetic x- and gamma ray photons. Together, these result in a high efficiency detector. Moreover, its higher band-gap ($E_{bg}=1.57$eV) allows the crystal to work effectively in room temperature conditions without thermal leakage currents dominating.

During the past years, the development of CZT technology has attracted considerable interest due to its high potential for many room temperature as well as elevated temperature x-ray and gamma ray detector applications. The widespread research and commercial applications of CZT detectors in medical imaging, environmental
monitoring and industrial process control are actively being pursued by a variety of companies, universities and laboratories around the world [43].

Nevertheless, the basic understanding and the technologies of CZT detectors are still at a reasonably early stage of investigation. A common problem observed with these detector materials is the low mobility and short lifetime of holes, and the tendency of the carriers to get trapped in deep levels within the forbidden band gap which results in poor charge collection and hence poor energy resolution. Recently, CdZnTe crystals, which have been prepared by the high-pressure Bridgman method, have exhibited a significantly better performance than earlier CdTe detectors. However, it is not clear whether this improvement is due to an increased mobility-lifetime product for holes, whether it is due to less leakage current under high electric fields or whether it is due to less defect-trapping [44]. The metal-semiconductor interface is an important area of study where the understanding of the chemical species formed at the interface, the inter-diffusion of the metal and the semiconductor and the mechanism of defect formation and the interaction of e-h pairs with the latter are critical [45].

3.6.1 CZT Crystal Structure

The group II elements form a range of solid compounds with the group VI elements of the periodic table like CdTe, ZnTe etc. The bonding of these compounds is thought to be covalent with varying degrees of polarity depending on the nature of the group VI elements. The lattice parameter of CdTe for good stoichiometric materials at room-temperature is about 6.48Å [46] and it is the largest of any of the II-VI compounds. The lattice parameter is evaluated using the empirical formula \(a=6.483-0.3803x\) [47]) and is found to vary linearly with zinc concentration from \(x =0\) to \(1\). The lattice parameter of \(\text{Cd}_{1-x}\text{Zn}_x\text{Te}\) has been determined by Ben-Dor and Yellin [48].

CdTe forms the diamond equivalent Zinc Blende structure comprising two interpenetrating face centred cubic crystals offset by one quarter of the crystal diagonal. The zinc blende structure of CdTe is shown in fig. 3.8[49] where the white atoms correspond to the Cd atoms at the vertex of every tetrahedron while the black ones to Te atoms at their centre.
3.6.2 Metal-Semiconductor Contacts

Detector contacts act as an electrode to collect the charges that are generated within the detector by incident radiation. Besides the bulk, metal-semiconductor contacts are also sources of leakage noise which often limits the performance of CZT detectors. When the metal and the semiconductor are placed in direct contact, the difference between their work functions forms two possible types of contacts either Schottky or Ohmic with a degree of interfacial diffusion occurring depending on electrode design and surface-processing methods as well as the types of material.

If the work function of the metal $\phi_m$ exceeds that of the semiconductor $\phi_s$, electrons will pass from the semiconductor into the metal, leaving behind a depletion region in the semiconductor in which the bands are bent upwards [fig. 3.9 (a) & (b)]. For an n-type semiconductor this produces a barrier which the electrons have to surmount in order to pass from the semiconductor into the metal. This results in rectifying properties and on the other hand, for a p-type semiconductor, this band bending does not affect the motion of holes and no rectification takes place rather showing an ohmic behaviour.
Chapter three : Radiation detection systems

Fig. 3.9. Illustration of different types of contacts.

If $\phi_m \leq \phi_s$, the bands are bent downwards [fig. 3.9 (c) & (d)]. This gives an ohmic contact for an n-type semiconductor and since holes have difficulty in passing underneath a barrier, a rectifying contact for a p-type semiconductor. Now we will focus our discussion on ohmic and Schottky contacts for n type material.

3.6.2.1 Ohmic contact

An ohmic contact is defined as a metal-semiconductor contact that allows the free exchange of either electrons or holes between a semiconductor and a metal. The ohmic contact acts as a source of charges. It supplies or receives variable amounts of charge, according to the bulk carrier density, while the bias voltage and the electric field near it remain constant [50]. This type of contact can supply the required current with a voltage drop that is small compared with the voltage drop across the active region. Once an ohmic contact forms, electrons from the metal are transferred to the semiconductor, being due to the electron affinity of the semiconductor. This causes alignment of the fermi level between the semiconductor and the metal. The highly localized electron charge from the metal effectively generates a very thin degenerately doped n-layer at the interface of the semiconductor. This drags the bottom of the conduction band to the fermi level [51]. If both contacts are ohmic in nature then the equilibrium charge carrier concentrations in the bulk will be maintained. In this case,
when electrons or holes are collected at one electrode, the same carrier species will inject at the opposite electrode to maintain the equilibrium

\[ \phi_m < \phi_s \]

so the main feature in this case is that there is no potential barrier between the metal fermi level and the bottom of the semiconductor conduction band. The quantity \( \phi_B \) is called the diffusion potential and is equal to the difference between the work function of metal and semiconductor by which the bands are bent. The barrier height is smaller than this by the amount \( (E_c - E_f) \) and can be expressed as \( q\phi_B = \chi_e - q\phi_m \). Where \( \chi_e = \phi_s - (E_c - E_f) \) is the electron affinity of the semiconductor.

3.6.2.2 Rectifying contact

Rectifying contacts, unlike ohmic contacts, hinder the entrance of charge carriers from the contacts to the bulk, but allows the reverse direction exit of charge carriers that have been generated within the bulk. So if rectifying electrodes are used, charge carriers initially removed by the application of an electric field are not replaced at the opposite electrode, and their overall concentration within the semiconductor will drop after application of an electric field. The leakage current can thus be reduced to a sufficiently low value to allow the detection of the added current pulse created by the
electron-hole pairs produced along the track of an ionizing particle. The simplest blocking contact is based on the Schottky barrier. This consists of a metal-semiconductor interface identical to that of an ohmic contact. The difference in this case is that the work function of the metal is significantly greater than that of the semiconductor. Thus, there exists a potential barrier between the fermi level of the metal and the conduction band of the semiconductor. Fig. 3.11 shows the band diagram of a Schottky contact [53].

\[
\begin{align*}
q\phi_n & = \frac{q\phi_m - q\phi_s}{(q\phi_m - \phi_s)} \\
q\phi_s & = q\phi_m - \phi_s
\end{align*}
\]

**Fig. 3.11.** A Schottky barrier blocking contact between a metal and an n-type semiconductor.

Under reverse bias, the electrons in the metal are faced by a potential barrier. Only those electrons in the high energy tail of the fermi distribution are energetic enough to surmount the barrier height and be injected into the semiconductor. This is called thermionic emission and is almost invariant to the electric field applied across the junction. This is because the rate at which electrons are thermally excited over the barrier is dependent only on the height of the barrier and the temperature of the fermi gas in the metal.

Au and Pt are often used as contacts for CZT detectors; they have work function of 4.8 eV and 5.2 eV respectively. So obviously for Pt, \( \phi_m > \phi_s \) which gives the condition for the selection of rectifying contacts on n-type CZT. In fact, the ideal situation is never reached in metal-semiconductor contacts because there is usually a thin oxide layer formed on the surface of the semiconductor. The value of semiconductor work function depends on the doping and the kind of crystal [54].
Chapter three: Radiation detection systems

The performance of the detector is largely dependent on how the contact behaves during operation. The intensive study of contacts has been stimulated by their importance in semiconductor technology, both as rectifying and as low resistance or ohmic contacts.

3.7 Electro-Optic Effects in CZT

Before we explain details about the electro-optic effects in CZT we should first define what an electro-optic effect is. When an electromagnetic (EM) wave interacts with an electric field, or with matter under the influence of an electric field, the direction of the electric component of the EM wave changes from its original path. Generally, most isotropic materials have a unique refractive index. Once light traverses through these materials the velocity of it remains same, no matter which orientation it passes through. However, some materials like glass, plastic, etc., display anisotropic behaviour which means that the direction of light changes depending on the orientation of the material with respect to the incident light beam. This makes the material birefringent with an ordinary \( n_0 \) and extraordinary \( n_e \) refractive index. In other words, birefringent materials, including crystals, have the ability to refract an unpolarized incident ray into two separate, orthogonally polarized rays, which in the general case deviate along different paths depending on the orientation of the material with respect to the incident ray. The velocities of the extraordinary and ordinary rays through the birefringent material vary inversely with their refractive indices. So the higher refractive index of the extraordinary beam will propagate slower than that of the ordinary beam as it has smaller refractive index. This difference in velocities of the two beams make them become out of phase. In fact, the birefringence results in an electric field dependent phase difference between two orthogonally polarized waves propagating in the material. So it gives the idea that it is possible to measure the electric field by exploiting electro-optic effects. There are two important electro-optic effects; Kerr effect and Pockels effect. Fig. 3.12 shows how the induced anisotropic refractive index differentiates between two light waves with perpendicular polarization.
Fig 3.12. Demonstration of the Kerr and Pockels electro-optic effect.

3.7.1 The Kerr Effect

All optically isotropic materials including liquids exhibit the Kerr effect. The two indices $n_0$ and $n_e$, are associated with the two orientations of the plane of vibration of the wave, namely, parallel and perpendicular to the applied electric field. The difference between these two indices is the birefringence ($\Delta n$) which results in phase change ($\varphi$). Isotropic materials which display the Kerr effect cannot sense the sign of the applied electric field so the effect has to be proportional to the square of the applied electric field, so it can be expressed as

$$\Delta n = \lambda_0 KE^2$$

and

$$\varphi = 2\pi dKE^2$$

Where $K$ is the Kerr constant, $\lambda_0$ is the wavelength of EM wave in vacuum and $d$ is the length of the medium.

The Kerr effect is proportional to the square of the electric field, and to achieve a detectable phase change it is generally needed to apply electric field of the order of $100kVcm^{-1}$ [56] which is difficult to achieve in a CZT detector.

3.7.2 The Pockels Effect

Unlike the Kerr effect, only a few materials (those that do not possess a centre of symmetry or a centre of crystallographic inversion) display the Pockels effect. Here it is worth explaining briefly about the inversion centre. It exists at a point in the crystal if there is no change in the atomic arrangement when each atom, a vector $\mathbf{r}$ away for
the point, is replaced by one \( r \) away [57]. If it happens that the lattice of particular materials remains unchanged then it can be said that the material has a centre of inversion. There are only thirty-two crystals that do not possess a centre of inversion. Zinc blende type lattice semiconductors such as most of the III-V's (GaAs) and II-VI's (CdTe, CZT etc.) group crystals among them, do not possess a centre of inversion, and therefore display Pockels effect. Interestingly, all crystals that exhibit the linear electrooptic effect are also piezoelectric that means the application of the electric field will deform the material resulting transformation of refractive index of the material. The change in refractive index is given by,

\[
\Delta n = n_e - n_0 = n_0 r_{41} E
\]

which results in a phase change (\( \phi \)):

\[
\phi = \frac{2\pi n_0^3 r_{41} d}{\lambda_0} \frac{E}{E}
\]

where \( \lambda \) is the free space wavelength of the incident light (850 nm in this work); \( d \) is the path length through the crystal (5 mm in this work), \( E \) is the mean electric field intensity along the optical path; \( n_0 \) is the field free refractive index and \( r \) is the Pockels electro-optic coefficient for CZT.

It can be seen from equation 3.5 that the Pockels effect is proportional to the electric field, unlike the Kerr effect. So the phase change will be considerable with the applied bias voltage. For example, a field strength of 500Vcm\(^{-1}\) is all that is needed to achieve a detectable phase change [58].

3.7.2.1 Electric Field Measurement

In order to measure electric field by exploiting Pockels effect it is necessary to quantify the induced phase shift within the detector. The basic experimental set-up that was used for this experiment will be shown in next chapter. The mechanism of phase shift measurement by exploiting the Pockels effect has been demonstrated in fig. 3.13.

An 850nm sub-bandgap IR laser beam was used to illuminate the detector. The IR beam was plane polarised with its \( E_i \) vector disposed at 45° angle to the direction of the applied \( E \)-field in the CZT detector. So the incident beam will be considered as a resultant coherent beam of two orthogonal plane waves. The component of electric vectors which is traversing in a plane perpendicular to the direction of applied electric
field will be perturbed while the other component which is traversing parallel to the electric field will be transmitted undisturbed. So the resultant transmitted components will be in phase with respect to its original phase. In this effect, the more intense the electric field within the detector, the greater the retardation of the perpendicular component. This has the effect of causing a linearly polarised beam to become progressively elliptically and eventually circularly polarised beam when the maximum phase shift of $\pi/2$ occurs [59]. By placing an analyser in front of transmitted beam, the phase state can be determined.

Suppose an electric field vector $\mathbf{E}_0$ is transmitted through the polarizer with an angle $\theta$ to the polarizing axis of a polarizing filter. So only its component $E_0 \cos \theta$, parallel to the transmission axis of the analyser will be passed through. Therefore, when the analyser is perpendicular to the polariser, or in other words we are using a cross polariser, no beam is transmitted at zero bias.

The transmitted intensity $I_t$ through the analyser is proportional to the square of its electric vector, $I_t(\theta) = E_0^2 \cos^2 \theta = I_0 \cos^2 \theta$, which is known as Malus Law [60]. For crossed polarisation, the transmitted intensity $I$, as a function of phase angle $\phi$, can be express using Malus' law:

$$I = I_0 \sin^2 \frac{\phi}{2}$$  \hfill (3.18)

where $I_0$ is the maximum transmitted light intensity passing through the uncrossed polariser at zero bias. We can rewrite the equation 3.18 using equation 3.17 as
Chapter three: Radiation detection systems

\[ I = I_0 \sin^2 \left( \frac{m_0^3 r_{41} d}{\lambda} E \right) \] (3.19)

By measuring the ratio of \( I/I_0 \) from the experiment shown in fig. 3.14, it is possible to evaluate the electric field value with the help of equation 3.19. Where the value of \( n_0 \) can be taken 3.0 and for CdTe, \( r = 4.5 \times 10^{-12} \text{ mV}^{-1} \) both for wavelength of 1\( \mu \)m [61].

![Fig. 3.14. Purity of polarization - Malus's Law](image)

3.8 Conclusion

This chapter has described the basic properties of a radiation detector including discussion of gas, scintillation and semiconductor devices. A detailed review of room-temperature semiconductor detectors has been conducted that has emphasised specific results relevant to CdZnTe radiation detectors.

As will be seen in chapter four, the electro-optic effect in CdZnTe is very important for characterisation of detectors, and a brief explanation of this effect has been given here. Based on the material presented in chapters 2 and 3, the remainder of this thesis is concerned with our experimental programme to investigate, fabricate and characterise wide band gap room temperature operation CdZnTe radiation detectors.
Chapter three: Radiation detection systems

References

[9] IOP events, Radiation safety manual, University of Surrey, UK.


Chapter three : Radiation detection systems


Chapter three : Radiation detection systems


CHAPTER FOUR

OVERVIEW OF EXPERIMENTS AND EQUIPMENT

4.1 Introduction

As we mentioned earlier, the CdZnTe detector as a room temperature semiconductor detector is still far away from its desired performance. Many people have been researching into different aspects of the detector. The aim of our investigation is to explore how to fabricate a reasonably good room temperature CdZnTe detector. The assignment I am working on is focussed on fabrication of contacts to CZT detector that reduce leakage current injection through the contact while achieving reasonably improved charge collection. In order to accomplish the ultimate task, it is imperative to understand the characteristics of the bulk as well as contact properties of existing CZT detectors and to trace out the relations among those characteristics. A sub-bandgap IR beam was used to illuminate the CZT detector and this helps to build an effective model for signal formation that includes the effect of carrier trapping and non-uniform electric field. Apart from this, localised pulsed beams provided information about signal generation and signal transport in conventional CdZnTe radiation detectors.

4.2 Brief Description of Overall Experiments

A general experimental set up is shown in fig. 4.1. A 5x5x5 mm$^3$ CdZnTe detector supplied by eV Products, a division of II-VI Inc, was mounted inside a diecast box using a spring-tensioned clip. The spectrometer grade detector had standard electroless gold contacts in planar geometry and the contacts were oriented inside the diecast box in the horizontal plane. This detector provided a reasonably good spectrum with a FWHM of 4.1 keV (7%) at 59.5 keV while used as a gamma-ray spectrometer. The detector was connected to a 4k multi-channel analyser through a standard (eV-550, A-1253) preamplifier and a shaping amplifier (Canberra 2022), set with a shaping time of 0.5 μs. A Tektronix (model TDS 544A) oscilloscope was used simultaneously to record the pulse shape at the output of the preamplifier. The intrinsic electronics noise of the system was measured using a pulser (Ortec model 480) connected to the test input of the preamplifier, giving FWHM value of 2.7 keV.
A stable 1 mW, 850 nm, semiconductor laser (Model APMT01) was used to irradiate the CdZnTe detector. The laser beam was focussed to a narrow beam waist using a BK7 lens of focal length 30cm. The beam passed through the CdZnTe detector in the direction parallel to the detector contacts. The detector assembly was connected to a manually operated micropositioner with 10 mm vertical travel, so allowing the beam to intersect the detector along a path parallel to but at any distance from the electrodes. A high speed small area PIN diode was used to record the transmitted beam which was connected to the above mentioned oscilloscope and MCA though a second charge sensitive preamplifier (eV-550, A1253) and shaping amplifier (Ortec 570). A certain amount of the beam would be reflected from the smooth and shiny surface of the crystal and this was also taken into consideration.

The laser was connected to a pulse generator (Thandar TG 105), providing minimum input pulse duration of 80 ns, although longer pulse durations were used as required. Using a high speed photodiode connected directly to the high impedance input of an oscilloscope, the output laser pulse was observed to match the input electronic pulse width exactly but with a delay of 160 ns. The input electronic pulse was also used to trigger the oscilloscope and was typically set to a pulse repetition frequency of 5kHz, although pulse repetition frequencies in the range 100 Hz to 10 kHz were also used.
A beam expander was used before the BK7 glass lens to produce a narrow beam waist with reasonable depth of focus (DOF). A small area high speed photodiode was used to detect the output laser pulse. To achieve a photo-induced signal in the CdZnTe detector small enough to simulate energy deposition during typical X-ray interactions (i.e. in the range 10 – 500 keV), a series of neutral density filters were used to attenuate the incident laser beam. The neutral density filter was placed a bit tilted with respect to the incident beam using a holder in front of the laser beam so that any reflection did not interfere with the initial beam. Glan-Thompson calcite polarisers had been used for creating orthogonal plane polarized light that exploit the Pockel effects to measure integral electric field along the optical path length within the CdZnTe detector. These polarizers have the advantage of being able to polarise a very broad range of light wavelengths well into the IR as well as give extremely high polarization purity (extinction ratio) which is important in keeping the zero field transmission through the system close to zero.

The experiments had to be carried out in complete darkness as stray light could give extra noise that could affect the actual signal. Details about the optical equipment and the experimental procedure will be described later this chapter and next.

4.3 Optical Instruments and Their Properties

4.3.1 Laser Diode

Laser action was first demonstrated by Maiman using ruby crystals pumped by a helical xenon lamp. The laser is a device that amplifies light by means of stimulated emission of radiation. It is generally used as a source or generator of radiation. To generate laser action, one needs to achieve significant population inversion in atomic energy states. Electrons can be elevated to excited states from the lowest available states by gaining energy, but no significant collection of electrons can be accumulated by absorption alone since both spontaneous emission and stimulated emission will bring them back down. So a population inversion cannot be achieved with just two levels. It is not important to explain details of how to achieve population inversion but we can only say that the pumping medium must be able to attain the necessary population inversion for laser action.
Coherence, monochromatic wavelength and collimated output are the main characteristics of laser light. Coherence arises from the stimulated emission process which provides the amplification. Since a common stimulus triggers the emission events which provide the amplified light, the emitted photons are in phase to each other. These phase relationships are maintained over a long enough time so that interference effects may be seen or recorded photographically. This coherence property is what makes holograms possible. Laser light consists of essentially one wavelength, having its origin in stimulated emission from one set of atomic energy levels.

Because of bouncing back between mirrored ends of a laser cavity, those paths which sustain amplification must pass between the mirrors many times and be very nearly perpendicular to the mirrors. As a result, laser beams are very narrow and do not spread very much.

The stability of temperature, electrical pulses, physical dimensions and input power are important attributes in a working laser. The laser employed for the experiment was a semiconductor diode laser. The lasing action in the diode results from the recombination of carriers injected across a semiconductor p-n junction. This laser was specifically designed to produce a stable beam of radiation set at a calibrated power of 1 mW. An internal Peltier cooler retained the laser diode at constant temperature which stabilised both the output power and wavelength. Power fluctuations were stated as less than 0.2% of set output over 24 hours.

The output of the laser diode itself is asymmetric, astigmatic and linearly polarised. Careful consideration therefore needs to be given to these factors when planning to use a laser diode in an optical system. Divergence of the beam is inconvenient, as most applications require a collimated or focussed output. Extra optics is required to converge or collimate the beam. The optical beam has different points of emission from the directions perpendicular and parallel to emitting surface. This effect is called astigmatism. The amount of astigmatism present depends primarily on the method chosen to confine the photons in the lateral direction.
4.3.2 Silicon Photodiode Detector

A silicon photodiode is a solid state light detector that consists of a shallow diffused pn junction with connections provided which can probe to required electronics. The cross section of a typical photodiode is shown in fig.4.2. The characteristics of pn junctions are well known. However, photodiode junctions are unusual because the top "p" layer is very thin. The thickness of this layer is determined by the wavelength of radiation to be detected. Near the pn junction the silicon becomes depleted of electrical charges. This is known as the "depletion region". The depth of the depletion region can be varied by applying a reverse bias voltage across the junction. When the depletion region reaches the back of the diode the photodiode is said to be "fully depleted". The depletion region is important to photodiode performance since most of the sensitivity to radiation originates there. The capacitance of the p-n junction depends on the thickness of this variable depletion region. Increasing the bias voltage increases the depth of this region and lowers capacitance until the fully depleted condition is achieved. Junction capacitance is also a function of the resistivity of silicon used and size of the active area.

A silicon photodiode can be operated in either the photovoltaic or photoconductive mode. The choice of operating mode hinges on the trade-off between the required
speed of response and the maximum noise that can be tolerated in the actual application.

4.3.2.1 Spectral Response

The wavelength of the radiation to be detected is an important parameter. The silicon photodiode exhibits a wide range of response from ultraviolet through the visible and into the near infrared part of the spectrum. The spectral response peaks in the near infrared region between 800 nm and 950 nm. Silicon becomes transparent to radiation of longer than 1100 nm wavelength. It is not therefore suitable for use at wavelengths appreciably longer than this. Ultraviolet light is, conversely, absorbed in the first 100 nm thickness of the silicon.

4.3.2.2 Photodiode Responsivity

The radiometric sensitivity of a photodiode, which is another important characteristic of this detector, is to state its short circuit photocurrent generated by the given light level from a well defined light source. Usually photodiode short circuit current is expressed as amps/cm$^2$ and radiant energy from light source as watts/cm$^2$. So it can be expressed as the absolute responsivity in amps per watt (A/W). A typical radiometric sensitivity of 0.6 A/W can be expected at the peak spectral response wavelength of 925 nm. A typical responsivity curve that shows A/W as a function of wavelength is given in fig. 4.3. In order to increase their sensitivity to light one can either increase the active area of the photodiode chip itself or use lenses to increase the effective active area. The relationship between active area and sensitivity tends to be linear: doubling the active area doubles the output current.
Chapter four: Overview of experiments and equipment

Fig. 4.3. Spectral responsivity as a function of wavelength of incident beam.

4.3.2.3 Quantum Efficiency (Q.E.)

A photodiode’s capability to convert light energy to electrical energy, expressed as a percentage, is its Quantum Efficiency, (Q.E.). The sensitivity of a photodiode may also be expressed in practical units of amps of photodiode current per watt of incident illumination. The QE is related to the photodiode’s responsivity by the following equation:

\[ Q.E(\%) = \frac{1.24 \times 10^5 \times R(A/W)}{\lambda(nm)} \]  

Operating under ideal conditions of reflectance, crystal structure and internal resistance, a high quality silicon photodiode of optimum design would be capable of approaching a Q.E. of 80%.

4.3.2.4 Dark Current

Low dark current is paramount when probing low intensity light. The photodiodes used in all experiments are PIN diodes, chosen for their low dark current, low leakage and noise characteristics as well as their response time and quantum efficiency. Applying a reverse bias across the photodiode increases its responsivity. However, the dark leakage current of the photodiode tends to increase with applied reverse voltage resulting in an increase in the amount of shot noise generated by the photodiode. In
general, a photodiode is operated in the photovoltaic mode when low noise is of prime concern and under applied reverse bias when maximum speed is needed.

4.3.2.5 Temperature Effects

Increasing the operating temperature of a photodiode device results in two distinct changes in operating characteristics. The first change is a shift in the quantum efficiency (Q.E.) due to changes in the radiation absorption of the device. The second change is caused by exponential increases in the thermally excited electron-hole pairs resulting in increasing dark current. However experiment shows Q.E does not significantly change at 800 -900 nm beam but the leakage doubles for each 8 to 10 deg C temperature increase. Selected properties of both the photodiodes are given in a table below:

<table>
<thead>
<tr>
<th>Properties</th>
<th>Large area photodiode</th>
<th>Small area photodiode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>50 mm²</td>
<td>0.3 mm²</td>
</tr>
<tr>
<td>Dark current</td>
<td>5 nA</td>
<td>2 nA</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.62 A/W @ 850 nm</td>
<td>0.4 A/W @ 850 nm</td>
</tr>
<tr>
<td>Rise time</td>
<td>2.4 µs</td>
<td>-</td>
</tr>
</tbody>
</table>

4.3.3 Polarizing Components

Light is a transverse electromagnetic wave, which has both an electric and a magnetic component. The transverse nature of an electromagnetic wave is quite different from any other type of wave. If the electromagnetic wave travels toward any particular direction then it would be observed that the vibrations of the wave occur in more than one plane and the directions of the oscillating electric and magnetic components are perpendicular to the direction of travel and to each other. A light wave which is vibrating in more than one plane is referred to as unpolarized light. Most incoherent sources emit rays that have electric fields with no preferred orientation, i.e. they are unpolarized. Although the concept of unpolarized light is difficult to visualise however, it is enough to say here that it vibrates in a variety of directions and needs to be transformed into polarized light that vibrates in a single plane. The process of transforming unpolarized light into polarized light is known as polarization. In order
to polarize the light there are four different methods; transmission, reflection, refraction and scattering. The most common method of polarization is transmission in which polaroid filter is being used. A polaroid filter, or in other words a polarizer, is an optical device which can transform the natural light to a certain form of polarized light. It is, in principle, capable of blocking the planes of vibration of an electromagnetic wave except the one which is parallel to the polarization axis. Certain chemicals with long-chain molecules are stretched across the filter material in such a way that each molecule is aligned in a specific direction. As unpolarized light strikes the filter, the portion of the waves vibrating in a direction parallel to the alignment of the molecules are absorbed by the filter.

![Diagram](image)

*Fig. 4.4. Polarization by transmission using polaroid filter.*

The basic concept of polarization is displayed in fig. 4.4. However, depending on the nature of the electric field vectors of polarized light, the various states of polarization can be illustrated. In general, the amplitudes of the electric field vectors are different from each other and the phase difference between them remains constant. In this circumstance, polarized light propagates elliptically toward the direction of travel. In certain cases, the form of polarized light can be changed subject to change of the amplitudes and the phase difference. If all the electric field vectors are oriented in the same direction or plane of polarization, although the magnitude and sign may vary in time, the beam is said to be linearly or plane polarized. But if the electric field vectors have equal magnitudes but differ in phase by $\pi/2$, the polarized light will transverse circularly. Both linear and circular polarization light can be considered as special cases of elliptical polarization.
4.3.3.1 Extinction Ratio

The extinction ratio of a polariser offers a measure of polarisation purity that means how effectively it distinguishes two perpendicular components of incident light. In the ideal case, when the transmission axis of both polarizer and analyzer are perpendicular to each other, in other word when the polarisation axes are crossed, no light will pass through the analyser i.e $I/I_0 = 0$. But in practice, it is difficult to achieve that level of performance by available polarisers. So the parameter called extinction ratio of a polariser can be introduced from which the quality of the polariser performance can be deduced. As an example, some crystal polarisers offer an extinction ratio of $10^5$ while dichroic components offer $10^3$ [1].

4.3.4 Neutral Density Filter

Neutral density (ND) filters uniformly attenuate the intensity of light over a broad spectral range. Attenuation is accomplished by either absorption or reflection. The former type consists of an absorptive material dispersed in an appropriate substrate; the latter comprises an appropriate substrate onto which partially reflective coatings are vacuum deposited. Since the latter type do not rely on absorption, they are ideally suited to use with high energy light sources such as lasers. ND filters are often required to prevent saturation or damage to a wide variety of detectors, including photodetectors. ND filters are calibrated in units of optical density (OD), which is defined as

$$D = \log_{10} \frac{I_0}{I_t}$$

(4.2)

Where $I_0$ is the initial intensity and $I_t$ is the transmitted of light. For example, OD=3 means the filter can attenuate 99.9% of its initial intensity and only 0.1% can pass through.

4.4 Optical Beam Waist Measurement

In order to exploit the internal characteristics of CZT crystal point by point, it is necessary that the laser beam should be well focussed with as small a diameter as possible. But the problem is that if we produce a very narrow beam, it will tend to diverge as it is not possible to produce a coherent beam of light that is both narrow and of zero divergence [2,3]. At some point need to compromise between beam width
Chapter four: Overview of experiments and equipment

and depth of focus. However, the laser beam was focussed by a BK7 glass lens down to a relatively large focal spot of 40µm and a beam expander was also used to make the depth of focus reasonably long.

![Beam spot geometry in Gaussian beam.](image)

The beam appears to diverge as a spherical wave after a certain distance from the beam waist. This divergence angle can be defined as

$$\tan \theta = \frac{4\lambda}{2\pi w_0} = \theta \quad (4.3)$$

where $w_0$ is the Gaussian beam radius at which the intensity of beam is 0.135 less than its axis value. However, the beam power is contained nearly 100% at beam waist diameter $2w_0$. Since the beam spot can be approximated by a point source, $\theta$ is given by geometrical optics as

$$\theta = \frac{D}{F} \quad (4.4)$$

Equating these two expressions gives the beam waist diameter

$$2w_0 = \left(\frac{4\lambda}{\pi} \right) \left(\frac{F}{D} \right) \quad (4.5)$$

We can define the depth of focus somewhat arbitrarily as the distance between the values of $x$ where the beam is $\sqrt{2}$ times larger than it is at the beam waist, then using the equation for Gaussian beam radius $w(x)$ we can determine the depth of focus:
Using equations (4.5) & (4.6) we can easily calculate the beam diameter and depth. For example, a lens of 30 cm focal length focuses a 4 mm diameter 850 nm IR laser beam. The diameter of the focal spot will be 80 µm and depth of focus will be 12 mm. The beam waist was measured by moving a razor-blade edge attached to an object of 300 µm slit. The object was placed on a micropositioner as the edge of the blade can move through the beam at the focal point. A large area Si photodiode was used to record the output. The active area of the photodiode was 50 mm² and was thus able to intercept the entire beam output avoiding any occultation losses. The sensitivity of the photodiode was 0.62 A W⁻¹ at 850 nm. The photodiode was then coupled to a d.c. preamplifier. The detector/amplifier combination had eight switched levels of gain, ranging from approximately 2 mW V⁻¹ to 600 mW V⁻¹. By measuring the intensity of the transmitted beam, the beam diameters within the CdZnTe crystal were determined to be 40 µm. Measurement of beam waist is shown in fig. 4.7.
4.5 Optical Calibration

4.5.1 Laser Beam Power Calibration

Laser output power is generally measured in d.c. mode using an integrating optical power meter. To calibrate the laser output power when in pulse mode, it was necessary to determine the equivalent power per pulse by inference from a time integrated measurement where the time between pulses was short compared to the integration time of the power meter. A calibrated integrating optical power meter (Anritsu ML 910B) was used in which the laser beam was directed onto the power meter sensor following attenuation by a neutral density filter. At laser pulse frequencies above 2kHz, the primary beam energy per 80 ns duration pulse was observed to be constant. At lower frequencies, the power per pulse was observed to drop. This occurred since the laser pulse frequency dropped below the integration time of the power meter. For all subsequent experiments, the power meter sensor was replaced by the small area (0.3 mm²) photodiode connected to preamplifier/shaping amplifier allowing a cross calibration at all laser pulse frequencies between optical power and shaping amplifier pulse height measured with an oscilloscope or multi-channel analyser. This data was used to normalise all subsequent intensity measurements as a function of laser pulse repetition frequency.

Stable energy of the laser beam is important to specify the trap levels and other facts between the bandgap of CdZnTe crystal. In principle, the laser beam is supposed to be monochromatic but in practice, the wavelength of output laser beam varies due to

![Fig. 4.8a. Experimental diagram of wavelength calibration](image1)

![Fig. 4.8b. Output laser beam as a function of wavelength.](image2)
some mechanical setup. So it is important to calibrate the wavelength of the output of the laser beam. It has been mentioned earlier that a 1 mW, 850 nm, semiconductor laser was used to illuminate the CdZnTe detector. To substantiate the laser beam energy we did another set of measurement to calibrate the wavelength of the output beam. In this experiment we used a calibrated monochromator. The experimental diagram is shown in fig. 4.8a. To calibrate the wavelength we used Ealing made stepper motorised monochromator covering the wavelength range 750 nm - 1.7 μm. For this experiment, the monochromator was controlled manually to select the wavelength range. The laser beam was transmitted through a 300 μm slit fitted on monochromator which gives 4.64 nm resolution of transmitted beam. The transmitted beam was recorded by a large area Si-photodiode which was connected with a Keithley 196 digital multi-meter through a specially built amplifier. The accuracy in measurement of intensity of the laser beam transmission through the monochromator was about 0.2%. The result is shown in fig. 4.8b. The FWHM value is about 5.5 nm which is sum of the FWHM values of monochromator and laser. So the FWHM value of laser is about 3 nm. The maximum transmission was found at wavelength 841 nm.

4.5.2 Reflected Beam Measurement

Basically this measurement is part of the main experiment. So the experimental set up was mainly the same but a beam splitter was placed in the path between the laser and the CdZnTe crystal. A schematic diagram of this experiment is shown in fig. 4.9. The intensity of the pulsed laser beam incident on, and reflecting from, the surface of the CdZnTe detector which was measured by manipulating a 50/50 dielectric beam splitter. The reflected beam was measured by a high-speed small area photodiode which was connected with a digital oscilloscope through required electronics. As the incident beam power is known, we can directly calculate how much is reflected from the detector surface. This experiment determined that 10% of the incident laser beam reflected from the surface, independent of the position on the crystal when under bias. Measurement of the transmitted beam as a function of position in the crystal show that about 48% of the incident beam is transmitted with a variation of 2% in transmission both under bias and at zero bias for a pulse.
repetition frequency of 5kHz. Since 48% and 10% of the intensity of the incident beam are transmitted through and reflected from the crystal respectively, the absolute energy deposition per optical pulse in the CdZnTe detector can therefore be estimated as $42 \pm 3\%$ of the incident beam energy per pulse.

![Diagram of reflected beam measurement](image)

**Fig.4.9. Schematic diagram of reflected beam measurement.**

### 4.5.3 Attenuation Uniformity of Neutral Density Filter

The output of the IR laser used is 1mW which is too intense to generate a realistic signal in a CdZnTe detector. To achieve a photo-induced signal in the CdZnTe detector small enough to simulate energy deposition during typical X-ray interactions (i.e. in the range 10 – 500 keV), neutral density filters were used to attenuate the incident laser beam. Typically, experiments were conducted with a filter of Optical Density (OD) 3, which allows 0.1% beam transmission. However, as we said earlier, the output of the laser beam is quite consistent but it passed through neutral density filter before incident on crystal surface. So it is reasonable to raise a question as to whether the filter itself attenuates the beam uniformly...
Chapter four: Overview of experiments and equipment

throughout its area. To observe the uniformity of the neutral density filter an experiment carried out with the setup shown in fig. 4.10a

![Experimental setup for uniformity of neutral density filter.](image)

The description of the instruments used in this experiment have been provided above. The neutral density filter was placed using a holder in front of the laser beam. The filter holder was then fixed on an x-y-z positioner so that the filter can move such that the laser beam could fall on any chosen position on the filter. On the other side of the filter a large area photodiode was placed to record the transmission beam. The transmission output was found to be uniform with 0.5% variation at various positions on the filter. The result is shown in fig. 4.10b.

4.6 Cryostat

In order to measure the detector characteristics under low temperatures, the detector crystal needs to be placed in a specially built optical cryostat based on the Oxford Instruments Microstat as shown in fig. 4.11. A 1.7 cm diameter and 0.8 cm thick ceramic holder ($p>10^{16} \Omega \text{cm}$) was located at the centre position within the cold finger of the cryostat. The crystal is placed into the $5 \times 5 \text{ mm}^2$ size through hole supported from the side by BeCu sprung contacts. This allowed the transmitted beam to be recorded from the other side of the cryostat. The cryostat was fixed with an x-y micropositioner which was then placed on an optical rail supported by an optical pillar.
The cryostat has temperature range of 77K to 500K adjusted by an ITC502 temperature controller. The temperature of the cold finger is measured with a calibrated Pt resistor and assured to an accuracy of ±0.1K. Liquid nitrogen is pumped around the cold finger by a diaphragm pump (GF3/VPZ 0233) with the flow adjusted by a needle valve in gas flow controller (VC51) on the output line. The desired temperature is achieved by balancing the nitrogen flow with the resistance heater attached to the cold finger which can be controlled by pre-selected option on temperature controller. The cryostat vacuum of base pressure $2 \times 10^{-6}$ mbar ($1.5 \times 10^{-6}$ torr) was achieved by a Pfeiffer TCP040 turbo pump backed with an Edwards E2M2 rotary pump.

Vibrations originated from the rotary pump which may affect the optical measurement, were minimised by fixing the vacuum hose firmly to the ground. Great care was taken to avoid picking up noise from cryostat outlets and other
external sources. The cryostat was electrically isolated from its base by insulator O-rings.

4.7 Noise in the System

Regular fluctuations in the current passing through or the voltage developed across the device appears as noise. This signal is undesirable in the device while measuring any physical quantities or to amplify small signals. So it is important to know the factors which contribute to the output signal and to optimise the operating condition by reducing the noise that appears from different sources. There are three types of electronic noise e.g. thermal noise, shot noise and flicker noise, each associated with different physical processes and have different characteristics.

Thermal noise occurs mainly in semiconductor devices and is caused by the random motion of the charge carriers. Room temperature gives enough thermal energy to the electrons in a semiconductor to make them move randomly and produce noise voltage at its output. The open circuit mean-square voltage \( <V^2_n> \) of thermal noise is given by [4,5]

\[
\langle V^2_n \rangle = 4kTBR
\]  

(4.8)

where \( k \) is the Boltzmann constant, \( T \) is the absolute temperature in K, \( B \) is the bandwidth in Hz, \( R \) is the resistance of the device. As for example, for a semiconductor material with 1kΩ resistance the root-mean-square voltage \( <V^2_n>^{1/2} \) measured with a 1Hz bandwidth is about 4nV [6].

Shot noise is associated with the flow of current which is the major noise in most semiconductor devices. The number of charge carriers available for conduction changes with time hence a steady electric current \( I_{dc} \) sees its instantaneous value fluctuate following a Gaussian distribution [7]. The mean-square noise current of shot noise for a p-n junction is given by

\[
\langle I^2_n \rangle = 2qBI
\]  

(4.9)
where I is the current, which is positive in the forward and negative in the reverse direction. In semiconductor devices, the mechanism of conduction is by way of minority carriers, and so this suffers from shot noise.

Another kind of noise appears during measurement particularly at low frequency. Flicker noise is distinguished by its peculiar spectral distribution which is inversely proportional to the frequency \(1/f\). 1/f noise is modelled by either voltage or current noise sources, taking the excess noise at low frequencies into account.

In the field of spectroscopy the electronic noise is assessed by means of two figures of merit: the signal-to-noise-ratio (SNR) and the equivalent noise charge (ENC). The SNR is the ratio of the mean signal pulse height to the root mean square (rms) of the noise signal:

\[
SNR = \frac{v_{\text{max}}}{\left\langle v_n^2 \right\rangle^{1/2}} \quad (4.10)
\]

The ENC is the necessary quantity of charge appearing on a pulse from the detector that would produce an output pulse of height \(\langle v_n^2 \rangle^{1/2}\)

\[
ENC = \frac{\left\langle v_n^2 \right\rangle^{1/2}}{v_{\text{max}}} \quad (4.11)
\]

Where \(Q\) is the deposited charge in the detector producing a signal pulse with amplitude \(v_{\text{max}}\).

From equations (4.10) & (4.11) we can relate SNR and ENC as

\[
ENC = \frac{Q}{SNR} \quad (4.12)
\]

If the total noise follows the Gaussian distribution then it can also be expressed in terms of FWHM. T. Menezes [8] explained in his work.

\[
ENC_{\text{preamplifier}}^2 = \frac{\text{FWHM}_{\text{total}}^2 - \text{FWHM}_{\text{system}}^2}{\text{Centroidpeak}^2} \cdot \left(\frac{v_{\text{test}} C_{\text{test}}}{V_{\text{test}} C_{\text{test}}}\right)^2 \quad (4.13)
\]
Where \[ \text{FWHM}^2_{\text{system}} = \text{FWHM}^2_{\text{function generator}} \times G^2 + \text{FWHM}^2_{\text{amplifier}} \]

If \( \text{FWHM}_{\text{system}} \) is known, \( \text{ENC}_{\text{preamplifier}} \) can be extracted from equation (4.13).

4.8 Conclusion

The basic experimental procedures, which will be followed in order to carry out the majority of the experiments in the rest of this thesis, have been described in detail. Some other associated technical experiments have been done for better conception of the whole apparatus, and these have also been explained in this chapter. The general description of equipment used for this purpose and their characteristics have also been detailed in this chapter. To reveal the results accurately, it was required to calibrate some of the equipment, and these calibration methods are also explained. Related requirements that need to be well understood in order to carry out the experiments successfully have also been highlighted throughout this chapter.
Chapter four: Overview of experiments and equipment

References


CHAPTER FIVE

BAND STRUCTURE OF Au-Cd$_{1-x}$Zn$_x$Te DETECTORS

5.1 Introduction

CdZnTe crystals are grown using the High Pressure Bridgman Method [1] by alloying CdTe with Zn, and they possess some distinct advantages over CdTe. The bandgap of ZnTe is substantially larger than the bandgap of CdTe so the resistivity is expected to be much larger (typically $10^9 - 10^{11}$ $\Omega$-cm) than that of CdTe[2]. The band-gap energy depends on the concentration of Zn, and is reported by Olega [3] et al. to be

$$E_0(x) = 1.510 + 0.606x + 0.139x^2 \text{ eV at 300K} \quad (5.1)$$

So the band-gap energy of Cd$_{0.9}$Zn$_{0.1}$Te is near 1.57 eV. Commercially available CdZnTe detectors exhibited good performance however, there are a lot of things to investigate and improve. Poor charge transport characteristics degrade the spectral performance of detectors while detector leakage current contributes substantially to the full-width-half-maximum of the photopeak.

For comparison with other published data, a representative energy spectrum for Am-241 using the same detector for which the majority of our experimental results were obtained is shown in fig.5.1. The detector was operated at room temperature (20°C) with a bias voltage of 500V. For reference, an electronic pulser peak is also shown. In this measurement, the detector was housed in a brass holder with beryllium entrance window with irradiation through the cathode. This resulted in a lower system noise than the measurements that are reported later with the more open detector housing shown in fig. 4.1.
Chapter five: Band structure of Au-Cd$_{1-x}$Zn$_x$Te detector

As shown in figure 5.1, radiation spectra using Au-CZT-Au detectors result in photopeak resolution which is poor at high energy (>100 keV) and there is undesirable tailing on the low energy side. The distortion in the photopeak arises from the fact that a large fraction of the total electric field is dropped over a few μm adjacent to the negative contact and that there exists little field in the bulk of the material [4]. Since the majority of the low energy photons interact at the front contact the result is a reasonably good spectrum. However, higher energy photons interact with almost equal probability through the detector volume.

Detector leakage current that is dominated by thermal excitation of charge carriers across the contact contributes substantially to the full-width-half maximum of the photopeak resulting in poor resolution. A pure Au-CZT-Au contact produces a Schottky barrier of height about 0.7-0.8 eV depending on the Zn concentration [5]. However, the actual barrier height in detector grade material has been measured to be around 0.9 eV. It has been reported in Paul De Antonis work [6] that the additional 0.2 eV barrier is due to a p-type gold doped region forming adjacent to the contact. To explain this additional 0.2 eV barrier in terms of Au diffusion between the contact and the intrinsic CdZnTe bulk material, a band model had been established. In order to follow up the fact of additional barrier height we analysed the contact structure further.

Fig 5.1. Representative energy spectrum with Au-CZT detector for Am-241 source.
in this work. It would be worth explaining the previous work [5] in this chapter as a cross-reference and comparison with the present work.

5.2 Theory

5.2.1 Barrier Formation

Once a metal is brought into intimate contact with a semiconductor from a certain level of vacuum, charge carriers will move across the junction from either side depending on the properties of metal and semiconductor materials. At thermal equilibrium, the fermi levels of both materials will be coincident and an electrostatic barrier will be formed. As a result the semiconductor bands will bend either upward or downward depending upon the differentiation between the work function of the metal and the semiconductor material.

\[ E_c - E_f \]

\[ q\phi_q \]

\[ q\phi_B \]

\[ q\phi_D \]

\[ q\phi_m \]

\[ q\phi_s \]

\[ E_v \]

\[ E_f \]

\[ E_c \]

\[ \delta \]

\[ W \]

\[ E_v \]

\[ E_f \]

\[ E_c \]

\[ q\phi_q \]

\[ q\phi_B \]

\[ q\phi_D \]

\[ q\phi_m \]

\[ q\phi_s \]

\[ E_v \]

\[ E_f \]

\[ E_c \]

\[ q\phi_q \]

\[ q\phi_B \]

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\[ E_c \]

\[ q\phi_q \]

\[ q\phi_B \]

\[ q\phi_D \]

\[ q\phi_m \]
Chapter five: Band structure of Au-CdZnTe detector

\( q\phi_D \) can be quantified as \( q\phi_D = q\phi_m - q\phi_s \) which appears in terms of a barrier for the carriers. The actual barrier will be larger than this by the amount of \( qV = (E_c-E_f) \). So the barrier height \( \phi_B \) will be

\[
\phi_B = q\phi_D + qV
\]

The \( q\phi_s \) can be expressed as \( q(\chi + V) \) where \( q\chi_s \) is the electron affinity to migrate measured between the vacuum level and bottom of the conduction band.

Once the gap between the metal and semiconductor decreases, the rate of migration of an electron to the metal will increase which results in the build up of negative charge at the metal surface. Consequently equal and opposite charge will appear at the semiconductor side. At this stage the gap will be apparently transparent to electrons and then the barrier height is simply the difference between the metal work function and the electron affinity.

So we can rewrite the expression of potential barrier as

\[
\phi_B = q\phi_m - q(\chi_s + V) = q(\phi_m - \chi_s)
\]

(5.3)

For high-resistivity CZT, \( \phi_s \) is given by

\[ q\phi_s = \chi_s + (E_c-E_f) = 4.3 \text{ eV} + \frac{E_g}{2} = 4.3 \text{ eV} + 0.8 \text{ eV} = 5.1 \text{ eV}. \]

where the electron affinity \( \chi_s \) of CZT \( \approx 4.3 \text{ eV} \) [7], the energy gap is 1.6 eV and the fermi level is assumed to be at mid gap.

5.3 Experiments

In this work, the Au-CdZnTe contact had been investigated in a number of spectroscopic grade radiation detectors provided by eV Products, a division of II-VI Inc. To analyse the proposed barrier in detail, a set of direct measurements of barrier height were undertaken. In this context, a sub-bandgap beam of infra-red light of wavelength 900-1800 nm was focussed through the bulk semiconductor onto the inner side of the contact surface. Reverse illumination was used to avoid absorption of the light in the contact itself. The photocurrent generated during illumination was
monitored by a picoammeter, with the detector biased at 500V. At each wavelength, the dark current was first nulled via a constant current source to allow the photocurrent to be measured. The incident optical power into the CdZnTe crystal was measured using a calibrated thermopile detector, which possessed a flat near IR response. It was shown that sweeping the wavelength from 1000 to 1800 nm to focus the beam from the monochromator onto the CdZnTe detector, even an achromatic lens could not prevent the focal point wander. A gold-coated reflection optics was used to eliminate the focal point problem. The reflectivity of gold in the infra-red is >99% and is utterly featureless. A schematic diagram of the experiment is given in fig 5.2.

Fig. 5.2. Schematic illustration of an experiment using IR illumination to determine the Schottky barrier height at the contact. Gold coated reflection optics were used throughout to minimise chromatic aberration in the focal point.

5.3.1 I-V Characteristics

There has been considerable discussion of the precise nature of the contact to CdZnTe radiation detectors over the past years, with the majority view being that they are “quasi ohmic”. This term does not convey what is actually happening at the contact, but does qualitatively explain the apparently linear I-V response for such detectors as shown in fig 5.3. Note that the gradient of the I-V curve is affected by the temperature at which the measurement is made. The higher the temperature, the greater the slope.
The straight line nature of fig. 5.3 indicates that current through the device is dominated by thermally generated charge carriers from the bulk material, and not through injection at the contacts. The implication is, therefore, that the contacts are rectifying. That is the contacts cannot freely inject charge carriers into the bulk semiconductor as would true ohmic contacts.

Fig. 5.3. The I-V response of a 5x5x5 mm$^3$ CdZnTe detector at room temperature.

5.3.2 Bulk Resistivity

The straight line nature of Fig 5.3 indicates that current through the device is dominated by thermally generated charge carriers from the bulk material, and not through injection at the contacts. That means unlike the true ohmic contacts, this contact is rectifying. Under this assumption, it is possible to calculate the bulk resistivity of the material to be $5\times10^9$ $\Omega$cm. It has been reported that the bulk resistivity of Au contact CdZnTe detectors was measured as $4.5\times10^{10}$ $\Omega$cm using a contactless method [8]. The advantage of the contactless method is that no current can be injected through the contacts, and so whatever the result is a true measure of bulk properties.
5.4 Investigation of Schottky Barrier

5.4.1 Barrier Height Measurement

We believe that the Au-CdZnTe contact present in these detectors is a schottky barrier for which the height is calculated as approximately 0.7 eV [9]. This corresponds to a room temperature leakage current of $10^{-5}$ Acm$^{-2}$. Typically, measured leakage currents are substantially smaller than this (e.g. $10^{-7}$ Acm$^{-2}$) which is presumably due to higher barrier height than calculated barrier height. However, to analyse the experimental data, it is convenient to produce a Fowler plot ($\sqrt{I_{ph}}$ vs $hv$) where $I_{ph}$ is the generated photocurrent and $hv$ is the incident photon energy. A Fowler plot of the measured data is shown in fig. 5.4. Experimental data points are shown, along with a linear regression fit to the data. The intercept on the energy axis indicates a contact schottky barrier height of $0.783 \pm 0.004$ eV with a correlation coefficient of 0.9974.

![Fowler plot showing a contact barrier height of 0.78 eV.](image)

5.4.2 Photovoltaic measurement

In this work, we tried to validate the above mentioned band model by an alternative method. As in ref [5] it has been mentioned that residues of the electroless gold-plating process, which are diffused into the semiconductor, are likely the candidates for this additional barrier.
To investigate the existence of the contact barrier, we chose to operate the detector in photovoltaic mode using controlled illumination with 850nm sub-bandgap IR sources. An electrometer with leakage current of less than 10fA was connected directly to the detector for recording the photogenerated potential without applying any external bias. Under illumination near contact regions, photocurrents are generated that demonstrate the presence of an internal electric field. The magnitude of the initial generated photocurrent was around 120pA. The electrometer was operated in constant current mode to null the photogenerated current and the voltage across the electrometer was measured using a digital multimeter. The magnitude of this photovoltage ultimately depends on the carrier concentration at the generation centre.

5.4.2.1 Experimental Set-up

Fig. 5.5 shows the basic experimental set-up. An equivalent circuit diagram in Fig. 5.6 demonstrates the response of the detector while operating in photovoltaic mode. The experiment was constructed on a pneumatically suspended optical bench. CZT crystals were mounted on a specially designed brass plinth in which the top contact was made by using a gold plated sprung contact that held the crystal gently against the plinth. The entire assembly was enclosed within a grounded metal case. The case was screwed to an x-y micropositioner which also allowed the crystal to be moved up and down with respect to a stationary optical probe.

The optical source used was a stable 850 nm laser that was focussed down to a narrow waist (around 20 μm diameter) with low angular divergence. This was achieved by using a precise optical system comprising BK7 glass lenses. The transmitted IR beam was monitored by a CCD camera and TV monitor. An electrometer with leakage current of less than 10 fA was used to record the photogenerated potential.
Fig. 5.5. Schematic illustration of an experiment to investigate the photovoltaic response of a CdZnTe detector.

Fig. 5.6. An equivalent circuit diagram to demonstrate the response of the detector while operating in photovoltaic mode.

5.4.2.2 Result and discussion

A series of measurements were undertaken in which the beam intensity was modified through the use of calibrated neutral density filters, and the position of illumination with respect to the contacts was altered using the micropositioner attached to the sample plinth. The results are shown in fig. 5.7.
Chapter five: Band structure of Au-Cd_{1-x}Zn_{x}Te detector

Whether high or low intensity illumination of a single contact was used, the photovoltaic potential recorded never exceeded 0.2V. When the opposite contact was illuminated the potential would invert, but again never exceed -0.2V. When both contacts were illuminated, an intermediate voltage was recorded. This effect is maximised for photon energies just below the band edge (at around 810 nm) when significant penetration into the bulk device occurs, but still the probability of electron-hole pair creation is large. The effect is still evident at 850 nm.

To explain this phenomenon, it is clear that there must exist a potential barrier, 0.2eV in height that is present in addition to the main Au-CdZnTe schottky barrier. This additional barrier forms a narrow depletion region in the vicinity of the contact. Under intense illumination of this region, electrons flow into the bulk semiconductor and holes are removed. This affects the level of the conduction (and valence) band in the bulk semiconductor, causing it to rise to the level of the conduction (and valence) band in the contact region. For an intrinsic semiconductor, this will drag the fermi level in the bulk semiconductor with it. The consequent effect in the external circuit is

Fig.5.7. Graph of photovoltage as a function of position for varying incident light levels.
to alter the electrical potential across the device when configured in photovoltaic mode. When the opposite contact is illuminated instead, the conduction band (and consequently the bulk Fermi level) drops to that of the contact region, thus causing a different potential to be generated across the device. From the measured external potential of 0.2V, it may be inferred that the additional barrier height is 0.2 eV in magnitude.

The measured data shown in figure 5.7 shows photovoltage measured as a function of beam intensity. To explain this data, it is necessary to note that the IR image through the detector shows many structural imperfections in the CdZnTe crystals. It is therefore likely that a fraction of the incident optical power will be scattered into the contact regions even if the primary beam illumination is incident well away from the contact. As a result, fig. 5.7 shows a non-zero potential even for illumination well away from the contact regions. However, as the beam intensity is reduced (by the addition of neutral density filters), the photovoltage in the mid-crystal regions drops away towards zero. This reflects the reduction in scattered beam intensity in the contact region. However, for primary beam illumination near to the contact regions, a similar photogenerated potential is recorded for all beam intensities. This shows that photogeneration in the region adjacent to the contact is very efficient.

5.4.3 Study of the source of proposed barrier

From the above experiments and discussion we are almost certain about the existence of additional barrier height. However we need to know the sources that is responsible for producing barrier height. In order to trace out the sources of the proposed barrier, an electron microprobe scan was obtained. The analysis of the output of the electron microprobe data showed the presence of small quantities of chlorine and aluminium in the vicinity of the contact. These are likely to be residues of the electroless gold plating process used to apply the contact. Chlorine acts as an n-type dopant in CdZnTe, while Au act as a p-type dopants. It is calculated that a barrier height of 0.2 eV will be generated by a p-type doping density of $10^9$ to $10^{11}$ cm$^{-3}$. Thus, we believe that the 0.2 eV barrier observed in the photovoltaic measurements is due to light Al and/or Au doping of the semiconductor in a region extending around 20 μm from the contact surface.
By combining the barrier heights due to the metal-semiconductor Schottky barrier (0.78 eV) and the π-type Al/Au doped region (0.2 eV), a full barrier height of 0.98 eV is obtained. This value is consistent with the measured thermally generated leakage current. Therefore, the proposed full band structure of the Au-π-i-π-Au CdZnTe detector may be summarised as in fig. 5.8 at zero bias. Under reverse bias, the corresponding band diagram is shown in fig. 5.9.

When operated in the reverse bias mode under normal conditions, the probability of carrier tunnelling through the 0.2 eV contact is small. However, when operating in high rate situations, the electric field, $E$, in the vicinity of the contact has been observed to increase [10]. Since the tunnelling current is proportional to $E^2$, the contact leakage current therefore increases rapidly. This results in leakage currents similar to those expected for a Schottky barrier height of 0.7 eV. Such phenomena are familiar to those interested in high rate X-ray detection.

Fig.5.8. Proposed band structure for a CZT detector with electroless gold contacts.
Fig. 5.9. Band structure for a CZT detector operating under reverse bias with electroless gold contacts.

5.5 Discussion

We believe that the proposed band structure for electroless gold contact CdZnTe detectors explains the observed phenomena associated with the manufacture and operation of such detectors. Experimental evidence has been presented for the existence of a metal-semiconductor schottky barrier combined with a lightly doped p-type region adjacent to it. The combined effect of these two is to produce a contact with a full barrier height of 0.9 eV. Clearly, this barrier height is critically dependent on the total doping density and thickness of the region adjacent to the schottky barrier.

5.6 Photo-Electronic Investigation of CdZnTe Spectral Detector

5.6.1 Introduction

Infra-red microscopy in CdZnTe is now a standard tool for analysis of mechanical quality in raw CdZnTe material [11]. However, the use of infra-red is not limited to microscopy and several workers have reported more detailed investigations [12,13].
The current work exploits the use of sub-bandgap infra-red in the pulsed regime whereby short (80 ns), localised optical pulses have been used to probe gold contact CdZnTe radiation detectors in the planar contact configuration.

We have previously used sub-bandgap infra-red imaging to probe both material structure and, by use of the Pockels effect, internal electric field [14]. This work was conducted using both scanning point IR and full crystal IR illumination for electric field measurement. This data showed that the high density of photo-induced charge in a fully illuminated and biased detector causes significant alteration in the electric field shape.

Using a combination of localised photovoltaic measurements and reverse illumination of the metal-semiconductor schottky contact, it has further been possible to analyse the band-structure of a Au-CZT-Au detector [15]. This work showed that there exists a doped region to a depth of around 20 \( \mu \text{m} \) under the contact (most likely due to diffusion of Au from the contact during annealing and fabrication of the detector) that acts to raise the effective barrier height by around 0.2 eV. The aim of the current work is to build on the previous results to study the effect of pulsed sub-bandgap IR illumination.

5.6.2 Varying Interaction Position

Photons incident on the detector generate charge carriers, while the field applied causes the charge carriers to drift toward their respective electrodes. If the interaction occurs near the cathode, the generated holes will be swept out very quickly through the near contact while the electrons have to travel all the way to other contact. The charge carriers contributing to the signal will have to travel from the point of interaction to the collection electrode which means that the induced current signal is mostly due to electrons. For interaction near the anode, holes mainly contribute to the induced signal current but the lower \( \mu \tau \) value of the holes indicates that those generated near the anode can hardly reach the collection electrode which causes further signal degradation. So the least preferable point of interaction in CZT is close to the anode as at this point the holes must traverse the entire length of the detector.
prior to collection at the cathode. So the interaction position is an important feature in the spectral response of a CZT detector.

In order to observe the effect of interaction position on spectroscopic performance, a side irradiation configuration was used. Here, the photon enters the crystal through one of the passivated surfaces perpendicular to the direction of electric field as shown in fig. 5.10. To locate the interaction position precisely the very narrowly focussed IR beam was chosen to irradiate the crystal.

![Fig. 5.10 Variation of interaction position.](image)

If interaction occurs near the anode, the holes have to drift the maximum length before collection. So the hole collection time [16] is

$$\tau_{\text{max}} = \frac{d}{v_h} = \frac{d}{\mu_h E} = \frac{d^2}{\mu_h V_b}$$

(5.1)

Where $d$ is the detector thickness, $V_b$ is the bias voltage, $E$ is the electric field in Vcm$^{-1}$ and $v_h$ is the drift velocity of hole in cms$^{-1}$.

As the point of interaction moves from the anode to cathode, the collection of holes is improved. At a certain point the collection time of holes and electrons will be equal and then the hole collection time is

$$\tau_{\text{min}} = \frac{x_m}{v_h} = \frac{(d - x_m)}{\mu_e}$$

(5.2)

From equation (5.1) & (5.2) it can be written
Chapter five: Band structure of Au-Cd$_{1-x}$Zn$_x$Te detector

\[ \tau_{\text{min}} = \frac{x_m d}{\mu_h V_b} \quad (5.3) \]

Where

\[ x_m = \frac{d\mu_e}{(\mu_e + \mu_h)} \quad (5.4) \]

is the distance from the cathode and the point of interaction for equal collection provided that uniform electric field exist across the detector.

The ratio

\[ \frac{\tau_{\text{slow}}}{\tau_{\text{fast}}} = \frac{(\mu_e + \mu_h)}{\mu_h} \quad (5.5) \]

is a measure of the intrinsic time spread function of the detector due to the mobilities of both charge carriers and is independent of detector dimensions. The lower the ratio the better the time response with a limiting value of 2 for \( \mu_e = \mu_h \). For currently available CZT detectors this ratio is approximately 11 which is somewhat worse than Ge (=3) or Si (=3.8) detectors.

5.6.3 Nature of Charge Collection Throughout the Crystal

Since the electric field is not homogeneous throughout the crystal, the probability of charge collection varies as a function of the position of charge generation. In fig. 5.11 we can see that near the negative contact charge collection is the highest as electrons and holes are both collected by their respective electrodes under the influence of the electric field since it is very strong at the cathode. In this case, the electrons will travel a comparatively long distance before being collected whereas holes will travel a very short distance. Therefore, the probability of electron and hole collection at this point is reasonable and the total collected charge may be written as

\[ \sum_{e,h} CC = N_h + f N_e \quad (5.6) \]

Where \( N_h \) is the number of holes,

\( N_e \) is the number of electron and

\( f \) is the charge collection factor (usually \( f < 1 \))
For excitation in the bulk, the generated electrons and holes are not collected fully because the holes have to travel a comparatively long distance. But due to the short lifetime of holes, most of the holes recombine before being collected and therefore the electrons are not generated as efficiently as at the cathode. In fact, the drift velocity of the charge carrier is slowing down for weak electric fields and hence, the probability of trapping or recombination is higher in the bulk material than at the negative contact. So the total charge collection will be the sum of the fraction of total holes and electrons that are collected from the generation at the generation centre. We can write

$$\sum_{e,h} CC = f_h N_h + f_e N_e$$  \hspace{1cm} (5.7)$$

Where $f_h$ is the hole collection factor

$f_e$ is the electron collection factor

At the positive end, although the electric field is fairly weak, the electron only has to travel a very short distance before being collected, and so the probability of trapping or recombination is negligible and hole collection is almost zero. So the total charge collection at the positive end is

$$CC = f_e N_e$$

where $N_e$ is the number of electrons generated.
collection in this case is simply the number of electrons collected and we can write the equation
\[ \sum_{e,h} CC = f_e N_e \]  \hspace{1cm} (5.8)

Where \( f_e \) is the electron collection factor (\( f_e = 1 \)).

### 5.6.4 Experimental Set-up

The basic experimental set-up has been described in chapter 4. In the experiments reported here, the infra-red beam transmitted through the CdZnTe detector was collected by a lens and refocused onto a small area (0.3 mm\(^2\)) photodiode. This photodiode was connected to an eV-550 preamplifier and Ortec 570 shaping amplifier (0.5 \( \mu \)s shaping time) with an intrinsic electronics noise of 1.2 keV. The excess noise introduced by pulse-to-pulse variation in laser output was 2.1 keV. The photodiode was used to record the intensity of the transmitted infra-red beam on a pulse-by-pulse basis.

The polarisation of the incident laser beam was oriented at 45\(^\circ\) to the electric field in the detector. An analyser polariser was mounted just in front of the photodiode. When the analysing polariser was aligned with the polarisation of the incident laser beam, the photodiode recorded transmission intensity. When the analysing polariser was rotated by 90\(^\circ\) with respect to the incident beam polarisation, the photodiode recorded magnitude of the electric field integral along the optical path within the detector. Both configurations were used in the experiments reported here.

#### 5.6.4.1 Optical Calibration

Generally, laser output power is measured in d.c. mode using an integrating optical power meter. To calibrate the laser output power when in pulse mode, it was necessary to determine the equivalent power per pulse by inference from a time integrated measurement where the time between pulses was short compared to the integration time of the power meter. A calibrated integrating optical power meter (Anritsu ML 910B) was used in which the laser beam was directed onto the power meter sensor following attenuation by a neutral density filter. At laser pulse...
frequencies above 2kHz, the primary beam energy per 80 ns duration pulse was observed to be constant at 5.9x10^2 pJ/pulse when using an OD=3 neutral density filter. At lower frequencies, the power per pulse was observed to drop. This occurred since the laser pulse frequency dropped below the integration time of the power meter. For all subsequent experiments, the power meter sensor was replaced by the small area (0.3 mm^2) photodiode connected to preamplifier/shaping amplifier allowing a cross calibration at all laser pulse frequencies between optical power and shaping amplifier pulse height measured with an oscilloscope or multi-channel analyser. This data was used to normalise all subsequent intensity measurements as a function of laser pulse repetition frequency (f_p).

To continue the optical calibration experiments, a 50/50 dielectric beam splitter was then used in the path between the laser and CdZnTe crystal such that the intensity of the pulsed laser beam incident on, and reflecting from, the surface of the CdZnTe detector could be measured by the small area photodiode detector. This experiment determined that 10% of the incident laser beam reflected from the surface, independent of the position on the crystal when under bias. Measurement of the transmitted beam as a function of position in the crystal show that about 48% of the incident beam is transmitted with a variation of 2% in transmission both under bias and at zero bias for a pulse repetition frequency of 5kHz.

![Energy deposition in CZT detector as a function of depth.](image)

*Fig 5.12. Energy deposition in CZT detector as a function of depth.*
Chapter five: Band structure of Au-Cd\textsubscript{1-x}Zn\textsubscript{x}Te detector

Since 48\% and 10\% of the intensity of the incident beam are transmitted through and reflected from the crystal respectively, the absolute energy deposition per optical pulse in the CdZnTe detector can therefore be estimated as 42 ± 3\% of the incident beam energy per pulse. The energy deposition is almost identical independent of the position of interaction from the cathode through to the anode. Deposited energy (in keV) as a function of laser excitation distance from the cathode (but parallel to the cathode) with the detector under bias of 500V with a laser pulse repetition frequency of 5kHz is shown in fig.5.12. Little variation in energy deposition is observed as a function of position in the crystal.

5.6.5 Results and discussion

5.6.5.1 Spectral Response.

The apparatus was located in a dark optics laboratory to minimise the effects of ambient light. The full-width at half maximum of the 59.5 keV full energy peak was 4.1keV (7\%) and full-width half maximum of test pulse was 2 keV. In fig. 5.14 there are three pulse height spectra obtained by irradiation of the CdZnTe detector with the infra-red pulsed beam instead of a radiation source at three different positions within the crystal. For completeness, a peak obtained by injecting electronic pulses into the test input of the preamplifier is also included.

![Fig 5.14. CZT pulse height spectra using IR pulsed beam.](image-url)
It is interesting to note the clear reduction in charge collection efficiency as the distance of the beam from the cathode is increased. The peak broadening introduced by laser instability (2keV) is similar to the statistical broadening introduced during a photon interaction.

5.6.5.2 Electric Field Measurement

As described in chapter 3, it is possible to measure integral electric field along the optical path length within the CdZnTe detector by exploiting the Pockels effect. The mechanism of Pockels effect has been demonstrated in fig. 3.12.

By analysing the intensity of the beam when passed through a crossed polariser, it is possible to measure electric field directly using the following equation

\[
I = I_0 \sin 2 \left( \frac{\pi n_0^3 r d}{\lambda} E \right)
\]  

(5.6)

where \(I_0\) is the maximum transmitted light intensity passing through the uncrossed polariser; \(\lambda\) is the free space wavelength of the incident light (850 nm); \(d\) is the path length through the crystal (5 mm), \(E\) is the mean electric field intensity along the optical path; \(n_0\) is the field free refractive index and \(r\) is the Pockels electro-optic coefficient for CZT. For an example \(n_0\) was taken as 3.0 and for CdTe, \(r=4.5 \times 10^{-12}\) mV\(^{-1}\) both for wavelength of 1\(\mu\)m [17].

Fig.5.15 shows electric field measurements conducted at a pulse repetition frequency of 5kHz near to the cathode as a function of detector bias voltage. Electric field is seen to increase linearly with applied voltage as expected. However, it is necessary to check that the measurement itself does not perturb the field. If internal electric field is being perturbed by the presence of the applied laser beam, then a non-linearity in a plot of photodiode pulse height (from the transmitted laser beam with crossed polariser) with laser pulse duration should be expected. This holds as long as the laser pulse duration is not longer than the integration time of the shaping amplifier.
Chapter five: Band structure of $\text{Au-Cd}_x\text{Zn}_{1-x}\text{Te}$ detector

Fig 5.15. Electric field measurement as a function of detector bias voltage.

Fig 5.16. Transmission output with cross polariser as a function of laser pulse duration.
Chapter five: Band structure of Au-Cd$_{1-x}$Zn$_x$Te detector

Fig. 5.16 shows such a plot in which there is a reasonably linear relation between photodiode pulse height and laser pulse duration for a pulse repetition frequency of 5kHz and detector bias voltage of 100V/mm. For a short laser pulse duration of 80 ns, it is clear that the internal electric field is not unduly perturbed by the action of generating photo-induced charge during the measurement.

Using the micrometer to adjust the distance of the incident laser beam from the cathode, a set of measurements were taken to determine the variation of electric field in the direction perpendicular to the contacts. Due to spatially localised variations in refractive index within the CdZnTe crystal, the transmitted beam altered direction marginally at each measurement position. It was therefore necessary to reposition the transmission photodiode detector to maximise recorded signal at each measurement point in the crystal. By keeping applied voltage constant and altering the position of interaction of the optical beam with the crystal, it is possible to visualise electric field within the crystal. Fig.5.17 is the result of such a measurement and shows a broadly linear decrease in electric field from cathode to anode. The laser pulse repetition rate was 5kHz with an applied bias of 700V. Note that the maximum electric field at the cathode is $1.95 \times 10^2$ Vmm$^{-1}$.

![E-field measurement at varying distance from the cathode to anode.](image)

Fig. 5.17. E-field measurement at varying distance from the cathode to anode.
5.6.5.3 Charge Collection Efficiency

An initial charge collection efficiency measurement was made using a Am-241 X-ray source. This showed charge collection efficiency of 84% for the region near to the cathode. Extending this to the optically induced signals, by knowing the absolute optical energy deposited in the crystal per optical pulse (pJ/pulse) and the calibration of the multi-channel analyser (electrons per channel), the energy required to generate an electron-hole pair with the sub-bandgap laser beam was calculated as 11.3±0.4 eV. For this calculation, it is assumed that the charge collection efficiency for optically induced signals is the same as that for X-ray induced signals. Equivalently, during optical excitation, one absorbed optical photon out of every 8 will generate an electron-hole pair on average. This indicates that the efficiency of photo-excitation due to the sub-bandgap infra-red beam is relatively poor, suggesting that photo-excitation of electrons into the conduction band occurs from poorly populated or difficult to ionise states most probably near to the band edge. The deposited energy was in the range 148 to 156 keV/pulse depending on interaction location for a pulse repetition frequency of 5kHz. The calibration of the multi-channel analyser was 9.5 electrons per channel.

Using a definition for charge collection efficiency of number of electrons detected/number of electrons generated, fig.5.18 shows charge collection efficiency as a function of bias voltage for irradiation near to the cathode and anode. Efficiency drops from 84% near the cathode to 43% near the anode.

A higher resolution scan along a single linear path from cathode to anode is shown in fig.5.19 for laser pulse repetition frequencies of 2kHz and 5kHz under detector bias of 500V. The vertical axis is the centroid channel of the laser induced peak determined using a multi-channel analyser. Close to the cathode, the signal drops due to the finite width of the optical beam (i.e. incomplete irradiation of the detector by the full area of the beam). Further reduction in signal is expected due to a dead layer under the contact due to the presence of a metal-semiconductor Schottky barrier. Also, some optical scattering is expected to occur at the abrupt metal-semiconductor junction that may reduce the efficiency of charge generation. In the bulk of the crystal, a broadly linear reduction in charge collection efficiency is
observed, in line with the expectations resulting from the electric field results presented in fig.5.19. Close to the anode, an increase in charge collection efficiency is observed that is attributed to photoelectric charge generation from the metal electrode.

![Fig. 5.18. Charge collection efficiency (%) as a function of bias voltage.](image1)

![Fig.5.19 CZT photopeak with distance from cathode as a function of pulse repetition frequencies.](image2)
5.6.5.4 Defects States in Crystal

A series of experiments were undertaken in which the laser pulse frequency was varied. All measurements were normalised to correct for laser output variation with frequency. A plot of centroid channel for the laser induced photopeak as a function of pulse frequency is given in fig.5.20. The laser pulse width was 80ns with an applied bias of 500V. Above 5kHz, the peak channel is essentially stable with frequency. However, below 5kHz, recorded pulse height drops significantly with reducing frequency. Superimposed in fig.5.20 is a plot of average energy required to create each detected electron. This shows that efficiency of charge generation and/or transport is poor at low frequencies compared to that at high frequencies.

![Graph showing correlation between CCE and charge generation/transportation with pulse repetition frequency.](image)

**Fig. 5.20. Correlation between CCE and charge generation/transportation with pulse repetition frequency.**

Both at high and low pulse frequencies, electron transportation has been demonstrated in fig 5.21 and fig 5.22. To explain these observed phenomena, considering electron transport only, it may be concluded that a set of defect states become populated with trapped electrons, and that these electrons may take part in photo-excitation by the sub-bandgap laser beam. Once excited, these electrons
transport to the anode through the conduction band. However, there is a probability that the mobile electron will become trapped on its passage to the anode. Depending on the depth of the trap, there is also a probability that the electron will be thermally excited from the trap and hence become able to continue its passage to the anode once more. If this process of trapping and de-trapping occurs within the time window of the shaping amplifier, then the electron is able to contribute to the measured signal.

Fig 5.21. Proposed charge transportation pattern at low frequency.

Fig 5.22. Proposed charge transportation pattern at high frequency.

At low pulse frequency (<1kHz), it may be seen that electrons generated through photo-excitation will have a significant probability of trapping as they transport to the anode. Even though they may also de-trap, this will not necessarily occur within the time window of the pulse shaping amplifier. When the period between successive optical pulses is similar to or less than the lifetime of the electron in the trap, then an equilibrium becomes established in which the majority of traps are filled. In this case, the probability of an electron reaching the anode within the time window of the shaping amplifier increases since the probability of it being trapped is reduced. The “edge frequency” of around 5 kHz (period of 120 µs) is potentially an
indicator of the lifetime of the electron in the trap, and so could in principle be used to calculate trap depth. However, to undertake this measurement it is necessary to evaluate this phenomenon as a function of temperature and this is the subject of an ongoing investigation.

5.6.5.5 Discussion

Sub-bandgap infra-red radiation is a sensitive probe for investigating the bulk and contact properties of CdZnTe radiation detectors. It has been shown that by exploiting the Pockels effect it is possible to probe electric field within the detector without unduly perturbing the field in the process of making the measurement. This shows the E-field in a commercial 5x5x5mm³ Au-CZT-Au planar detector to increase linearly with bias voltage near the cathode, but to decrease linearly with depth into the device, with the detector remaining under-depleted even at 500V bias.

By simply adjusting the frequency of the pulsed optical beam, systematic variation in charge collection efficiency was observed under otherwise identical irradiation conditions. A model to explain this observed phenomena has been suggested although this model requires further validation.

5.7 Conclusion

This chapter has compiled the published data available for a commercially available AuCZTAu detector and has added to this considerable new information. These experimental results give good understanding of the advantages and limitations of the CZT detector which are helpful in establishing a programme of detector fabrication.

The band structure of the commercial electroless Au-contact CZT detectors has been studied to determine the barrier height. The near contact region of the detector bulk was also investigated and on the basis of experimental evidence, a band model has been proposed.
The contact as well as bulk properties of commercial Au-contact CZT detectors have also been investigated using sub-bandgap IR laser probe and the basic properties, and especially the electric field distribution, have been analysed.
Chapter five: Band structure of Au-Cd$_{1-x}$Zn$_x$Te detector

References


Chapter five: Band structure of Au-Cd$_{1-x}$Zn$_x$Te detector


CHAPTER SIX

CONTACT FABRICATION of CdZnTe DETECTOR

6.1 Introduction

The wide bandgap semiconductors, and especially Cadmium Zinc Telluride (CdZnTe), have attracted much attention as room-temperature x- and γ-ray detectors. They possess a unique combination of the necessary material properties of high photon detection efficiency, high bulk resistivity, good photoconductivity and acceptable electrical transport properties [1] that are required to fabricate a good spectroscopic grade detector.

However, material defects due to the presence of chemical and structural inhomogeneities such as grain boundaries, pipes and precipitates limit the yield of the material [2]. Carrier transport is governed also by defects like vacancies, impurities, stoichiometric variation etc., which limits the carrier mobility and lifetime. However, recently, the HPB growth method has yielded high resistivity boules with large volume that help to enhance the detector performance to a reasonable level. But like other semiconductor devices, the performance of a final CZT detector depends heavily on every single step in the fabrication process like surface preparation, surface treatment and most importantly, the design of electrical contacts. Besides bulk material, the electrical contact plays a significant role in determining the performance of a detector. The operation of metal-semiconductor contacts is still not well understood. Frequently the bulk and surface contributions are difficult to differentiate and are often misinterpreted. So it is one of the vital areas of research into CZT devices where it is necessary to put in an extensive effort to understand the facts comprehensively. In this work, we have tried to concentrate on contact fabrication on some CZT samples with various configurations and to study the characteristics of the fabricated devices.

In this chapter we will describe the contact fabrication procedure in detail. The CZT crystal wafer (approximate size 15cm x 12cm x 6mm) used for contact fabrication, was provided by eV Products, a division of II-VI Inc. There was not
much information about the growth conditions of the HPB CZT but it was said to be slightly n-type and "low grade" material. It has been found from PL measurement that concentration of Zn in this wafer was about 10 to 12 percent and the band-gap was about 1.57 eV as shown in Fig 6.1(a) & (b) respectively [3]. CZT crystals were processed in our own laboratory.

![Figure 6.1](image)

*Fig. 6.1. PL intensity measurement of CZT wafer (a) Zn concentration (b) Energy band-gap.*

### 6.2 Crystal Growth

Cd$_{1-x}$Zn$_x$Te (CZT) has traditionally been grown by the Bridgman method whilst the CdTe detectors is usually grown by the Travelling Heater Method (THM). For both processes, high purity polycrystalline CdTe and CZT are prepared by several zone refining techniques using standard procedures. Although the detector materials were provided by a commercial crystal manufacturer (eV Products), it is worth describing the growth procedure.
6.2.1 High Pressure Bridgman Method

Crystal growth with the Bridgman technique has briskly been pursued not only because large single crystals are easily obtained and growth rates are much faster, but also because the crystal grower has to some extent the freedom of controlling the type and the conductivity by controlling the deviation from stoichiometry.

The high pressure Bridgman (HPB) process was derived from the Bridgman process which itself was developed for growing a variety of single crystal materials. In the Bridgman process, elements Cd, Zn and Te are loaded in a tall narrow cylindrical graphite crucible (115mm diameter) [4] that in turn is loaded into the steel pressure vessel which possesses high tensile strength at elevated temperatures. The pressure vessel fits tightly into a die, which is a thick walled cylinder made of tungsten carbide. Tungsten carbide is very hard and tough even at high temperature. A piston made of similar material fits into the die enclosing the steel vessel. The entire cluster of steel vessel, die and piston is then placed into the furnace. The furnace is filled with argon or helium gas to prevent oxidation of the various tungsten carbide components.

The temperature and pressure are then raised to 1100°C and 100+ atm respectively and maintained for a period of several days whilst the crystal is grown. The thermal gradient for uniform re-crystallisation is achieved by individually controlled heating elements arranged vertically one above the other. Thermocouples are attached to the outside of the die to record temperature profile which is incorporated with a computer controlled power regulator that drives the heating elements. The schematic diagram is shown in Fig. 6.2 [5].
Chapter six: Contact fabrication of CdZnTe detector

![Schematic diagram of crystal grower by high pressure Bridgman method.](image)

**Fig 6.2.** The schematic diagram of crystal grower by high pressure Bridgman method.
Once the crystal is grown, the furnace temperature is slowly lowered until the system returns to ambient condition, at which time the furnace is unloaded. The entire process takes approximately 28 days to complete. The CZT boule of size about 150mm long and 90mm diameter still contains precipitates of tellurium, dislocations and grain boundaries. The portion of a crystal grown in this system that was provided to us by eV Products is shown in fig. 6.3a. The CZT boule was then sliced into the desired size using an ID saw and examined for defects through an IR microscope.

![Fig 6.3a. Raw CZT crystal grown by high pressure bridgman method.](image)

![Fig. 6.3b. CZT and CdTe crystals of various sizes.](image)

The use of a high pressure system during growth has some distinct advantages on the yields. As Cadmium has high vapour pressure, it is difficult to control its losses. However, the pressure in this HPB system is higher than the cadmium vapour pressure which prevents cadmium losses during growth. So the Cd vacancies will be reduced and this helps to improve the stoichiometry of the crystal. However, the crystal in this method still contains vacancies, dislocations and grain boundaries. The resistivity of the best material is around $5 \times 10^{10} \Omega \text{cm}$ [6].
6.2.2 Travelling Heater Method (THM)

The Traveling Heater Method (THM) is a solution growth process in which polycrystalline feed material, with an average constant composition, is progressively dissolved under the influence of a temperature gradient between two interfaces, followed by deposition, in single crystal form, onto a seed of the same composition. In this process, a Te solvent zone is passed slowly from one source ingot end to the other. The polycrystalline source is dissolved at one end of the solvent zone and the high-purity crystal [7] grows at the other end. The THM process ensures a constant macro-scale composition in the grown crystal. Since the process takes place at a temperature below the melting point, contamination from the container is also reduced. The reduced operating temperature also leads to a lower ambient pressure within the growth environment, and a reduced risk of ampoule fracture.

![Diagram of CdTe crystal growing system by Travelling Heather Method](image)

*Fig. 6.4. The schematic diagram of CdTe crystal growing system by Travelling Heather Method.*

In THM, a carbon coated silica boat, loaded with zone refined CdTe and excess tellurium, is placed within a horizontal silica tube. The silica boat is then heated uniformly to a temperature just below the melting point of tellurium. Additional
Chapter six: Contact fabrication of CdZnTe detector

heat from a movable heater melts the tellurium at one end of the boat. The heater is slowly moved down the length of the boat at a rate of a few millimetres per day. The molten tellurium slug deposits CdTe onto the growing boule at the retreating end of the slug. The advancing hot end of the tellurium dissolves the polycrystalline CdTe and maintains saturation. Usually, the horizontal silica boat is connected with another silica boat containing cadmium or tellurium that is heated up separately for vaporisation of its contents. Thus it is possible to grow CdTe in the silica boat with an independently controllable overpressure of cadmium or tellurium. Simultaneous zone refining ensures that excess tellurium and residual impurities are reduced in the single crystal boule. A diagram of the system is shown in Fig. 6.4. The high resistivity is obtained by compensating the native defects with Cl introduced in the solvent under the form of CdCl₂. Until recently, this was the most efficient proven method to grow homogeneous semi-insulating CdTe crystals useful for nuclear detection. The resistivity of THM grown CdTe tends to be around $10^9\Omega\text{cm}$ [8]. A CdTe boule grown in travelling heater method provided by Eurorad is shown in Fig. 6.5.

A limitation of THM is the low growth rate, typically over an order of magnitude less than those associated with melt growth techniques. The growth rate in THM is limited by the transport rate of the slowest constituent species through the solution zone and by the morphological instability of the growth interface.

Fig. 6.5. A CdTe wafer from a boule grown by THM.
6.2.2.1 Control of electrical conductivity

During crystal growth electrical conductivity can be controlled by annealing Cd or Te as desired. Cadmium vapour annealing of CdTe introduces excess cadmium atoms into the crystal while Tellurium vapour annealing introduces tellurium atoms or removes cadmium atom from it. In both cases, the result will be excess tellurium atoms. Annealing in cadmium or tellurium vapour transforms the crystal resistivity to \(10^3 - 10^6\ \Omega\text{cm}\) for either n-type or p-type respectively [9]. Proper annealing can produce high resistance CdTe, but pure CdTe is not a good detector material. The material is activated by addition of dopants, mainly donor materials chlorine or indium. Indium replaces cadmium in the crystal lattice and chlorine replaces tellurium. So the donor doped crystal is expected to become highly conductive in which subsequent tellurium annealing transforms the donors into a compensated state resulting in high electrical resistance.

6.3 Detector Crystal Selection

The CZT crystals used in this work have mainly been grown by the High Pressure Bridgman Method (HPBM) as it gives higher electrical resistivity as well as larger active volume yields. However, crystal uniformity is still a problem in these methods. Apart from this, the grown crystals contain various defects like grain boundaries, precipitates, cracks etc. These features cause a major degradation in the performance of a detector. So only the best part of the boules are taken for detector fabrication after examination with IR microscopy. The provided crystal wafer shown in fig. 6.3(a) was large enough to require cutting into individual devices of suitable size. Therefore, the CZT wafer was sliced using an Inside Diameter (ID) Diamond saw to yield slices of material of various desired dimensions such as 6x6x6 mm\(^3\) and 12x6x6 mm\(^3\) using the laboratory facility at University of Durham as we do not have appropriate instrument for cutting the crystal. Some samples of CZT crystal of various dimensions are shown in fig. 6.3b.

For spectral grade material, superior crystallinity and high bulk resistivity is required [10] but it has been mentioned earlier that the crystal wafer received was
large grained and multi-crystalline. So more or less all of the crystal pieces that were produced contained a grain boundary. However, we picked up the best crystals among them for this work.

6.4 Surface Preparation

Surface preparation (polishing and chemical etching) is an intermediate step which plays a vital role in determining the contact characteristics and the surface leakage current, which are often the dominant factors influencing detector performance. Chemical etching is aimed at restoring the surface stoichiometry and removing the damage layer that exists due to cutting and surface preparation.

In order to remove the cutting damage from the wafers and to get to the desired dimension, crystals were mechanically polished in two steps. Firstly, coarse polishing was done to reduce the size from 6x6x6 mm\(^3\) to 5x5x5 mm\(^3\) using 1000 grade carborundum. Once the crystal was polished down to the desired size, final polishing was done using 1 micron diamond paste until a shiny surface was achieved. It should be mentioned that the less rough the surface is, the lower the leakage current [11].

As CZT crystals are very delicate, special care should be taken during polishing. To maintain the planarity of the crystal, it is necessary to apply homogeneous pressure across the surface. In order to accomplish the job properly, a specially built crystal holder shown in fig. 6.6 was used for polishing which is able to hold
Chapter six: Contact fabrication of CdZnTe detector

the crystal parallel with the polishing material while continuous, homogeneous, pressure was put upon the crystal during polishing.

6.5 Chemical Etching

During crystal growth nonstoichiometry is one of the problems in CZT detectors. This nonstoichiometric material is believed to result in a tellurium-rich surface layer having a conductivity that is greater than the underlying stoichiometric CZT material. It is therefore enviable to remove nonstoichiometric material from the crystal surface, thereby reducing the conductivity of the crystal surface layer. In order to remove the conducting agents, chemical treatment is likely to be better than other methods. Apart from this, the damage caused by cutting and mechanical polishing is removed by chemical etching while the planarity (smoothness) of the crystal is improved [12,13]. This is particularly important immediately before the application of the electrical contacts to help remove the native oxide layer on the surface [14].

Various etching solutions exist but only a few are suitable for nuclear detector surface treatment. Br-methanol solution is the most standard one used for chemical etching. Chemical etching of CdTe and CZT is typically done by the standard bromine-methanol solution. There is no established indication about how long the detector should be chemically etched. To identify the role of etching on detector performance two identical detector crystals from same boule were chosen. Detectors D-1 & D-2 (5x5x3 mm³), equipped later with Schottky contacts, were etched for 3 minutes and 5 minutes respectively in 1% Br-Methanol solution. The rest of the fabrication procedures were followed exactly same for both the samples. Fig. 6.7 presents the typical dark current-voltage (I-V) characteristics for each surface treatment at room temperature. It can be seen from the figure that the leakage current of D-1 is more than an order of magnitude higher than that of D-2. It should be mentioned here that the detector performance depends on various factors including the materials growth so it will not be easy to make final comment on the basis of the results shown in Fig. 6.7. However, it had been noticed that longer etching time gives less leakage current than the shorter etched one.
However, all the samples were rinsed using gradually diluted Br-methanol and finally in pure methanol. Samples were then quickly blow dried with pressurised nitrogen gas. Finally samples were kept in iso-propyl-alcohol to avoid oxide layer formation until they were placed in vacuum for evaporation of their metal contacts.

6.6 Preparation of Electrical Contact

Detector contacts have mainly been formed by the thermal evaporation technique. The aim is to optimise a reasonably good contact which will give lower leakage current and good charge collection efficiency and consequently better energy resolution compared to conventional detectors. In this chapter we will reflect on the fabrication procedure in detail rather than the forms of contact and their behaviour. Various metals e.g. Au, In, Al were used to form contacts on CdTe and CZT detector substrates. The previous paragraph explained how the detector crystals were prepared for making contacts. After surface preparation, the crystals were then placed on appropriately shaped holes on top of the thermal evaporator stage with their desired face down to make sure the contact metal deposited on the entire area of the detector surface. It has been reported that the bare surface around the contact leads to the surface leakage current [15]. The evaporator basket which
Chapter six: Contact fabrication of CdZnTe detector

is right underneath of the stage, was filled by the desired metal and then covered by the airtight bell jar. High purity (99.999%) Au (4N+), In (4N+) and Al (4N+) provided by Goodfellow Cambridge Ltd. were used in contact fabrication. The vacuum system was then switched on until the vacuum pressure went down to around $5 \times 10^{-6}$ torr. A photograph of the vacuum system is shown in Fig. 6.8.

![Fig. 6.8. Photograph of Vacuum Chamber.](image)

Once evaporation completed on one side, the bell jar was opened by allowing air into it and the crystal repositioned with the opposite face of the crystal facing down. When the Al:In contact was grown, the Al and In metal filled two separate baskets and these were evaporated one at a time, first Al and then In. The thickness of the contact was kept within 60nm for better radiation penetration. This task was done very efficiently as the air may come onto the contact to form Aluminium oxide.

Five configurations of detector contact were fabricated e.g. Au-S-Au, Au-S-In, Au-S-Al, Au-S-In:Al, Au-O-S-Au with different sizes of crystals in different batches.
Among them, to fabricate the Au-O-S-Au detector, an oxide layer was developed on one of CZT contact surfaces before gold contact deposition to reduce surface leakage current. The desired crystal surface was oxidized in ambient conditions for 10 minutes [16] by using an aqueous solution of 15% hydrogen peroxide (H$_2$O$_2$;H$_2$O). The freshly oxidized samples were immediately placed into the high vacuum system under a pressure of 5x10$^{-6}$ torr for gold evaporation.

### 6.7 Surface Passivation

Several reports address the need for passivation of CdTe and CdZnTe surfaces [17-21]. Leakage current which can arise from the bulk of the material as well as the surface of the detector, limits the detector performance in terms of energy resolution and charge collection efficiency. Surface leakage current can often become more significant than bulk leakage for the high resistivity semiconductor detector. The DC component of the dark current can be blocked from the preamplifier of the readout channel by ac coupling. However, the noise associated with the dark current has ac components that are not blocked by the coupling capacitor and are integrated on the feedback capacitor of the charge sensitive preamplifier, degrading resolution. So surface leakage current should be minimised to enhance the detector performance in terms of energy resolution.

The CZT surfaces have been found to contain electrically conductive Te precipitates which form probable stable phase high resistivity layers of TeO$_2$, CdTeO$_3$ and ZnTeO$_3$ during oxidation of CT and CZT [22-25]. These help to reduce the surface leakage current. A recent Raman micro-spectroscopic study [26] identified TeO$_3^{2-}$ as the dominating surface species formed during oxidation of CZT.

The I-V measurement of newly fabricated devices were taken at room temperature. The observed I-V characteristics are ohmic and Schottky as expected. The graph in Fig.6.9(a) is linear which indicates practically ohmic contacts while Fig 6.9 (c) is Schottky in nature with the Au contact negative. As fresh contacts, the former detector was highly conducting with leakage current about 95nA at 100V and the resistivity was calculated to be 5x10$^8$ Ωcm. The latter detector was showing 48nA leakage current at a bias voltage of -200V at the Au contact. As the detector was
Schottky in nature we could not evaluate resistivity for this detector like the former one. Devices were passivated by an aqueous solution of 15% hydrogen peroxide \( \text{H}_2\text{O}_2:\text{H}_2\text{O} \) for 30 second. The \( \text{H}_2\text{O}_2 \) solution forms an oxide layer with a thickness in the range of 21-44 nm and it has been reported that saturation level has been reached after 5 minutes etching [27]. However, longer than 30 second passivation did not reduce the leakage current further but often resulted in failure to collect spectrum from that detector. There is the possibility of the formation of nonstoichiometric surface oxides, but we do not have any evidence to make comment on this. However, surface conductivity of the ohmic detector was reduced by 2 orders of magnitude after passivation which was typically achieved with an etching time of 30 seconds.

(a)

(b)
The leakage current was reduced to 5nA and the resistivity was increased to $2 \times 10^{10} \ \Omega \text{cm}$. The leakage current of the Schottky detector was also reduced by 3 times. However, these reductions in leakage current after passivation only lead to a
small improvement in detector performance. For example, the energy resolution of the Am-241 59.53 keV gamma ray peak was reduced from 4.8 keV to 4.4 keV and 5.6keV to 5.4 keV as shown in Fig. 6.9(b) & (d) respectively.

6.8 Fabricated Devices

Seven CZT detectors have been fabricated with different contact configurations. Detail of the fabrication procedures have been described earlier in this chapter. To help in analysis of the data presented in chapter seven and eight, a summary of the fabricated detectors is included in table-6.1.

Table-6.1. Summary of the fabricated devices including preparation method.

<table>
<thead>
<tr>
<th>Batch no.</th>
<th>ID</th>
<th>Detector materials</th>
<th>Size (mm³)</th>
<th>Surface preparation*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B1S4</td>
<td>Au-CZT-In:Al</td>
<td>5x5x2.5</td>
<td>MB +M+ CS₂ +IPA</td>
</tr>
<tr>
<td>1</td>
<td>B1S1</td>
<td>Au-CZT-Au</td>
<td>5x5x5</td>
<td>MB +CS</td>
</tr>
<tr>
<td>2</td>
<td>B2S4</td>
<td>Au-CZT-Al</td>
<td>5x5x3</td>
<td>MB +M+ CS₂ +IPA</td>
</tr>
<tr>
<td>2</td>
<td>B2S6</td>
<td>Au-CZT-Al</td>
<td>4x4x2.5</td>
<td>MB +M+ CS₂ +IPA</td>
</tr>
<tr>
<td>3</td>
<td>B3S5</td>
<td>Au-O-CZT-Au</td>
<td>5x5x3</td>
<td>MB +M+ CS₂ +IPA</td>
</tr>
<tr>
<td>4</td>
<td>B4S1</td>
<td>Au-CZT-In</td>
<td>5x5x5</td>
<td>MB +M+ IPA</td>
</tr>
<tr>
<td>4</td>
<td>B4S2</td>
<td>Au-CZT-Al</td>
<td>5x5x5</td>
<td>MB +M+ IPA</td>
</tr>
<tr>
<td>-</td>
<td>C1S1</td>
<td>Au-CZT-Au</td>
<td>5x5x5</td>
<td>-</td>
</tr>
</tbody>
</table>

6.9 Discussions

The detailed procedure of contact fabrication has been discussed in this chapter. The importance of each step in the fabrication process has been pointed out clearly and also the parameters which may cause an adverse effect on the detector performance have been covered in this discussion.

* MB=> Methyl Bromide, M=> Methyl, CS₂ => Calcium Disulphide, IPA => Isopropyl Alcohol
References


CHAPTER SEVEN

Detector Characterisation and Study of Contact Structure

7.1 Introduction

In this chapter, the basic characteristics of the fabricated and commercial devices are analysed in detail. On the basis of these characteristics, effort will be made to correlate these characteristics to find out the optimal detector performance. We will also try to focus on band structures in association with the internal electric field distribution.

7.2 Current-Voltage (I-V) Characteristics

A current-voltage characteristic of a detector is one of the important features to predict the performance of that particular detector. In order to operate the detector, we need to apply bias voltage that causes leakage current to be generated depending on the detector materials and the configuration of the metal-semiconductor interface.

Lower leakage current reduces the associated electronic noise as well as allowing the use of a higher bias voltage that improves the charge collection efficiency. It is therefore essential to keep the leakage current as low as possible. The highest resistivity of CZT detector achieved so far is about $2.5 \times 10^{11} \ \Omega \cdot \text{cm}$. If a 5mm thick slab of CZT with 5x5 mm$^2$ surface area is fitted with ohmic contacts, the electrical resistance between the faces would be $5 \times 10^{11} \ \Omega$. An applied voltage of 500V (100V/mm) would therefore cause a leakage current through the CZT of 1nA. The peak current generated by the radiation-induced charge carriers is usually similar to this. For example, a 50 keV photon can produce 10,000 charge carriers (average 5eV energy needed to produce an ion pair) which are collected in 0.5μs, so that

$$I = \frac{q}{t} = \frac{10,000 \times 1.6 \times 10^{-19}}{5 \times 10^{-7}} = 3\text{nA} \quad (7.1)$$

A plot of applied bias voltage against leakage current is a measure of the basic characteristics of the detector and gives good insight into its operation.
In this study, I-V characteristics of some newly fabricated CZT and CdTe detectors have been analysed. Measurement of the I-V characteristics of CZT and CT devices was performed at room temperature as well as low temperatures.

The I-V characteristics of the commercial electroless AuCZTAu and evaporated AuCZTAu back to back contact detectors is shown below to be linear as expected with low leakage current and high resistivity. The leakage current was found to be 2nA for electroless AuCZTAu and about 15nA for evaporated AuCZTAu detector at 200V bias. The resistivity can be calculated as

\[ \rho = \frac{V}{I} \times \frac{A}{d} \Omega \text{cm} \quad (7.2) \]

where \( V \) is the bias voltage, \( I \) is the measured leakage current, \( A \) is the area of the detector and \( d \) is the detector thickness. So the resistivity of electroless AuCZTAu detector for 0.5 cm thick and 0.25 cm\(^2\) area will be \( 5 \times 10^{10} \Omega \text{cm} \).

![Current vs. Voltage Graph](image)

**AuCZTAu (C1S1)**

5x5x5 mm\(^3\)

\( I_L = 2 \text{nA per for 200V in 0.25mm}^2 \text{ area, } \rho = 5 \times 10^{10} \Omega \text{cm} \)**

126
AuCZTAu (B1S1)
5x5x5 mm³
Iₗ=15 nA for 200V in 0.23mm² area,
ρ = 5.9 x 10⁹ Ωcm

Fig. 7.1 The current-voltage characteristics of back to back contact CZT detectors (a) electroless AuCZTAu (b) evaporated AuCZTAu

Among the devices we fabricated, the B2S4, B4S1 and B4S2 devices show good rectifying behaviour with low leakage current for a negatively biased Au contact and achieved reasonably high resistivity as shown in fig. 7.2 & 7.3.

AuCZTAI (B2S4)
Iₗ=8nA for 200V @Au -Ve
ρ = 1.6 x 10⁹ Ωcm

AuCZTln (B4S1)
Iₗ=30nA for 200V @ Au -Ve
ρ = 5 x 10⁹ Ωcm

Fig. 7.2 The current-voltage characteristics of CZT Schottky detectors
Chapter seven: Detector characterisation and study of contact structure

Fig. 7.3 The current-voltage characteristics of CZT Schottky detector.

Two more devices, AuCZTIn:Al (B1S4) and AuCZTAI (B2S6), are expected to be rectifying and exhibit non-linear I-V characteristics but with high leakage current as shown in fig. 7.4. This was found likely to be due to electrical shunt paths through the orthogonal surfaces of devices that dramatically reduce after passivation as discussed in previous chapter.

Fig. 7.4 The current-voltage characteristics for thin Schottky devices.
Chapter seven: Detector characterisation and study of contact structure

7.2.1 Temperature Dependence I-V Characteristics

In order to see the temperature effect on current-voltage (I-V) characteristics of CZT detectors we carried out an experiment under different temperature conditions. A 5x5x5 mm³ CZT detector was placed in a specially built ceramic (ρ >10¹⁶ Ωcm) holder with BeCu sprung contacts at both ends for electrical contact of the detector. The ceramic holder was then fixed on to a Peltier cooled cold plate using heat sink solution in a vacuum chamber under 2x10⁻² torr pressure. The cold plate temperature was controlled by applying a suitable current to the Peltier device. The detector output was connected to a Keithley 487 Picoammeter via a load resistance. The value of the applied voltage and the corresponding current measurement was controlled using computer software. A plot of I-V for various temperatures is shown in fig7.5.

![Image](image.png)

**Fig. 7.5 The current-voltage characteristics of AuCZTAu detector at various temperatures.**

The leakage current decreases significantly at lower temperature as expected. Wide bandgap semiconductor detectors like CZT should have reasonably low leakage current as the barrier height at the metal-semiconductor junction is high enough to
hinder the transport of thermally generated electron-hole pairs through the junction. Only those electrons in the high energy tail of the Fermi distribution are energetic enough to surmount the barrier and be injected into the semiconductor. The rate at which electrons are thermally excited over the barrier depends on the height of the barrier and the temperature of the Fermi gas in the metal.

The value of the saturation current density is given by [1]

\[ J_{ST} = A^{**}T^2 \exp \left( -\frac{\phi_B}{kT} \right) \]  

(7.3)

Where \( A^{**} \) is called the effective Richardson constant [2] with the value of 120 AK\(^{-2}\)cm\(^2\) for electron emission from a clean metal surface. \( T \) is the absolute temperature. Under reverse bias, the barrier height will remain unaffected and a small current independent of the applied bias voltage is observed. At constant bias voltage of 500V the leakage current greatly increases with the temperature but decreases with the bandgap energy. However, current density dominates to increase with temperature exponentially. A plot of leakage current in log scale against temperature (T) is shown in fig 7.6 and gives a straight line as expected.

![Fig 7.6 Leakage current vs temperature.](image-url)
7.3 Charge Collection Efficiency

The charge carriers generated while the x- or gamma-ray photon interact in the detector then drift with velocity $\mu V/d$ (where $\mu$ is the mobility of the charge carrier, $V$ is the applied bias voltage and $d$ is the detector thickness) toward their respective electrodes due to the applied electric field. If all the generated charge carriers are collected, then 100% charge collection efficiency can be said to have been achieved, but practically it would not be possible as various intrinsic and extrinsic factors act to restrict achieving the desired goal. The generated charge carriers are likely to be trapped or recombine on their way before being collected by the electrodes. The amount of carrier loss depends on the purity of detector material, crystal structure, detector fabrication methods etc.

The drift velocity of charge carriers are expected to increase with the applied electric field at low and intermediate field strengths but at higher fields it increases more slowly with the field and eventually saturates as we explained in chapter 3. The calculated value of the carrier velocity from a good quality 5x5x5 mm$^3$ size AuCZTAu detector is around $1.35 \times 10^6$ cm/s so the time required to collect the carriers is about 0.4$\mu$s provided that they can reach the electrode. So further increment of electric field will not make any difference in terms of charge collection. In this section, endeavour was made to determine the charge collection efficiency of various commercial as well as fabricated devices. In order to do that the experimental set-up had to be calibrated using an electrical pulser. If the value of the preamplifier 'test input' capacitance is known, a pulser can be used to give an absolute system calibration with a reasonable accuracy.

Fig. 7.7 shows the basic experimental set-up. An eV-550 charge sensitive preamplifier (test input = 1pF) was connected to an ORTEC 570 amplifier with shaping time 0.5 $\mu$s. A ORTEC 480 precision pulse generator was used to calibrate the system via the test input of the preamplifier. Whilst the calibration is carried out, the scope and preamplifier must both be connected in the circuit, since the pulse amplitude measured on the scope depends on the correct loading of the pulser. The detector should also remain connected to the detector input of the amplifier throughout, since the system gain changes slightly if the preamplifier input capacitance varies. The
output of the shaping amplifier was connected to a four channel digital oscilloscope (model TDS 544) and then to the MCA input. The attenuated

Fig. 7.7 Schematic diagram of MCA calibration using pulser signal.

output from the pulser to the test input of the preamplifier was also sent to the digital oscilloscope. The pulse averaging mode on the oscilloscope was used to improve the noise on the very small pulser signals. Then the pulse height spectra were acquired from the Multi Channel Analyser (MCA) for different pulser amplitude. For each pulser amplitude, the peak to peak height of the pulser signal and corresponding centroid channels in MCA were noted down.

The total generated charge for the applied pulser signal can be calculated as

\[ Q_{\text{pulser}} = V_{\text{pulser}} \times C_{\text{test}} \]  

(7.4)

So the total number of e\(^{-}\) produced can be estimated by

\[ e^{-} = \frac{Q_{\text{pulser}}}{1.6 \times 10^{-19}} \]  

(7.5)

Using the accepted W-value for CZT of 5eV [3-5], the energy deposited into the detector can also be estimated as
Chapter seven: Detector characterisation and study of contact structure

\[ E_{\text{CZT}}(\text{keV}) = e^x W_{\text{CZT}} / 1000 \quad (7.6) \]

A calibration graph of \( E_{\text{CZT}} \) (keV) against MCA peak centroid in channel number was plotted in fig 7.8. A linear regression applied to this graph gives a gradient (keV/ch) and an intercept (keV).

![Graph showing calibration plot for CZT detector.](image)

**Fig. 7.8. Calibration plot for CZT detector.**

The corresponding channel number of the 59.5 keV gamma peak of Am-241 can easily be figured out from the above graph. That channel number can be considered to correspond to 100% charge collection of the Am-241 peak. Now acquiring centroid peak channel using various CZT detectors at different bias voltages, we can work out the charge collection efficiency for various detectors. The charge collection efficiency of commercial AuCZTAu and fabricated AuCZTAu detectors was evaluated using the above calibration curve to be 84.4% and 79.1% respectively at a bias voltage of 600V as shown in fig 7.9. It can be noticed that the locally fabricated device gives less charge collection efficiency compared to the commercial Au-CZT-Au detector. However, charge collection efficiency of both detectors is saturating at about 600V.
Chapter seven: Detector characterisation and study of contact structure

![Graph](image)

**Fig. 7.9** Charge collection efficiency of 5x5x5 mm³ AuCZTAu detectors.

The charge collection efficiency of fabricated Schottky devices AuCZTIn (B4S1), AuCZTAI (B4S2) and AuCZTAI (B2S4) were found about 89.8% at 400V, 85.2% at 350V and 88% at 300V respectively which is shown in fig. 7.10. It can be seen that the charge collection efficiency is considerably higher than both AuCZTAu detectors even at lower applied bias voltage.

![Graph](image)

**Fig. 7.10.** Charge collection efficiency of various Schottky devices.
Chapter seven: Detector characterisation and study of contact structure

7.4 Mobility-Lifetime Product

The mobility-lifetime (μτ) of charge carriers is the fundamental figure of merit to enumerate detector performance in terms of charge collection as it only depends on the intrinsic properties of material. The mean free path or trapping length is given by the quantity μτE where μ is the mobility, τ is the average carrier lifetime and E is the electric field applied. The electric field depends on the metal semiconductor nature. In order to increase the mean free path the mobility-lifetime (μτ) product needs to be maximised. The best performance of a detector is obtained under conditions where the charge carrier mean free paths are much longer than the detector thickness, preferably by more than an order of magnitude [6] so that almost all of the charge generated by absorption of x- or gamma-rays can be collected at the electrodes. The reported charge carrier mean drift or lifetime range from 50 ns to 300 ns for holes and from 100 ns to 1 μs for electrons [7]. The measured charge carrier mobilities for CdTe and Cd$_{0.8}$Zn$_{0.2}$Te are 1000 cm$^2$/V.s and 1350 cm$^2$/V.s for electrons and 80 cm$^2$/V.s and 120 cm$^2$/V.s for holes respectively at room temperature [8]. So the calculated value of mobility-lifetime product is about $1.35 \times 10^{-4}$ to $1.35 \times 10^{-3}$ cm$^2$/V for electrons and $6 \times 10^{-6}$ to $3.6 \times 10^{-5}$ cm$^2$/V for holes.

In this study, mobility lifetime (μτ) product for charge carriers of commercial as well as fabricated CZT detectors has been estimated by employing low energy γ-ray spectroscopy. The evaluation of μτ product of the electrons and holes is generally derived by fitting the bias dependence of the CCE obtained from gamma-ray spectroscopy to the Hecht equation [9] shown in equation 7.7.

$$\text{CCE} = \frac{Q}{Q_0} = \frac{\mu_e \tau_e V}{d^2} \left[ 1 - \exp \left( \frac{1 - \frac{x}{d}}{\mu_e \tau_e V/d^2} \right) \right] + \frac{\mu_h \tau_h V}{d^2} \left[ 1 - \exp \left( \frac{- \frac{x}{d}}{\mu_h \tau_h V/d^2} \right) \right]$$  (7.7)

where x is the range of 59.5 keV γ-ray in CdZnTe and is calculated to be 0.6 mm (linear attenuation coefficient of CZT for 59.5 keV energy photon is 37.79 cm$^{-1}$) [10], d is the detector thickness, Q is the total charge collected, $Q_0$ is the total charge collected.
generated, \( \mu_e(\mu_h) \) is the drift mobility of electrons (holes) and \( \tau_e(\tau_h) \) is the carrier lifetime of the electrons (holes).

The fitting of a finite number of measured results to the calculated models with two parameters is very inaccurate and inconclusive [11]. In order to get more accurate result, one polarity of the charge carriers needs to be considered at a time. In this context, a low penetrating radiation source like alpha particles or low energy x- and gamma radiation is suitable to use for irradiation, as higher penetrating radiation may generate charge carrier in the bulk in which both carriers to some extent will contribute in the resulting signal. Although the penetrating range of 59.5 keV Am-241 \( \gamma \)-ray source is comparatively higher than for alpha particles, in this study a 59.5 keV Am-241 \( \gamma \)-ray source had been used for irradiation, as it can be justified in such way that the penetration depth of 59.5 keV in CdZnTe detector material is small compared to the thickness (2.5 mm to 5mm) of the detectors. Furthermore, as has been reported, the hole lifetime is an order of magnitude of smaller than that of the electrons. The detector had been irradiated through negatively biased front contact, so only the mobility-lifetime product of electrons \( (\mu_e\tau_e) \) can be evaluated, as the holes will sweep out very quickly through the near contact and the electrons will travel all the way to other contact. This means that the induced current signal is mostly contributed by electrons. Unlike \( \mu_e\tau_e \) product, evaluation of the \( \mu_h\tau_h \) product is rather difficult, as irradiation of positively biased front contact does not yield spectral peaks.

In order to get a more accurate result, one of the two terms on the right hand side of equation 7.7 has to be ignored. Since only electrons are likely to be contributing to the induced current pulse, the second term of equation (7.7) can be ignored. By reversing the bias or irradiating through the positively biased electrode, the corresponding expression can be applied for holes provided that the hole transport is good enough to produce a full energy peak in the pulse height spectrum.

Fig. 7.11 shows a typical bias dependence of the CCE obtained from \( \gamma \)-ray spectra for commercial Au-CZT-Au 5x5x5 mm\(^3\) detector (C1S1). The circles are the experimental points while the line is a fit to the first term in Equation 7.7. From this analysis \( \mu_e\tau_e \) is estimated for various commercial as well as locally fabricated CZT
detectors as shown in Table 7.1. From Fig. 7.12 can easily be seen that the fabricated AuCZTIn (B4S1) and AuCZTAl (B4S2) Schottky devices give higher $\mu_e \tau_e$ product than the commercial AuCZTAu detector. However, all other CZT detectors although give lower $\mu_e \tau_e$ values but still comparable to other reported data [12-14].

![Bias dependence of the CCE to extract $\mu_e \tau_e$](image)

**Fig. 7.11. Bias dependence of the CCE to extract $\mu_e \tau_e$**

![Histogram of $\mu_e \tau_e$ value of various CZT detector.](image)

**Fig. 7.12. Histogram of $\mu_e \tau_e$ value of various CZT detector.**
**Table 7.1. Mobility-lifetime product of electron of various detectors.**

<table>
<thead>
<tr>
<th>Detector type and size</th>
<th>Detector ID</th>
<th>$\mu_t \tau_e \text{ cm}^2/\text{V at room-temp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AuCZTAu; 5x5x5 mm$^3$</td>
<td>B1S1</td>
<td>7.47 x 10$^{-4}$</td>
</tr>
<tr>
<td>AuCZTIn:Al; 5x5x2.5 mm$^3$</td>
<td>B1S4</td>
<td>5.57 x 10$^{-4}$</td>
</tr>
<tr>
<td>AuCZTIn; 5x5x3 mm$^3$</td>
<td>B2S4</td>
<td>8.55 x 10$^{-4}$</td>
</tr>
<tr>
<td>AuCZTIn; 4x4x2.5 mm$^3$</td>
<td>B2S6</td>
<td>7.75 x 10$^{-4}$</td>
</tr>
<tr>
<td>Au-O-CZT-Au; 5x5x3 mm$^3$</td>
<td>B3S5</td>
<td>5.29 x 10$^{-4}$</td>
</tr>
<tr>
<td>AuCZTIn; 5x5x5 mm$^3$</td>
<td>B4S1</td>
<td>1.62 x 10$^{-3}$</td>
</tr>
<tr>
<td>AuCZTAI; 5x5x5 mm$^3$</td>
<td>B4S2</td>
<td>1.43 x 10$^{-3}$</td>
</tr>
<tr>
<td>AuCZTAu; 5x5x5 mm$^3$</td>
<td>C1S1</td>
<td>9.93 x 10$^{-4}$</td>
</tr>
</tbody>
</table>

**Reported value**

<table>
<thead>
<tr>
<th>Material</th>
<th>Reference</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdZnTe</td>
<td>Ref. [12]</td>
<td>2.3 x 10$^{-3}$</td>
</tr>
<tr>
<td>CdZnTe</td>
<td>Ref. [13]</td>
<td>8 x 10$^{-4}$</td>
</tr>
<tr>
<td>CdZnTe</td>
<td>Ref. [14]</td>
<td>2 x 10$^{-3}$</td>
</tr>
</tbody>
</table>
7.4.1 Temperature Dependence $\mu T$ Product

The charge carriers drift within the crystal has been hindered due to defect states like impurities, irregularities etc., in the crystal. The carrier mobility has mainly been affected due to lattice interaction and impurity interaction. If the lattice warms up, the lattice scattering component will increase due to interaction of carriers with phonons (which are caused by lattice vibration) and the mobility will decrease. The mobility from phonon interaction $\mu_L$ [15] is given by

$$\mu_L = \frac{1}{\left(\frac{m^*}{2} \frac{T}{2}\right)^{\frac{3}{2}}} \quad (7.8)$$

From equation (7.8), it can be seen that the mobility decreased with the temperature as well as with effective mass, $m^*$. However, at lower temperature, the lattice scattering becomes less important, but the carriers are more likely to be scattered by impurities since the carriers are moving more slowly.

The impurity concentration increases with the temperature as they are ionized at even room temperature. So the higher impurity concentration results in more carrier scattering with the lattice which significantly affects the mobility. The mobility from ionized impurities $\mu_I$ can be described [16] by

$$\mu_I = \frac{\frac{3}{2}}{\left(\frac{1}{2} m^* N_i^{-1}\right)^{\frac{1}{2}}} \quad (7.9)$$

Where $m^*$ is the conductivity effect mass and $N_i$ is the ionized impurity density. From equation (7.9) it can be seen that the mobility is expected to decrease with the effective mass but to increase with the temperature.

The combined mobility [17] will then be from equations (7.8) & (7.9)

$$\mu = \left(\frac{1}{\mu_L} + \frac{1}{\mu_I}\right)^{-1} \quad (7.10)$$
From the above equations it is found that the mobility decrease due to lattice scattering and ionized impurity scattering is proportional to $T^{-1.5}$ and $T^{-1.5}$ respectively. In the range 200-320K this ideal situation is not always the case as mobility also depends on other scattering mechanisms. However, from equation 7.10, it can roughly be estimated that the mobility decreases with temperature by the rate $4 \times 10^5 \text{cm}^2\text{V}^{-1}\text{s}^{-1}\text{K}^{-1}$.

On the other hand, the lifetime of charge carriers is a material parameter that depends very much on the density of carrier traps and recombination centres within the crystal. Lifetime is determined by the rate of recombination of electrons and holes. As the temperature lowers, the carriers move more slowly. The occupancy of shallow trap centres initially is low so the probability of trapping of the slower carrier is very high. So it is expected that the lifetime of the charge carrier will be significantly shorter at lower temperature and the resulting $\mu\tau$ product is likely to be smaller as the temperature goes down.

In order to see this effect, we carried out an experiment. For this, a 5x5x5 mm$^3$ AuCZTAI detector was placed in a cryostat. The basic structure and mechanism of the cryostat has been explained in chapter 4. A 7.4 GBq Am-241 $\gamma$-ray source was used to irradiate from the side of the detector. Since the source was highly radioactive, it was kept in a properly shielded container with 0.2 mm diameter collimator. To avoid irradiation to the bulk of the detector a 3x3x2 cm$^3$ brass made block with 100 $\mu$m width slit was placed in front of it as shown in fig. 7.13.

The radiation source and the slit were placed as close to the detector as possible to minimise the irradiation to other places than the expected area. The detector (cryostat), collimator and the source were placed on an optical rail and a micropositioner was used to align the beam line. Irradiation towards the bulk from the negative contact would affect evaluation of the $\mu\tau$ product as we discussed earlier. Taking into consideration this point, detector irradiation was kept within the limit of 100$\mu$m from the negative contact.
Temperature of the detector was controlled by the cryostat system. Charge collection efficiency was calculated from collected photopeak data at different bias voltages for various temperatures. Charge collection efficiency was plotted against bias voltage from which $\mu_c\tau_e$ was extracted for different temperatures. A plot of $\mu_c\tau_e$ against temperature is shown in fig. 7.14. The straight-line regression has a correlation coefficient of 0.9999 and $\mu_c\tau_e$ decreased with temperature as expected. From the gradient of the graph, the rate of the mobility-lifetime product decrease with temperature was determined to be $4 \times 10^{-5}$ cm$^2$V$^{-1}$K$^{-1}$.
7.5 Electric Field Measurement

The performance of any CZT detector in terms of charge collection and hence the energy resolution is greatly dependent on the internal electric field distribution. It has been reported [18-21] that the electric field distribution in commercial AuCZT is non-uniform and tends to concentrate on the cathode side, extending only half the distance across the detector. From the assessment of charge collection efficiency of the fabricated devices, we predict that the E-field is likely to prolong through the bulk to the back contact.

7.5.1 Experimental Procedure

To observe this effect we performed the E-field measurement experiment. Details about this experiment have been discussed in chapter 5. The same experimental procedure was followed but in the experimental set-up the detector was placed into the cryostat in order to measure the electric field at low temperature. Regarding the noise in the measurement system, it can pick up from various sources mainly if the system has not properly grounded, so great care should be taken to minimise the leakage noise. While the system runs under low temperature, condensation may happen by which water vapour may be absorbed by the detector. This may cause degradation in the detector performance. So before the flow of liquid nitrogen was started, the cryostat was backed by a rotary pump to achieve vacuum with pressure at around $10^{-4}$ torr.

Endeavours were to try to measure the electric field distribution within the bulk of all the in-house fabricated CZT and CT devices as well as commercial CZT and CT. But this task was very tough, as it needs very careful concentration and temperament to do that. In some cases, the IR beam used to illuminate the detector was either not transmitted or transmitted as a distorted beam through the bulk of some of the detectors. This might have been due to either surface roughness or structural defects that cause light dispersion. However, good output was achieved after a great care taken during measurement.
Chapter seven: Detector characterisation and study of contact structure

The detector was placed in the cryostat in such a position that it could be scanned horizontally from cathode toward the anode with respect to the stationary incident laser beam using an x-y positioner. A set of measurements was taken at various positions with an interval of 0.5 mm at the saturation bias voltage of each detector. Due to spatially localised variations in refractive index within the CdZnTe crystal, the transmitted beam altered direction marginally at each measurement position. It was therefore necessary to reposition the analyser as well as photodiode detector to maximise recorded signal at each measurement point in the detector. Once the room-temperature measurement completed the detector was cooled down by liquid nitrogen flow to the cryostat. The same experiment was repeated at -20°C.

7.5.2 Results

Equation 5.1 was used to generate the values of E-field. The E-field calculation had associated with it an error of ±5% that was derived from the signal to noise ratio of the final average trace from oscilloscope. The calculated E-field values were plotted against the distance from the cathode to observe the field distribution throughout the detector thickness. The electric field distributions for both the commercial and the fabricated AuCZT-Au 5x5x5 mm³ detectors are shown in Fig. 7.15. In order to compare with the commercial detector electric field distribution, values for the fabricated devices were normalised to 700V. Normalisation can be done as the electric field is linear with bias voltage shown in Fig 5.13. A broadly linear decrease in the electric field of the commercial detector was observed from the cathode to the bulk with the maximum electric field at the cathode of 1.95x10³ Vcm⁻¹ which decreased down to 4.9x10² Vcm⁻¹ at the middle of the bulk for an applied bias of 700V. The Au-CZT-Au detector that was fabricated in our laboratory showed a reasonably flat field distribution at the cathode side down to a depth of 2mm into the bulk before decreasing broadly linearly towards the anode. The maximum electric field recorded at the cathode was around 1.54x10³ Vcm⁻¹ for an applied bias voltage of 600V which then dropped down to 5.1x10² Vcm⁻¹ at 3.5 mm at the bulk.
Chapter seven: Detector characterisation and study of contact structure

Fig. 7.15. E-field distribution in commercial and fabricated AuCZTAu 5x5x5 mm³ detectors.

The results of electric field distribution in the fabricated AuCZTIn(Al) Schottky devices are plotted in Fig. 7.16. Field distribution pattern is noticeably different compared to the back to back AuCZTAu detectors. The strong electric field observed at the cathode almost linearly prolongs up to approximately two-third of the thickness and then decrease gradually near the back contact. The electric field distributions of commercial as well as fabricated devices at low temperature are shown in Fig. 7.17.

Fig. 7.16. E-field distribution in fabricated Schottky detectors.
The fields at low temperature mainly concentrate at the cathode region and tend to drop sharply within about 2mm into the bulk. The pattern appearance in the following figures of electric field distribution was reproducible for a particular detector and a particular track.

![E-field distribution of commercial and fabricated devices at low temperature.](image)

**Fig. 7.17.** E-field distribution of commercial and fabricated devices at low temperature.

### 7.5.3 Discussion

The result shown in Fig. 7.15 of electric field distribution in AuCZTAu 5x5x5 mm³ was observed to be concentrated near the cathode and merely expand up to the middle of the bulk with virtually no field in the other half of the detector. So the generated charge carriers illuminated by photons near the cathode drift towards their respective electrodes due to the influence of the applied electric field. The ionized ions left behind form a depletion region on the cathode side in which the internal electric field is enhanced. With distance toward the anode the electric field is deteriorating, so the carriers move comparatively slower as they approach the anode since the drift velocity depends on applied electric field. So the probability of carrier trapping increases before they reach the electrode. This field distribution in AuCZTAu can be associated with the proposed energy band diagram shown in Fig 7.18. With applied
bias voltage, the band is tilted with a small bump within around 20μm at cathode region that we explained in chapter 5.

![Diagram](image)

*Fig. 7.18. Proposed energy band diagram of AuCZTAu detector.*

Unlike the AuCZTAu detector, the electric field of AuCZTIn(Al) Schottky devices extends up the about two-third across the detector length. At the back contact, In(Al) diffuses into the bulk to produce a highly n⁺ type doped region where the band bends further to create a depletion region and eventually enhance the small electric field. The charge carriers therefore generated by illumination near the cathode drift towards the respective electrodes due to the influence of the applied electric field. In the low field region at the back contact, the built-in electric field (from the back contact) drags charge carriers towards the contact so helping the electric field to be extended towards the back contact. However, the electric field is still under depleted which restricts full charge collection and consequently has an affect on energy resolution.

The proposed band diagram sketches in Fig. 7.19 (a) & (b) help to understand the electric field distribution explained above.
Fig. 7.19. Proposed band diagram for AuCZTIn(Al) Schottky devices (a) without bias (b) with bias.

7.6 Spectral Response

In this section, the X- and γ-ray spectroscopy characteristics of various fabricated as well as commercial CZT detectors will be discussed.
7.6.1 Experimental Set-up

To acquire various radiation spectra for the commercial and in-house fabricated CZT detectors, the conventional experimental set-up was used that is shown in Fig. 7.20. The detector was held in a sprung loaded brass holder with a beryllium entrance window. The detector was connected to an ORTEC 570 shaping amplifier with gain of 200 via an eV products 550 charge sensitive preamplifier (3.6mV/fC). The output of the shaping amplifier was connected to a multi-channel analyser (MCA) that was installed in a computer. The MCA was used to collect spectra using the driver software PCAII. The detectors were operated with saturated bias voltage supplied by a Canberra 3122D power supply.

![Fig. 7.20 Schematic diagram of spectroscopic measurement.](image)

7.6.2 Spectroscopic Measurement

The X- and gamma-ray spectroscopy was performed using the low energy gamma-ray sources Am-241, Ba-133, Co-57 with activities of 7.4GBq, 0.04MBq and 0.04MBq respectively. The detection efficiency of CZT detectors for the gamma energy range up to 136 keV is almost 100%. The intrinsic electronics noise of the system was measured using a precision pulse generator (ORTEC model 480) connected to the test input of the preamplifier. This gave a FWHM value of 2.2 keV. The shaping time of shaping amplifier was chosen to be 0.5 μsec. This time is long enough to collect electrons as the electron transition time \( t_e \) in 5mm thick CZT detector is \( t_e = d^2/\mu V = 0.4\mu\text{sec} \) where, \( d \) is the detector thickness, \( \mu \) is the mobility of electron in CZT 1350cm²V⁻¹S⁻¹ [22] and \( V \) is the applied voltage. Increases in the shaping time above
0.5 μsec were found to degrade the spectral resolution. The photopeaks of Am-241 and Co-57 obtained from an AuCZTAu detector for different shaping times are illustrated in Fig.7.21 & 7.22. The FWHM attained for 0.5μs is considerably lower than that of ≥1.0μs.

**Chapter seven: Detector characterisation and study of contact structure**

![Fig.7.21 Am-241 photopeaks for different shaping time.](image1)

![Fig.7.22 Co-57 photopeaks for different shaping time.](image2)
It can be noticed in Co-57 spectra that the 136 keV line gradually disappeared with increasing shaping time while the noise on the screen appeared at the lower energy side. The reason may be that the longer shaping time allows both the detrapped as well as the other slower carriers to contribute to the signal which results in poor spectral resolution.

Fig. 7.23 shows the FWHM as a function of electric field for 0.5μs shaping time. The FWHM value decreases with the increase of electric field that clearly indicates the improvement in energy resolution of higher E-fields. However, this improvement will continue until the electric field expansion is reached in the saturation stage. Further increase in electric field will no longer improve the resolution. Rather, carriers tunnelling through the contact will start to have an adverse affect on energy resolution.

![Graph showing FWHM as a function of E-field](image.png)

*Fig. 7.23 FWHM as a function of applied E-field.*
7.6.2.1 Am-241 Spectra

The 59.5 keV (I_r=35.3%) gamma photon of the Am-241 source interacts near the contact in a CZT detector (mass attenuation coefficient 6.298 cm^2/gm), so almost the entire photon energy is absorbed within a fraction of millimetre in the detector and the result is a reasonably good spectrum. Figure 7.24 shows the spectra of Am-241 observed with various CZT detectors equipped with back-to-back Au contact and Au-In Schottky devices. The FWHM of the 59.5 keV line of Am-241 was found to be lowest at 7% (4.1 keV) for the B4S1 AuCZTIn 5x5x5 mm^3 detector with bias voltage 400V when compared to other CZT detectors of similar dimension. This value is also comparable to other reported values of 6% [23-27]. If we compare two similar dimension Schottky devices AuCZTIn (B4S1) and AuCZTAl (B4S2), the AuCZTIn device gives better resolution than AuCZTAl device.

7.6.2.2 Ba-133 Spectra

Ba-133 gives a wide range of gamma energy photons with the main photon energy of 356.01keV (I_r=61.9%) and 80.99keV (I_r=35%). The high energy photon interacts in CZT with almost equal probability through the detector volume, so the 356.01 keV line is not expected to be seen on the screen. However, the lower energy peak like 80.99 keV photon can be expected to be detected at saturation bias voltage. Fig. 7.25 shows the Ba-133 spectra obtained by various CZT detectors. The spectrum possesses the 80.99 keV peak along with the x-ray peaks at the low energy side of the spectrum. The Schottky devices give the FWHM for the 80.99 keV gamma of about 9%, the same as the commercial CZT detector does, but the low energy x-ray peaks are better resolved by the commercial device.
Chapter seven: Detector characterisation and study of contact structure

**Fig. 7.24** Spectra of Am-241 source obtained by various CZT detectors.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Size (mm)</th>
<th>Bias (V)</th>
<th>Gain</th>
<th>Source</th>
<th>FWHM</th>
<th>Pulser (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1S1, AuCZTAu</td>
<td>5x5x5</td>
<td>500</td>
<td>200</td>
<td>Am-241</td>
<td>8%</td>
<td>2.2</td>
</tr>
<tr>
<td>B1S1, AuCZTAu</td>
<td>5x5x5</td>
<td>500</td>
<td>200</td>
<td>Am-241</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>B4S1, AuCZTIn</td>
<td>5x5x5</td>
<td>400</td>
<td>200</td>
<td>Am-241</td>
<td>7%</td>
<td></td>
</tr>
<tr>
<td>B4S2, AuCZTAl</td>
<td>5x5x5</td>
<td>350</td>
<td>200</td>
<td>Am-241</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>B2S4, AuCZTAl</td>
<td>5x5x3</td>
<td>300</td>
<td>200</td>
<td>Am-241</td>
<td>10%</td>
<td></td>
</tr>
</tbody>
</table>
Chapter seven: Detector characterisation and study of contact structure

C1S1, AuCZTAu 5x5x5 mm³
Bias=500V, gain=200
Ba-133 source
FWHM=10%

B4S1, AuCZTIn 5x5x5 mm³
Bias=400V, gain=200
Ba-133 source
FWHM=9%

B4S2, AuCZTAl 5x5x5 mm³
Bias=350V, gain=200
Ba-133 source
FWHM=10%

B2S4, AuCZTAl 5x5x3 mm³
Bias=300V, gain=200
Ba-133 source
FWHM=10%

Fig. 7.25 Ba-133 photopeaks obtained by various CZT detectors.
Chapter seven: Detector characterisation and study of contact structure

**C1S1, AuCZTAu 5x5x5 mm³ detector**
- Bias=500V, gain=200
- Co-57 source
- FWHM=9%

**B4S1, AuCZTIn 5x5x5 mm³ detector**
- Bias=400V, gain=200
- Co-57 source
- FWHM=11%

**B4S2, AuCZTA1 5x5x5 mm³ detector**
- Bias=350V, gain=200
- Co-57 source
- FWHM=12%

**B2S4, AuCZTA1 5x5x3 mm³ detector**
- Bias=300V, gain=200
- Co-57 source
- FWHM=9%

*Fig. 7.26. Co-57 photopeak obtained from various CZT detectors.*
Chapter seven: Detector characterisation and study of contact structure

7.6.2.3 Cobalt-57 Spectra

The main photopeak energy of 122keV ($I_P=85.5\%$) from Co-57 can be absorbed within about 1.5 mm into CZT detector. The probability of photoelectric absorption of this energy is about 92% [28]. The detectors were operated at saturation bias voltage and irradiated through the cathode by a Co-57 source. The photopeaks obtained from various detectors are shown in fig. 7.26. The FWHM of is about 9% for the commercial AuCZTAu device at a bias voltage of 500V while the Schottky devices give a bit higher value except for the thinner devices which gives almost similar results to the commercial device. These values, when compared to the other reported values of 6.1% [29] and 7.1% [30], are a bit high.

The details of the photopeaks of Am-241, Ba-133 and Co-57 obtained by various detectors are shown in Table 7.2. From the value of the peak to total ratio, it can be seen that the fabricated Schottky devices are showing better performance than the commercial one. It should be mentioned here that although the current-voltage characteristics of all the fabricated devices have been collected, not all of them give presentable spectra. Possible reasons are discussed later in this chapter.

7.6.3 Temperature Dependence Spectra

The detector has principally been operated at low temperature to reduce the dark leakage current for the low energy spectral measurement. A high resistivity CZT detector gives improved performance at room temperature. However, an assessment of temperature dependent performance is useful to some extent as it can be used to establish a range of operational temperatures. It should be mentioned that there are various components of CZT detectors like generation-recombination rate, mobility-lifetime product, trapping-detrapping process etc. which are very much temperature dependent, so at this stage it is difficult to make conclusive comment on the basis of the spectral response. Nevertheless, in this section we tried to concentrate to see the temperature effect on radiation spectra. In this regard, an experiment was carried out using a source with a similar experimental set-up to that shown in section 7.4. The detector was irradiated from the side near the cathode using a 7.4 GBq Am-241 source. The spectra obtained for various temperatures are shown in fig. 7.27. It can be
Table 7.2 photopeak details obtained by various CZT detectors.

<table>
<thead>
<tr>
<th>Detector type</th>
<th>ID</th>
<th>Applied bias voltage</th>
<th>Peak position (channel)</th>
<th>FWHM% (59.5 keV peak)</th>
<th>Peak position (channel)</th>
<th>FWHM% (80.99 keV peak)</th>
<th>Peak position (channel)</th>
<th>FWHM% (122 keV peak)</th>
<th>Peak-to-total ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>AuCZTAl 5x5x5 mm$^3$</td>
<td>C1S1</td>
<td>500V</td>
<td>456</td>
<td>8%</td>
<td>682</td>
<td>10%</td>
<td>1032</td>
<td>9%</td>
<td>0.44</td>
</tr>
<tr>
<td>AuCZTAl 5x5x5 mm$^3$</td>
<td>B1S1</td>
<td>600V</td>
<td>444</td>
<td>10%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AuCZTAl 5x5x5 mm$^3$</td>
<td>B4S1</td>
<td>400V</td>
<td>415</td>
<td>7%</td>
<td>705</td>
<td>9%</td>
<td>961</td>
<td>11%</td>
<td>0.63</td>
</tr>
<tr>
<td>AuCZTAl 5x5x5 mm$^3$</td>
<td>B4S2</td>
<td>350V</td>
<td>373</td>
<td>8%</td>
<td>709</td>
<td>10%</td>
<td>956</td>
<td>12%</td>
<td>0.65</td>
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<tr>
<td>AuCZTAl 5x5x3 mm$^3$</td>
<td>B2S4</td>
<td>300V</td>
<td>390</td>
<td>10%</td>
<td>535</td>
<td>10%</td>
<td>896</td>
<td>9%</td>
<td>0.65</td>
</tr>
</tbody>
</table>
Chapter seven: Detector characterisation and study of contact structure

seen that the photopeak is shifting almost linearly but narrowly toward the lower energy side with the decrease in temperature and below 240K the peak drastically reduced and spectra consists only the low energy noise. It seems that the detector apparently froze below this temperature and became unusable. The peak shift with temperature is shown in the inset. It has already been discussed in the previous section that the mobility-lifetime product is proportional to the temperature. It has also been seen in section 7.5.2 that the electric field shrinks toward the cathode region at low temperature. So this phenomena was attributed to be due to either defect properties in the crystal which affect the mobility-lifetime product and hence carrier transport properties or due to weakening of electric field at low temperature.

It can also be said that at room temperature most of the generated charge carriers are being collected within the time window of shaping amplifier. However, at low temperature carriers move more slowly since the value of mobility-lifetime product is less so a smaller number of carriers are able to pass through the fixed time window of shaping amplifier to contribute to the signal. This phenomenon can be demonstrated by the output signal of the preamplifier shown in fig. 7.28. It can be seen that the magnitude of the fast signal $V_f$ is bigger than the magnitude of slow signal $V_s$ so the photopeak shifts at lower energy side can be expected. Temperature dependent spectroscopy of CZT detectors to high energy photons has been reported elsewhere [25,31-32].
Chapter seven: Detector characterisation and study of contact structure

![Graph Illustration](image)

Fig. 7.29. Illustration of the temperature dependent spectral response using preamplifier signal.

### 7.7 Summary

The characteristics of the various commercial and in-house fabricated CZT detectors have been presented in this chapter through a systematic series of measurements.

In the final chapter of this thesis, the performance of each detector is analysed individually and final conclusions are drawn.
Chapter seven: Detector characterisation and study of contact structure

References

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Chapter seven: Detector characterisation and study of contact structure


[28] WINXCOM Program (V 1.0.1) by Klaus Bjorn Jensen, Henrik Levring and Nicolas Paul-Marie Guilbert.


Chapter seven: Detector characterisation and study of contact structure


CHAPTER EIGHT

CONCLUSION

8.1 Summary of Fabricated Devices

8.1.1 Electroless Au Contact CZT Detector (ID# C1S1)

The electroless Au contact spectral grade CZT detector was provided by the eV Product, a Division of II-VI Inc. The straight-line nature of the current-voltage characteristics of this detector with low leakage current (I_L=2nA @200V in 0.25 cm^2 area, \( \rho=5 \times 10^{10} \, \Omega \text{cm} \)) indicates that current through the device is mainly due to thermally generated charge carriers from the bulk material, and not through injection at the contacts. This suggests that the contacts are rectifying.

The low leakage current literally allows one to use higher bias voltage which helps to get better charge collection and consequently good resolution can be expected and the low energy tailing should be small. Reasonably good \( \mu \tau \)-product for electrons (9.93x10^{-4} cm^2/V-s) helps to increase the carrier mean free path that enhances the charge collection efficiency. From the above discussion, we should expect very nice performance with this detector but however, practically if we look at the spectra collected by this detector, it is not as good as expected. One of the potential reasons of it might be the electric field distribution within the bulk. As we saw in Fig.7.15, the electric field is strong (1.95x10^3 V/cm at 700V) at the front contact (but linearly decreasing toward the bulk extending up to about 3mm of a 5mm thick detector). There is virtually no electric field at the back contact which limits the detector performance. Although with increasing bias voltage the electric field intensity increases a bit, but the field distribution does not change above 800V.

8.1.2 AuCZTAu Detector (ID # B1S1)

This device was fabricated in our laboratory. Contacts were formed by evaporating Au on highly polished CZT crystal surfaces. The current-voltage characteristic is linear and the same as C1S1, but the leakage current is almost one order of
magnitude higher than the commercial one (15 nA @200V in 0.23cm² area, $\rho=5.9 \times 10^9 \ \Omega$ cm). The mobility-lifetime product for electrons is reasonably good (7.47 x $10^{-4}$ cm²V⁻¹) which enhances the charge collection efficiency up to 80% at 600V. The detector exhibits a comparatively weak electric field at the cathode (1.54x10³ V/cm at 700V) compared to the commercial device but the most important thing is that the field is under depleted like the commercial device. So we should not expect good performance from this detector. The photopeak of Am-241 obtained from this detector shows poor resolution with high leakage current at the low energy side.

8.1.3 AuCZTIn Schottky Detector (ID # B4S1)

This detector was fabricated in our laboratory using the evaporated Au and In deposition technique. The current-voltage characteristics of this detector exhibit rectifying nature. The leakage current is about 30nA at 200V with a negatively biased Au contact. The resistivity of the detector was estimated at about 5x10⁹Ω cm and the mobility-lifetime product was found to be 1.13x10^3 cm²V⁻¹ which is very much comparable with other reported values [1-3]. The electric field distribution in AuCZTIn 5x5x5 mm³ is remarkably different from the commercial AuCZTAu detector. The field was found to be very strong at the front contact (1.26x10³ V/cm for 400V) and almost linearly extended up the two-third of the detector thickness, eventually decreasing near the back contact. With these promising characteristics very good performance can be expected with this detector. The spectra obtained from this detector gave good energy resolution (FWHM 7% (4.1keV) at 59.5keV). It also produces the 80.99keV gamma-ray peak of Ba-133 and 122keV of Co-57 source with reasonably good FWHM (8%) and (11%) respectively, but the detector performance is still not satisfactory.

8.1.4 AuCZTAI Schottky Detectors (ID # B2S4 & B4S2)

Like the B4S1 detector, the B2S4 and B4S2 detectors were also fabricated using the evaporated Au and Al deposition technique. Both detectors show rectifying behaviour as expected with leakage current a bit less in the 3mm thick detector (8nA) than the 5mm thick detector (20nA) for 200V respectively at the negatively biased Au contact. The bulk resistivity is found to be 1.6 x10⁹ Ω cm and 2.5x10⁹
Chapter eight: Conclusion

Ωcm and the mobility-lifetime product 8.55x10⁻⁴ cm² V⁻¹ and 8.8x10⁻⁴ cm² V⁻¹ respectively, which are smaller than for the B4S1 detector but still comparable with other reported values. The electric field is found to be very strong in the 3mm thick (B2S4) detector (1.52x10³ V/cm for 300V) even when compared to the field distribution of B4S1 & B4S2 at the cathode, and the distribution pattern in both detectors is pretty much similar to the B4S1 detector. So the performance of these detectors can be expected to be more or less the same as the B4S1 detector.

The spectral response for the 59.5 keV, 80.99 keV and 122keV peaks from Am-241, Ba-133 and Co-57 sources respectively for both detectors were seen to be similar to that from the B4S1 detector.

8.2 Summary of CZT Detector Performance

From the above discussion it can be seen that the basic characteristics of the Schottky devices prepared on CZT are reasonably good and well presentable. Comparatively low leakage current at detector operation voltages was found which helps to reduce the peak broadening. The good μτ value enhances the energy resolution in the spectra. The internal electric field extended to most of the detector volume which is believed to give rise to a very good charge collection efficiency and hence improved energy resolution. Although Schottky devices showed promising performance they are still not satisfactory. There are some possible reasons which may restrict the detector performance. Electric field distribution is one of the potential candidates that may limit the detector performance.

Although the field in Schottky devices is very strong at the cathode and extends through almost two-thirds of the volume, it can be noticed that the field then decreases near the back contact. This is thought to be due to diffusion of In (Al) into the CZT bulk, which makes that region a highly n-type. As we discussed in chapter 5, Au diffused into the bulk to create a p-type surface, so the whole structure of the device can then be regarded as a p-i-n detector which establishes a built-in field between the bulk and the In (Al) alloyed back contact. This built-in field, adding up with the applied field, results in the extended electric field in the
bulb of the detector. Adversely, once Indium (Aluminium) diffuses into the bulk, it forms defect complexes in that region inside the crystal which degrades the detector performance.

**Fig. 7.30. Illustration of E-field distribution pattern in CZT Schottky device.**

**Fig. 7.31. Proposed band structure at the back contact of Schottky device.**
Chapter eight: Conclusion

Fig. 7.32 displays the probable band model for the Au-CZT-Au back to back detector under bias. Unlike Schottky devices, the Au diffused into the π-region of the AuCZTAu from both sides produces the symmetric Au-π-CZT-π-Au detector which has been discussed detail elsewhere [4-5].

![Band Model Diagram](image)

**Fig. 7.32. Proposed band model for Au-Au back to back contact CZT detector.**

8.3 Final Conclusions

This thesis has presented a considerable quantity of experimental data on the investigation, fabrication and characterisation of CdZnTe radiation detectors. It has been shown that it is possible to fabricate true rectifying junctions, ohmic contacts, Schottky barriers and metal-oxide contacts to CdZnTe bulk material.

The devices fabricated in our laboratories have shown good spectral performance and wider depletion regions than conventional commercial devices.

Based on extensive characterisation of these fabricated devices, we have been able to suggest possible band structure for the devices, and further research will be able to build on this data with the goal of fabricating optimised radiation detectors in the future.
Chapter eight: Conclusion

References


