Charge carrier transport in THM grown CdTe

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Abstract

Cadmium telluride (CdTe) has long been regarded as a good material for the use as a solid state ionising chamber. Since the advent of well controlled liquid phase growing processes, such as the traveling heater method (THM), single crystal CdTe has been available. To improve detection processes further one must understand the parameters effecting charge transport, especially the role of crystal defects (such as the prevalent tellurium inclusion) in deviating the behavior from the 'ideal' crystal.

This work focuses on induced charge and current pulses studied as a function of temperature and with spatial resolution in single crystal CdTe grown by EURORAD. The electron and hole $\mu \tau$ product is individually derived for each piece of material as is the electron and hole mobility. These values are all within the range of accepted values for good quality spectroscopic grade material given in the literature.

To complement the electrical characterisation several non destructive optical methods are carried out. These include Lang X-ray topography and infrared microscopy, both of which allow the structural quality of the material to be assessed. From these measurements it is clear that we are in possession of several samples with a high density of tellurium inclusions. The effect of these defects on charge transport is observed using time resolved ion beam induced charge (IBIC) imaging.

Temperature dependent mobility is investigated and results are compared to a model of scattering mechanism in CdTe. Voltage dependent trapping/detrapping is also observed leading to the conclusion that a multiple trapping/emission process is taking place and finally electric field profiling is undertaken and the results compared to other techniques given in the literature.
Acknowledgements

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Thanks to my mum and dad for all the things that parents do, you do them very well and I am eternally grateful. Also thanks to Philip, Gran, Grandad and all the Griffith's: Nain, Heulwen, Ron and Lesley all those 'little' things have been much appreciated.

Lastly thanks to Emily for all the comfort during the long hours of stressful 'homework' that it has taken to eventually finish this project. This is for you.

*I love deadlines. I especially like the whooshing sound that they make when they fly by.*

Douglas Adams (1952-2001)
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$\gamma(e/h)$ Material specific constant (of electrons/holes respectively)
$\Delta Q_{\text{induced}}$ Induced charge
$\Delta t$ Time interval
$\varepsilon_0$ Permittivity of free space
$\Theta$ Debye temperature
$\kappa_0$ Low-frequency relative dielectric constant
$\kappa_\infty$ High-frequency relative dielectric constant
$\lambda$ Non carrier specific drift length
$\lambda_e$ Mean electron drift length
$\lambda_h$ Mean hole drift length
$\Phi_w(x)$ Weighting potential
$\mu$ Non carrier specific mobility
$\mu_{\text{rad}}$ Deformation potential scattering controlled mobility
$\mu_{\text{att}}$ Attenuation coefficient of a material
$\mu_{\text{tr}}$ Trap controlled mobility
$\mu_e$ Electron mobility
$\mu_h$ Hole mobility
$\mu_{\text{im}}$ Ionised impurity scattering controlled mobility
$\mu_{\text{ni}}$ Neutral impurity scattering controlled mobility
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{po}$</td>
<td>Polar optical scattering controlled mobility</td>
</tr>
<tr>
<td>$\mu_{total}$</td>
<td>The total mobility calculated using Matthiessen's rule</td>
</tr>
<tr>
<td>$\tau_{10-90%}$</td>
<td>10-90% Rise time</td>
</tr>
<tr>
<td>$CCE$</td>
<td>Charge collection efficiency</td>
</tr>
<tr>
<td>$c_l$</td>
<td>Longitudinal elastic constant</td>
</tr>
<tr>
<td>$d$</td>
<td>Device thickness</td>
</tr>
<tr>
<td>$E_A$</td>
<td>Energy barrier of a trap</td>
</tr>
<tr>
<td>$EBIC$</td>
<td>Electron beam induced charge</td>
</tr>
<tr>
<td>$E_D$</td>
<td>Deformation potential constant</td>
</tr>
<tr>
<td>$E_g$</td>
<td>Band gap</td>
</tr>
<tr>
<td>EURORAD</td>
<td>Manufacturers of CdTe used in this study</td>
</tr>
<tr>
<td>$\bar{E}_w(x)$</td>
<td>Weighting field</td>
</tr>
<tr>
<td>$e$</td>
<td>Electron charge</td>
</tr>
<tr>
<td>$\epsilon_{pz}$</td>
<td>Piezoelectric constant</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>$\langle I \rangle$</td>
<td>Averaged excitation potential per electron</td>
</tr>
<tr>
<td>$I$</td>
<td>Incident beam intensity</td>
</tr>
<tr>
<td>$I_o$</td>
<td>Attenuated beam intensity</td>
</tr>
<tr>
<td>IBIC</td>
<td>Ion beam induced charge</td>
</tr>
<tr>
<td>IBIL</td>
<td>Ion beam induced luminescence</td>
</tr>
</tbody>
</table>
### LIST OF SYMBOLS AND ABBREVIATIONS

- **$k$**: Boltzmann constant
- **$LBIC$**: Laser beam induced charge
- **$M$**: Reduced mass of the unit cell
- **$m^*$**: Non carrier specific effective mass
- **$m^*_e/h^*_h$**: Effective mass (of electrons/holes respectively)
- **$m_e$**: Rest mass of the electron
- **$m_o$**: Mass of electron
- **$MCA$**: Multi-channel analyser
- **$N_A$**: Number of acceptors
- **$N_D$**: Number of donors
- **$N_f$**: Number ionised defects
- **$N_d$**: The effective density of states
- **$N_o$**: The number of initial charge carriers
- **$N_t$**: The density of traps
- **$N_u$**: Number un-ionised defects
- **$n$**: The average electron density
- **$n_{ehp}$**: Number of electron hole pairs produced per ionising event
- **$p$**: The average hole density
- **$PET$**: Positron emission tomography
- **$PICTS$**: Photon induced current transient spectroscopy
- **$PIXE$**: Proton induced X-ray emission
LIST OF SYMBOLS AND ABBREVIATIONS

\[ Q \] Collected charge
\[ Q_0 \] Created initial charge

\[ T \] Temperature
\[ T_{dr} \] Non carrier specific drift time
\[ THM \] Traveling heater method

\[ V_a \] Volume of unit cell
\[ v \] Non specific drift velocity
\[ v_e \] Electron drift velocity
\[ v_h \] Hole drift velocity

\[ W_{ehp} \] Average energy consumed to create an electron-hole pair

\[ XBIC \] X-ray induced charge

\[ Z \] Atomic number
\[ Z_1 \] Heavy charged particle atomic number
\[ Z_2 \] The target atomic number
1 Introduction

1.1 Cadmium Telluride

II-VI semiconductors, owing to their direct and large band gap, are technologically im­
portant materials for radiation detector and solar cell applications, the compound CdTe
is possibly the most interesting of this group. For many years CdTe has been a focus for
research based on improving solar cell efficiency. The direct band gap of CdTe at approx­
imately 1.44eV [3] is ideal for absorbing the maximum amount of the solar spectrum [27].
Most of the research in this area involved the use of polycrystalline material, which was
easy and relatively cheap to produce. Thanks to the development of growth processes such
as the traveling heater method (THM) and modified Bridgman, single crystals of CdTe
were produced with increasing quality. As a result new avenues of possibility were realised
in gamma ray and X-ray spectroscopy.

CdTe is a well suited medium for the detection of gamma rays and X-rays. Unlike
silicon and germanium, the more established materials used in radiation detectors, CdTe
has a larger band gap. As a result CdTe can be operated at higher temperatures and does
not require the sometimes limiting presence of cryogenic cooling apparatus [38]. Since
the average atomic number of CdTe is 50 compared to 14 in silicon and 32 in germanium
[58] there is more absorption of X and gamma rays than in either Si or Ge. With higher
resistivity, which provides lower leakage currents, make CdTe an interesting material for
1. **INTRODUCTION**

radiation detection purposes.

### 1.1.1 Radiation detection properties

CdTe has a cubic zinc blend structure with atomic numbers of 48 and 50 and a density of \( 6.06 \text{g/cm}^3 \) [51]. Charge carrier mobilities are of the order of \( 1100 \text{cm}^2/\text{Vs} \) for electrons and \( 100 \text{ cm}^2/\text{Vs} \) for holes (see table 1.1). The dominant gamma ray interaction process is photoelectric absorption up to approximately 250keV and it has an average ionisation energy of 4.43eV per electron hole pair. The majority of quality CdTe crystals are grown via the traveling heater method. Doping with Cl compensates the native and background defects associated with CdTe and its growth and produces semi-insulating material.

As mentioned previously a major use of CdTe is in the development of efficient solar cells. This application only requires high absorption of solar radiation to develop electrical currents. Thus polycrystalline material is particularly suitable due to its relative abundance and low cost. For other applications such as medical imaging and gamma and X-ray spectroscopy polycrystalline material is unsuitable. Thanks to the development of improved growth methods through the years, specifically solvent growth methods such as THM, several manufactures have produced high quality single crystal CdTe material. CdTe devices are now at a stage where single crystals, with low defect densities, and moderate size are available to produce devices of uniform charge collection and thus good spectroscopy. A major advantage that CdTe has over Ge is that due to its large band gap of 1.44eV it is able to operate at room temperature without the limiting thermally generated current seen in Germanium devices. A major advantage that CdTe has over Si is that its average atomic number of 50 is able to provide more photoelectric absorption of incident high energy photons, thus increasing its photopeak efficiency.

Unlike Si or Ge, CdTe suffers from poor hole transport, which tends to limit signal amplitudes and spectral resolution. Several methods exist to correct for the poor hole
1. INTRODUCTION

<table>
<thead>
<tr>
<th>Material</th>
<th>Atomic Number (Z)</th>
<th>Bulk Resistivity ($\Omega \text{cm}$)</th>
<th>Electron Mobility ($cm^2/Vs$)</th>
<th>Hole Mobility ($cm^2/Vs$)</th>
<th>Electron Lifetime ($s$)</th>
<th>Hole Lifetime ($s$)</th>
<th>FWHM @122keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdTe</td>
<td>48,52</td>
<td>$10^9$</td>
<td>1100</td>
<td>100</td>
<td>$3 \times 10^{-8}$</td>
<td>$2 \times 10^{-8}$</td>
<td>3.5keV</td>
</tr>
<tr>
<td>Ge</td>
<td>32</td>
<td>50</td>
<td>3900</td>
<td>1900</td>
<td>$&gt; 10^{-3}$</td>
<td>$10^{-3}$</td>
<td>400eV</td>
</tr>
<tr>
<td>Si</td>
<td>14</td>
<td>$&lt; 10^4$</td>
<td>1400</td>
<td>480</td>
<td>$&gt; 10^{-3}$</td>
<td>$2 \times 10^{-3}$</td>
<td>550eV</td>
</tr>
</tbody>
</table>

Table 1.1: Some typical material parameters for CdTe, Ge and Si [18].

The first method involves the discrimination of events produced by holes and electrons and preferentially rejecting the hole contribution [64]. This method dramatically improves energy resolution but at the expense of photopake efficiency. The second method involves reducing the contribution of holes to the induced signal by fabricating devices with pixellated anode contacts. This technique also increases energy resolution dramatically but requires complex readout electronics as well as reducing photopake efficiency [46]. Obviously if the cathode is illuminated and an ionising event occurs close to the cathode, hole involvement in the induced charge is minimal, so CdTe has intrinsically better energy resolution to low energy photons. Either method is only effective if the material shows good electron transport properties. In this work the electron transport performance of THM CdTe is assessed.

Table 1.1 shows some typical material parameters for CdTe, Ge and Si. As is clear from this table CdTe will probably never better Si or Ge in terms of charge transport or charge collection, but its major attraction is that it is free from the limitations of liquid nitrogen temperature cryogenics (as is needed for Ge detectors) and has a higher atomic number compared to silicon.

1.1.2 Industrial and medical uses for CdTe devices

Where cryogenic cooling is not suitable for an application most processes use scintillator based detectors. Thus CdTe devices compete directly with scintillation detectors in most
medical and industrial applications. For medical applications, especially imaging, photopeak efficiency and contrast resolution are important parameters. For most industrial applications contrast resolution is also important along with a wide dynamic detection range. [19].

In a medical environment some applications of CdTe may never replace current technology. A good example is in positron emission tomography (PET) which uses 511keV photons produced in positron annihilation to image a subject. Thus 511keV photons must be detected with as high a photopeak efficiency, and in time coincidence. The current equipment typically involves an array of Bi$_4$Ge$_3$O$_{12}$ (BGO) scintillators coupled to photomultiplier tubes. These detectors have a lower energy resolution compared to CdTe based detectors, but their higher effective atomic number and higher densities produce much better photopeak resolution. Where CdTe based devices are making some progress is in the field of nuclear gamma camera design. Gamma cameras are usually based on NaI scintillators coupled to a photomultiplier tube. A radionuclide is ingested by the patient and its uptake and distribution in a specific organ is imaged by measuring the intensity of gamma ray emissions. NaI in contrast to CdTe has a similar mass absorption co-efficient [19], where as CdTe has better energy resolution to low energy gamma rays usually encountered in nuclear medicine procedures (<150keV) and has better spatial resolution. This coupled with the fact that NaI based gamma cameras are large and immobile make the use of CdTe to produce small and mobile detectors and attractive possibility. Indeed such cameras are being produced by EURORAD using CdTe based detectors.

Industrial applications of radiation detection that would benefit from a high atomic number, room temperature detector are numerous. One example is in the field of surveying nuclear material [88]. Assaying of scrap metal and nuclear material usually requires a highly portable tool able to distinguish uranium, plutonium and thorium all of which is possible using CdTe based detectors. Another industrial role for CdTe based detectors is in X-ray
astronomy. The high photopeak efficiency, small size and no cryogenic cooling needs makes CdTe an ideal material for long term space based missions. Indeed a CdTe based X-ray detector was sent to Mars on the pathfinder mission.

The majority of problems with the progress of CdTe exist due to the challenge of growing defect free, large area, thick and uniform single crystals. As the growth process involves high temperature and two starting materials, the opportunity for the introduction of impurities is considerable. To overcome some of these problems purification of the melt using THM is carried out. This process however leaves native defects and still large concentrations of background impurities. The thermal gradients within the growth melt, due to uneven distribution of heat causes voids, tellurium inclusions and during cooling tellurium precipitates. Cracks are also likely to form when removing the grown CdTe from its growth boule. All these factors limit the size, quality and ultimately the usefulness of the material.

The mobility-lifetime product ($\mu\tau$) product for both electrons and holes is a standard measure of detector material quality. Its calculation can be used to compare the quality of different CdTe devices. Looking at the spatial variation of the $\mu\tau$ product over the active area of a device can also be useful in quantifying the uniformity of the device. Looking at the individual components of the $\mu\tau$ product can also shed some light on quality of the charge transport within the device. If this data is collected with spatial resolution, the effect of non uniform structures within the material (observable using infrared microscopy) can be seen. This information is important for the sustained development of better material. This thesis is primarily concerned with methods of characterisation of CdTe devices grown by EURORAD. As well as the calculation of $\mu\tau$ and its components both with and without spatial resolution, the IV characteristics are measured to look at the resistivity and higher bias properties including leakage current. The temperature variation of mobility to investigate the scattering mechanisms in CdTe are also carried out.
1. **INTRODUCTION**

### 1.1.3 Thesis overview

The only CdTe material that was commercially available for many years was polycrystalline and thus was only suitable for solar cell devices and not for spectroscopic purposes as grain boundaries strongly effect the detector signal. This situation proceeded for many years until the refinement of growth techniques produced single crystal material with a low enough density of inhomogeneities that could be used for spectroscopic applications. Over the last decade the growth techniques have been further refined in order to produce large homogeneous single crystal CdTe material. Unfortunately due to the nature of growing compound semiconductors there still exists the problem of inhomogeneities that can effect the charge collection of a device. Further insight into the effect defects have on charge collection is presented in this work.

- Chapter 2 begins with an overview of the types of radiation used in this work and how they interact with matter, specifically CdTe. Afterwards the physics of charge induction due to ionising radiation is introduced and the effects of different parameters, such as the effects of trapping on the induced charge is discussed. The chapter concludes with a brief discussion on ion beam induced charge.

- Chapter 3 begins with an overview of the two major types of CdTe growth, namely the traveling heater method (THM) and Bridgman growth. There is then a discussion of the defects seen in CdTe, which includes electrical and structural defects. Afterwards there is a discussion on the effects of different types of scattering mechanisms have on the mobility of charge carriers in CdTe. The chapter concludes with a brief overview of the contacts that can be applied to CdTe and their inherent features.

- Chapter 4 introduces the experimental methods that have been used in this study. It gives a description of the optical characterisation techniques, the non-contact tech-
1. INTRODUCTION

In this work, the particle induced techniques, as well as a description of the IBIC facility at the University of Surrey

- Chapter 5 begins the discussion of results on EURORAD CdTe. This chapter is concerned with the general characterisation of material quality both structurally and electrically. The geographical localisation of material defects is reported in several samples, the IV characteristics of all samples used in this study is then carried out to see if the contacted samples are useable for further investigation. Finally the mobility-lifetime product is measured, which gives an insight into the spectroscopic quality of the material. This chapter forms the ground work for the following two chapters.

- Chapter 6 is primarily concerned with the use of the laser induced time of flight technique to extract fundamental parameters such as mobility from current pulses. The chapter begins with a brief overview of the system and the general commissioning experiments carried out. It then progresses to the evaluation of the mobility with decreasing temperature, and the modeling of different scattering mechanisms to explain this data. The chapter then discusses an observable thermal detrapping event seen below 200K in several samples and concludes with a discussion on the production of electric field profiles from current pulses.

- Chapter 7 concludes the discussion of experimental results on EURORAD CdTe. It extends the work of chapter 5 by looking at spatially localised charge transport for several samples. The observed variation in these values over the area of the detector is then compared to the infra red images taken in chapter 5, in an effort to observe the effects of defects on charge transport. The induced charge pulses are also interrogated for signs of defect interference in the charge transport. The chapter concludes by discussing some of the more unusual observations that were made.
Chapter 8 concludes the thesis by summarising the results and discussing possible avenues for further investigation.
2 Semiconductor radiation detectors

2.1 Radiation detector material interactions and creation of charge carriers

In order to use CdTe as a radiation detector and to fully understand some characterisation techniques used in this thesis it is necessary to understand the processes that occur when radiation interacts with the detector material. General interaction mechanisms are discussed in this section. In general when a particle penetrates a material most energy loss occurs due to interactions between the particle and the atomic electrons. Excitation of the electrons occur that can lead to ionisation and as a consequence can lead to secondary processes such as the emission of characteristic X-rays, Auger electrons and luminescence photons.

2.1.1 X and γ rays

There are many ways γ-ray and X-ray photons interact with matter, of these the three most prevalent processes are photoelectric absorption, Compton scatter and pair production. Each one has a photon energy range over which it is most likely to occur and each process varies with the material properties in different ways.

The predominant method of energy absorption at low photon energy is via photoelectric
absorption. In this process a photon incident onto a material is completely absorbed. A photoelectron is produced with a kinetic energy equal to the original photon energy less the binding energy of the photoelectron. Not only is a photoelectron produced but the absorber atom is left ionised. The vacancy is usually repopulated via electron capture of an electron from the material surrounding the atom or by reorganisation of electrons in less stable orbitals within the same atom. If reorganisation occurs electrons existing in higher orbitals lose energy in order to populate a more stable state. This lost energy presents itself as a characteristic X-ray, usually these characteristic X-rays are absorbed by further photoelectric absorption involving less tightly bound electrons in higher orbitals, the result of which is the production of secondary photoelectrons. In some cases instead of characteristic X-ray production an Auger electron may be released to carry away excitation energy. Thus following the original photoelectric absorption a complex process may ensue.

A rough approximation for the probability of a \( \gamma \) or X-ray undergoing photoelectron absorption is given in equation 2.1, where \( k \) is a constant, \( Z \) is the atomic number of the absorbing material, \( E \) the energy of the photon, and \( n \) a number that varies between 4 and 5 over the gamma ray energy.

\[
\tau_{\text{pea}} = k \times \frac{Z^n}{E^{3.5}} 
\]  

(2.1)

From equation 2.1 it is clear that the probability of photoelectric absorption is enhanced for materials with a high atomic number and for low photon energies.

If a photon incident onto an atom is not absorbed but transfers only part of its energy and is deflected through an angle, then the energy loss it experiences is due to Compton Scatter. This process involves the incident photon and a stationary electron, the incident photon is deflected through an angle \( \theta \) with respect to its original direction, and the electron moves away at an angle as a recoil electron. For small photon scattering angles (\( \theta \)) very
little energy is transferred to the electron. However all scattering angles are possible so the energy transferred can vary from 0 up to a large fraction of the photon energy, however some energy is always retained by the original photon. The probability of a Compton Scatter process depends on the number of electrons available in the target material and so the probability increases linearly with the atomic number, Z.

If the energy of the incident photon exceeds 1.02MeV the process of energy loss by pair production is energetically possible. In this interaction the photon disappears and is replaced by an electron-positron pair. Any excess energy over the 1.02 MeV threshold originally carried by the photon appears as kinetic energy shared by the electron and position. When the positron slows it annihilates to produce two annihilation photons of energy 0.511 MeV. The time it takes for the positron to annihilate is so quick that the annihilation photons appear to be in coincidence with the pair production interaction. The probability of pair production varies approximately with $Z^2$, practically however even if the photon does carry an energy of 1.02MeV the probability remains low and only becomes significant at higher energies.

Equation 2.2 relates the incident beam intensity ($I_o$) to the attenuated beam intensity ($I$) via an exponential function of the thickness ($x$) of the attenuating medium and the attenuation coefficient ($\mu_{att}$).

$$I = I_o e^{-\mu_{att}x}$$ (2.2)

The attenuation coefficient can be used to compare the attenuation properties of different materials. Figure 2.1 shows the attenuation coefficient ($\mu_{att}$) over an energy range in CdTe. From this it can be seen that pair production is responsible for most attenuation at high energy where as photoelectric absorption dominates attenuation at low energies with Compton Scatter occupying the middle to low energy regime.
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2.1.2 Heavy charged particles

Heavy charged particles, such as protons and $\alpha$ particles, loose energy within matter primarily due to the interaction of the Coulomb field of the particle with the Coulomb field of the atomic electrons. When a heavy charged particle enters an absorbing medium it interacts with many electrons simultaneously and energy is lost due to momentum transfer from the heavy charged particle to the atomic electrons. Each interaction only causes a small amount of energy loss so many interactions are required for the heavy charged particle to come to rest. As the particle travels through the absorbing medium the path it takes tends to be quite straight because the particles momentum is so high compared to the electrons. As the particle travels along its path atomic electrons become excited and some become ionised and move off the path taken by the heavy charged particle. If these secondary electrons, termed delta rays, have enough energy, secondary ionisations are likely. The range of a particle in a certain material is defined as the distance the particle has zero energy.

Figure 2.1: Attenuation co-efficient for $\gamma$-rays and X-rays in CdTe with a 50:50 stoichiometry, calculated in XCOM [?].
Figure 2.2: Calculation of stopping power using SRIM for 2 MeV protons and 5.49 MeV α-particles incident on CdTe

and it depends on the stopping power of the absorber material. The stopping power is the energy loss per unit distance in the absorber material and is mathematically described by the Bethe-Bloch formulae, the non relativistic form of which is given in equation 2.3. Here \( m_e \) is the rest mass of the electron, \( e \) the charge on the electron, \( Z_1 \) the heavy charged particle atomic number, \( Z_2 \) the target atomic number, \( v \) the velocity of the heavy charged particle and \( \langle I \rangle \) the averaged excitation potential per electron, which is typically \( Z \times 11 \text{eV} \).

\[
S = \frac{dE}{dx} = \frac{4\pi e^4 Z_2}{m_e v^2 Z_1^2} \left[ \ln \left( \frac{2mv^2}{\langle I \rangle} \right) \right] 
\]  

(2.3)

It is useful to plot the stopping power against distance in an absorber material to show the effects of energy loss as a particle travels, this type of plot is known as a Bragg curve. SRIM 2003 [89] was used to calculate a Bragg curve for two typical heavy charged particles in CdTe used in this work and is given in figure 2.2. From this curve one can see the particle interaction as predicted by the Bethe-Bloch formulae (equation 2.3). The energy
loss \(-dE/dx\) increases to a maximum as the energy \(E\) of the particle falls. For many complex materials there are few measurements of stopping power and few well defined values of \(\langle I \rangle\). As a result prediction is often required when calculating stopping power in a complex material, and prediction is often based on Bragg’s rule, which states that the total stopping power of a compound is the sum of the stopping powers of each element, \(i\) with atomic number \(Z_i\), which make up the compound, weighted by their respective atomic fractions in the material, \(\eta_i\).

\[
\frac{-dE}{dx} = \sum_i \eta_i \left( \frac{dE}{dx} \right)_i
\]  

(2.4)

SRIM 2003 uses equation 2.3 and Bragg’s rule (equation 2.4) to calculate stopping power in materials.

The time it takes for a heavy charged particle to stop and therefore deposit its energy into a target material can also be defined. For a non-relativistic particle the time to stop, \(t\) (in seconds), is given in equation 2.5, where \(m_p\) is the particle mass in atomic mass units, \(R\) the range, in meters, of the particle in the material under investigation and \(E\) the energy of the particle before it enters the material in MeV.

\[
t = 1.2 \times 10^{-7} R \sqrt{\frac{m_p}{E}}
\]  

(2.5)

For protons and alpha particles traveling in CdTe the ranges are in the order of tens of micrometers, thus for this work the stopping times are of the picosecond order and as such are beyond the time resolution of any of the experiments discussed.
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2.1.3 Electrons

Electrons instead of following a straight path like heavy charged particles are subject to large deviations in path direction. This results in the electron taking a random path through matter before coming to rest. The energy loss of an electron not only depends on the Coulomb interaction but also from radiative processes. Spontaneous emission of Bremsstrahlung is common as an electron moves through matter but due to the low mass of electrons this energy loss process can be small for all but the very high energy electrons. If any Bremsstrahlung is produced it is usually of a low energy and so is absorbed in the material in which it was produced, this is specifically true for CdTe with its high atomic number. The ratio between radiative energy loss \( (dE/dx)_r \) and Coulomb energy loss \( (dE/dx)_c \) can be approximated as in equation 2.6 where \( E \) is the electron energy in MeV and \( Z \) the atomic number of the material it moves through.

\[
\left( \frac{dE}{dx} \right)_r \approx \frac{EZ}{700} \left( \frac{dE}{dx} \right)_c
\]  (2.6)

2.1.4 Creation of charge carriers

Semiconductor detectors normally respond to radiation via a pulse mode of operation. Incident ionising radiation creates electron hole pairs within the semiconducting material in direct proportion to the energy deposited [58]. Given an ionising photon or particle of energy \( E \), the number of electron hole pairs \( n_{ehp} \) will be \( E/W_{ehp} \), where \( W_{ehp} \) is the average energy it takes to produce one electron-hole pair. This value is independent of radiation type and is a fundamental material constant. For CdTe the \( W_{ehp} \) value is approximately 4.43eV[58].

In principle the minimum energy required to excite an electron from the valence band to the conduction band and thus create an electron hole pair is only the band gap energy
Figure 2.3: Band gap versus mean energy to create electron hole pairs \( W_{ehp} \) for several different materials, based on the original presented by Owens et al [58]

The number of charge carriers produced is subject to some statistical fluctuation. An estimate can be made regarding the amount of inherent fluctuation by assuming that the formation of each charge carrier is a Poisson process. A limiting resolution \( R \) due only to statistical fluctuations in the number of charge carriers is given in equation 2.7 [37] where \( N \) is the number of charge carriers produced.

\[
R = \frac{2.35}{\sqrt{N}} \tag{2.7}
\]
Thus from equation 2.7 it is clear that the statistical resolution is only dependent on the number of charge carriers. Due to the relatively small energy required to create electron hole pairs in semiconductors the number of charge carriers produced is larger than other detector mediums, as a result the attainable resolution is greater than in other types of detector. The achievable values of $R$ can be lower compared to the predicted values based on Poisson statistics, this is because the production of each individual charge carrier is not independent. The Fano factor is introduced to quantify the departure of the observed statistical fluctuations and is defined as the ratio of observed variance in $N$ over the Poisson predicted variance ($N$) [37], thus the statistical limit to the resolution is given by equation 2.8.

$$R = 2.35 \sqrt{\frac{F}{N}}$$

Obviously a perfect detector would only be limited by statistical fluctuations. In reality other sources of fluctuation in the detection chain combine to reduce the overall resolution of the detector.

### 2.2 Formation of signals from semiconductor radiation detectors

Figure 2.4 shows a diagram of a semiconductor contacted with two planar contacts. An ionising particle or photon penetrates the front contact (F) and generates a cloud of electrons and holes within the material. These drift out of the generation region (the thickness of which depends on the type of excitation pulse) due to an electric field (E) derived from the application of a bias voltage (V). Depending on the polarity of the bias voltage (and therefore the field) either electrons or holes are drawn across the bulk of the semiconduc-
Figure 2.4: Diagram illustrating the time of flight principle on a sample of thickness (d) with a field (E) in response to a voltage (V).

邀tor to the back contact (B). It is the movement of these charge carriers that create the induced current that is seen if one connects the device into an external circuit. Either the induced charge or induced current can be observed and each has its obvious advantages and disadvantages.

2.2.1 The Shockley-Ramo theorem

In a semiconductor radiation detector the process of charge generation occurs as follows:

- An incident γ-ray, X-ray or ionising particle interacts with the semiconductor device (which at its simplest is a piece of semiconductor material with two planar contacts on either end) and generates a number of electron-hole pairs.

- These electron-hole pairs drift under the influence of an applied electric field and induce a charge Q on the electrodes.

- The induced charge Q is converted into a voltage pulse using a charge or current sensitive pre-amplifier, where ideally the output voltage is proportional to the initial deposited energy.
One can calculate the induced charge $Q$ on the electrode by using the Shockley-Ramo theorem [63, 70], which uses the concept of a weighting potential ($\Phi_w(x)$) to describe the coupling between a moving charge ($q$) and the resultant induced charge on a particular electrode. Thus at a position $x$ the induced charge $Q$ is given by equation 2.9.

$$Q = -q\Phi_w(x) \quad (2.9)$$

The induced current, $i(t)$, produced by the moving point charge $q$ can also be similarly calculated using the same theorem by defining a weighting field ($\vec{E}_w(x)$) as in equation 2.10

$$\vec{E}_w(x) = \frac{d\Phi_w(x)}{dx} \quad (2.10)$$

Thus the induced current $i$ is given by 2.11[31]

$$i = q\vec{v} \cdot \vec{E}_w(x) \quad (2.11)$$

where $\vec{v}$ is the instantaneous velocity of a point charge $q$ and $\vec{E}_w(x)$ is the weighting field. The weighting field can in principle be calculated for any electrode geometry and has the units of $(\text{length}^{-1})$. For infinitely large planar contacts with a separation $d$ the weighting field is simply $1/d$. Substituting this into equation 2.10 and using equation 2.9 it is possible to show that for infinitely large planar contacts the induced charge on either contact ($dQ$) due to a moving charge ($q$) moving in an electric field $E$ is given by equation 2.12, where $V$ is the potential difference between the two contacts.

$$VdQ = qEdx \quad (2.12)$$
As the electric field $E$ in the absence of space charge is given by $E = \frac{V}{d}$ then equation 2.12 becomes equation 2.13.

$$dQ = \frac{qdx}{d}$$

(2.13)

This represents only one single charge carrier, a more realistic case would be to factor in the effects of many charge carriers and the two different types of charge carriers created in semiconductors, namely electrons and holes. So for a number of charge carriers equation 2.13 becomes equation 2.14 where $N_0$ is the number of charge carriers and $\lambda_e$ and $\lambda_h$ the mean drift lengths of electrons and holes respectively.

$$Q = \frac{qN_0}{d} (\lambda_e + \lambda_h)$$

(2.14)

The Charge Collection Efficiency (CCE), which is defined as the charge collected ($Q$) over the charge created ($Q_0$) (see equation 2.15) is fundamentally controlled by the electron and hole mean drift lengths. In the absence of trapping, the electron and hole drift lengths can be much greater than the device thickness, consequently the device exhibits 100% CCE. If the mean drift lengths are limited by carrier trapping to such an extent that they are smaller than the device thickness, then the CCE is fundamentally limited.

$$\text{CCE} = \frac{Q}{Q_0} = \frac{Q}{qN_0}$$

(2.15)

The Hecht equation: Charge collection efficiency due to trapping.

For compound semiconductors like CdTe, the low material purity creates traps within the bulk which act to reduce the mean drift length of the electrons and holes which also reduces the CCE. A generalised carrier population $N(x)$ at a distance $x$ from the point of origin is given by equation 2.16, where $N_0$ is the number of initial charge carriers.
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\[ N(x) = N_0 \exp\left(-\frac{x}{\lambda}\right) \]  

(2.16)

Thus given a radiation event a distance \( x \) below the cathode of a planar device of thickness \( d \), the number of electrons that reaches the anode is given by equation 2.17 and the number of holes that reaches the cathode is given by equation 2.18.

\[ n(d - x) = n_0 \exp\left(-\frac{d - x}{\lambda_e}\right) \]  

(2.17)

\[ p(x) = p_0 \exp\left(-\frac{x}{\lambda_h}\right) \]  

(2.18)

Using these two equations and equation 2.14 it is possible to calculate the induced charge due to trapping, which is given in equation 2.19

\[ Q = \frac{qN_0}{d} \left[ \lambda_e \left(1 - \exp\left(\frac{x - d}{\lambda_e}\right)\right) + \lambda_h \left(1 - \exp\left(-\frac{x}{\lambda_h}\right)\right) \right] \]

(2.19)

Substituting equation 2.19 into equation 2.15 gives an expression for the depth dependent charge collection efficiency \( CCE(x) \) (equation 2.20) which is termed the Hecht equation [32].

\[ CCE(x) = \frac{Q(x)}{N_0 q} = \frac{\lambda_h}{d} \left(1 - \exp\left(-\frac{x}{\lambda_h}\right)\right) + \frac{\lambda_e}{d} \left(1 - \exp\left(-\frac{x - d}{\lambda_e}\right)\right) \]

(2.20)

Where \( \lambda_h \) and \( \lambda_e \) are the mean carrier drift lengths, \( x \) the depth of interaction and \( d \) the width of the detector. Electron and hole drift lengths can be defined in terms of mean carrier drift velocities \( v_e, v_h \) and mean carrier lifetimes \( \tau_e, \tau_h \) as shown in equation 2.21.

\[ \lambda_e = v_e \tau_e \quad \text{and} \quad \lambda_h = v_h \tau_h \]  

(2.21)
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For non saturated drift velocities the drift velocity is the product of the carrier mobility and electric field \( v = \mu E \), so the carrier drift lengths can be expressed in terms of the mobility-lifetime product as shown in equation 2.22

\[
\lambda_c = \mu_c \tau_c E \quad \text{and} \quad \lambda_h = \mu_h \tau_h E
\]  

(2.22)

From equation 2.22 it is possible to see that short drift lengths are produced due to poor mobility or short lifetime. It is often not possible to de-convolve the \( \mu \tau \) product to see which of the two parameters is causing poor drift lengths so the \( \mu \tau \) product is often quoted as a parameter that defines the fundamental charge transport of the material under investigation. Martini and McMath [50] were possibly the first to use equation 2.22 to parameterise the Hecht equation (equation 2.20) in terms of carrier lifetime and mobility instead of drift length.

The single carrier Hecht equation.

If charge carriers are produced very close to the irradiated electrode the charge transport will only depend on one type of charge carrier, which makes the derivation of the \( \mu \tau \) product easier. For example if charge carriers are produced near to the cathode (on illumination of the cathode) then holes only have a very short distance to drift compared to the electrons, thus the hole component can be ignored. The opposite is true if one irradiates the anode, that is the electron component can be ignored. Using this assumption one can reduce the full Hecht equation given by equation 2.20 to a single carrier Hecht equation for either holes or electrons. Equation 2.23 gives the reduced equation for electrons and holes parameterised using carrier mobility \( (\mu) \) and lifetime \( (\tau) \)

\[
GCE = \begin{cases} 
\frac{\mu \tau E}{d} \left[ 1 - \exp \left( -\frac{d}{\mu \tau E} \right) \right] & \text{for electrons} \\
\frac{\mu \tau E}{d} \left[ 1 - \exp \left( -\frac{d}{\mu \tau E} \right) \right] & \text{for holes}
\end{cases}
\]  

(2.23)
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By using a source of ionising radiation that creates charge carriers near to the illuminated electrode equation 2.23 can be used to extract the $\mu r$ product from a plot of CCE as a function of electric field strength; thus providing a powerful tool to characterise the charge transport properties of a particular device.

### 2.2.2 Extraction of mobility using the time of flight method (ToF).

As stated previously it is possible, using a plot of CCE as a function of electric field strength and fitting this data with the single carrier Hecht equation, to calculate a value of $\mu r$. It is not possible from this data to de-convolute the $\mu r$ product in order to investigate each value separately. There are however other techniques that can be employed to find the carrier mobility and thus allow for $\mu r$ product de-convolution. One of these techniques is the time of flight (ToF) method.

ToF is most commonly performed using an ionising radiation that deposits energy close to the irradiated contact, such as a laser pulse with a photon energy larger than the band gap, a proton beam, or alpha particles. The duration of the ionising event should be much smaller than the drift time of the charge carriers and so depends on the material under investigation as well as the sample thickness ($d$). The carrier drift velocity ($v$) is related to the mobility ($\mu$) and electric field ($E$) by equation 2.24.

\[ v = \mu E \]  
\[ (2.24) \]

In the absence of space charge the electric field is a linear function of device thickness and is given by equation 2.25. The drift velocity is a function of the drift time $T_{dr}$ and is given in equation 2.26. By substituting both these equations into equation 2.24 it is possible to produce equation 2.27.
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\[ E = \frac{V}{d} \quad (2.25) \]

\[ v = \frac{dV}{T_{dr}} \quad (2.26) \]

\[ \mu = \frac{d^2}{T_{dr}V} \text{ rearranging gives } \frac{1}{T_{dr}} = \frac{\mu}{d^2V} \quad (2.27) \]

Hence from a plot of $1/T_{dr}$ against $V$ it is possible to extract the mobility from the gradient. The transit time can be collected from the analysis of either the current or charge pulse derived from a detector in response to an ionising event.

Current pulse time of flight measurements.

For simplicity only one charge carrier is considered for the remainder of the chapter (electrons). The full equations regarding two carrier transport can be derived by adding the corresponding hole contributions to the presented equations. The current induced due to electron movement from cathode to anode over the entire thickness of the device is constant, given an infinite carrier lifetime and constant electric field. If the lifetime is comparable to the drift time then the number of free carriers and thus the current decays exponentially from an initial current $I_0$. Once the carriers reach the anode the current falls to 0. The current at different times can be described by the equations given in 2.28.

\[ I(t) = \begin{cases} 
0 & \text{for } t < 0 \\
I_0 \exp \left( -\frac{t}{T_{dr}} \right) & \text{for } 0 < t < T_{dr} \\
0 & \text{for } t > T_{dr} 
\end{cases} \quad (2.28) \]

Measurement of current pulses is the most common time of flight method used in the literature [24]. A fast ionising pulse from a laser or alpha particle generates charge carriers
Figure 2.5: Sketch of an ideal current pulse, with an infinitely long carrier lifetime.

close to the irradiated electrode, which under the influence of an electric field drift through
the device and induce a current pulse on the electrodes. An external circuit consisting
of a low impedance high bandwidth current amplifier creates a voltage pulse in response.
When the carriers reach the far contact the current pulse terminates.

Figure 2.5 shows a sketch of an ideal current pulse. At time $t_0$ the charge carriers are
produced and begin to move under the applied field. At $t'$ the current reaches the back
contact and the current pulse ends. The drift time $T_{dr}$ is calculated by measuring the
width of the current pulse as shown in figure 2.5. Once the drift time is calculated over
several different bias voltages the mobility can be calculated using the technique outlined
in section 2.2.2.

Charge pulse time of flight measurements.

By allowing the current created to pass through an integrating charge preamplifier one
produces a charge pulse that can be used to find the transit time of the charge carriers.
Use of a charge amplifier is beneficial to produce signals with improved signal to noise
compared to the current signal. The use of this technique is only possible when the drift
time is much greater than the preamplifier rise time. As fast charge preamplifiers can
have rise times in the range 20 - 50 ns the use of this technique can be applied to II-VI materials which have much longer drift times. The output voltage of a charge pre-amplifier is proportional to the integrated induced current \( Q(t) = \int I(t) \, dt \) and can be described by the equations given in (2.29):

\[
Q(t) = \begin{cases} 
0 & \text{for } t < 0 \\
Q_o \frac{T_{dr}}{T_{dr}} \left(1 - \exp\left(-\frac{t}{T_{dr}}\right)\right) & \text{for } 0 < t < T_{dr} \\
Q_o \frac{T_{dr}}{T_{dr}} \left(1 - \exp\left(-\frac{T_{dr}}{T_{dr}}\right)\right) & \text{for } t > T_{dr}
\end{cases}
\]  

(2.29)

The drift time of charge carriers is obtained from the rise time of a charge pulse. The rise time is extracted from the charge pulse shape using some form of algorithm. Figure 2.6 shows a sketch of a 10-90% risetime algorithm. Directly from this the 10-90% rise time \( (\tau_{10-90\%}) \) is derived. To obtain the drift time \( (T_{dr}) \) from this value an addition of 20% must be added to the transit time, assuming that the pulse shape is a straight rising edge. Once the drift time is calculated over several different bias voltages the mobility can be calculated using the technique outlined in section 2.2.2.
2.2.3 The effect of varying charge transport parameters on the induced current and charge.

Through a careful analysis of the features in an induced charge signal it may be possible to deduce some fundamental material properties. To see how this can be done figure 2.7 shows some modelled induced charge pulses produced by varying only one parameter from the Hecht equation given by 2.30. Equation 2.30 is essentially equation 2.29 re-parameterised in terms of mobility \((\mu)\), electric field \((E)\) and lifetime \((\tau)\), where \(Q_o\) is the initial charge produced by an ionising event.

\[
Q(t) = \begin{cases} 
0 & \text{for } t < 0 \\
\frac{Q_o \mu E}{d} \left(1 - \exp\left(-\frac{t}{\tau}\right)\right) & \text{for } 0 < t < T_d \\
\frac{Q_o \mu E}{d} \left(1 - \exp\left(-\frac{T_d}{\tau}\right)\right) & \text{for } t > T_d 
\end{cases} \tag{2.30}
\]

From this equation it is assumed that charge is induced at the cathode at a time \(t=0\). The pulse with the largest amplitude is common to all the panels in figure 2.7 and is produced using the parameters: \(\mu_e = 985\text{cm}^2/\text{Vs}, d = 1\text{cm}, E=1000\text{V/cm},\) and \(\tau_e = 5.1\mu\text{s}\). The other pulses in each panel are produced by changing a particular parameter in equation 2.30 to produce a 10% and a 20% pulse height reduction from the common pulse. This modeling method was initially carried out by Amman et al.\[2\].

Figure 2.7a shows the effects of reducing the electron lifetime to 2.4\(\mu\)s and 1.5\(\mu\)s respectively. This reduction increases the curvature of the induced charge pulses which is in turn due to increased trapping. A curvature in an induced charge pulse is indicative of a reduction in the lifetime. Figure 2.7c shows the effects of reducing the electric field to 460V/cm and 290V/cm respectively. This reduction increases the pulse rise time due to a decrease in the carrier velocity associated with a decrease in the electric field (see equation 2.26). Similarly a reduction in the carrier mobility to 460\text{cm}^2/\text{Vs} and 290\text{cm}^2/\text{Vs} (figure
Figure 2.7: Calculated induced charge signals. In each panel the pulse with the largest height was determined using typical transport properties as mentioned in the text. The other pulses were determined by adjusting the following properties to produce a 10% and a 20% pulse-height reduction: a) electron lifetime, b) electron mobility, c) electric field, and d) the charge generated at the cathode. Based on reference [2].
Figure 2.8: Calculated induced current signals. In each panel the pulse with the largest height was determined using typical transport properties as mentioned in the text. The other pulses were determined by adjusting the following properties to produce a 10% and a 20% pulse-height reduction: a) electron lifetime, b) electron mobility c) electric field, and d) the charge generated at the cathode. Based on reference [2].

2.7b) produces the same elongation of carrier rise time, again due to the decrease in carrier velocity associated with a decrease in the mobility (see equation 2.26). Figure 2.7d shows the effects of reducing the charge generated at the illuminated contact (in this case the cathode) by 10% and 20% respectively. This fractional decrease causes the same fractional decrease in the pulse amplitude.

Differentiation of the charge pulses shown in figure 2.7 produces the current pulses shown in figure 2.8. A distinct increase in the curvature of the top of the current pulse between the beginning of the pulse and the end of the pulse is clearly observed in Figure 2.8a, which is indicative of reducing the lifetime. This is in contrast to the change of $\mu$ and electric field ($E$) (as shown in figures 2.8b and c), which shows no increased curvature but a distinct elongation of the transit time coupled with a decrease in amplitude. The elongation of the pulse can be attributed to lower carrier velocity whereas the lower amplitude is due
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Figure 2.9: Calculated induced charge signals determined by adjusting the trapping fraction at a trapping site to produce a 10% and a 20% pulse-height reduction [2].

to the conservation of the area under the current pulse which equals the initial charge. The reduction of charge generated at the illuminated contact also shows no increased curvature but does show a reduction in pulse amplitude.

The presence of non-uniformities such as tellurium inclusions can be inferred from the analysis of the morphology of charge pulses. Amman et al. [2] have proposed that the existence of a non-uniformity within the bulk of the material will produce a discontinuous charge pulse of the type that cannot be modeled using equation 2.30. Figure 2.9 shows a current pulse shape that may be present if a localised trapping site existed at the midpoint of the device. This pulse shape was confirmed by localising its presence with the presence of tellurium inclusions within the bulk.

2.2.4 Thermally induced re-emission of charge carriers.

The time that a charge carrier spends in a trap is controlled by the temperature of the system. The physical reason for this is that the charges trapped by a defect site need to overcome an energy barrier ($E_A$) in order to become free charge carriers again. The probability that this occurs increases with an increase in temperature. For a thermally activated emission of an electron into a conduction band the relationship between emission
time $\tau^*$ and temperature $T$ is given by equation 2.31, taken from reference [71].

$$\tau^* = \frac{1}{\gamma_e \rho_e T^2 \exp \frac{E_A}{k_B T}}$$  \hspace{1cm} (2.31)

where $\gamma_e$ is a material specific constant defined by equation 2.32 and the expressions for $v_{th}$ and $N_\nu$ are defined in equations 2.33 and 2.34 respectively.

$$\gamma_e = v_{th} T^{3 \frac{1}{2}} N_\nu T^{-3 \frac{1}{2}}$$  \hspace{1cm} (2.32)

$$v_{th} = \frac{3k_B T}{m_e^*}$$  \hspace{1cm} (2.33)

$$N_\nu = \frac{m_e^* k_B T}{h^2}$$  \hspace{1cm} (2.34)

Where $k_B$ is Boltzmann's constant, $h$ Plank's constant and $m_e^*$ is the electron effective mass. Looking at these equations it is clear that the material constant $\gamma_e$ is temperature independent. Therefore the emission time can be approximated by equation 2.35.

$$\tau^*(T) \approx \frac{1}{T^2} \exp \left( \frac{E_A}{kT} \right)$$  \hspace{1cm} (2.35)

Emission of charge carriers out of traps influences the induced current and charge pulses. The main indicator for de-trapping is a non-zero current for times larger than the transit time of the charge carriers. Considering only one carrier type and one trap type for simplicity there are three cases that allow for the interpretation of the induced currents.

- $\tau^* << T_{T_r}$: In this scenario the de-trapping time is much smaller than the transit time, which means that the time the charge carriers spend in a trapped state can be neglected. The resulting current or charge pulse is very similar to a current or charge
pulse that has no trapping.

- $\tau^* > \tau$ and $T_{dr} < \tau$: Here the carrier lifetime is much smaller than the de-trapping time and the transit time. Thus under these conditions trapped charge carriers are not re-emitted more than once. A non zero current may then be produced by thermal emission after the transit time, which follows an exponential decay that is proportional to $\exp(-t/\tau^*)$.

- $\tau^* \geq \tau$ and $T_{dr} >> (\tau + \tau^*)$: If the detrapping time is equal to or larger than the lifetime and the transit time is much larger than the sum of the lifetime and the de-trapping time then carriers are trapped and re-emitted multiple times on their transit through the material. Thus the current produced remains constant until most carriers are collected. This case is analogous to the trap free case but by replacing the mobility with a trap limited mobility, which takes into account the time for multiple trapping and de-trapping events.

Of the three cases discussed only the second case ($\tau^* > \tau$ and $T_{dr} < \tau$) is useful for the analysis of trap energies in techniques such as photon induced current transient spectroscopy (PICTS). The non zero current after the transit time is proportional to $\exp(-t/\tau^*)$ thus measurement of this exponential component for a set of pulses as a function of temperature can be used to extract the emission time $\tau^*$ and using equation 2.35 an Arrhenius plot of $\log\tau^*T^2$ against inverse temperature, which can be used to find the activation energy of the trap ($E_A$). The other two cases involve either (1) no distinguishable thermally emitted current after the transit time, or (2) emission involving several traps in which case the analysis of the trap (or traps) energy cannot be resolved using equation 2.35.
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2.2.5 Ion beam induced charge (IBIC)

The ion beam facility at the University of Surrey has the ability to produce a micrometer size (typically < 5 \(\mu\text{m}\)) beam of protons of energies of a few MeV, this facility is the basis of all ion beam induced charge (IBIC) experiments carried out in this study. The specifics of the ion beam and IBIC setup are described in section 4.3.

Ion irradiation, like other ionising radiations, can be used to excite electron hole pairs in CdTe. Ion irradiation penetrates to a well maintained depth several micrometers into a device (37\(\mu\text{m}\) in CdTe [89]) at this depth most of the proton energy is deposited. This is in contrast to gamma and X-ray radiation, which either deposit their energy at the near surface or throughout the material, depending on the energy. If the energy is low then energy deposition may occur at the near surface, as a result defects in this region may cause surface recombination [42]. If the energy is high energy deposition will occur throughout the device, causing a depth dependence to the energy deposition. Both these scenarios cause difficulties when using gamma and X-rays for basic material characterisation. Other irradiation methods such as electrons have advantages over proton beams in that they are easier (and cheaper) to form into a micrometer probe. However due to the increased straggling in electrons compared to heavier ions [4] the volume of interaction is a limiting factor. The probed volume of a proton beam is not just a function of the size of the beam spot, straggling (which can create delta rays that can increase the probed volume, but to a lesser extent compared with electrons) and diffusion of the created electron hole pairs all add to an increase of the probed volume.

A proton microprobe is a versatile piece of equipment for investigating the device and material properties of semiconductors. Due to its pulse mode of operation it is well suited to the investigation of radiation detectors [34, 87]. The technique has been further developed by several groups and CdTe based devices have been investigated using digital IBIC (also called TRIBIC) [52, 77] which involves the acquisition of time resolved induced charge...
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pulses to calculate spatially resolved charge carrier transit times. IBIC has also been combined with other ion beam analysis techniques like ion beam induced luminescence (IBIL) [5] and proton induced X-ray emission (PIXE) [49] to acquire further material information.
3. Growth and defects of Cadmium Telluride

3.1 Melt growth of CdTe

There are a wide number of techniques used to grow CdTe crystals of suitable quality for radiation detection reported in the literature. With regard to growth from the liquid phase a few techniques such as the traveling heater method (THM) [84], the Bridgman method [40, 62] and zone refining techniques [83] have produced good quality material that can be used as spectroscopic grade radiation detection material. Most crystals used in radiation detection devices are grown by either the Bridgman method or the traveling heater method and as such these two techniques deserve further discussion.

Figure 3.1 shows the liquidus curve for the CdTe binary system. It shows a broad asymmetric curve with a maximum melting temperature of 1092°C at the stoichiometric composition. Having an excess of Te or Cd in the melt drastically reduces the melting temperature of the binary system. Indeed a 10% Te excess can lead to a 200°C decrease of the melt temperature. Figure 3.1 puts into context the main differences between the Bridgman and traveling heater growth methods. Bridgman methods occurs at (or very near to) stoichiometric conditions meaning that the melting temperature occurs at 1092°C. In contrast THM occurs in an excess of Te (or Cd), which significantly reduces the melting
temperature. This one difference has a profound effect on the size and quality of grown CdTe crystals.

### 3.1.1 The Bridgman growth method

The basic Bridgman growth method proceeds with atomic equivalents of Cd and Te being loaded into a silica ampoule. This ampoule is then lowered through a series of different heated zones. Figure 3.2 shows a schematic diagram of the basic Bridgman apparatus as well as the furnace profile. The temperature of T2 (see figure 3.2) is used to melt the loaded material and so is at a temperature exceeding the melt temperature of CdTe as given by the liquidus curve shown in figure 3.1. The temperature of the last zone is used to produce solidification and so must be lower than the melt temperature (1098°C) of CdTe. In order to grow monocrystals, many aspects of the basic Bridgman technique has been investigated. Of major importance for monocrystalline growth is the shape of solid-liquid interface, the pressure above the melt the growth ampoule and the purity of the starting
material. If the solid-liquid interface is concave within the melted region, growth tends to occur from the walls of the growth ampoule which tends to favour polycrystalline growth [40, 88]. A flat region is preferred but due to convection currents within the melt a convex solid-liquid interface is more easily achieved, this causes growth from the centre of the solution which is more likely to produce single crystals.

Pressure in the sealed ampoule at a stoichiometric composition can develop a maximum vapor pressure of 7atm at 1030°C [88], which could rupture the ampoule and cause explosions. To stop this the Bridgman method was modified to include a controllable overpressure by holding an excess of Cd above the melt at a relatively low temperature in an extended ampoule [40] as shown in figure 3.2. This overpressure also prevents sublimation, which can cause inhomogeneities within the growing crystal. At such high temperatures the silica ampoule is a large source of contamination and can add impurities such as O, Si, Na and many other elements [30], but due to the high pressures involved other ampoule materials such as graphite cannot be used due to their lower strength. In order to use a
graphite ampoule the Bridgman method was further modified to contain a high pressure jacket around the furnace and growth ampoule [62] resulting in the so called high pressure Bridgman technique. Other methods of modified Bridgman growth involve the use of ampoule rotation [9], which homogenises any thermal inhomogeneities present in the growth apparatus. For all the effort the Bridgman technique has produced some large and high resistivity devices that can be used for radiation detection purposes, but there are still issues with limited size (due to polycrystallinity) and impurities.

3.1.2 The traveling heater growth method

In contrast to the Bridgman process discussed previously the traveling heater method is an off-stoichiometric growth technique. This has benefits in that the melt temperature of component parts is lower than the stoichiometric melt due to the excess component acting as a solvent. This lower temperature reduces the contamination from the ampoule. According to the Cd-Te liquidus curve given in figure 3.1 both Cd or Te can be used as solvents. However Te is preferred as the solvent because the partial pressure evolved from a Te rich melt is less than if the melt was Cd rich, Te also has a restricted solubility in Cd-rich melts.

The traveling heater method proceeds in much the same way as the Bridgman process. An annular heater is used to produce a melt region and the growth ampoule is lowered through the heater producing a moving melt that deposits grown CdTe as it moves. A schematic of the basic THM process is given in figure 3.3. Due to the temperature profile in the melt produced by the heater the top of the melt is hotter than the bottom of the melt \( T_1 > T_2 \) in figure 3.3. Thus the solubility of \( \text{Cd(Te)} \) in the \( \text{Te(Cd)} \) rich solution is higher at \( T_1 \) than the solubility of \( \text{Cd(Te)} \) at \( T_2 \). This causes transport of \( \text{Cd(Te)} \) from the hotter \( T_1 \) interface to the cooler \( T_2 \) interface and so causes crystal growth at the cooler interface.
As in the Bridgman method many aspects of the THM process have been investigated in order to increase the monocrystalline yield of the grown crystal, and the solid–liquid growth interface plays a major part in crystal monocrystallinity. A convex shape into the melt region is again preferred which tends to reduce polycrystalline formation due to nucleation at the ampoule wall. It also depletes the middle of the growing crystal of excess tellurium, which reduces the formation of tellurium inclusions in the middle of the growing crystal but increases their formation at the sides. A convex growing interface is achieved by careful apparatus design, specifically by increasing axial heat flow and reducing lateral heat flow as well as slow progression through the heated zone [84, 69]. The use of a solvent region is useful in that the solubility of impurities contained in the feed material is less than the solubility of cadmium or tellurium (depending on the excess), so there is a certain amount of purification that occurs during growth. Use of a solvent is however detrimental in the fact that if supercooling occurs at the growth interface excess solvent
can become trapped in the solid crystal. Tellurium precipitates can also occur due to the retrograde solubility of Te in CdTe and so inhomogeneous crystals can form. Even though the temperature of the growth is less than in the Bridgman method there is still an issue of contamination of the crystal by impurities especially at the ampoule wall. Most CdTe grown for radiation detection purposes is grown by the traveling heater method and the material used in this study was grown by EURORAD by THM.

3.2 Defects in CdTe

Defects in CdTe can be detrimental to the function of radiation detectors. Too many defects can reduce the spectroscopic capability of detectors by a number of different processes. Primarily defects act as trapping sites that impede the drift of charge carriers and so reduce the spectroscopic capability of the material. Much is done at the growth stage to avoid the introduction of defects, but due to the natural and unavoidable instabilities inherent in growing CdTe, growth of a large monocrystal is still a complex affair. Defects are roughly characterised as structural and electrical. Both are introduced at the growth stage but structural defects are due to instabilities in the growth procedure and electrical defects are introduced due to impurities present in either the starting materials or the growth vessel.

3.2.1 Structural defects

The major structural defect present in CdTe is the presence of excess tellurium or cadmium in the crystalline matrix. The presence of the constituent elements is a result of two different processes [67, 88]. The first process generates structures known as precipitates while the second generates inclusions. This nomenclature is used by some authors to differentiate between the two types but many authors use the generalised 'precipitate' to
mean any circular dark contrast object present in infrared microscopy images. Precipitates are formed due to the retrograde solubility of either Cd or Te during the cooling of the CdTe crystal [88]. That is an excess of either Cd or Te can exist in solid CdTe as defects that take up interstitial sites. During cooling, because CdTe solidifies before either Cd or Te, these interstitials are able to diffuse through the CdTe solid crystalline matrix and form pockets of Te or Cd precipitates at nucleation sites such as grain boundaries, voids, or dislocations. If the cooling is slow enough large well distributed precipitate formation can be avoided as they collect near other defects or the surface. Inclusions by comparison are caused by instabilities at the growth interface. Supercooling traps the solvent (Te or Cd) in the solid CdTe. This solvent is also able to move through the solid matrix and collects in the same manner around other defects like dislocations, grain boundaries or indeed already formed precipitates. Inclusions and precipitates not only differ in their nucleation but their size. Inclusions tend to be greater than $1\mu m$ whereas precipitates tend to be less than $1\mu m$. As a result precipitates tend to be outside the resolution of infrared microscopy systems, whereas inclusions are very much visible. The shapes of inclusions viewed by infrared microscopy systems vary. Many authors have observed a tetrahedral shape tellurium inclusion [60] but also inclusions with a circular and hexagonal have also been observed [6, 67]. These shapes can however be modified due to thermal gradients, or pressure, so many shapes of inclusion are possible. Indeed [67] has observed irregular inclusions formed due to the movement of the solvent due to temperature gradients.

Other defects in CdTe crystals are the presence of multiple crystals in a growth ampoule, and therefore the presence of grain boundaries. There are a number of reasons why the growth is not monocrystalline. Spurious nucleation can occur at the ampoule wall forming another crystal this is more likely to occur due to a concave growth interface [69]. Slight differences in the conditions at the growth interface can also form sub-grains. As a result careful design of the apparatus and careful control of heat gradients is an important
3. GROWTH AND DEFECTS OF CADMIUM TELLURIDE

consideration. Twin formation is also a major problem in CdTe growth and also occurs due to growth accidents [16], but this time along specific crystal planes, again careful control of the growth interface can reduce the presence of twins. Dislocation formation in CdTe crystals is also a problem and these occur during growth and during the cooling phase. Dislocations can propagate from a seed crystal into the growing crystal and dislocations produced at peripheral regions (such as sticking at the ampoule wall) can propagate into the middle of the crystal [61]. Defects such as Cd or Te inclusions can also form dislocations around their periphery as shown by [6]. To completely avoid defects is difficult job and usually a CdTe crystal is grown and then surveyed for defect concentration using a number of different processes. A relatively defect free monocrystal is then located and cut from the grown crystal. [39]

3.2.2 Electrical defects and compensation of CdTe

Defects in CdTe can produce additional energy levels within the band gap. These invariably effect the characteristics of the device and can detrimentally effect the device function. Most electrical defects are a result of impurities or defects entering the CdTe crystal during growth, whether it be from extrinsic elements or more intrinsic stoichiometrically induced defects.

If one considers the hypothetical pure CdTe crystal, which is free from extrinsic impurities, the only defects present are Frenkel like defects as sketched in figure 3.4. These can include cadmium vacancies (V$_{\text{cd}}$), cadmium interstitials (Cd$_i$) cadmium antisites (Cd$_{\text{cd}}$), tellurium vacancies (V$_{\text{te}}$) tellurium interstitials (Te$_i$) and tellurium antisites (Te$_{\text{cd}}$). Considering a THM grown crystal one comes to the conclusion, due to the excess of tellurium at the growth interface, that most defects will be due to cadmium vacancies (V$_{\text{cd}}$), tellurium interstitials (Te$_i$) and tellurium antisites (Te$_{\text{cd}}$). Of these three defects cadmium vacancies tend to form singly (V$_{\text{cd}}^+$) and doubly (V$_{\text{cd}}^-$) ionised states both of which act as
Vacancy ($V_{\text{Te}}$)

Interstitial ($\text{Te}^*$)

Antisite ($\text{Cd}_{\text{Te}}$)

Figure 3.4: Illustrates Frenkel defects in CdTe. Specifically shown are a tellurium vacancy ($V_{\text{Te}}$), a cadmium anti-site ($\text{Cd}_{\text{Te}}$) and a tellurium interstitial ($\text{Te}^*$) acceptors. In the literature the ($V_{\text{Te}}^-$) state has an energy level ranging from $E_v + 0.65 \text{eV}$ [78] to $E_v + 0.735 \text{eV}$ [39], whereas the ($V_{\text{Te}}^+$) has an energy ranging from $E_v - 0.38 \text{eV}$ [29, 10] to $E_v + 0.47 \text{eV}$ [39]. By contrast the tellurium antisites is a donor impurity and is resident in the middle of the band gap at an energy tentatively defined in the range $E_v + 0.66 \text{eV}$ [22] to $E_v + 0.74 \text{eV}$ [39]. The tellurium interstitials normally have the time during the cooling stages of growth to aggregate into precipitates and thus form neutral defects [23].

Crystals grown from the melt contain more than intrinsic defects. Extrinsic impurities are present in enough concentration during growth to add many distinct energy levels into the band gap. These defects have two main sources: impurities in the starting material and impurities in the apparatus. From the apparatus the main source of impurity is from the quartz ampoule. This can contain Al, Fe, Ti, K, Li and other elements in significant quantities to contaminate the CdTe crystal especially at the high temperatures that are used for growth. The same can be said for the impurities of the growth material, even if commonly achievable 6N pure Cd and Te is used there still exists the possibility of contamination. The use of growth using a solvent zone through which impurities have a low diffusivity is useful, as in the THM process. This, coupled with a graphitised quartz
ampoule and the lower temperature associated with THM, can lead to significant reductions in the concentration of impurities, but even with the purest of starting elements and the most well designed growth apparatus some impurities will still be present.

These impurities will take up positions within the CdTe crystal and act as either donors or acceptors depending on their electrical configuration. Common single acceptors are formed via the substitution of metal atoms by atoms with only one s electron. Thus metals like (Na, K, Cu, Ag, Au)_{Cd} can form shallow acceptor states within the band gap [59]. Similarly atoms with three p electrons will appear as single acceptors if substitutional onto a tellurium site, thus metals like (C, Si, Ge, Sn)_{Te} can form single acceptor states. With regards to donors, elements like Cl, In, Br and I can take substitutional sites on tellurium and form single donors, these commonly form complexes with the intrinsic deep defects in CdTe, specifically \( V_{cd}^- \), to form cadmium vacancy-donor complexes (ionised or neutral) that act as acceptors.

As most applications of CdTe require the use of low leakage current and high resistivity the presence of donors and acceptors in a material does bring up the question of compensation. For a material to have a high resistivity the number of charge carriers at room temperature must be as low as possible or indeed the number of donors should equal the number of acceptors. There are several ways of achieving this: either grow stoichiometric impurity free crystals or introduce donors (acceptors) to compensate for the acceptors (donors). Exact compensation of shallow donors \( (N_D) \) or acceptors \( (N_A) \) by adding shallow acceptors or donors would require that \( N_A = N_D \) to about one part in \( 10^8 \) throughout the ingot [35], a task that is quite unrealistic. The more likely compensation mechanism is thought to involve either a deep acceptor \( (N_{DA}) \) or a deep donor \( (N_{DD}) \) depending on the shallow level surplus. The effect of the deep level in compensation was first proposed by Neumark [56] and was applied to GaAs by Johnson [35] and to CdTe by Fiederle [23] and is shown in figure 3.5.
Using the basic equations of charge neutrality and carrier density it was shown that high resistivity material could be produced via compensation of shallow donors or acceptors by a deep acceptor or deep donor, providing that the deep donor or acceptor was within 0.25eV of the intrinsic fermi-level. This process could originate from the presence of native defects such as $V_{\text{cd}}$ which would provide a deep acceptor state in the range $E_v + 0.65\text{eV}$ to $E_v + 0.735$ or by a deep donor state such as $\text{Te}_{\text{cd}}$ (in the range $E_v + 0.66$ to $E_v + 0.74$). A deep level could also be present due to extrinsic defects such as (Ge, Sn, V, Ti)$_{\text{cd}}$ [21] but it is difficult to see how these defects are accidently introduced in the concentration required at the growth stage.

### 3.3 Factors effecting mobility in CdTe

At low electric fields in a semiconductor the drift velocity ($v_d$) of charge carriers in the crystal lattice is proportional to the electric field strength ($E$) and the proportionality constant is defined as the drift mobility $\mu$ (see equation 2.24). Charge carrier mobility is
3. GROWTH AND DEFECTS OF CADMIUM TELLURIDE

heavily dependent on the existence of scattering mechanisms within the bulk of a semiconductor. There are many scattering types present in semiconductors but mostly they can be categorised as either impurity scattering or phonon scattering. Figure 3.6 illustrates the common scatter mechanisms found in semiconductors, and what follows is a brief description of the main carrier scattering mechanisms that effect CdTe.

3.3.1 Defect scattering

The first main type of scattering in semiconductors is scattering by defects. If a defect is ionised then the resulting Coulomb field can effect the transit of a charge carrier and thus effect the mobility. The mobility can also be effected by a neutral impurity but without the long range Coulombic effect.

Ionised impurity scattering

Impurity scattering involves the presence of foreign atoms within the semiconductor bulk, these atoms act as scattering centers especially when they are charged. Larger impurity
concentrations lead to lower mobilities as the number of scattering events increases. If the impurity is ionised, the scattering is due to electrostatic forces and as a result the scattering depends on the time of interaction between the carrier and the foreign atom. The slower the carriers the greater the scatter cross-section. As the temperature of the atom increases so to does the carrier velocity (as carrier velocity is related to the thermal velocity of the carriers) therefore the interaction time decreases and so too does the scattering cross-section. As a result ionised impurity scattering is heavily dependent on temperature. The mobility due to ionised impurity scatter is given in equation 3.1 [73].

\[
\mu_{im} = \frac{128(2\pi)^{1/2}(kT)^{3/2}(\varepsilon_0\kappa_0)^{2}}{q^3m^*^{1/2}N_I} \left[ \ln(1 + \beta) - \frac{\beta}{1 + \beta} \right]
\]  

(3.1)

Where \( \varepsilon_0 \) is the permittivity of free space, \( \kappa_0 \) is the low frequency relative dielectric constant, and \( m^* \) the effective mass. The variable \( \beta \) is given by equation 3.2 where as the number of free charge carriers at a thermal equilibrium \( (p') \) and the number of ionised defects \( (N_i) \), is given by equation 3.3.

\[
\beta = \frac{24m^*(kT)^{2}(\varepsilon_0\kappa_0)}{e^2\hbar^2p'}
\]

(3.2)

\[
p' = p + \frac{(p + N_D)(N_A - N_D - p)}{N_A} \quad \text{and} \quad N_I = p + 2N_D
\]

(3.3)

Ionised impurity scattering is important in impure and non-stoichiometric compounds like CdTe, it is not so prevalent in the more pure single Silicon and Germanium crystals. If the concentration of ionised impurities is independent of temperature and ionised impurity scatter is dominant then the mobility varies as \( T^{3/2} \).
Neutral impurity scattering

With neutral atoms there is no long range effect due to the Coulomb potential of the atom as there is with ionised impurities. Hence the interaction between charge carriers and neutral atoms is by Coulombic scattering with the electron cloud. The free carriers can also interact with a neutral atom by polarising it or exchanging places with a bound electron. These interaction methods make assessing the magnitude of neutral impurity scattering very difficult. However for a hydrogen like neutral impurity the effect on the mobility is given by equation 3.4[15].

\[ \mu_{NI} = \frac{m^*e^3}{20\hbar^3 N_u (4\pi\varepsilon_0\kappa_0)} \]  

(3.4)

Where \( N_u \) is the number of un-ionised defects and is given by equation 3.5

\[ N_u = N_D - N_A - p \]  

(3.5)

As can be seen from equation 3.4 there is no theoretical temperature dependence for neutral impurity scatter, but in practice as the temperature falls the number of ionised impurities falls and so at very low temperatures there may be an increase in the number of neutral defects which may increase the effect that neutral impurity scattering has on the carrier mobility.

3.3.2 Phonon scattering

If a free charge carrier were to move through a perfectly periodic crystal structure where no atom was away from its Bravais lattice site then the mobility would be constant throughout the crystal. However due to thermal vibrations there is a net displacement from the ideal periodicity within a crystal. If an atom is displaced from its equilibrium position the
forces of the bonds tend to try and force it back into place, this causes the atom to oscillate at its equilibrium position. Certain modes of oscillation can effect the interatomic spacing between the atoms (can compress or dilate the unit cell), which can have implications on the potentials within a crystal and therefore effect the mobility. These modes of vibration are termed phonons and the interaction between these and charge carriers results in charge carrier scattering. There are several types of phonon scattering processes, each of which has a specific way of altering the unit cell and thus each has a specific way of effecting the mobility of charge carriers.

**Acoustic deformation potential scattering**

The acoustic phonons in a crystal can scatter carriers by two different and independent processes, these are the acoustic deformation potential scatter and the piezoelectric scatter. With regards to the former mechanism the acoustic phonon vibration that causes the maximum amount of displacement of the unit cell is the longitudinal component (LA), there is little effect on the size of the unit cell from the transverse component (TA) [36]. Thus longitudinal acoustic phonons will produce a modulation of the unit cell and thus a modulation of the periodic potential within the crystal in space and time. It is this modulation that scatters the free charge carriers traveling within the crystal. The acoustic deformation potential scattering limited mobility is given by equation 3.6 [47].

\[
\mu_{ad} = \frac{2\sqrt{2}\pi \hbar^4 c_l}{3E_D^2 (m^*)^{5/2} (kT)^{3/2}}
\]  

(3.6)

Where \( E_D \) is the deformation potential constant and \( c_l \) is the longitudinal elastic constant. If acoustic deformation potential scattering is dominant then the mobility varies as \( T^{-3/2} \).
Piezoelectric scattering

The second type of scattering caused by acoustic phonons is piezoelectric scattering. This occurs in crystals which lack a centre of symmetry, which accounts for all compound semiconductors. The variation in the unit cell caused by the LA phonons polarises the ions, which in turn produces an internal electric field. This field causes the scattering of free charge carriers. The piezoelectric scattering limited mobility is given by equation 3.7 [73].

\[
\mu_{pz} = \frac{16\sqrt{2\pi}}{3} \frac{h e_0 \kappa_0}{m^* q^2 c K^2 (kT)^{1/2}}
\]  

(3.7)

and

\[
K^2 = \frac{e_{pz}^2/c_i}{e_0 \kappa_0 + e_{pz}^2/c_i}
\]  

(3.8)

Where \(e_{pz}\) is the piezoelectric constant. If piezoelectric scattering is dominant then the mobility varies as \(T^{-1/2}\).

Polar optical scattering

Polar optical phonon scattering is analogous to piezoelectric scattering for acoustic phonons. The unit cell is polarised by the longitudinal component of optical phonons, which again disturbs the periodicity of the crystal lattice. This produces a temporal and spatial varying field, which scatters the free charge carriers and thus affects the mobility. The polar optical scattering limited mobility is given by equation 3.9 [85].

\[
\mu_{po} = 0.199 \left( \frac{T}{300} \right)^{1/2} \left( \frac{e}{e_0^*} \right)^2 \left( \frac{m_0}{m^*} \right)^{3/2} (10^{22} M) (10^{23} V_0) (10^{-13} \omega_0) \left( \exp \left( -\frac{\hbar \omega_0}{kT} \right) \right)
\]  

(3.9)
where $M$ is the reduced mass of the unit cell, $V_a$ is the volume of the unit cell and $\Theta$ is the Debye temperature. If Polar optical scattering is dominant then the temperature variation of the mobility is not as straightforward as with the other scattering mechanisms discussed. Burshtein et al. [7] have shown that mobility due to phonon optical scatter varies with temperature as $T^{-1}$.

**Trap controlled mobility**

The effect of mobility with changing temperature in CdTe was investigated by [82]. Figure 3.7 shows the main findings for electrons and figure 3.8 shows the main findings for holes.

For electrons as temperature increases the mobility due to ionised impurity scattering increases, as predicted by equation 3.1. The mobility due to optical phonon scatter decreases, as predicted by equation 3.9. Overall the mobility increases with decreasing temperature. For holes however the overall mobility decreases with a decrease in temperature. This is primarily due to the larger effective mass of holes (vacant crystal sites) relative to electrons, which increases the ionised impurity and optical phonon scatter thus causing a decrease in the overall mobility.

Another factor influencing the mobility of charge carriers is related to the trapping that occurs in the CdTe bulk. Consider a charge carrier under the influence of an applied electric field spends a time $t$ traveling towards an electrode. If during this time it falls into a trap of energy $E_A$ and is released in a time $t'$ the mobility is then reduced by the ratio of the time the carrier is free to move to the total time spent undergoing this cycle. With the presence of traps the mobility can become trap controlled if the trapping time is long compared to the transit time of the carriers. The trap controlled mobility ($\mu_d$) is given in
Figure 3.7: Mobility variation with changing temperature for electrons in CdTe. Where $\mu_{Im}$ is the mobility due to ionised impurity scattering, $\mu_{po}$ is the mobility due to polar optical phonon scattering, $\mu_d$ is the trap controlled mobility and $\mu_{total}$ is the mobility when considering just $\mu_{Im}$ and $\mu_{po}$. [82]
Figure 3.8: Mobility variation with changing temperature for holes in CdTe. Where $\mu_{Im}$ is the mobility due to ionised impurity scattering, $\mu_{po}$ is the mobility due to polar optical phonon scattering, $\mu_d$ is the trap controlled mobility and $\mu_{total}$ is the mobility when considering just $\mu_{Im}$ and $\mu_{po}$.[82]
equation 3.11 where \( N_t \) and \( N_d \) are the density of traps and the effective density of states respectively.

\[
\mu_d = \mu \left( 1 + \frac{N_t}{N_d} \exp \left( \frac{E_A}{kT} \right) \right)
\]  

(3.11)

An example of trap controlled mobility in CdTe is given in the data presented by Suzuki [82]. A good fit to experimentally derived data was achieved by producing a theoretical plot from equation 3.11. It seems that in the Suzuki data the electron mobility becomes trap controlled at lower temperatures and at higher temperatures there seems to exist a optical phonon controlled mobility.

### 3.4 Production of devices from CdTe material.

Semiconductor contacts are usually metal-semiconductor junctions that fall into two distinct types: rectifying (Schottky) and ohmic. A Schottky contact is a non-passive diode contact that can rectify current because of a potential barrier that exists due to the creation of a depletion region at the metal-semiconductor interface. As a result a Schottky contact can limit current flow and is termed active. An ohmic contact is a non-blocking contact that does not rectify current flow. It is also a non-injecting contact in that it is passive as it has no potential barrier. Essentially an ohmic contact has a non-active role and just conveys charge in and out of the device. Contacts onto CdTe material are an extremely important factor that can determine the performance of a device. Ideally one would like either a pure ohmic or Schottky contact unfortunately it is not a simple matter to produce either on CdTe. There are many steps of surface preparation and metal deposition to ensure a good contact.
3.4.1 Surface preparation and contact formation.

Leakage current which flows through a biased detector in the absence of a signal is the leading source of electronic noise, which is capable of degrading the device energy resolution. Both surface and bulk currents contribute to detector dark current [68]. A good initial treatment of the surface before the addition of metal can reduce the surface leakage current and increase the performance of the device. The first surface preparation step usually involves mechanical polishing using decreasing sizes of an alumina grit suspension to remove large scale surface variations. This process adds a degree of mechanically induced surface defects, which are removed by the second surface preparation step, an etch. In the case of CdTe the most commonly used etch is a solution of 1-10% bromine in methanol. Once these steps have been carried out the surface should have a mirror finish and must be contacted with metal immediately to avoid the formation of an oxide on the surface.

The formation of an ohmic contact onto CdTe is problematic but there are two theoretical ways in which an ohmic contact can be created. The first being to select a metal whose work function is smaller than the semiconductor work function. If this is the case, when intimate contact between the metal and semiconductor occurs there will be no barrier. The second way of producing an ohmic contact is to alter the width of the Schottky barrier so that the probability of tunneling through the barrier is high. Unfortunately due to the high work function of CdTe their are no metallic elements that have a higher work function that could provide a direct ohmic contact [53]. Therefore to produce an ohmic contact onto CdTe a rectifying junction must be produced that has a thin enough barrier that quantum mechanical tunneling can occur. As the barrier width is related to the width of the depletion region, a thin barrier can be achieved by using a higher doping concentration at the surface of the semiconductor. This can occur via the formation of an interstitial layer between the metal and semiconductor, or the in-diffusion of contact material into the semiconductor. As a result most metal that is deposited onto CdTe forms a rectifying
Schottky contact, the nature of which can be altered by careful surface preparation. Of all the metals that are available for contacting gold or platinum are usually employed as contacts for CdTe nuclear detectors [30]. The metal is usually deposited by electroless deposition but can also be evaporated onto the surface.
4 Experimental Setup

To characterise a material fully in terms of its ability to detect radiation a large number of techniques can be employed. They can broadly be represented by optical methods and electrical methods. Electrical methods are primarily used to investigate the charge carrier drift, and are useful in cross comparing different materials and assessing the spectroscopic performance. Optical methods are usually employed to investigate the structural properties of materials. These methods can show if a material has a high number of in-homogeneities, which may have detrimental effects on detector performance. Used together these broad spectrum of techniques can be used effectively in fully characterising a detector material.

This chapter is primarily concerned with describing the various optical and electrical techniques used in this study. We start with a description of the optical methods, namely infrared microscopy and X-ray topography. We then proceed to a description of the electrical methods used, namely: bulk mobility-lifetime measurements by radiation induced time of flight and mobility measurements by laser and radiation induced time of flight both at room temperature and at low temperatures.
4. EXPERIMENTAL SETUP

4.1 Optical Methods

4.1.1 Infrared Microscopy

The optical absorption coefficient of CdTe falls rapidly at wavelengths longer than the band edge and so the material is effectively transparent for wavelengths greater than 830nm (see figure 4.1). Consequently transmission IR imaging is a convenient and non-destructive method of surveying inclusions and extended defects in CdTe. All transmission infrared microscopy images were acquired using a silicon CCD camera, a motorised X-Y stage, a halogen lamp and a microscope objective orientated as in the sketch given in figure 4.2.

The motorised X-Y stage allowed for the sample to be vertically mounted and moved with 50mm of travel in each axis. The halogen lamp provided broad band illumination of the sample and transmission images were acquired through the material using a micro-
scope objective coupled to a CCD camera. The camera was an IR enhanced silicon CCD camera produced by JAI (model: CV M50IR) which had an extended response to 900nm and provided a video output to the frame grabber in the controlling computer running dedicated LabVIEW software. The field of view for a single image was $500\mu m \times 430\mu m$ giving an imaging resolution of $<1\mu m$. The focal plane of the image, which covered a depth range of approximately $100\mu m$ within the sample, could be positioned within the sample by manually adjusting the Z position of the objective. Large area images up to $50mm \times 50mm$ were automatically acquired by moving the sample holder on the X-Y stage and constructing a composite image from the many individual frames.

4.1.2 X-Ray Topography

The Lang Topography experiments were performed by Dr. A. Keir of Quinetiq at room temperature using a Lang camera set out in the Bragg geometry similar to that given in figure 4.3. In X-ray diffraction the sample is orientated with respect to the X-ray beam so that a set of lattice planes is set at the Bragg angle for strong reflection, the resultant diffracted beam is examined photographically. Any deviation in the lattice results in a difference in the diffraction conditions in the X-ray beam and so a contrast difference in
4. EXPERIMENTAL SETUP

4.2 Electrical Characterisation

4.2.1 Current Voltage (IV) Characterisation

The current response to voltage for all samples in this study have been measured using a Keithley 487 picoampere meter, which also included a voltage source which was used as the bias supply. The sample was connected in series with a 10kΩ resistor to protect the circuit, but as all investigated samples have a considerably larger resistance the trends of the current voltage behavior reflect the sample properties. The samples were sealed in a light tight box and voltage was applied in defined steps by the LabVIEW computer controlled Ampere meter. At each voltage a user defined time was allowed to elapse before the current was measured in order for the steady state current to be recorded.

Temperature dependent IV measurements were carried out using the same picoameter as described above and an Oxford Instruments Microstat Cryostat. This comprised of
4. EXPERIMENTAL SETUP

a continuous flow nitrogen source with heatable sample stage. The pressure within the cryostat was kept at $10^{-1}$ mbar in order to prevent condensation. The temperatures between 300K to 77K with a temperature stability of ±0.5K was maintained using an external temperature controller (an Oxford Instruments ITC 502) that, using correctly set PID settings, heated the sample stage to offset the continuous nitrogen flow. A good thermal connection between the sample stage and sample was achieved by mounting the sample onto a ceramic piece and using thermal compound between the sample stage and ceramic. Steady state temperature was assumed to have been achieved after 1 hour of the target temperature being reached.

4.2.2 X-Ray detection

In order to look at the effectiveness of the devices in this study X-ray spectroscopy was used. To produce X-rays a variable energy X-ray source (VEX) was used. This consisted of six different metals on a rotatable disc and an annular $^{241}$Am primary source. The geometry of the VEX source is shown in figure 4.4. Moving the metal under the gamma emitting $^{241}$Am produced characteristic X-rays specific to the metal target. As the primary $^{241}$Am source is orientated above the target metal and shielded the intensity of $^{241}$Am gamma rays received by the detector is minimal, but due to scatter there is some detectable response of these 60keV gamma rays.

For our experiments the metals Barium and Terbium were used as targets. Barium characteristic X-rays consist of a $K_\alpha$ peak at 32.06keV with a relative intensity of 84% and a $K_\beta$ peak at 36.55keV with a relative intensity of 16%. Terbium characteristic X-rays consist of a $K_\alpha$ peak at 44.23keV with a relative intensity of 76% and a $K_\beta$ peak at 50.65keV with a relative intensity of 24%.
4. EXPERIMENTAL SETUP

4.2.3 Induced Charge Pulses

Amplitude method

In order to measure the charge collection efficiency of the devices in this study the response of the device to external alpha radiation was measured. The system employed a chain of nuclear electronics as drawn schematically in figure 4.5.

The sample was placed into an Oxford Instruments Microstat cryostat and connected up to the external electronics. An $^{241}$Am source emitting alpha particles with an energy of 5.49MeV was placed about 5mm from one face of the device. To stop any reduction in the energy of the alpha particles traveling from source to device the pressure inside the cryostat was kept to $\sim 10^{-1}$mbar. A bias voltage ($V_b$) was applied onto the sample via a pre-amplifier, and any induced charge was initially passed to the ORTEC 142A preamplifier, then on to an ORTEC 570 shaping amplifier, each shaped and amplified pulse was then digitised and binned according to amplitude in a pulse height histogram using an MCA. Many pulses were recorded over a time in order to build a pulse height spectrum with enough statistics to resolve any peaks. These spectra were then saved to disk and analysed off-line. The pulse amplitudes were calibrated into charge collection efficiency using a
4. EXPERIMENTAL SETUP

charge terminator with a capacitance of 1.87pF. This calibration was compared to the calibration using a silicon PIN diode with assumed 100% charge collection efficiency to ensure reliability. Several CCE spectra were taken at different bias voltages. The change of CCE with bias voltage was then plotted and the reduced Hecht equation (equation 2.23) was used to fit to this data. From this fit the $\mu\tau$ value was calculated. To see the effect of charge collection (and $\mu\tau$) with changing temperature the Oxford Instruments Microstat Cryostat was used to lower the temperature of the sample in a manner previously described in 4.2.1.

Transit time method

In order to gather information regarding the mobility of a device time resolved information must be collected. The preamplifier pulses were collected from the ORTEC 142A charge sensitive pre-amplifier (which showed a characteristic rise-time of 23ns [43]) and digitised using an oscilloscope. Each digitised waveform was saved individually to allow for off-line analysis.
4. EXPERIMENTAL SETUP

During subsequent analysis each waveform was first baseline corrected. The maximum amplitude from this baseline corrected pulse was then calculated so as to give a value for $A_{total}$. Simultaneously both the 90% and 10% values of $A_{total}$ were calculated and the corresponding times ($\tau_{10\%}$ and $\tau_{90\%}$) were extrapolated from the time information. The difference between the two times is defined as the 10%-90% transit time ($\tau_{10\%–90\%}$).

Once the 10%-90% transit time was measured a correction of 20% was added to produce the full transit time. Using this corrected value $1/\text{Transit time}$ was plotted against $V/d^2$ ($V$ being the voltage and $d$ being the device thickness). From this the mobility is calculated from the gradient as outlined in section 2.2.2.

4.2.4 Induced Current Pulses

Current pulses in this study were produced by a pulsed semiconductor laser with a wavelength of 635nm and a power of 3mW. To get short pulses the laser was TTL modulated via an arbitrary waveform function generator (BNC Model 632), which in turn was triggered by a programmable precision pulse generator (BNC Model PB-5). A measure of the duration of the laser pulse was made using a silicon PIN diode and was found to be approximately 40ns. The use of the laser produced significantly larger amplitude current
pulses than those from alpha particles, which made possible the collection and analysis of individual pulses. The pulses were amplified by a high bandwidth current amplifier (FEMPTO model DHPCA-100) with a gain of $1 \times 10^5$ V/A and a bandwidth of 14MHz. The current pulses were then digitised by a Tektronix TDS 5104B 1GHz oscilloscope and recorded to file using a computer running specially designed LabVIEW software. A sketch of the equipment is given in figure 4.7.

In this experiment the sample was connected electrically inside an Oxford Instruments Microstat, which had a quartz optical window to allow transmission of the laser pulses. The laser was focussed to a spot of approximately $0.5\text{mm} \times 0.5\text{mm}$ on to the surface of the semitransparent contact (10-15nm of gold) of the sample. Once all focussing and alignment was complete a vacuum of $10^{-1}\text{mbar}$ was introduced into the cryostat. Bias voltage was applied to the illuminated contact via a computer controlled HV supply and a biasing network (originally proposed by Fink et al [24]). The experiment was carried out...
over the temperature range 100K to 300K. For low temperature runs the temperature was controlled via an Oxford Instruments ITC 502 as previously described in 4.2.1.

Offline analysis of current pulses

The goal of offline analysis was to measure the transit time of the charge carriers. By calculating the transit time at several different bias voltages and plotting $1/\text{Transit time}$ against $V/d^2$ ($V$ being the voltage and $d$ being the device thickness) the mobility was calculated from the gradient as outlined in section 2.2.2. The shape of the current pulses is shown as a sketch given in figure 4.8. The transit time of this pulse shape is defined by Ehrenberg [17] as the time that coincides with half the rising edge amplitude subtracted from the time that coincides with half the falling edge amplitude (shown in figure 4.8). To find the trailing edge time an algorithm was developed that firstly baseline corrected all the pulses to 0V then by finding the maximum voltage ($A_{\text{max}}$) of the pulse, and the minimum voltage ($A_0$) was able to find the half maximum of the rising edge ($((A_{\text{max}} - A_0)/2)$, then by interpolating this voltage value to the time axis the trailing edge time was found.

Calculation of the leading edge was a little more involved, and three algorithms were
developed in the LabVIEW environment and compared to one another. The inherent advantages and disadvantages of each algorithm are explained below.

The first algorithm is sketched in figure 4.9. This finds the discontinuity point \( Z \) by means of the intersection of two lines. The first line was produced by applying a linear regression to a section of the pulse before the discontinuity point. The second line was produced by applying a linear regression to a section of the pulse after the discontinuity point. Then by finding the intersection of the two lines it was possible to define the amplitude where by the discontinuity occurs \( (A_{\text{dis}}) \). Using this value and the previously derived minimum amplitude \( (A_0) \) the leading edge time was found by interpolating the half amplitude voltage \( ((A_{\text{dis}} - A_0)/2) \) on to the time axis.

The second algorithm is sketched in figure 4.10. This involved the single differentiation of a current pulse and the application of a linear regression between the maximum and minimum in the differentiated plot. By finding where this line crosses the \( x \)-axis it was possible to find the discontinuity point \( Z \).

The final algorithm implemented is shown in figure 4.11. This third algorithm began by locating two points and constructing a line between them. The two points are shown
4. EXPERIMENTAL SETUP

Figure 4.10: The construction lines used to find the discontinuity point Z by means of differentiation.

Figure 4.11: The construction lines used to find the discontinuity point Z by means of the maximum difference between voltage values of the line and the current pulse. The discontinuity is found where this difference is at a maximum.
by the red lines in figure 4.11. Using the equation of this line an array of voltages was computed. The difference between the voltage values computed and the data voltage values in the time interval defined by the two points was calculated. The discontinuity was found at the maximum voltage difference between the line and the data. This value allowed for the computation of $A_{dis}$ and so using the value of $A_0$ previously calculated, the midpoint of the falling edge was located ($(A_{dis} - A_0)/2$). By interpolating this voltage value onto the time axis the leading edge time was located.

To compute the transit time the leading edge time was subtracted from the trailing edge time. This was done for each current pulse and a histogram of transit time was developed for each bias voltage using a minimum of 300 pulses.

To compare the three leading edge time algorithms, a data set of 100 current pulses was used and a histograms of transit time was produced for each algorithm and are shown in figure 4.12. Of the three algorithms described, the differential algorithm had most problems in its implementation. Due to noise in the pulse the differential plot was extremely noisy. Thus finding the minimum was problematic. In order for the algorithm to work a running average needed to be performed, where by a minimum of 20 data points were averaged to produce one point. The benefits of this algorithm lie in the fact that it is possibly the most accurate method but because it is extremely noise dependent it was not used to compute transit times in this study. Computing the leading edge time by intersecting tangents performed without needing any averaging to produce a distribution of transit times similar to the differential algorithm. However a much finer distribution was produced when using the maximum difference algorithm. For this reason the maximum difference algorithm was used to compute transit times in this study.
4. EXPERIMENTAL SETUP

4.3 Surrey Microbeam

4.3.1 Accelerator and Microbeam Chamber

The Surrey microbeam consists primarily of three main components: an accelerator (a 2MV Tandetron made by High Voltage Engineering Europe) which accelerates ions from the source to the energy required; a focussing system which consists of three quadruplet magnets engineered by Oxford Microbeams Ltd and a large diameter (21cm outside diameter) experiment chamber which contains the sample under investigation and all necessary detectors and instruments used for a certain procedure. Permanently situated in the microbeam chamber are the lithium drifted silicon detector used for PIXE analysis a Silicon PIN diode for STIM analysis a Faraday cup to assess beam current and a microscope to provide information during focusing of the beam and to locate sample features. The relative orientations of each piece of equipment in the microbeam is given in figure 4.13.

For an IBIC experiment the sample is mounted onto a sample stage and is lowered into the chamber from the top, the sample is then orientated to face the beam. All necessary

Figure 4.12: Un-calibrated transit time histograms from three different leading edge time algorithms.
4. EXPERIMENTAL SETUP

Electrical connections are then taken to a flange plate containing through put connections, the sample is then connected to an external pre-amplifier (which also provides a bias voltage during the experiment). Once the sample and all necessary equipment are placed into the microbeam chamber, it is sealed up and the pressure inside reduced to $10^{-5}$ mbar. A proton beam is then focussed onto the sample stage, but before it is incident onto the sample, the beam size is measured using proton induced X-ray emission (PIXE) analysis. This process requires the proton beam to be raster scanned over a copper grid with a $12.5 \mu m$ pitch size. The PIXE spectrum obtains counts as it passes over the copper metal, once enough statistics are obtained the beam spot size is defined by the distance in which the intensity increases from 10% to 90% of its maximum. The beam spot size is typically rectangular in shape with dimensions of $3 \mu m$ and $4 \mu m$. A PIXE analysis requires a large beam current in order to obtain reasonable statistics. As IBIC requires a beam current of several fA the beam current is reduced by either controlling the source or reducing the objective slits in the beam line. Once a stable beam current of the amplitude required is achieved only then is the beam incident onto the sample. During a typical IBIC experiment the beam is raster scanned over the sample, quickly in the vertical direction and slowly in the horizontal direction. The maximum scan size is $2.5 mm \times 2.5 mm$ with a granularity of 256 pixels by 256 pixels.

4.3.2 Analogue IBIC

Analogue IBIC proceeds in much the same way as in section 4.2.3. The induced charge signal derived from the sample in response to proton irradiation is passed to an ORTEC 142A charge sensitive pre-amplifier and then on to an ORTEC 572 shaping amplifier and finally digitised by an MCA connected to a control computer. The pulse height of the induced signal and the X-Y position of the beam is simultaneously recorded by the control software (OMDAQ by Oxford Instruments Ltd) and written as a listmode file. Pulse height
images are derived by averaging the recorded pulse height in each pixel, these images were calibrated into CCE in the manner discussed in section 4.2.3.

**Mobility-Lifetime ($\mu\tau$) Imaging**

To obtain a map of spatially resolved mobility-lifetime ($\mu\tau$) for the sample under investigation a data set of pulse height images calibrated into CCE for several different bias voltages was obtained. Using this data the CCE against voltage was plotted for each pixel. As the IBIC experimental procedure uses protons to generate charge carriers, the interaction occurs several microns below the illuminated contact. If the sample is several millimeters thick the induced charge for one charge carrier can be ignored (if the illuminated contact is positively biased then hole transit can be ignored and vice versa) so it is possible to simplify the full Hecht equation into the single carrier form as given in 2.23. By fitting this single carrier Hecht equation to the CCE vs voltage plots at each pixel it is
possible to derive the $\mu t$ value from the fitted parameters. This process was implemented in the LabVIEW environment by Dr A. Lohstroh. The actual fitting procedure employs the Levenberg-Marquardt algorithm and is described in reference [44].

### 4.3.3 Digital IBIC

Collected in tandem with analogue data is time resolved information that is used to extract parameters such as drift time and mobility. The time resolved information is collected using the digital IBIC imaging system shown schematically in figure 4.14. Induced signals from an ORTEC 142A charge sensitive pre-amplifier are past via an ORTEC 579 fast filter amplifier to an Acqiris 4 channel digitiser. The digitised waveforms are then written as listmode files along with X-Y scan information. Each signal produced by an event is digitised and recorded in such a manner. Of the four digitiser channels one is occupied with the IBIC input and a second is occupied with a signal from an ORTEC 572 shaping amplifier, which provides a trigger pulse for the IBIC data.

Rise time analysis of the pre-amplifier pulses occurs in real time using the algorithm described in section 4.2.3. From this, spatially resolved drift time maps can be computed.
4. EXPERIMENTAL SETUP

By taking a number of drift time maps at several different bias voltages and producing a plot of $1/\text{transit time}$ against $V/d^2$ for each pixel a spatially resolved mobility map can also be produced. The data is stored as a listmode file in order for the majority of analysis to occur off line.

4.3.4 Samples used in this study

The eight samples used in this study can be separated into three groups. Those contacted by EURORAD, those contacted in-house and those contacted for Ion beam studies. Samples 1-3, 2-1, 2-3 and 3-3 were prepared in-house into planar devices by thermal deposition of gold. All the samples were first washed in acetone and then isopropanol (IPA) to remove any grease or dust. A 2\% by volume solution of methanol-bromine was prepared in advance and the freshly washed samples were placed in the methanol bromine etchant for no more than two minutes (which should remove approximately $20\mu\text{m}[65]$). The samples were removed and immediately submerged into methanol and then into IPA. After thorough washing in IPA the samples were dried using a nitrogen gun. The samples were then transferred to the evaporation vessel and a vacuum introduced around the samples. Gold was then evaporated through a shadow mask onto the sample surface. In order to contact both sides it was necessary to crack the vacuum and turn the sample before re-establishing the vacuum. All samples were contacted on one side with $100\mu\text{m}$ of gold where as on the other side a semitransparent layer of $10-15\text{nm}$ was deposited. To protect this thin layer during formation of the device (laying down wires etc) a thick $100\text{nm}$ of gold was deposited onto one quadrant of the sample to provide a more durable surface (see figure 4.15).

After contacts were deposited the samples were laid onto specially prepared ceramic pieces that had gold conductive areas deposited onto them. The samples were laid thick contact ($100\text{nm}$) down onto the gold section of the ceramic, a contact between the gold on the sample and the gold on the ceramic was achieved using carbon paint. A wire
was attached to the thick gold quadrant on the top of the sample and connected onto a gold track on the ceramic (see figure 4.15). All gold thicknesses were measured using the thickness monitor on the evaporation unit and some were independently checked using a stylus profiler.

Samples 2-4 and 3-1 were prepared into devices for use in ion beam studies. This study needed to have a reference system in order to correlate infrared images with IBIC images. A metal mask was applied to achieve this, which consisted of two 'L' shaped gold pieces that bounded an area equal to the maximum scan size of the IBIC system (2.5mm by 2.5mm). A sketch of the mask and its dimensions are shown in figure 7.18. This mask was applied by evaporating 100nm of gold through a shadow mask in an evaporator after the samples were etched in a 2% by volume methanol bromine etchant for no more than two minutes. Once the mask was applied on both the front and back surface of the sample it was imaged using the infrared microscopy set-up described in section 4.1.1. After this process the sample was returned to the evaporator to deposit a metal contact onto the area bounded by the 'L' shaped mask. It was decided that this layer should be semitransparent.
4. EXPERIMENTAL SETUP

so it could be used in laser time of flight experiments discussed in chapter 6.

Only one face was covered with a semitransparent (10-15nm) gold layer and is termed the front contact. The back face was completely covered with 100nm of gold, in order to form a durable back contact able to be set onto a ceramic base using gold dag. Once the back contact was set onto ceramic the front contact was electrically connected using the same gold dag. In order to maintain the integrity of the thin semitransparent gold contact the electrical connection to the front surface was made to the thicker (100nm) 'L' shaped masks. The entire front contact structure can be seen in the photograph shown in figure 7.19. Gold dag was used instead of carbon dag (as is used with other samples) to produce a more durable bond able to withstand the sometimes harsh handling environment of the ion beam.

By contrast samples Eur-1 and Eur-2 were contacted by EURORAD using a contactless platinum deposition process. Eur-1 was fully immersed into the contact solution and an unknown thickness of platinum was deposited onto its surfaces. The sides of the contacted sample were then cut off to produce a planar device. It was laid down onto a ceramic piece in much the same way as previously discussed but with silver paint (silver 'electro-dag') instead of carbon paint. Eur-2 was contacted by EURORAD in much the same way but the top contact was initially a 3x3 pixel array. These pixels were connected

Figure 4.16: Diagram of the mask applied to the front and back surfaces of sample 2-4.
### 4. EXPERIMENTAL SETUP

**Table 4.1: Sample parameters, contact material and known contact thickness.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Contact material</th>
<th>device thickness (cm)</th>
<th>Top contact thickness (nm)</th>
<th>Bottom contact thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>Gold</td>
<td>0.215 ± 0.001</td>
<td>10 ± 1</td>
<td>100 ± 1</td>
</tr>
<tr>
<td>2-1</td>
<td>Gold</td>
<td>0.217 ± 0.001</td>
<td>10 ± 1</td>
<td>100 ± 1</td>
</tr>
<tr>
<td>2-3</td>
<td>Gold</td>
<td>0.217 ± 0.001</td>
<td>10 ± 1</td>
<td>100 ± 1</td>
</tr>
<tr>
<td>2-4</td>
<td>Gold</td>
<td>0.216 ± 0.001</td>
<td>15 ± 1</td>
<td>100 ± 1</td>
</tr>
<tr>
<td>3-1</td>
<td>Gold</td>
<td>0.215 ± 0.001</td>
<td>15 ± 1</td>
<td>100 ± 1</td>
</tr>
<tr>
<td>3-3</td>
<td>Gold</td>
<td>0.215 ± 0.001</td>
<td>10 ± 1</td>
<td>100 ± 1</td>
</tr>
<tr>
<td>Eurd-1</td>
<td>Platinum</td>
<td>0.135 ± 0.001</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Eurd-2</td>
<td>Platinum</td>
<td>0.795 ± 0.001</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

together using silver paint and the whole sample was put onto ceramic in the same manner as Eurd-1.
5 Quality of EURORAD CdTe:Cl

In order to assess the quality of the material and the resultant detector two independent experimental methods were performed on several CdTe:Cl samples prepared by EURORAD. Firstly non-contact and non-destructive infrared microscopy and X-ray topography were used to investigate the material quality and secondly electrical characterisation methods were used to investigate the charge transport properties of the devices.

The fewer inhomogeneities and defects that are present within a detector, the better the overall performance [2]. Thus the fewer tellurium inclusions, tellurium precipitates, and grain boundaries that a piece of material has, the better the charge transport and the overall spectroscopic performance of the detector. Infrared microscopy is used in this chapter to investigate the presence of inhomogeneities within the material. CdTe is transparent to near infrared, whereas inhomogeneities, such as tellurium precipitates and inclusions, are not. Thus inhomogeneities are visible as regions of dark contrast in infrared images. In the literature most precipitates have dimensions (10-30nm [67]) that are outside the 1μm micron resolution achievable using our apparatus. However tellurium inclusions are larger (1μm [67]) and so are visible. The depth of inhomogeneities will also be discussed as we were able to scan through the depth of the sample by changing the focal depth of the infrared microscope.

The use of X-ray topography will be discussed as a method of looking at the crystallinity of a limited sample set. As the Lang apparatus was used in the reflection geometry only
the quality of the near surface was investigated. Nevertheless it will be shown that this is a useful method to observe crystal orientations, stress and dislocations at or near the surface.

Once the optical, non-contact characterisation methods were concluded, contacts were evaporated onto most of the samples used in this study and electrical characterisation was then carried out. Current voltage characteristics will be shown to be useful in the calculation of material resistivity and deep energy levels. Alpha particle spectroscopy will be shown to be useful in calculating both electron and hole mobility-lifetime product of the material at room temperature and at low temperatures, and analysis of charge carrier drift time will be shown to be useful as a method of calculating the electron and hole mobility. Both mobility-lifetime product and charge carrier drift time parameters are well used in the literature to compare and contrast devices.

All of these methods are useful for the comparison of material and devices. Several samples were used in this study and a general overview of each is given in section 4.3.4. With regards to charge carrier transport, it will be shown that the samples are of comparable quality to devices reported in the literature.

5.1 Investigation of material uniformity

The formation of tellurium precipitates, tellurium inclusions and defects such as twins and dislocations, which are introduced into CdTe during growth, are major problems in the fabrication of radiation detection devices. To assess the quality of EURORAD material several techniques were employed. A scanning infrared microscopy system (as described in section 4.1.1) was used to locate regions of enhanced infra-red absorption, both on the surface and within the bulk of the material, to give an idea of the material uniformity. Lang topography, as described in section 4.1.2, was also used to locate material in-homogeneities,
stress and crystal orientation on or near to the surface of the material.

**Infra red microscopy**

The sample Eurd-1 measured 2.5cm in diameter and was grown by EURORAD using the traveling heater method (THM). It was initially sent as bare material with a mechanically scribed grid pattern of pixels on the front face. The grid pattern was for registration purposes and each pixel on the grid had a pitch size of 2.4mm. A full area infrared microscopy image was produced over 12 hours by scanning the sample in a raster scan and taking multiple small images which were stitched together in post-processing. The image
Looking at figure 5.1 there are several extended defects which act as regions of increased infrared absorption. Most of these features are concentrated around the edges of the sample (as shown by the insert in figure 5.1), but some are present in the central regions of the sample. Usually these areas of increased absorption are attributed to tellurium defects such as inclusions or precipitates and in Eurad-1 have a mean diameter of approximately 15 μm. It has been suggested by some authors that the diameter of tellurium precipitates will not exceed 3-10 nm [67], which is below the intrinsic resolution of our infrared microscopy system (≈ 1 μm). The defects visible in figure 5.1 therefore may be tellurium inclusions. To look more closely at the morphology of the inclusions a detailed scan at a higher resolution was performed at two regions defined by the blue squares in figure 5.1 and is presented in figure 5.2.

Looking at 5.2 it is clear that the extended defects marked A do not exhibit the classic shapes (triangular, hexagonal or circular) associated with tellurium inclusions well documented in the literature [6, 60] and shown in figure 5.3. This does not mean that they are not tellurium inclusions as the shape can be modified by different growth conditions and become elongated [72], indeed the inclusions marked A in figure 5.2 do show some
triangular morphology at there edges. Similar shape tellurium inclusions as those given in figure 5.2 are also presented by Rudolph et al [67] (see figure 5.3), so it is likely that they are tellurium inclusions. Other regions of contrast are marked B and C in figure 5.2. Unlike the inclusions marked A, which have a focus below the surface of the sample, features B and C are located only at the surface. This indicates that these are surface defects and in the case of the defect marked C most likely surface scratches.

Infrared microscopy studies were carried out on 10 further samples received from EURORAD. Of these Sample 2-4 has the highest inclusion density across the sample set with approximately 18 inclusions/mm² and an average inclusion size of 10μm. By contrast sample 3-1 has the lowest inclusion density and smaller mean inclusion size, with approximately 6 inclusions/mm² and an average inclusion size of 7μm. Both samples have a high density of high contrast features suggesting that they are of lower quality compared to Eurd-1 which has approximately 0.6 inclusions/mm² and an average inclusion size of 7μm.

In contrast to Eurd-1 the samples measured 5mm × 5mm and were 2.15mm thick. The scan was performed in a similar manner as with Eurd-1 but due to the much smaller size, the time for acquisition for a full image was significantly reduced (approximately half an hour). The images shown in figure 5.4 and figure 5.5 are of the full area of the samples with the focus of the probe forming lens at the front face and the back face respectively.
Figure 5.4: Full infra red image of sample 2-4 made of many smaller images. The contrast and brightness of both images was altered slightly in post processing in order to bring out detail.

The black 'L' shaped structures, clearly visible in the center of the images, are thermally-evaporated gold location marks that define a region for a subsequent ion beam study (the markers define the maximum scan size of a 2MeV proton ion beam, see chapter 7).

Looking at figures 5.4 there is a disparity between the concentration of inhomogeneities between the front and back images, most likely caused by a larger number of inhomogeneities closer to one face than the other. For example sample 2-4 has 4 inclusions/mm² at the front surface and 18 inclusions/mm² near to the back surface. Sample 2-4 also has a large concentration of visible inhomogeneities in one corner, this region is bordered in white in figure 5.4, where as the inhomogeneities in sample 3-1 are more diffuse. Sample 2-4 has more inhomogeneities in contrast with sample 3-1.

The regions of low contrast in figures 5.4 and 5.5 are misleading in the fact that although they point to the presence of inhomogeneities within the material they distort the size. As the inhomogeneities may be lying outside the present focal plane they will be de-focused and may seem larger than they physically are. Thus it is not possible, from just two images, to assess fully the size and shape of in-homogeneities within the samples. Several scans were taken at different focal positions allowing us to image the volume of the sample and
Figure 5.5: Full infrared image of sample 3-1 made of many smaller images. The cross-
hair lines visible are from slight misalignment between successive images. The contrast 
and brightness of both images was altered slightly in post processing in order to bring out 
detail.

thus to try and assess the size and shape of the inhomogeneities.

Figure 5.6 shows the transmission infrared photograph of an area in sample 3-1 (marked
in white in figure 5.5) when the focusing point was set to a distance of 1.16mm below the
surface. Several small regions of reduced infrared absorption approximately 6μm in size
are visible (marked by the red lines in figure 5.6) and these dark areas clearly exhibit
the triangular morphology associated with tellurium inclusions. These inclusions are also
distributed along lines and not randomly within the sample. This could indicate the
presence of dislocations decorated by inclusions as observed by [67]. Other inclusions lying
along a line are visible in this sample, indeed some are marked by the blue lines in figure
5.6, however these lie outside the focal plane and so are not in focus. Other regions of the
sample contain inclusions that do not lie along lines but are randomly distributed within
the sample as shown in figure 5.7.

In sample 2-4 several well defined circular regions of high infrared absorption were
located within the bulk of the sample. Some of these structures are shown in figure 5.8
5. QUALITY OF EURORAD CDTE:CL

Figure 5.6: Transmission infrared photograph of an area in sample 3-1 at a depth of 1.16mm below the sample surface. In focus inclusions are marked with the red brackets and inclusions lying outside the present focal plane are marked with blue brackets.

Figure 5.7: Transmission infrared photograph of an area in sample 3-1 at a depth of 1.16mm below the sample surface. In focus are randomly distributed inclusions (marked with red arrows) that contrast the inclusions shown distributed along lines in figure 5.6.
Figure 5.8: Transmission infrared photographs of the same area but at different focus points. The top most figure is at a distance of 1.0mm below the sample surface and the bottom most is at a depth of 1.26mm below the sample surface. In focus inclusions are marked with an arrow.
and are similar to shapes seen in the literature which are reproduced in figure 5.3. Figure 5.8 shows two images of the same area but the top most image is when the focusing point was set to a distance of 1.0mm below the surface and the bottom most when the focusing point was set to a distance of 1.26mm below the sample surface. No inclusions with the other morphologies were observed in sample 2-4. Most of the inclusions in this sample are circular and are distributed randomly within the sample, rather than decorating a dislocation. Most inclusions in sample 2-4 and 3-1 were distributed at all depths within the sample volume.

**Lang Topography**

To further assess the quality of the sample Eurad-1, X-ray diffraction studies were carried out using the Lang topography set-up, as described in chapter 4.1.2. This method allows one to see regions of crystal discontinuity, lattice strain and dislocation. The image produced in figure 5.9 is a composite of two topographs taken at different orientations. The largest part of the sample has a surface orientation near to the (711) and the next-largest region is near a (432) surface. Over 90% of the sample area was imaged using two topographs. It stands to reason that the two regions imaged by the two topographs are misorientated relative to one another by an angle greater than the dispersion of the incident X-ray beam.

Within the smaller topograph (bounded by the blue line in figure 5.9) further contrast differences can be seen towards columns D and E. This is also a sign of relative misorientation, but as it was imaged in the same topograph, the mismatch is of an angle less than the dispersion of the X-ray beam. This could be due to a small misalignment. Within the larger topograph there are obvious areas of large diffuse contrast difference. This could be due to the small misalignment between regions of high contrast (black regions) and regions of low contrast (white regions) due to stress in the crystallographic planes. Also visible in the large topograph is an extended region of patchy contrast marked by the red
Figure 5.9: A Lang topography image of sample EURD-1. The image is a composite of two images (one outlined in blue), both images cover 90% of the sample area.

region in figure 5.9, which is possibly due to a surface defect. The fact that the inclusions seen in figure 5.1 are not seen in the Lang image given in figure 5.9 could mean that they are too deep for the Lang technique in a Bragg geometry to image. Apart from the obvious dislocation at the boundary of the two main topographs the sample seems to be relatively free from dislocations, the scratches throughout the sample are probably due to polishing marks. Overall the sample seems to be free of large scale defects and has a low dislocation density.

Another EURORAD CdTe sample was imaged using the Lang technique. Again the system was set up in the Bragg geometry and a photographic plate was exposed to Bragg reflected X-rays from a point X-ray source. The image shown in figure 5.10 is from a single topograph, the full area of the circular wafer is shown by the drawn circle. Only part of the full area of the sample was imaged using one topograph. The rest of the sample area that is not imaged is thus in a different orientation, which could mean the presence of
Figure 5.10: A Lang topography image of sample of EURORAD grown CdTe. The image is of one topograph imaging only part of the sample area. The whole sample area is shown by the drawn circle. The topograph was taken using a 620 reflection and shows a surface orientated to the 432 plane. The zoomed region of the lang image shows the contrast variations that are characteristic of an inclusion.

another crystal. Of the area that was imaged there is clearly areas of low contrast (whiter areas) to the left and right of the imaged area either side a region of high contrast (black areas). This suggest a slight mismatch in orientation between the areas due to stress within the material. Within the imaged area there are also lines of low and high contrast some marked by arrows in figure 5.10. These are consistent with dislocations within the material. Also present within the imaged area are small round regions of low contrast. A closer inspection of the image reveals a bright central region of low contrast bordered by a ring of high contrast (see the zoomed area in figure 5.10), this structure is possibly due to presence of near surface inclusions within the material at a depth sensitive to Lang XRT in the Bragg geometry. Similar images attributed to inclusions in CdTe are given in figure 5.11 which are taken from reference [26].
Figure 5.11: Lang topography contrast images of CdTe taken from [26]. The contrast is attributed to inclusions.

5.2 Resistivity and leakage current

After the optical and X-ray characterisation procedures had been completed, the samples were contacted as described in section 4.3.4. Various electrical characterisation measurements were then carried out, firstly the devices current-voltage and resistivity was investigated and then the charge transport properties were studied.

5.2.1 Room temperature IV: A method for investigating resistivity and leakage current

Current-voltage (IV) characteristics of all the devices were investigated at room temperature over the voltage range of ±300V using the apparatus described in section 4.2.1. Voltage was applied through the top contact and varied in 0.1V steps from 0 ± 1V then in 1V steps to ±300V. The current was recorded after waiting for a pre-determined time (typically twenty seconds) in order that the system could reach a stable state. Details of the IV curve did not depend on the direction in which the voltage scan was taken providing a steady state current was reached.

Figure 5.12 shows the IV curves for all samples. Leakage currents below $4 \times 10^{-6} \text{A cm}^{-1}$ were observed for all devices at 300V bias, corresponding to an average field strength of 300V/cm. At voltages between $\pm (0V-1V)$ all current was found to vary as $V^{1.0}$, suggesting
Figure 5.12: Current density vs voltage for all samples.

Figure 5.13: IV response to positive bias in sample 2-3. There are clearly three gradients within this data set.
that at this low voltage the response is completely ohmic. At higher bias ($\pm (1V-100V)$) all IV response was found to vary as $V^{1.1-1.2}$. At larger still voltages ($>100V$) all IV response was found to vary as $V^{2.5-3.4}$. This is shown by sample 2-3 in figure 5.13. The deviation from ohmic characteristics to a super linear increase of current is believed to be due to surface leakage currents. Indeed it has been shown that addition of a guard-ring to devices can remove the superlinear behavior, by removing the surface leakage currents.

The current voltage characteristics can be used to deduce the resistivity. Equation 5.1 shows the relationship between the current ($I$) and the voltage ($V$) so that the gradient of an IV curve will be related to the resistivity ($\rho$), the surface area ($A$), and thickness ($t$). Thus by applying a linear regression to the IV data the resistivity ($\rho$) can be calculated.

$$I = \frac{A}{\rho t} \times V \quad (5.1)$$

However one must be careful in choosing which part of the data to use in calculating $\rho$. Figure 5.13 shows the IV response to positive bias in sample 2-3. There are clearly three gradients within this data set. From 100V-300V it is obvious that there is a super linear increase in the current. As this increase is possibly due to surface currents and not due to the sample this region is not appropriate to calculate the material resistivity. At 1V-100V the deviation from ohmic behavior is less obvious, but using a Log-Log IV curve and applying a linear regression the current variation is found to be $V^{1.2}$, slightly deviating from ohmic behavior, again possibly due to surface leakage currents. This small change will obviously effect the calculated resistivity and as there is a surface leakage component in this region this resistivity will not be correct. At the lower bias range (0V-1V) the current voltage characteristics does approach a linear behavior, and the bulk resistivity of the material dominates the measured IV data [39].

The device resistivity was deduced from the low voltage region 0.1V to 0.5V to avoid
Figure 5.14: Current vs voltage plots of the region used to calculate resistivity in all samples. The small discontinuity observed at zero bias voltage is due to a null-offset error in the picoammeter.

surface leakage effects at higher bias. An example of this region being used to calculate resistivity is shown in figure 5.14, as can be seen there is no significant difference between the resistivity calculated from the positive or negative voltage data (a situation which holds true for all samples investigated), so an average of the two was used to derive the resistivity values for the samples given in table 5.1. All the resistivities measured were at the top of the range often quoted in the literature for CdTe:Cl [13].

The leakage current of a detector is an important parameter as it will effect the energy resolution of a radiation detection device. Figure 5.15 shows the effect of leakage current on the spectroscopic performance of a detector when connected to a regular spectroscopy system. A pulser signal is injected into the system, initially with no bias on the sample.

This produces a peak in the pulse height spectrum with a FWHM of 0.03%, which reflects the electronic noise in the system due to the combination of the preamplifier and the detector capacitance. On biasing the device to +300V the leakage current increases the pulser FWHM over ten times to 0.4%. The FWHM of the pulser, when bias is applied,
5. QUALITY OF EURORAD CDTE:CL

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness cm(±0.005)</th>
<th>Resistivity Ωcm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>0.215</td>
<td>(8.4±0.2)×10^9</td>
</tr>
<tr>
<td>2-1</td>
<td>0.217</td>
<td>(4.5±0.3)×10^9</td>
</tr>
<tr>
<td>2-3</td>
<td>0.217</td>
<td>(5.0±0.3)×10^9</td>
</tr>
<tr>
<td>2-4</td>
<td>0.216</td>
<td>(7.2±0.3)×10^9</td>
</tr>
<tr>
<td>3-1</td>
<td>0.215</td>
<td>(8.4±0.5)×10^9</td>
</tr>
<tr>
<td>3-3</td>
<td>0.215</td>
<td>(4.6±0.3)×10^9</td>
</tr>
<tr>
<td>Eur-1</td>
<td>0.135</td>
<td>(8.5±0.4)×10^9</td>
</tr>
<tr>
<td>Eur-2</td>
<td>0.795</td>
<td>(3.9±0.4)×10^9</td>
</tr>
</tbody>
</table>

Table 5.1: Resistivity and maximum current density data for all samples used in this study.

Figure 5.15: Pulse height spectrum acquired using a pulser connected to sample 2-3, showing the effect of leakage current on the FWHM of the pulser peak. The spectrum offset to the right is the pulser signal with no bias set onto the device. The other spectra show the FWHM of the pulser with +300V applied at different temperatures. This data corresponds to a current in the detector of 95nA (297K) to 0.09pA (150K)
can be made to approach the intrinsic FWHM of the system by lowering the temperature of the device. Figure 5.15 shows this effect as the device is cooled to 150K, when the device current drops from 95nA at 297K to 0.09pA at 150K. Even at this low temperature the FWHM still does not equal the intrinsic resolution, but gains are made. Thus it is important to fabricate a device so that the leakage current is low as possible in order for the device to be effective as a room temperature radiation detector.

As CdTe is primarily used as a gamma and X-ray detector, the effectiveness of the devices being produced in this study at detecting X-rays was investigated. For this a VEX X-ray source consisting of an $^{241}$Am gamma source incident onto an array of interchangeable metal targets was used. The metals emitted characteristic X-rays in response to bombardment of 60keV $^{241}$Am gamma rays. Changing the metal target changed the energy of the X-ray being produced see section 4.2.2 for further details.

Figure 5.16 shows the response of sample 3-1 to characteristic barium X-rays. Clearly visible is the main $K_\alpha$ peak at 32.06keV, which at -130V has a FWHM of 3.4keV. As the
bias is increased the FWHM becomes broader due to the increase of leakage current as is shown in the insert of figure 5.16. Also observable in the Ba X-ray spectrum given in figure 5.16 is the Ba $K_{\beta}$ peak at 36.55keV, which is of less amplitude compared with the $K_{\alpha}$ as the probability of its production is less. Also visible, next to the $K_{\beta}$ peak, is a weak peak due to $^{241}$Am gamma rays leaking from the VEX source.

When irradiated with barium X-rays the resolution is such that, even at high bias voltage, the individual peaks can still be resolved. With X-rays that have peaks closer in energy the increase in leakage current has more of a detrimental effect. Figure 5.17 shows the response of sample 3-1 to terbium (Tb) characteristic X-rays. Clearly visible at -130V are individual structures such as the Tb $K_{\alpha}$ peak at 44.23keV, the shoulder produced by the $K_{\beta}$ X-ray peak at 50.65keV and the $^{241}$Am gamma response. Even though the device does not completely resolve of the $K_{\alpha}$ and $K_{\beta}$ X-rays, they are never the less visible. The spectral quality degrades at higher bias as the individual structures are no longer resolved due to higher leakage current which causes spectral broadening.
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From figures 5.16 and 5.17 it is clear that the increase in leakage current is a problem in the devices. However, whilst these effects may limit the use of the detectors in gamma and X-ray spectroscopy, all samples can still be used to investigate fundamental charge carrier properties of the CdTe material. As a result of these electrical measurements it was clear that the resistivity and device leakage currents were good enough that the devices could be used for further investigation into device charge transport.

5.2.2 Deep level investigation using low temperature resistivity

As mentioned previously the leakage current of the detector due to thermally generated charge carriers reduces as one gets lower in temperature. This obviously has benefits for the overall energy resolution of the system as is shown in the insert of figure 5.15. As the detector decreases in temperature the FWHM of the pulser decreases until it is nearly comparable to the electronic resolution. The reduction in leakage current in sample 2-1 is shown in figure 5.18. At temperatures below 220K the current values become affected by the lower limit of the apparatus used. This obviously creates a limit below which IV characteristics are not physical. It is also possible to use low temperature IV data to look at the change of resistivity of the device and thus investigate the free carrier controlling mechanism of the device.

In order to study the resistivity variation as a function of temperature it became necessary to take temperature dependent I-V data. This was achieved using the same ammeter as in previous I-V studies and a nitrogen flow cryostat as described in section 4.2.1. The samples were loaded into the cryostat and placed onto the copper cold finger using a thermal compound to ensure good heat transfer. The cryostat was then pumped down to a vacuum of approximately 10^-1 mbar and samples were then brought down to temperature using the associated temperature controller and a dewar of liquid nitrogen. The samples were reduced to a particular temperature and allowed to equilibrate at this temperature.
for one hour. Once cooled the I-V data over 0±1V was taken, and the process repeated for several different temperatures. The data was taken over the temperature range 290K (room temperature) to a minimum of 240K in 5K steps, and a resistivity calculated over the range ±0.1V to ±0.5V at each temperature. A typical I-V data set is shown in figure 5.19a for sample 2-3. As one can see from this figure the resistivity is increasing as the temperature falls, due to the decrease of charge carriers in the system. If one subscribes to the logic that the compensation in CdTe:Cl is due to a deep level as discussed in section 3.2.2, then the charge carrier concentration only depends on the concentration of the deep level, its energy, and its associated shallow level [56, 22]. If the resistivity can be described by equation 5.2 (where \( k \) is the Boltzmann constant and \( T \) the temperature) as it is in [11, 25], then an Arrhenius plot of resistivity vs temperature will yield the activation energy \( (E_A) \) of the deep level that controls the free charge carriers and therefore the resistivity.
Arrhenius plots for samples Eurd-1, 2-3 and 2-1 were plotted and are given in figure 5.19b. As can be seen from this figure the activation energy calculated varies from 
\((0.66\pm0.04)\text{eV} \) (Eurd-1) to 
\((0.70\pm0.01)\text{eV} \) (sample 2-3). Within this energy range is the well documented cadmium double vacancy \((V_{\text{cd}}^-)\), which many authors state has an energy level ranging from \((E_v+0.65)\text{eV} \) to 
\((E_v+0.735)\text{eV} \) [39, 78]. This would make the deep level an acceptor. According to Neumark [56] the shallow level excess must be of a donor type to be compensated by a deep acceptor \((N_{DA})\). This is not hard to achieve in a chlorine doped CdTe as chlorine acts as a shallow donor \((N_D)\). Even if one takes into account the production of shallow acceptors \((N_A)\) by association of \(\text{Cl}_e\) with \(V_{\text{cd}}^-\) then there is still a possibility for an excess of shallow donors \(((N_D - N_A) > 0)\), to be compensated by a deep acceptor \((N_{DA})\).
There is evidence that the $V_{cd}^{-}$ intrinsic defect may not be as deep as previously thought. Experiments by Emanuleisson [20] give $V_{cd}^{-}$ an energy of $(E_{v}+0.47)eV$, if this value is believed then its function in the compensation mechanism is in doubt as it is not within 0.25eV of the intrinsic fermi level (0.75eV) of CdTe, and therefore cannot provide the high resistivities observed [23]. Another candidate for the deep level observed is the tellurium antisite ($Te_{cd}$) which has been tentatively assigned the an energy lying in the range $(E_{v}+0.66)eV$ to $(E_{v}+0.74)eV$ [39, 22]. If this is the case then the deep level is a donor ($N_{DD}$) and so the excess shallow levels must be acceptors ($(N_A - N_D) > 0$). This is believable in undoped CdTe but less likely in chlorine doped CdTe as is the case here. Based only on resistivity data it is therefore likely that a deep donor is responsible for compensation and high resistivities, but we cannot say what type of defect, or indeed extrinsic impurities, are responsible for this defect. It seems that, from the literature, the most likely candidate for this deep level in Cl-doped CdTe is $V_{cd}^{-}$ although compensation from $Te_{cd}$ cannot be excluded.

Other authors have applied the same technique in observing the change in resistivity with decreasing temperature to find the main level that controls the resistivity in CdTe:Cl. Most authors have found that this level is within 0.25eV of the mid band gap. Table 5.2 is an overview of some of the work available in the literature.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Attribution</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.63eV</td>
<td>$V_{cd}^{-}$</td>
<td>[33]</td>
</tr>
<tr>
<td>0.71eV-0.73eV</td>
<td>$V_{cd}^{-}$</td>
<td>[57]</td>
</tr>
<tr>
<td>0.69eV</td>
<td>$V_{cd}^{-}$</td>
<td>[11]</td>
</tr>
<tr>
<td>0.54eV</td>
<td>$V_{cd}^{-}$</td>
<td>[38]</td>
</tr>
</tbody>
</table>

Table 5.2: An overview of some of the work available in the literature which attributes the main level that controls the resistivity in CdTe:Cl to a doubly ionised cadmium vacancy ($V_{cd}^{-}$).
5.3  Room temperature charge transport and drift time as a method of assessing material quality

The charge transport of the devices made for this study were investigated using alpha-particle spectroscopy as a function of bias voltage. The experimental procedure is described in section 4.2.3. Both electrons and holes were investigated, therefore the shaping time of the shaping amplifier was selected between 0.5\(\mu\)s and 10\(\mu\)s, depending on the polarity, so as to include the whole of the pre-amplifier rising edge. Bias was applied to the devices on the irradiated contact, and because the range of 5.49MeV \(\alpha\) particles is small compared with the device thickness, it was assumed that charge transport was either dominated by electrons or holes depending on the bias polarity. All pulse height spectra were typically gathered over 10 to 15 minutes, each spectrum was individually calibrated into CCE and the peak centroid of each spectrum was calculated using a Gaussian shape with an error of less than \(\pm1\%\) CCE.

In order to analyse the drift time the pre-amplifier pulses were acquired simultaneously with the pulse height spectra. This was done in order to calculate the mobility of the charge carriers in the devices. The system used is described in section 4.2.3. The data was gathered using an ORTEC 142A charge sensitive pre-amplifier which showed a characteristic rise-time of 23ns. Each pulse that was collected was subject to interrogation by a 10%-90% pulse rise time algorithm (as described in section 4.2.3) in order to collect the 10%-90% transit time, which was corrected by addition of 20% to reveal the drift time. The transit time values were histogramed and the peak centroid of the resultant peak was calculated using a Gaussian shape.
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5.3.1 Room temperature charge transport

Electrons

A typical electron pulse height spectrum calibrated into CCE representative of all samples studied is shown in figure 5.20. Under steady bias conditions no shift in the peak centroid was observed over the experimentally measured time. This coupled with the fact that no pulses were observed at 0V both before or after gathering a pulse height spectrum indicate that polarisation in the devices is either short lived or non-existent.

The long tail seen at low bias is a result of incomplete charge collection. As the bias is increased so too does the charge collection and the spectrum approaches a more symmetrical shape. This reduction in the distribution of charge collection is shown by the decreasing FWHM of the peaks with increasing bias voltage (see the insert of figure 5.20). At higher bias the width of the peak is no longer limited by the incomplete charge collection, but is instead limited by statistical fluctuations in the number of charge carriers produced per ionising event, the noise of the external electronics and the leakage current.
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Figure 5.21: Two example fits to the variation of CCE with bias voltage for two samples (sample 2-4 and 3-1). The data for these plots was derived from the electron alpha spectra of which figure 5.20 is an example.

As we are assuming that only one type of charge carrier is responsible for the induction of charge, in this case electrons, it is possible to calculate the $\mu_e \tau_e$ product from alpha spectra using the simplified Hecht equation (equation 2.23). By plotting the peak centroid as a function of changing bias voltage, a Hecht plot can be produced. Fitting the simplified Hecht equation to this data, with only the voltage and CCE as free parameters, leads to a value for $\mu_e \tau_e$. This was done for all samples, the values for which are displayed in table 5.3. Examples of the fit achieved to a Hecht plot in two samples (sample 2-4 and 3-1) is given in figure 5.21. The values obtained for the $\mu_e \tau_e$ product in all samples are well within the range of spectroscopic grade material given in the literature [30, 18].

Holes

Hole pulse height spectra in contrast to the electron data exists at a far lower CCE, due primarily to the poor hole transport in CdTe. Figure 5.22 shows representative hole spectra.
taken using sample 1-3. As the bias increases the peak broadness increases. This is shown by the insert in figure 5.22, the FWHM of the peaks increases with increasing bias voltages. This is in contrast to the electron data where the FWHM decreases with increasing bias voltage. A possible explanation is that in general as one increases the voltage across a detector the leakage current increases. Thus the broadening of peaks due to leakage (FWHM_{leakage}) also increases. In contrast as one increases the voltage the mobility and lifetime of charge carriers increases as shown in figures 5.23 and 5.21, thus the broadening of peaks due to charge tapping (FWHM_{charge}) will decrease. The total variation of FWHM with voltage will depend on these two factors (FWHM_{leakage} and FWHM_{charge}). With holes due to the poor $\mu_h\tau_h$ there is very little improvement in FWHM_{charge} and so the increase in FWHM_{leakage} dominates the total increase in FWHM with voltage.

As with electrons, the hole data did not show any sign of polarisation. The $\mu_h\tau_h$ product was calculated using the single carrier Hecht equation and all the values for the samples studied are given in table 5.4, typical fits are shown in figure 5.23. All values of hole $\mu_h\tau_h$ are similar to literature values [30].
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Figure 5.23: Two example fits to the variation of CCE with bias voltage for two samples (sample 2-4 and 3-1). The data for these plots was derived from the hole alpha spectra of which figure 5.22 is an example.

5.3.2 Room temperature drift time and lifetime

Drift Time

If one can measure a decrease in the rise time of a charge transient with increasing voltage then a plot of inverse carrier transit (1/T) against V/d\(^2\) (where d is the thickness and V the applied bias), can be used to calculate mobility (see equations 2.24). This theory assumes that the velocity is proportional to the applied field [17]. The mobility of either type of carrier can be measured by choosing the polarity of the applied voltage (V) accordingly. If the line cuts the 1/T axis there is the possibility of limited carrier lifetime [80] as shown in figure 5.25.

Typical linear plots of 1/T against V/d\(^2\) for both holes and electrons in sample 3-1 are shown in figure 5.24. Similar plots were constructed for all samples used in this study and sample 3-1 is representative of them all. Values of electron and hole mobility for all the samples are given in tables 5.3 and 5.4 respectively.
Figure 5.24: Typical plots and fits used to calculate the mobility in this case sample 3-1.

Figure 5.25: Effect of limited lifetime on a plot of inverse carrier transit (1/T) against V/d^2 for varying lifetime.
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Figure 5.26: Electron drift velocities in CdTe as a function of electric field in the temperature range between 370K and 77K [8].

All plots, for all samples, showed a straight line correlation similar to sample 3-1. No saturation of drift velocity is observed, which suggests that over the bias range used the drift velocity is proportional to the applied electric field. According to [8] the saturation field is approximately 15kV/cm at 300K (see figure 5.26). The intercept of the inverse transit time plots given in figure 5.24 (and for all other samples) pass through the origin. This suggests that the charge drift is not lifetime limited. All values of mobility calculated are within the range (1000 cm²/Vs for electrons and 70 cm²/Vs for holes) given in the literature for good quality CdTe [30].

Lifetime

Having experimentally derived values for the mobility ($\mu$) and the mobility-lifetime product ($\mu\tau$), it is a simple process to obtain values for the effective carrier lifetime ($\tau$). Typical electron and hole lifetimes for all samples are given in tables 5.3 and 5.4. These values are all within the microsecond range for both electrons and holes. In general the hole lifetimes are shorter than the electron lifetimes, but there is a large variation in electron lifetimes.
across the samples. A typical hole lifetime for good quality CdTe is 2µs [58] whereas the electron lifetime is only slightly longer at 3µs [58]. The samples in this study appear to have better lifetime than the values quoted in the literature. Hole lifetimes are frequently at 3µs whereas the electron lifetimes are frequently above 4µs. This would suggest that the samples used in this study are of high quality.

Looking at the histogramed transit times for Eurd-1 in figure 5.27. At bias voltages greater than -40V all the transit times are shorter than the calculated lifetime (1µs), thus there should be no lifetime limited behavior at these bias voltages. Lower than -40V however the transit times are larger than the calculated lifetime. Thus at these bias voltages there should be some lifetime limited behavior where there is a significant reduction in the initial number of charge carriers during drift of the charge across the device thickness. This is indeed the case. Figure 5.28 shows typical charge pre-amplifier pulse shapes at three different bias voltages for electrons. Of the three only the low bias (-20V) pulse shows a curved pulse near to the end of transit indicative of charge trapping and lifetime limited behavior [2, 17]. At higher bias voltages (greater than -40V) prompt, non curved, charge pulses are observed, suggesting minimal charge trapping and no lifetime limited behavior.
For electrons this situation is similar for all samples investigated, in that lifetime limited behavior is only present at low bias where the drift time is longer than the lifetime.

Figures 5.28 and 5.27 show a contrasting story for holes. The transit times of all investigated bias voltages are longer than the calculated lifetime (1.9µs). Thus even at high bias lifetime limiting behavior and significant charge trapping is present. This is shown by the charge pulse shapes in figure 5.28. Both pulses show the characteristic curved shape of lifetime limited drift. Again this situation is common in all investigated samples. This effect is unsurprising in CdTe due to the low mobility and large number of hole traps within the material.
Table 5.3: $\mu_e \tau_e$, $\mu_e$ and $\tau_e$ data for all samples used in this study.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\mu_e \tau_e$ (cm$^2$/V)</th>
<th>$\mu_e$ (cm$^2$/Vs)</th>
<th>$\tau_e$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>$(2.4 \pm 0.1) \times 10^{-3}$</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2-1</td>
<td>$(3.1 \pm 0.2) \times 10^{-3}$</td>
<td>$1200 \pm 16$</td>
<td>$(2.6 \pm 0.1) \times 10^{-6}$</td>
</tr>
<tr>
<td>2-3</td>
<td>$(9.3 \pm 0.3) \times 10^{-3}$</td>
<td>$1091 \pm 8$</td>
<td>$(8.5 \pm 0.2) \times 10^{-6}$</td>
</tr>
<tr>
<td>2-4</td>
<td>$(4.8 \pm 0.2) \times 10^{-3}$</td>
<td>$1118 \pm 11$</td>
<td>$(4.3 \pm 0.1) \times 10^{-6}$</td>
</tr>
<tr>
<td>3-1</td>
<td>$(7.0 \pm 0.2) \times 10^{-3}$</td>
<td>$1171 \pm 11$</td>
<td>$(6.0 \pm 0.2) \times 10^{-6}$</td>
</tr>
<tr>
<td>3-3</td>
<td>$(3.8 \pm 0.2) \times 10^{-3}$</td>
<td>$917 \pm 25$</td>
<td>$(4.1 \pm 0.2) \times 10^{-6}$</td>
</tr>
<tr>
<td>Eurd-1</td>
<td>$(1.1 \pm 0.1) \times 10^{-3}$</td>
<td>$1096 \pm 23$</td>
<td>$(1.0 \pm 0.1) \times 10^{-6}$</td>
</tr>
<tr>
<td>Eurd-2</td>
<td>$(5.9 \pm 0.3) \times 10^{-3}$</td>
<td>$1003 \pm 22$</td>
<td>$(5.8 \pm 0.3) \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Table 5.4: $\mu_h \tau_h$, $\mu_h$ and $\tau_h$ data for all samples used in this study.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\mu_h \tau_h$ (cm$^2$/V)</th>
<th>$\mu_h$ (cm$^2$/Vs)</th>
<th>$\tau_h$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>$(2.7 \pm 0.1) \times 10^{-4}$</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2-1</td>
<td>$(3.0 \pm 0.2) \times 10^{-4}$</td>
<td>$89 \pm 6$</td>
<td>$(3.4 \pm 0.3) \times 10^{-6}$</td>
</tr>
<tr>
<td>2-3</td>
<td>$(2.4 \pm 0.1) \times 10^{-4}$</td>
<td>$90 \pm 5$</td>
<td>$(2.7 \pm 0.2) \times 10^{-6}$</td>
</tr>
<tr>
<td>2-4</td>
<td>$(2.4 \pm 0.1) \times 10^{-4}$</td>
<td>$80 \pm 1$</td>
<td>$(3.0 \pm 0.1) \times 10^{-6}$</td>
</tr>
<tr>
<td>3-1</td>
<td>$(2.4 \pm 0.1) \times 10^{-4}$</td>
<td>$72 \pm 5$</td>
<td>$(3.3 \pm 0.3) \times 10^{-6}$</td>
</tr>
<tr>
<td>3-3</td>
<td>$(1.9 \pm 0.2) \times 10^{-4}$</td>
<td>$71 \pm 3$</td>
<td>$(2.7 \pm 0.2) \times 10^{-6}$</td>
</tr>
<tr>
<td>Eurd-1</td>
<td>$(1.9 \pm 0.1) \times 10^{-4}$</td>
<td>$99 \pm 10$</td>
<td>$(2.0 \pm 0.2) \times 10^{-6}$</td>
</tr>
</tbody>
</table>
5.3.3 Low temperature mobility lifetime: a preliminary investigation into charge transport limiting mechanisms

The effect of a reduction in the temperature on the mobility-lifetime product was also investigated. Figure 5.29 shows the results. There is an obvious decrease of the electron mobility-lifetime product as one decreases the temperature. Several authors have shown that the mobility of electrons in CdTe increases with a decrease of temperature, due to the increase of phonon optical scattering mechanisms and the reduction of acoustic phonon scatter. Thus if the mobility increases, then for the $\mu \tau$ to decrease the lifetime must significantly decrease. The fundamental process of this is that traps have an energy barrier which at room temperature electrons can quickly overcome and continue to drift. The occupation time for charge within shallow traps is therefore very short at room temperature. Therefore the time for this trapping and detrapping event is so short compared with the drift time that it is negligible. At lower temperatures the electrons have less energy and thermal emission of charge from shallow traps is reduced. Therefore the trapping detrapping time becomes more prominent thus more of the electrons become trapped and the lifetime is reduced. A thorough investigation into the effects of temperature on mobility will be presented in Chapter 6

5.4 Summary

The experiments presented in this study have allowed a relative comparison of several material parameters. Firstly the uniformity of the material was examined using infrared microscopy, which over the sample set found a range of defect concentrations. From the literature it was assumed that most dark contrast in the infrared images was due to tellurium inclusions [67]. Eurd-1, proved to be the most free of tellurium defects, the central regions having sparse contrast features in the infrared images (see figure 5.1). Most defects in
Figure 5.29: The effect of a reduction of temperature on the electron mobility-lifetime product of Eurd-1. The dashed line is an aid to the eye and shows nothing physical.

Eurd-1 were concentrated at the edges of the sample, a possible remanence of the thermal gradient during growth.

The other samples used in this study all showed more tellurium defects (contrast features in the infrared images) compared to Eurd-1. The two samples that represented the range of defects over all the samples were sample 3-1 and sample 2-4. Sample 3-1 showed the least number of defects over its area. The classic triangular morphology of tellurium inclusions was observed in this sample (see figure 5.6). These inclusions were found ordered along lines at various focal depths throughout the sample. It is thought that these structures are decorating dislocations within the material. Other shapes of infrared contrast were also observed at various focal depths. The classic triangular morphology of inclusions can be altered by thermal effects and become more rounded. This coupled with the limited resolution of the system lead to the conclusion that these structures were also tellurium inclusions. By contrast to the triangular inclusions the circular inclusions did not organise into lines and were more distributed throughout the entire sample volume. Sample 2-4 defined the maximum amount of observed tellurium defects in a sample. Like sample 3-1
circular tellurium inclusions were observed throughout the volume of the sample. Unlike sample 3-1, sample 2-4 showed a large concentration in one area (see figure 5.4) and more defects closer to one surface than the other.

Lang topography was carried out on two samples in order to investigate the crystallinity of the material. Over 90% of Eurorad-1 was imaged using two topographs at different orientations. This suggests that there were at least two parts of the sample that were significantly misorientated with respect to one another. This points to the existence of at least two different crystal orientations. Within the individual topographs contrast variation existed. This suggests regions of slight relative misalignment, which could indicate strain within the material. Another sample was imaged using Lang topography, and less than 60% was imaged using one topograph, thus suggesting that there was more than one crystal in the sample. Also visible in this sample were lines of contrast that pointed to lines of dislocation, and regions of circular contrast that pointed to the existence of an inclusion. As the Lang equipment was setup in the Bragg geometry only near surface defects were observed. Although there were regions of stress and the possibility of dislocations and grain boundaries, both samples were several centimeters in diameter, and for such large samples the uniformity was felt to be excellent as was the low density of dislocations.

After Lang and infrared images were completed all samples were contacted. Eurorad-1 was sent back to EURORAD for electroless deposition of platinum and all other samples were contacted in house using thermal evaporation of gold (see section 4.3.4 for a full description). The current voltage characteristics at room temperature and at low temperature were then measured using the apparatus described in section 4.2.1. All samples were found to have leakage currents at high bias (300V, 100V for Eurorad-1) of no more than $4 \times 10^{-6} A cm^{-2}$. This large leakage current was thought to be due to surface leakage currents, as no guard ring was present on any device. The current variation was found to be proportional to $V^{1.2-1.5}$ at 1V-100V where as at bias voltages of greater than 100V the
variation was found to proceed as $V^{2.5-3.4}$. This deviation from ohmic behavior is thought to be due to processes at the contact and surface leakage. As the surface leakage current cannot be deconvolved from the leakage current (no guard ring) no further work was carried out using the higher bias current-voltage data. By contrast the low bias regime of 0V-1V showed, ohmic behavior as the current varied as $V^1$. This range was used to calculate the resistivity of all the samples. All the resistivities measured were at the top of the range often quoted in the literature for CdTe:Cl [13].

High leakage currents have an obvious effect on the spectroscopic performance of a device. The more leakage current, the more noise, the poorer the resolution. One can improve the leakage current by lowering the temperature, but most devices using CdTe as detectors need then to operate at room temperature. To see the effectiveness of the devices in this study for spectroscopy a sample was exposed (individually) to barium and terbium X-rays and a spectrum acquired. Figure 5.16 and 5.17 show the results. At low bias voltage the detector is able to resolve all the main features of a barium irradiation. At high bias, the FWHM of the main barium X-ray peak was found to increase but as the features in barium are all well separated in energy the leakage current increase in FWHM was not an issue. The same cannot be said for terbium spectroscopy. As the two main X-ray peaks are close in energy an increase in leakage current can render the features unresolvable and severely hamper spectroscopic performance. Unfortunately due to the high leakage currents in our samples detailed spectroscopy is not possible. However it was decided that there was enough resolution to carry out alpha spectroscopy using an $^{241}\text{Am}$ source as a means to define basic charge transport phenomenon.

The resistivity variation with decreasing temperature are also investigated in this chapter. The same low voltage range of IV was used as in room temperature resistivity calculations. It was found that the resistivity increased with a decreasing temperature. Using the relationship between resistivity and temperature given by references [11, 25], it was
5. QUALITY OF EURORAD CdTe:Cl

possible to extract an energy of the defect level that controls excess charge carriers. It was found for several samples that the energy level was mid band gap at 0.70eV. The defect responsible, from a search of the literature, could either be a cadmium double vacancy (V$_{\text{Cd}}^{2-}$) or a tellurium antisite (Te$_{\text{Cd}}$). The actual defect cannot be known from just low temperature resistivity measurements.

The mobility-lifetime product was calculated from the variation in the peak centroid of an $^{241}$Am alpha particle spectrum with changing voltage. This value is well defined in the literature as a means to compare the charge transport of samples. All sample gave values of hole and electron $\mu\tau$ that are within the range for good quality CdTe given in the literature. Also derived from the response of the detectors to alpha particle irradiation were charge preamplifier pulse shapes, by suitable interrogation of the rise time of these pulses a plot of $1$/transit time ($1/T$) against $V/d^2$ (where $V$ is the applied bias and $d$ the thickness of the detector) was produced from this the mobility of the electrons and holes in all the samples was derived. Again all samples gave values of hole and electron $\mu$ that are within the range for good quality CdTe given in the literature. From the experimentally derived $\mu\tau$ and $\mu$ values it was a simple step to calculate the effective carrier lifetime ($\tau$). From the values of lifetime and the transit times histogramed from the charge preamplifier pulses it was clear that at low bias voltages lifetime limited behavior was present, at higher bias the transit time was short enough that there was no lifetime limitations. However, for holes, lifetime limited behavior persisted for all investigated bias voltages.

The effect of decreasing temperature on the electron mobility-lifetime product was also investigated, and found to decrease over the temperature range 120-290K. Several authors have said that the mobility increases with a decrease in voltage due to the increase of optical phonon scatter and the decrease of acoustic phonon scatter. As a result if the electron mobility increases and the electron mobility-lifetime product decreases then the lifetime would have to significantly decrease. A more thorough investigation into the effects
of electron mobility is discussed in chapter 6
6 Drift time analysis of CdTe by current time of flight.

Current time of flight (ToF) is a robust method of measuring charge transport within a device. It allows us to measure the transit time of charge carriers as well as observe the electric field within a device. It normally consists of a method of exiting electron hole pairs, usually a laser (although an alpha source is also used in this chapter), a system of lenses to focus the laser and appropriate electronics chain in order to amplify and record the current pulses. The equipment used for all experiments in this chapter and the algorithm used to measure the transit time of current pulses is described in section 4.2.4. If a laser is used then it is imperative it can be produce a pulse shorter than the drift time of the sample under investigation. The wavelength of the laser must also be shorter than the band edge of the sample under investigation in order that the pulse is absorbed near to the surface. CdTe is effectively transparent to wavelengths greater than 830nm, so the 635nm laser used will be fully absorbed near to the device surface. All samples investigated using laser ToF had semitransparent gold contacts (less than 15nm) applied, in order that the laser is not completely absorbed by the metal contact. Most authors who have used current ToF methods in CdTe have done so by averaging several subsequent pulses, using an oscilloscope, to produce pulses with a satisfactory signal to noise ratio [8, 24]. Presented in this chapter ARE ToF investigations using single pulses, with no
subsequent post processing.

6.1 Initial calibration of the ToF system

In order to proceed with measurements the energy delivered by the laser and any time constraints imposed by the laser pulse duration and electronics bandwidth was investigated. In order to do this the 635nm laser was focused onto a silicon pin diode, biased to its depletion voltage. The signal produced by the silicon in response to the laser was connected to an oscilloscope with a 50Ω termination and individual pulse shapes were recorded to disk. Any attenuating media, such as the quartz window of the cryostat lid, was present in their normal configuration. The resulting pulse from the silicon is shown in figure 6.1. In order to calculate the energy from this pulse it is necessary to assume that the silicon is 100% efficient in stopping the laser pulses. By integrating the pulse the charge deposited by the laser pulse in the silicon can be found. From this the number of charge carriers can be derived and so by dividing the number of charge carriers by the energy of formation of electron hole pairs in silicon (W=3.6eV/ehp) the energy of the pulse can be calculated. In this case the energy was found to be 94MeV. The duration of the pulse was also measured from the same silicon pulse with a FWHM of 41ns. This is in contrast to the limit imposed by the bandwidth of the current pre-amplifier, which was approximately 14MHz, which corresponds to a limiting risetime of 71ns. This limit is shown in figure 6.2, which shows the same laser-induced pulse in CdTe, after amplification through a FEMTO current amplifier with a 14MHz bandwidth. In this figure it is clear that the rising edge of the pulse is entirely due to the system electronics.

From the estimation of laser pulse energy it was felt that the energy may be too high and thus may effect charge transport within the device. To investigate if there was indeed any effect, the mobility of devices was measured as a function of varying laser beam energy.
Figure 6.1: Silicon PIN diode response to a laser pulse showing the current into a 50Ω termination. The integral of the pulse gives the charge deposited by the laser which is then calibrated in terms of energy equivalent in silicon.

Figure 6.2: Laser induced current pulse from sample 2-3 showing the bandwidth limit in time of the 14MHz current amplifier.
To reduce the energy, neutral density filters were used to attenuate the laser beam. Several such filters were used in order to attenuate the laser in graduated increments from 100% to 10%. Figure 6.3 shows transit time vs voltage plots used to calculate mobility in sample 2-1 for two different beam transmissions (100% and 10%). From figure 6.3 it is clear that both plots have a good correlation and they both yield very similar mobility values. Figure 6.4 plots the variation of mobility with changing optical transmission from the samples 2-1, 2-3 and 2-4. For each sample there does not seem to be any significant change in mobility with changing energy.

Looking at figures 6.3 and 6.4 it is clear that reducing the energy of the laser pulse does not have a significant effect on the transit time and mobility calculation of the devices, it does however have an effect on the signal to noise ratio of the induced pulse. Looking at the insert in figure 6.3 the induced pulse with lowest transmission has a correspondingly reduced amplitude. This obviously leads to lower signal to noise ratio and thus a less well resolved pulse. Since there does not seem to be a significant change in the charge transport with the larger 94MeV pulse, it was decided to use the un-attenuated laser for future measurements, to maximise the signal to noise ratio of the pulses.

Another consideration in commissioning the time of flight system was the choice of bandwidth of the current amplifier. Obviously a larger bandwidth allows for the detection of quicker pulses however at the expense of reduced amplifier gain. Since we wanted to capture single-shot current pulses without averaging, the amplifier had to be used with a large enough bandwidth to resolve the shortest pulses whilst having a large enough gain to rise above the intrinsic noise of the system. A bandwidth of 14 MHz with a gain of $1 \times 10^6$ was the optimal bandwidth/gain combination for the collection of pulses without averaging. It was decided to see if this bandwidth in some way limited the collection of data. To do this the transit time vs voltage for the 14MHz bandwidth setting was compared to data collected with an amplifier band width of 80MHz. Obviously to collect the data using the
Figure 6.3: Transit time vs voltage in sample 2-1 for two different laser transmissions. It is clear that both laser transmissions produce very similar mobility values, showing that the laser energy does not have a significant effect on charge transport within the devices. The insert shows the difference in pulses between the two laser transmissions.

Figure 6.4: Shows the change in mobility values with changing transmission for three different samples.
6. DRIFT TIME ANALYSIS OF CdTe BY CURRENT TIME OF FLIGHT.

80MHz setting the oscilloscope was required to do averaging to resolve the pulses. Figure 6.5 shows the two data sets and the associated mobility values. This data shows that there is no significant difference in the measured transit time between the 14MHz and 80MHz bandwidth settings, over the bias range shown.

Another consideration in the time of flight setup was the repetition rate of the laser. Too high a pulse repetition rate may interfere with the electric field profile inside the detector due to the high charge injection rate, however too low would effect the statistics achievable in a sensible amount of time. To look at the differences between a large pulse repetition rate (2kHz) and a low pulse repetition rate (2Hz), the transit time of a device was measured as a function of bias voltage and the mobility calculated from these plots. Figure 6.6 shows the two plots collected using the different pulse repetition rates. As can be seen there appears to be no discernable difference between the two. It was decided as a result to use the 2kHz repetition rate as it provided a faster event rate and hence better
6. DRIFT TIME ANALYSIS OF CdTe BY CURRENT TIME OF FLIGHT.

6.2 Room Temperature time of flight investigations.

6.2.1 Time of flight current pulse morphology

A typical room temperature laser stimulated (cathode irradiated) current pulse is shown in figure 6.7. The width of the incident laser pulse was 41ns. Some of the morphology of this pulse has been discussed previously, that is the initial rise time is a function of the bandwidth limitation of the system. The rest of the shape however gives direct information about the charge transport processes in the material. The decay of the current pulse from the maximum near to the cathode is due to the decreasing electric field that occurs between the cathode and the anode as observed by Cola [12] (see also section 6.4), However this decrease according to Cola should be linear, the exponential decrease seen in our typical

Figure 6.6: Variation of transit time with changing bias voltage and associated mobility values for two different laser pulse repetition settings in sample 3-3.
6. DRIFT TIME ANALYSIS OF CdTe BY CURRENT TIME OF FLIGHT.

Figure 6.7: A typical laser stimulated current pulse taken at -120V in sample 2-3 due to electron drift. The dashed line shows the bandwidth limitations that affect observations of charge transport near to the cathode and the solid line shows the end of transit. The exponential decrease of current is consistent with charge trapping superimposed onto a linearly decreasing field. The non-zero current after the end of transit is due to dispersive charge transport.

Room temperature pulses is almost certainly due to electron trapping in the bulk. Indeed this charge trapping probably results in the non-zero current after the end of transit line shown in figure 6.7, due to dispersive charge transport [7].

6.2.2 Drift velocity investigation

From the initial calibration of the time of flight system, it was decided that an unattenuated laser pulse was to be used to obtain maximum signal to noise at a repetition rate of 2kHz to obtain good statistics within a reasonable time. It was also decided that a bandwidth setting of 14MHz with an associated gain of $1 \times 10^6 V/A$ was to be used. The 14MHz bandwidth corresponds to a minimum rise time limit of 71ns. At this point a comparison between the alpha and laser stimulated pulses may be of use. Figure 6.8 shows
the transit time variation as a function of voltage in sample 3-3 when stimulated by alpha pulses and by 2kHz laser pulses respectively. As can be seen there is very little difference between the mobility values assessed from each of these plots. There is however a difference in the correlation of the data points in each of the graphs. The laser, because of its larger amplitude, allows for less distribution in the calculated values of transit time as it provides a less ambiguous assessment of the end of transit using the algorithm described in section 4.2.4. Hence the correlation and error is better than for the alpha stimulated pulses where the distribution of calculated transit time values is larger due to the smaller signal and thus a more ambiguous estimation of the end of transit. The difference between the alpha stimulated pulse and the laser stimulated pulse is shown in figure 6.9.

Of course there are other issues to be taken into account, one major point is that the laser is much more sensitive to local variations in material quality (because of its focus)
where as the alpha transient currents occur over the whole surface of the device due to the un-collimated nature of the source. Another issue of concern is the sensitivity of the laser to surface effects such as surface recombination [41] which could reduce the number of charge carriers present, but looking at figure 6.8 and the good agreement of mobility values between the two techniques there does not seem to be any significant effect.

To look at the variation in mobility between samples, plots of the variation of transit time with changing voltage for each sample prepared with a semitransparent contact were taken. Figure 6.10 shows these plots taken at room temperature (297K) and the corresponding mobility values calculated from the gradients. The majority of the samples investigated have an electron mobility value within the range 900-1000 cm²/Vs which according to the literature is indicative of good quality material [88]. Only sample 2-1 has a low mobility value at 795 ± 9cm²/Vs. The low value of sample 2-1 could be due to a localised effect however when the same measurement was made using an un focused alpha source the value for mobility derived was 749 ± 7cm²/Vs, which leads to the conclusion

Figure 6.9: The difference between an alpha induced current transient and a 2kHz laser induced current transient at 297K and -200V. The induced charge (integral) of each pulse is 5.4MeV and 90MeV energy equivalent.
that sample 2-1 is of lower quality than the other samples.

As a final observation in this section its seems clear that there is no bandwidth limitations over the bias range used and no saturation of mobility. The minimum transit time recorded was of the order 200ns well within the rise time of the preamplifier (71ns), and the maximum electric field used was no more than 1.5KV/cm which is well below the threshold for field dependent charge carrier mobility which according to the literature is present at fields of more than 12KV/cm in CdTe [8].

6.2.3 Temperature dependent drift velocity measurements

To look at the carrier transport limiting mechanisms present in CdTe it becomes necessary to look at the variation of the transit time with temperature. A plot of the transit time variation against temperature is given in figure 6.11, it shows that as one cools the sample the transit time gets shorter and shorter, as a result the gradient of the plots in figure 6.11
Figure 6.11: Variation of transit time with decreasing temperature. As the temperature falls the number of phonon collisions reduces so the transit time of the carriers decreases, thus the gradient of a 1/transit time vs voltage increases.

get progressively steeper, which indicates that the mobility is increasing. This is indeed the case and figure 6.12 shows the trend for four samples in the 200K-297K temperature range. The physical reasoning for this can simply be explained as the reduction in phonon scattering as the temperature (and therefore the number of phonons) is reduced.

However this is a very simplistic interpretation and further detailed analysis is required. From the theory of scattering mechanisms in semiconductor materials outlined in section 3.3 it is clear that the relationship between mobility and temperature for the different mechanisms have a very clear and distinct temperature dependence. The temperature dependence of several scattering mechanisms is reviewed in table 6.1. Thus if mobility was limited purely by non-polar optical scattering for example, the gradient of a common log log plot of mobility against temperature would yield a gradient of -3/2.

Several authors have analysed the mobility variations against temperature to extract more detail regarding the mobility limiting mechanisms [7, 55]. However this method
Figure 6.12: Variation of mobility with decreasing temperature measured using a 2kHz laser pulse. As the transit time reduces so the mobility of the charge carriers increases. All samples follow this general trend.

<table>
<thead>
<tr>
<th>Scattering process</th>
<th>Power-law temperature dependence, N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-polar optical</td>
<td>-3/2</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>-1/2</td>
</tr>
<tr>
<td>Deformation potential</td>
<td>-3/2</td>
</tr>
<tr>
<td>Ionised impurity</td>
<td>3/2</td>
</tr>
<tr>
<td>Neutral impurity</td>
<td>0</td>
</tr>
<tr>
<td>Alloy</td>
<td>-1/2</td>
</tr>
<tr>
<td>Polar optical</td>
<td>-1</td>
</tr>
</tbody>
</table>

Table 6.1: The theoretical temperature dependence of some scattering mechanisms, where $\mu \propto T^N$
has its limitations. To obtain a gradient equivalent to the temperature dependence of one of the scattering mechanisms requires it to be the dominant scattering mechanism in the system. If however there are competing mobility limiting scattering mechanisms this technique does not allow them to be differentiated. An example of such an analysis is given in figure 6.13 by Burshtein et al [7], here the gradient of a common log log plot of mobility against varying temperature is approximately -1.1. This value indicates that the dominant scattering process may be polar optical scatter (with a temperature dependence of -1) but the error on the fit could equally lead to a gradient of -1.5 which would suggest scattering by deformation potential. It is therefore only possible to say that the mobility limiting processes are due to scattering involving phonons. A similar analysis to that of [7] was carried out for EURORAD CdTe samples.

The variation of mobility with decreasing temperature was carried out on four CdTe samples using the laser time of flight system. Over the 200-300K temperature range the mobility was calculated from the transit time in the aforementioned procedure. Plots of
mobility against temperature for the four samples were produced and are distributed over figures 6.14 and 6.15. This data shows that the gradient of these plots is very close to the 1.1 given by [7]. However as discussed above it is only possible to say that the mechanism that may be responsible for the reduction of mobility in these CdTe samples is charge carrier scattering by phonon interactions.

However, scattering mechanisms do not act independently, and to resolve which scattering mechanism is responsible for limiting the mobility and to what degree requires a more detailed analysis.

Simulation of electron scattering mechanisms in CdTe

In order to look into more detail of the effect of different scattering processes in CdTe it became necessary to simulate the mobility variation with changing temperature. To do this the equations defining mobility variation with temperature outlined in 3.3 were com-
6. **DRIFT TIME ANALYSIS OF CdTe BY CURRENT TIME OF FLIGHT.**

**Figure 6.15:** A common log plot of mobility variation against decreasing temperature for sample 3-3 and 2-1.

puted. From these independent and individual scattering equations the effect of individual scattering mechanisms on the total calculated mobility in a system can be obtained using Matthiessen's rule [1, 86], which for electrons (e) is described by equation 6.1.

\[
\frac{1}{\mu_{TOT}} = \sum_{i=0}^{n} \frac{1}{\mu_i^e}
\]  

Thus the total mobility \(\mu_{TOT}\) can be calculated from the scatter-limited mobilities \(\mu_i^e\) of each scattering mechanism. There are many scattering mechanisms that can be responsible for mobility variations in semiconductors. However some mechanisms can be neglected as there effect is negligible. In order to proceed a few assumptions are made:

First we assume that there is a minima at the center of the Brillouin zone (at \(k = 0\)), which allows us to assume that intervally scattering is neglected (as it does not occur for direct gap semiconductors). The second assumption is that the dislocation density in the CdTe under investigation is very low and so dislocation scatter can be neglected. From
These assumptions the remaining scattering mechanisms that could come into play are deformation potential ($\mu_{ad}$), piezoelectric ($\mu_{ps}$), ionised impurity ($\mu_{im}$), neutral impurity ($\mu_{NI}$) and the polar and non-polar optical phonon scatter ($\mu_{po}$). According to [74] the non-polar optical mode scattering is very weak due to the direct gap nature of CdTe thus it can be neglected. From the simple analysis given above the most important mechanisms are probably the polar optical mode and the ionised impurity scattering mechanisms but all could contribute appreciably to the scattering in CdTe. All the remaining scattering mechanisms mentioned above were included into a model implemented in Mathcad to calculate the total scattering-limited mobility, using Matthiessen’s rule, that best fits the experimental data. The code was produced originally by Dr D Lancefield for work in GaAs but was modified and then applied to CdTe. Figure 6.16 shows the calculated temperature dependence of the individual scattering mechanisms as obtained from the Mathcad script. The temperature dependence for each of the mechanisms is as given in table 6.1.
6. DRIFT TIME ANALYSIS OF CdTe BY CURRENT TIME OF FLIGHT.

The model was applied to the data from several samples. In order to achieve the best possible fit two free parameters were varied, these being the acceptor density and the compensation ratio (and by definition the donor density). The concentration of ionised defects \( N_I \) is given by equation 6.2. Where \( N_d \) is the concentration of donors and is a free parameter and \( n \) is defined by equation 6.3 for p-type material, where \( E_g \) is the band gap of CdTe, \( k \) the Boltzmann constant and \( T \) the temperature. The concentration of neutral impurities \( (N_N) \) used in the calculation for neutral impurity scattering is defined by equation 6.4, where \( N_a \) is the concentration of acceptors in the material. The other parameters required were obtained from other independent measurements and were not free parameters and were assumed to be constant (see table 6.2).

\[
N_I = n + 2N_d 
\]

\[
\frac{n(n + N_d)}{N_d - N_a - n} = constant \times \exp\left(- \frac{E_g}{kT}\right) 
\]

\[
N_N = N_a - N_d - n 
\]

As can be seen in figure 6.17 the fit to the experimental data is reasonable but there is significant difference between the model and the data below 220K and in the 260-300K range. This is partially explained by uncertainty in some of the constants used to calculate the mobilities for the various scattering mechanisms, specifically the acoustic deformation potential energy. For CdTe the deformation potential is calculated to be in the region 2.5-3eV [74]. However some authors have used higher values, up to 9.5eV to obtain a satisfactory fit [66]. In this data the use of a higher acoustic deformation potential energy only serves to obtain a better fit at higher temperature, however the resulting fit to the lower data points is worse (figure 6.18). Thus a temperature dependence of one or several
6. DRIFT TIME ANALYSIS OF CdTe BY CURRENT TIME OF FLIGHT.

<table>
<thead>
<tr>
<th>constant</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>effective mass ($m^*$)</td>
<td>$0.112 m$ [48]</td>
</tr>
<tr>
<td>donor concentration</td>
<td>$5.5 \times 10^{16} cm^{-3}$  [82]</td>
</tr>
<tr>
<td>compensation</td>
<td>90%</td>
</tr>
<tr>
<td>acceptor concentration</td>
<td>$4.7 \times 10^{16} cm^{-3}$</td>
</tr>
<tr>
<td>concentration of ionised defects</td>
<td>$1.0 \times 10^{17}$</td>
</tr>
<tr>
<td>Low-frequency relative dielectric constant ($\kappa_0$)</td>
<td>10.76 [48]</td>
</tr>
<tr>
<td>High-frequency relative dielectric constant ($\kappa_\infty$)</td>
<td>7.21 [48]</td>
</tr>
<tr>
<td>density</td>
<td>$5.78 \times 10^{3} kg/m^3$  [48]</td>
</tr>
<tr>
<td>velocity of sound in CdTe</td>
<td>$2.66 \times 10^3 m/s$</td>
</tr>
<tr>
<td>acoustic deformation potential ($E_D$)</td>
<td>$3eV$ [74]</td>
</tr>
<tr>
<td>piezoelectric constant</td>
<td>$0.035 C/m^2$ [48]</td>
</tr>
<tr>
<td>lattice constant</td>
<td>$6.41 \AA$ [48]</td>
</tr>
<tr>
<td>Debye temperature of LO phonons ($\theta_{LO}$)</td>
<td>$246 K$ [48]</td>
</tr>
</tbody>
</table>

Table 6.2: Some less common constants used in the modelling of the scattering mechanisms.

Figure 6.17: A common log plot of electron mobility variation against decreasing temperature calculated for CdTe. Various different scattering mechanisms are used to calculate the fit to the experimental data labeled ($\mu_{\text{total}}$). The scattering mechanisms used in the calculation are: polar optical ($\mu_{\text{po}}$), ionised impurity ($\mu_{\text{im}}$), deformation potential ($\mu_{\text{ad}}$), and neutral impurity ($\mu_{\text{NI}}$). Also shown is the experimentally measured drift velocity for sample 2-4.
Figure 6.18: A common log plot of mobility variation against decreasing temperature for sample 2-4. The different fits show the variation of the deformation potential within the model, better fits are achievable using larger deformation potential energies.

of the fixed parameters may be responsible for the poor fit, indeed Segall et al [74] have suggested that the effective mass \(m^*\), and the Debye temperature of LO phonons \(\theta_{LO}\) all vary with temperature. Thus it is not realistic to expect a perfect fit using this model. However, even though the model has its limitations it is able to be used to make predictions regarding the scattering mechanisms present in CdTe.

Figure 6.17 shows the best fit achievable to the experimental data from sample 2-4. The total mobility is calculated \(\mu_{total}\) using Matthiessen's rule (see equation 6.1) and the scattering mechanisms: polar optical \(\mu_{po}\), ionised impurity \(\mu_{Im}\), neutral impurity \(\mu_{NI}\), deformation potential \(\mu_{ad}\), and piezoelectric \(\mu_{pe}\). Figure 6.19 shows the effect of removal of one scattering mechanism from the overall calculation. From this figure it is clear that at room temperature the mechanism with greatest effect to the overall calculation is polar optical scatter \(\mu_{po}\). Its removal from the calculation causes a 22% increase in the calculated room temperature mobility, removal of ionised impurity \(\mu_{Im}\), neutral impurity \(\mu_{NI}\)
Figure 6.19: A common log plot of mobility variation against decreasing temperature for sample 2-4. The effects of the different scattering mechanisms are shown by omitting one mechanism at a time. This shows that the mobility is mostly dependent on polar optical scatter.

and deformation potential (μ_{ad}) scattering only changes the calculated mobility by 1%. By far the least change occurs when μ_{ps} is removed from the calculation.

At 200K the situation is similar, where polar optical scattering dominates the system, but the effect of ionised impurity scatter increases. In our model an increase of 7% in the overall calculated mobility was recorded by removing μ_{1m} from calculations, up seven times from room temperature measurements. Below 200K no experimental data is present, but commenting on the model, it seems that the effect of ionised impurity scatter becomes more prevalent and the effect of polar optical scatter becomes less dominant, the other mechanisms also have less effect at lower temperatures except for neutral impurity scattering (μ_{NI}) which due to its temperature in-dependence remains constant.

In conclusion it seems that over the 200K-300K range polar optical scattering mechanisms is dominant in the system, but some attenuation of mobility is caused by ionised
impurity scattering in the same range. This conclusion is similar to that shown by the simple analysis given in figures 6.15 and 6.14 and by [7], but is also similar to the more complex analysis given by [82] who also suggests that the polar optical scattering is the strongest scattering mechanism in CdTe above 200K.

Current pulse shapes below 200K

As shown in figure 6.20 it is clear why the calculation of mobility at temperatures lower than approximately 200K becomes difficult. There appears to be a collapse of the amplitude at
Figure 6.21: Time evolution of pairs of single pulse shapes in sample 2-3 at a constant 170K and -150v. Part a) shows the sample irradiated by a 2kHz laser. Part b) shows the sample irradiated with a 2Hz laser and part c) shows the sample irradiated by a laser in single shot mode. All pulses are single events.

The start of the pulse at low temperatures. This collapse could be due to the presence of a space charge build up at the top contact of the sample, thus the field at this region falls and so too does the induced current. As a result of this non-uniform field it would be unwise to calculate mobility using these pulses. Another feature of the pulses at low temperature (below 200K) is the presence of a long lived tail. This tail could be due to the emission of charge after the prompt transit has finished. The tail therefore creates ambiguity as to where the transit has stopped and thus uncertainty in the calculation of transit time.

If the pulses were being effected by trapped charge, then reducing the rate of charge
injected per second should allow a greater fraction of trapped charge to be emitted and hence reduce the equilibrium space charge distribution in the sample. To test this idea the laser was pulsed at the lowest frequency that the system would allow (2Hz). A comparison between the pulses generated by a 2kHz laser and a 2Hz laser in the same sample (sample 2-3) at the same temperature (170K) and same bias voltage (-150V) is shown in figure 6.21. It is clear that the leading edge of the pulse collapses within seconds of applying a 2kHz laser, but on application of a 2Hz laser there is no further collapse after nearly half an hour of irradiation. Sequences of single pulse shapes at fixed temperature and voltage are also shown in figure 6.21. These pulses were created using a single laser pulse 60 seconds apart. It does seem from this information that a 2Hz laser can produce similar pulse shapes as those associated with a single laser pulse. Even at these lower repetition rates (2Hz and single shot) the pulse shapes at 170K are not consistent with room temperature pulses at the same bias. It may be that even at a low repetition rate there is still trapping and thus space charge formation within the device. This is confirmed by figure 6.22, which shows that there is a collapse using a 2Hz laser, but it is not as marked as when using a 2kHz laser. For this reason it was difficult to quantitatively measure the low temperature mobility in CdTe for temperatures below 200K.

6.3 Trapping and de-trapping mechanisms observed in CdTe

At low temperatures, the reduced leading edge of the current pulse shapes is also associated with the creation of a long-lived pulse tail related to re-emission of trapped charge. Thus a measurement of the shape of the tail region at the end of the transit should yield a de-trapping time. An algorithm was developed for the off-line analysis of de-trapping in current pulses. The algorithm is based on the assumption that the pulse can be split into
Figure 6.22: Variation of pulse shapes in sample 3-3 under illumination by a 2kHz laser (left hand plots) and variation of pulse shapes in the same sample under illumination by a 2Hz laser (right hand plots). All pulses were taken at 150v. The collapse of the pulse is at different temperatures depending on the frequency of illumination. Both pulses do however show some type of collapse. All pulses are single events.
Figure 6.23: Example of the de-trapping algorithm at work. The pulse is cut at part A and part B, the natural log of the amplitude of this region is taken and the emission time found by taking the gradient. This algorithm operates on a pulse by pulse basis and a histogram built.

two distinct regions the fast and slow region. The fast region contains information about the charge drift within the device and the slow region contains the de-trapping information required. The point where the fast region becomes the slow region is difficult to exactly define, so the algorithm described in section 4.2.4 was used. This overestimates the length of the fast region and so some of the slow region is removed, however this is more desirable than the opposite. A typical pulse shape is shown in figure 6.23.

In order to calculate a de-trapping time from the pulse tail, we assume the physics model that charge is thermally emitted from a trap over a timescale longer than the prompt drift time. There are now two options to consider: If the de-trapping time is much faster than the transit time, then the average time that the charge carriers spend in the traps is negligible, and so the carriers drift by multiple trapping/detrapping mechanisms. If however the de-trapping time is much longer than the lifetime of the charge carriers then under these conditions carriers are not re-emitted from the traps more than once. Thus the
6. **DRIFT TIME ANALYSIS OF CdTe BY CURRENT TIME OF FLIGHT.**

Figure 6.24: a) shows three histograms produced by the de-trapping algorithm at three different voltages and b) shows the variation of de-trapping time with bias voltage at 200K in sample 2-3. Both show the obvious voltage dependance of de-trapping time in the sample.

Current induced after the initial carrier transit (fast region) follows an exponential decay proportional to $\exp(-t/\tau)$ where $\tau$ is the de-trapping time. Thus by plotting common log of current vs time and retrieving the gradient of a linear fit an emission time ($1/\tau$) can be determined and hence the de-trapping time.

This method is similar to that used in the analysis of photo induced current transient spectroscopy (PICTS) pulses. Once the current pulse is captured (figure 6.23) a suitable limit to the slow region is defined by the threshold where the amplitude drops to 1.2 times the rms noise of the pulse (where the rms noise is calculated from the first 1% of the pulse trace). Once the timing limits are defined, a linear fit is used to obtain the gradient and hence the emission rate. Many current pulses (no less than 150) were then analysed to produce an emission rate histogram, from which the peak centroid was found using a gaussian fitting routine. The peak centroid was then converted into de-trapping time by taking the reciprocal.

Using this algorithm it was possible to produce a plot of de-trapping time against...
voltage for a sample where de-trapping is obviously present. This was done at 200K on sample 2-3 as shown in figure 6.24. It is clear from both (a) and (b) in figure 6.24 that the de-trapping time recorded is voltage dependent. The same analysis was performed on four other samples and again there was a strong voltage dependance similar to sample 2-3 shown in figure 6.24. An explanation for voltage dependance could be due to the charge transport occurring due to multiple trapping and de-trapping events instead of a single emission. As the charge travels it becomes trapped in a trap with a short decay time that is far less than the observation time, the trap is then emitted and moves thus inducing a current until it encounters another trap of a similar decay time, it is then trapped and emitted before the observation time ends and then moves from the trap, again inducing a current. The trapping and emission from multiple traps cannot be resolved in the system and so multiple trapping and de-trapping events produce one exponential tail. The decrease in the de-trapping time as voltage increases can be explained within the multiple trap model because the time the charge spends between traps can be shortened by increasing the velocity of the charge carriers by increasing the electric field. Thus the time spent in the traps does not change but the time between trapping events is shortened, hence reducing the observed effective emission time.

Temperature dependence of de-trapping in CdTe

From equation 2.31 the temperature dependance of the de-trapping time (which is the inverse of the emission rate) leads to an arrhenius plot of the form $\ln(T^2\tau)$ as a function of inverse temperature. The gradient of this plot yields an energy value which can be related to the activation energy of the trap concerned. In order to find the activation energy of the most prominently emitting trap in the system the de-trapping time was measured for several samples over a range of temperatures. At each temperature the de-trapping time was calculated using the algorithm described previously. As the de-trapping time in these
6. DRIFT TIME ANALYSIS OF CdTe BY CURRENT TIME OF FLIGHT.

Figure 6.25: Detrapping time as a function of bias voltage in sample 3-3. The detrapping time is voltage dependent which could point to multiple trapping and detrapping events. The insert is an Arrhenius plot of the natural log of detrapping time at 200v. The gradient of which should give trap energy of the most prominently emitting trap.

As can be seen from 6.25 the detrapping time increases with decreasing temperature and increases with increasing voltage. Thus as the temperature decreases the probability for re-emission of charge carriers from the trap is low due to the small amount of available energy in the system.

In order to assess the energy of the most prevalent trap emitting in the system the detrapping times at the highest bias were taken in order to produce the arrhenius plot given in the insert of figures 6.25 and 6.26. From these plots it was calculated traps with energies of 0.0074eV and 0.04eV respectively were present. These are very shallow levels and there are no reported traps of this energy in the literature. Since the transport involves multiple trapping/detrapping (voltage dependent $\tau$) the simple thermal emission is not valid and the shallow traps reported are un-physical.
6. DRIFT TIME ANALYSIS OF CdTe BY CURRENT TIME OF FLIGHT.

Figure 6.26: Detrapping time as a function of bias voltage in sample 2-3. The detrapping time is voltage dependent which could point to multiple trapping and detrapping events. The insert is an Arrhenius plot of the natural log of detrapping time at 200V. The gradient of which should give trap energy of the most prominently emitting trap.

6.4 Internal Electric field profile within CdTe

6.4.1 Production of electric field profiles

The electric field profile \(E(x(t))\) can be reconstructed from the voltage vs time \(V(t)\) pulses recorded in a time of flight experiment provided that a priori information about mobility is known [24, 75]. Figure 6.27 shows the reconstruction of the electric field profile at -100v for sample 3-3. The technique first proceeds by applying limitations on the pulse. In figure 6.27 part a, the solid line shows the extent in time where the rise time of the pre-amplifier ends (71ns), everything after this point is 'real'. The dashed line shows the end point of the transit, it is at this point that the pulse is cut and everything after it ignored. Knowing the gain of the current amplifier (in this case 10^6V/A) the current pulse is produced (figure 6.27 part b). The integral of the current pulse (equation 6.5) then
Figure 6.27: The method used to obtain the electric field profile from current pulses as described in the text. The data is from sample 3-3. The final result (g) shows the measured electric field profile in the device.
produces the charge pulse (figure 6.27 part c) which allows us to calculate the total charge \( Q \) produced in an event. The magnitude of the current pulse is proportional to the drift velocity of the electrons by Ramo's theorem (see equation 6.6). From this equation a velocity against time plot can be produced by multiplying the current pulse \( i(t) \) by \( \frac{d}{Q} \) where \( d \) is the detector thickness (figure 6.27 part d).

From equation 6.7 and figure 6.27 part d it is possible to produce figure 6.27 part e and as the time base of this plot is equal to the time base of 6.27 part d it is possible to plot figure 6.27 part f. From this plot it is simply a matter of dividing the velocity by the mobility in order to achieve a plot of electric field \( E(t) \) against distance into the device \( x(t) \) (figure 6.27 part g). The function displayed on this plot is therefore the reconstructed electric field profile in the device \( E(x(t)) \).

\[
Q = \int i(t) \quad (6.5)
\]

\[
i(t) = \frac{v(t)Q}{d} \quad (6.6)
\]

\[
x(t) = \int v_{de}(t) dt \quad (6.7)
\]

6.4.2 Electric field profiles in CdTe

The method outlined in section 6.4.1 was used to produce electric field profiles in three CdTe samples. Figure 6.28 shows the field profiles obtained from the analysis of time of flight pulses obtained from sample 2-1. These pulses are representative of the other three samples. From the field profiles given in figure 6.28 there appears to be a minimum field next to the cathode, which quickly rises to a maximum a small distance from the cathode, the field then falls towards the anode. One reason why there may be a local field
minimum near to the cathode, as discussed by Fink et al [24] is due to the build up of charge carriers at the near surface near the cathode due to a energetic stimulus producing many million electron-hole pairs along a very small cylindrical track. These charge carriers are not separated instantly by the external electric field as they provide shielding for one another. This shielding is eventually broken down as more and more charge carriers move under the external field influence. Thus this effect, known as the plasma effect, causes a delay in the start of carrier drift, and a perceived drop in the electric field using the time of flight method.

The second reason for an apparently low field near to the cathode is due to bandwidth limitations. The bandwidth of a system will dictate the time for which the electronic rise time is present in the system. In our system the bandwidth represents a minimum rise time of 71ns. The bandwidth converted into thickness is also shown on the electric field profiles given in figure 6.28. As can be seen from this figure the end of the rise time occurs
after the perceived electric field minimum and so our system is bandwidth limited near to
the cathode, so the extent of any plasma effect is not measurable. Fink et al [24] have
been able to observe the plasma effect near to the cathode as their bandwidth of 500Mhz
is greater than our system.

Nevertheless both bandwidth limitations and plasma effects are due to the experimental
setup. The actual field under normal bias conditions should decrease from the cathode to
the anode linearly, and to observe this requires a method that does not disturb the charge
equilibrium of the system. Such a system outlined by Cola et al [12] uses the Pockels effect
to image the electric field of a device without injecting charge carriers. This method shows
that there is no minimum near to the cathode in CdTe instead a linear decrease in field
from the cathode to the anode as shown in figure 6.29.

It is clear that the time of flight system for measuring the electric field profiles in CdTe
has its disadvantages, but the method is still able to show the field after any bandwidth or
plasma effect limitation have passed. Indeed the profiles presented in figure 6.28 show that
the field decreases from the cathode to the anode. The non linear behavior of the decrease

Figure 6.29: Electric field profile calculated from Pockels effect image in a reference
Pt/CdTe/Pt detector biased at 50 V. A high field is seen at the cathode [12].
shown in figure 6.28 could be due to trapping within the bulk, since the sample's CCE is less than 100%. A system where the charge carrier equilibrium is not disturbed, such as the optical system outlined by Cola et al [12] is obviously more advantageous.

6.5 Summary

It has been shown that the laser stimulation of current pulses is a robust method of investigating, in detail, the charge transport properties and electric field profiles of CdTe. It has been shown that an unattenuated laser beam can be used to measure the transit times of electrons without effecting the charge transport within the system thus allowing large signal to noise to be produced that allow for an unambiguous estimation of the transit time. Although there are benefits the limitations of the system mean that the transport near to the cathode cannot be seen due to bandwidth limitations. At above 200K it has been shown that this technique works well in investigating electron charge transport.

It has also been shown that the limiting mechanism for charge carrier scattering in the 200K-300K temperature range is due to optical phonon scattering, with a component due to ionised impurity scatter, which according to the model becomes the most dominant scattering mechanism at the 100K-150K temperature range. Other scattering mechanisms, such as neutral impurity scatter and deformation potential scatter, do not seem to have an effect on the overall temperature dependence of mobility.

An interesting phenomenon was also observed at temperatures of less than 200K, that appeared in all samples. The beginning portion of the current pulse collapsed at low temperatures, a result of possible increased trapping due to the low temperature in the near surface region. The increased tail at the end of charge transport is possibly due to the de-trapping of this charge, its voltage dependance due to the hopping charge transport responsible for the dispersive current [7].
For all these experiments only the average response of the device has been investigated. An extension to this work would be to consider the spatial variations of charge transport in different regions of the device. This technique using a highly focussed proton beam, is presented in the next chapter.
7 Spatially resolved charge transport

The spacial uniformity of CdTe material is an extremely important property for a host of real applications. The use of detectors in medical imaging for example requires excellent charge transport uniformity across the device in order for maximum functionality.

Several methods are able to investigate the charge transport over the detector area. These include laser beam induced charge (LBIC), X-ray induced charge (XBIC), electron beam induced charge (EBIC), alpha particle induced charge and proton (or ion beam) induced charge (IBIC).

LBIC methods are attractive because of the relatively easy set up of a mapping system and the low cost and easily accessible components. The energy of laser systems can easily be selected using a suitable laser and the high signal to noise ratio provided can be extremely advantageous. However laser systems are effected by the large density of charge carriers created in the near surface region where surface states may give rise to a high rate of recombination.

X-ray excitation provides a method where by the system is tested in much the same way as it is required to be used (the detection of gamma and X-rays), as well as providing a narrow well defined probe. The draw backs of using X-ray excitation is that even with low energy X-rays the depth of interaction is not accurately known and therefore one cannot ignore the hole component of the charge transport. Also the equipment required to produce such fine X-ray probes require the use of large and expensive synchrotrons.
Electron beam induced current (EBIC) is also a method where the spatial variation of charge transport can be measured. The excitation pulse provides an excellent signal trigger as well as fast signal rise times [17]. However, the random walk behavior of electrons in CdTe as described in section 5.3, make the interaction depth difficult to judge.

Alpha particles from an $^{241}$Am source can be used to investigate the spatial uniformity of charge transport, providing they can be collimated enough to provide a useful spatial resolution. Amman et al [2] managed to produce a beam collimation of 300$\mu$m using a standard alpha source to measure the electron trapping nonuniformity in CdZnTe. The obvious advantages of this technique is the relatively easy and inexpensive set-up. However, the disadvantages include the low spatial resolution compared to other methods and the length of time to acquire a full map of charge transport (up to seven days in the case of Amman et al [2] for a 2.5mm by 2.5mm sample).

A proton beam can also be used to provide a well-resolved probe to look at the spatial distribution of charge carriers in CdTe. This obviously requires the use of a proton source and a suitable accelerator to reach the required energy. Protons, like alpha particles, provide a probe that causes excitation at a well-known depth in CdTe, specifically 35$\mu$m below the contact at 2MeV (calculated using SRIM [89]). In this case the charge induced is only due to one type of charge carrier depending on the bias configuration, thus allowing for the use of the single carrier Hecht equation (see equation 2.23). An MeV energy proton beam can be well-formed to a beam of several micrometers, and can be used to acquire good quality images in approximately 30 minutes per scan. Although the apparatus to carry out IBIC is large and expensive, the technique does provide excellent resolution and spatial information, as well as imaging the spatial uniformity due to electrons and holes independently, without the complexity of X-ray microscopy and without the surface effects due to LBIC.

This chapter is primarily concerned with the investigation of spatially resolved charge transport.
transport in two CdTe samples stimulated using a proton beam (IBIC). All IBIC experiments were carried out at the University of Surrey microbeam. It will be shown that electron and hole charge transport across a sample can be quite different, owing to the high density of hole traps within the system. It will also be shown that the charge transport investigated using a proton beam is highly sensitive to the sample surface and diffusion of charge carriers outside the electrode. The spatial distribution of carrier lifetime will be shown, and its variation linked to the spatial variation of traps within the system. It will also be shown that the internal structure has a marked effect on charge transport.

7.1 Initial calibration of Surrey Microbeam

As mentioned previously in section 4.3 the microbeam line at the University of Surrey is connected to a 2MeV Tandetron accelerator from High Voltage Engineering Europe. The proton beam is formed into a micro probe using quadrupole magnets from Oxford Microbeams Ltd [28]. For observing spatial distribution of charge collection in our samples it was necessary to first measure the beam size. In order to do this a copper grid (placed onto the sample stage above the sample to be investigated) consisting of 2000 lines/inch (which is approximately 12.5µm repeat distance [28]) was scanned and the copper K-shell X-rays were observed using a cooled 80mm² Si(Li) detector placed 25mm close to the copper grid, using proton induced X-ray emission (PIXE). As the data in the ion beam was collected on an event by event basis (listmode) the information from the data acquisition software contained the x and y scan voltages (which allows for an instantaneous position of the beam spot) along with the energy pulses from the Si(Li) PIXE detector at each beam position. Thus it was possible to construct a two dimensional map of the spatially localised Cu K-shell X-ray emission (a PIXE map). A PIXE map used to determine the beam size in the experiments in this chapter is shown in Figure 7.1.
Figure 7.1: Image derived from the proton induced X-ray emission of a 12.5μm by 12.5μm copper grid. The peaks shown underneath the PIXE image show the line scans as indicated in the PIXE image. By measuring the 10-90% of these peaks it is possible to estimate the beam size. From these peaks it is obvious that both the X and Y beam directions are of a similar size approximately 4μm FWHM.
7. SPATIALLY RESOLVED CHARGE TRANSPORT

The beam spot size is defined as the distance in which the intensity of the PIXE response increases from 10% to 90% of its maximum value in both the horizontal and vertical axis [43](as shown in figure 7.1). From figure 7.1 it was possible to calculate the beam spot size to be approximately 4\(\mu\)m by 4\(\mu\)m. In order for the PIXE data to be acquired in a reasonable time a high beam current was used, far too much current for an IBIC experiment. Once the PIXE measurement was completed the object slits in the beam line were closed to reduce the beam current to the fA range.

The energy of the proton beam was set to be approximately 2070keV which according the SRIM Monte Carlo modeling software provides a depth of penetration of 37\(\mu\)m. The accelerator provides an extremely stable beam that varies less than 5% over several hours of use [79].

7.2 Spatially resolved charge collection and mobility lifetime product (\(\mu T\)) of sample Eurd-1

Sample Eurd-1 was specifically designed for ion beam studies. It consisted of a large circular piece of CdTe (approximately 2.5cm in diameter and 1mm thick). One face was scored with lines to make a grid pattern with spacing of 2.5mm that was used to reference the area of the sample so IBIC images could be easily compared to infrared microscopy and Lang X-ray topography images. The material was received un-contacted thus allowing infrared transmission microscopy and Lang images of the sample to be collected using the apparatus described in section 4.1.1 and section 4.1.2. Once optical and surface measurements were completed the sample was returned to EURORAD for contacting (see section 4.3.4). On its return electrical measurements were carried out to look at its bulk electrical properties. A manageable leakage current of 4.78\(\times\)10\(^{-7}\)A/cm\(^2\) at -100V bias was recorded and its spectroscopic capabilities showed an energy resolution of no more than 8% when detecting
5.49 MeV alpha particles. The electron and hole $\mu_0$, $\mu$ and $\tau$ were also found to be within the range given in the literature (tables 5.3 and 5.4 give these parameters). Once the bulk measurements were carried out the sample was taken to the ion beam for further study.

Eurd-1 was mounted into the microbeam chamber so that the proton beam would be orthogonally incident on the scored face. Before the beam was incident onto the sample, the beam spot size was measured to be approximately 4 $\mu$m by 4 $\mu$m and the beam fluence was reduced, by closing the object slits, to less than 1 kHz thus providing a beam current of approximately 50 pA. The beam was then raster scanned over a defined area, in this case 2.5 mm by 2.5 mm, which corresponds to the maximum imaging area. The signals that were produced by the sample in response to the proton beam were collected on an event by event basis (see section 4.3) and recorded to a file along with the x and y scan voltages, thus allowing the system to generate maps of the energy signals produced. Protons of energy 2.07 MeV were used to image charge transport in Eurd-1.

With the protons incident onto the cathode a sequence of IBIC scans was acquired at bias voltages of -10, -20, -30, -40, -50 and -80 volts. With the protons incident onto the anode a sequence of IBIC scans was acquired at bias voltages of +80, +120, +150 and +200 volts. The maps that are produced first by the OMDAQ control software are false colour maps, with each colour representing the mean energy of all the events occurring at each pixel, termed Ebar maps [28]. A calibration was performed, as described in section 4.2.3, on the Ebar maps to produce suitably normalised charge collection efficiency (CCE) maps. These CCE maps (given in figure 7.2) show exactly the same features as the associated Ebar maps but, have a quantitative calibration.
Figure 7.2: CCE images (on the left) and associated pulse height spectra (on the right) for electrons in Eurd-1, derived from events from all pixels in each map.
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7.2.1 Charge collection uniformity of Eurid-1

Electrons

The CCE maps given in figure 7.2 show generally good charge collection efficiency, with CCE approaching 100% at higher bias. The scribed regions are clearly visible bordering the good response regions. Also visible is a near horizontal region of poor response that bisects the IBIC images. This line feature continues on into other pixels next to the scanned region. The spectra in figure 7.2 also shows the spectra produced by averaging the maximum CCE in each pixel of the associated IBIC map. The sequence of spectra shows the peak broadening as the bias is increased due to the increase in leakage current. Figure 7.3 shows a close up of a CCE image taken at -10V, along with a y-projection taken along the white column shown in the CCE image (the line feature is denoted as region A in this figure).

The scribed regions and feature A can be seen clearly as reduced CCE in the vertical projection given in figure 7.3. Feature A has the same drop in CCE as the scribed lines which are marked B and C. However, unlike the scribed lines, feature A is not visible in any infrared microscopy (see section 5.1) nor in the Lang topography images (see section 5.1) of the scanned region, it is also not visible in surface photographs. It is believed that this region is due to a scratch on the sample, possibly below the contact, that was introduced by transport or handling.

In the ion beam control software (OMDAQ) it is possible to gate preferentially onto structures within a spectrum and compile an Ebar map that uses just the events in the defined region. By creating an Ebar map just with the events in the main peak, as shown on the right in figure 7.4, it is clear that most of the counts in the main peak are from areas of good response. The areas of poor response, which include the scribed lines and feature A, create a low energy background (labelled Y in the spectrum shown in figure 7.4). The
Figure 7.3: Part I shows an electron CCE image of the scanned region of sample Eurd-1 taken at -10v. The white column shows the position of the y projection given in part II. Regions marked A, B, C and D are marked on the CCE image (part I) and on the y projection (part II).

Figure 7.4: Figure shows a spectrum acquired at -50v. The right image shows an Ebar map produced when just events in the photopeak (marked X on the spectrum) are included. The image on the left shows an Ebar map produced from low energy events below the photopeak (marked Y in the spectrum).
Ebar map created by gating over this contains only counts from the low response regions (see the left image in figure 7.4). This data confirms that the scribed region of the device do produce events, but with a significantly reduced pulse height.

The excellent uniformity of CCE is also visible in the y projection given in figure 7.3. There is hardly any variation in CCE between structures A and B, there is however more variation in CCE between the structures A and C. Also region D is clearly visible that has a reduction in CCE of 20% compared to the projection average. Other regions of poorer CCE response (similar to structure D) are also clearly visible in the CCE images, these include a line structure marked E and a smaller region marked F both are shown in figure 7.3. These regions can not be shown to be due to any visible physical defect either in the near surface Lang images or the bulk infrared microscopy images (see section 5.1).

Holes

Due to the poor mobility of holes in CdTe charge collection approaches only 60% at the highest bias used. However the hole CCE images, like their electron counterparts, have excellent uniformity (see figure 7.5).

Due to the higher leakage currents present in the positive polarity the hole data is subject to more noise and broader main peaks. The scribed border regions and scratch, visible in the electron CCE maps, are again visible in the hole CCE images. The fine structure (specifically region D) is not visible in the y projection of figure 7.6, but is however faintly visible in the CCE image above the projection. From figure 7.5 it is clear that there is less variation of CCE at low bias voltages compared to electron CCE. This is possibly due to the higher bias used for hole collection. The smallest voltage was +80v for holes compared to -10v for electrons and as the phenomenon causing variation of CCE seems to occur at low bias for electrons the faintness of these regions in the hole data may be due to the significantly higher bias used and possibly the higher leakage current
broadening the response. In order to ascertain the mechanism for these lower CCE regions it becomes necessary to further process the ion beam data.

7.2.2 Mobility-lifetime ($\mu \tau$) maps of Eurdi-1

Electrons

The production of mobility lifetime maps from the CCE data is a powerful quantitative measure to assess variations in charge transport across the device [76]. It also tends to bring out greater contrast of features than in CCE maps or Ebar images. Using the acquired CCE images, a set of voltage versus CCE data for each pixel position was obtained and the $\mu \tau$ product for each pixel was extracted by fitting the single charge carrier Hecht equation (equation 2.23) using a Levenberg-Marquardt algorithm. The entire process is described by Lohstroh et. al in [44].
Figure 7.6: Part I shows a hole CCE image of the scanned region of sample Eurd-1 taken at +150\text{v}. The white column shows the position of the y projection given in part II. Regions marked A, B, C are marked on the CCE image (part I) and on the y projection (part II).

Figure 7.7: Part I shows a $\mu_0 \tau_e$ image created from a series of CCE images at different voltages. Typical Hecht fits are shown on the left for two regions where the electric field is constant. Regions that were visible on the previous CCE images are also shown, namely structures A, B, C, D, E and F. Part II shows a y-projection taken along the white column shown in part I.
The electron mobility-lifetime ($\mu_e\tau_e$) image produced from Eurd-1 is shown in Figure 7.7. The calculated $\mu_e\tau_e$ values are only valid for regions of the device where the electric field strength is constant. This includes most of the scanned area but not the scribed gaps where the electric field is smaller and in the scratch (marked A) running across the device. It is evident from figure 7.7 that there is a large variation in the $\mu_e\tau_e$ values. It is possible to see islands of smaller $\mu_e\tau_e$ that correlate with regions of poor CCE. For example a large line running diagonally across the sample (marked E) is equivalent to the feature (also marked E) shown in figure 7.3. The region marked D in figure 7.7 is equivalent to the region also marked D in figure 7.3, and the same is true for the region marked F. It seems that the poor CCE regions have led to poorer $\mu_e\tau_e$. This is clear from the fits presented in figure 7.7. In regions of higher $\mu_e\tau_e$ the CCE values at low bias are higher than those from regions with lower $\mu_e\tau_e$. Thus the CCE variation at the lower bias seem to be causing the distribution of $\mu_e\tau_e$. From the $y$ projection given in figure 7.7 it is clear that the CCE variations at low bias are symptomatic of a reduction in $\mu_e\tau_e$ of up to 40% from the projection average.

However even the low $\mu_e\tau_e$ values shown are still within the range of acceptable values found in the literature [18]. The Hecht map of Eurd-1 shows $\mu_e\tau_e$ values ranging from good $2 \times 10^{-3}\text{cm}^2/\text{V}$ to excellent $1 \times 10^{-2}\text{cm}^2/\text{V}$. Most of the scanned area has a $\mu_e\tau_e$ value in the range $5 \times 10^{-3}\text{cm}^2/\text{V}$ to $7 \times 10^{-3}\text{cm}^2/\text{V}$ as is shown in the projection given in figure 7.7.

Holes

A similar process was applied to the hole data and is shown in figure 7.8. The $\mu_h\tau_h$ variation shown is very uniform. The values vary from $1.6 \times 10^{-4}\text{cm}^2/\text{V}$ to $1.8 \times 10^{-4}\text{cm}^2/\text{V}$, again similar to those quoted elsewhere in the literature [18]. Unlike the electron mobility-lifetime data there is far less variation in the hole $\mu\tau$ value. Regions of lower $\mu_h\tau_h$ are only 10%
Figure 7.8: Part I shows a hole mobility lifetime map for EurD-1. Typical Hecht fits are shown on the left for two regions where the electric field is constant. Part II shows a y projection along the white column shown in part I, which shows the variation of $\mu_h\tau_h$ in the y-axis. The structures visible in part I of figure 7.7 are less visible in the hole $\mu_h\tau_h$ image.

less than regions of higher $\mu_h\tau_h$. The structures that are visible in the electron $\mu_e\tau_e$ data are faintly visible in figure 7.8, specifically structures D, E and F. Structure D is shown in the y-projection in figure 7.8.

So far it has been shown that the ion beam can be used to form a well resolved micro-probe that is able to produce maps of the spacial variation of CCE in CdTe. The sample discussed, EurD-1, has been shown to have good charge collection efficiency as well as excellent $\mu_e\tau_e$ of greater than $5.0 \times 10^{-3}$ cm$^2$/V and good hole $\mu_h\tau_h$ values of greater than $1.6 \times 10^{-4}$ cm$^2$/V. The uniformity of the electron $\mu\tau$ has a greater variation than the hole $\mu\tau$. Unfortunately it is not possible to de-convolve the $\mu\tau$ product to see if the poorer
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response regions are either mobility limited or lifetime limited with just the analogue data. Fortunately the Surrey IBIC system allows for the collection of digital data that can be processed to allow for such a de-convolution.

7.3 Drift, mobility and lifetime of charge carriers in Eurd-1

Acquired simultaneously with Ebar maps of Eurd-1 were pre-amplifier pulse shapes. These pre-amplifier signals were digitised in real time, with a maximum 1ns time resolution [77] and the 10-90 rise time was calculated (see section 4.3), thus allowing the calculation of drift time by adding a 20% correction. Digital data was taken over the same range of bias voltages as the analogue data thus several drift time maps at different bias voltages were produced. Figure 7.9 shows typical electron drift time maps acquired alongside the CCE images given in figure 7.2. Although the analogue and digital data was acquired simultaneously with the same spatial resolution, due to the limitations of the digitiser, figure 7.9 has fewer events compared to the CCE maps.

The LabVIEW software that controls and records the data has several pulse analysis algorithms that can be performed on and offline. All pulses are first baseline corrected prior to further processing, the option of filtering the data is also present. One such software filtering algorithm involves a Fast Fourier Transform (FFT) to remove high frequency noise in the digitised pulses. The FFT algorithm was used extensively in the offline processing of the digital data from Eurd-1, due to the persistence of an intermittent electronic noise of unknown origin. Figure 7.10 shows an electron preamplifier output pulse taken at -50v before and after filtering. The rise time shape (in this case approximately 500ns) is preserved but the high frequency noise is removed.
Figure 7.9: Drift time maps (on the left) from the Eurd-1 showing progression with increasing bias voltage. Also shown (on the right) are the Drift time spectra calculated for all pixels in each rise time map.
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7.3.1 Drift time uniformity of Eurd-1

The drift time maps shown in figure 7.9 show good uniformity across the scanned region. Features that are visible in the drift time maps include the inter-pixel scribed region and the scratch that bisects the scanned area. The spectra on the right hand side of figure 7.9 show the drift time spectrum over the entire map, the spectrum broadness is due to the variation of drift time across the region. At the edges, near to the inter-pixel scribed lines and the scratch, the drift time increases. Where there are events in the scribed regions, the drift time is longer, this suggests that a low electric field is present between the pixels. For example figure 7.11 shows the drift time map from Eurd-1 taken at -40V. Along the line indicated by the white column the drift time increases from an average of 600ns to as high as a 1μs at the edge. This is clearly shown in the x-projection also given in figure 7.11. This lengthening of the drift time is thought to be due to the decreasing field strength that occurs towards the end of the contact, close to the scribed or scratched regions [14]. The effect can also be seen in the CCE images given in figure 7.2 where the CCE value falls closer to the edge.

![Figure 7.10: Example of the FFT algorithm applied to a noisy pre-amplifier pulse from Eurd-1. The noise was believed to be from a poorly grounded sample stage.](image-url)
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Figure 7.11: Part I shows a drift time map taken at -40v in Eurd-1. Part II shows an x-projection along the line shown in part II. The projection clearly shows an increase in drift time towards the scribed edges.

7.3.2 Shape of charge pre-amplifier pulse shapes as a method to determine charge transport characteristics.

Preamplifier pulse shapes with 10-90% rise times of no shorter than 200ns were recorded from Eurd-1, well above the risetime of the ORTEC 142A pre-amplifier (10-30ns [43]). Conversely no rise times longer than 5μs were observed, well within the decay time of the pre-amplifier (70μs [43]). The fact that there were no pulses recorded over 5μs from the sample, even at low bias, indicates that there is no charge de-trapping present within the sample at room temperature (297K). This again points to the good quality of Eurd-1.

The pre-amplifier pulse shapes of the regions D and E previously discussed were investigated, along with two other areas namely region G (near to the contact edge) and a control region (CR). The control region was an area of good charge collection and charge transport properties. Pulse shapes from regions D, E and G were compared to this control region in
order to determine any changes of charge transport. Figure 7.12 shows the location of the regions on a $\mu_0 \tau_0$ map as well as some pulse shapes from these regions. The pulse shapes are plotted on the same axis as a pulse from CR to aid contrast. It is clear from the pulse shapes and part I of figure 7.13 that the regions D, E and G yield pulses of less amplitude compared with the control region.

According to section 2.2 and references [2, 17] a lower induced charge signal at the cathode would yield a reduction in the pulse height. However, as the charge ($Q_0$) only appears as a pre-factor in the induced charge signal equation (equation 2.23), a reduction in pulse amplitude is all that will occur (figure 2.7). It is clear that the pulses in figure 7.12 show an increased curvature in their rise, specifically towards the end. This curvature suggests that the reduction in amplitude is not due to a variation in the induced charge but due to an increase in the trapping (see section 2.2 and references [2, 17]).
Figure 7.13: Part I shows the variation of the pulse amplitude across the 4 regions defined in figure 7.12 at -10v. Part II shows the same variation in the same regions but this time at -50v.

However the amplitude variation seen at low bias disappears at high bias as all pulses become equivalent in amplitude to the pulses seen in the control region (CR) (see part II of figure 7.13). Figure 7.14 shows that the curved shape that suggests trapping at low bias also disappears as the pulses become more prompt.

It is thought that the shape at low and high bias can be explained by a variability of lifetime across the sample. At low bias the drift velocity of charge carriers is lower compared at higher bias, and hence the carrier drift time is long. If the effective lifetime of the carriers is less than the mean drift time, then trapping will occur, and the pulse shapes will be subject to an increased curvature. If the effective lifetime is significantly longer than the drift time then full charge collection will occur and no curvature will be observed. Regions D, E and G therefore suggest areas of reduced electron lifetime compared to the control region. To experimentally show the variation of lifetime across the sample it is possible to divide a map of $\mu_e \tau_e$ by the mobility map.
Figure 7.14: $\mu_e \tau_e$ map showing the positions of regions D, E, G and the reference area, CR. Plotted around this map are examples of pre-amplifier pulse shapes at -50V from the regions compared to a pulse shape from CR.

### 7.3.3 Mobility and lifetime of charge carriers in Eurd-1

Plotting the inverse of the drift time (nominally 20% more than the rise time) against bias voltage and calculating the mobility from the gradient pixel by pixel allows the construction of a mobility map from the rise time data (see section 2.2.2). This provides a powerful quantitative method to image drift mobility within the device. This process was carried out for Eurd-1 using the drift time data given in figure 7.9, to produce the mobility map given in figure 7.15. From this map several structures that are common to all maps previously discussed are visible. The scratch that bisects the scan area is shown as well as the scribed regions that border the scan area. The scratch is shown as feature A in the y projection presented in figure 7.15 where as the scribed regions are shown as features B and C.

Looking at the mobility map presented in figure 7.15, apart from the large structural features the mobility appears very uniform, this is confirmed by the y projection in the same
Figure 7.15: Part I shows an electron mobility map of pixel 15 of Eurd-1. Uniform mobility is visible over the entire active area of the pixel. This Mobility map was produced from the drift time maps given in figure 7.9.

The average mobility across the entire scanned area has a value of \((986 \pm 15) cm^2/Vs\), very close to the \((1050 \pm 20) cm^2/Vs\) calculated from alpha experiments (see section 5.3) and other values that appear in the literature [30]. The mobility map is only valid for regions of uniform electric field and so does not produce meaningful results in the scribed and scratched regions.

The mobility map shown in figure 7.15 is a result of fits to the inverse of transit time \((1/T)\) against \(V/d^2\) (where \(V\) is the voltage and \(d\) the thickness) plot on a pixel by pixel basis, three such fits are reproduced in figure 7.15. The fits from the control region (CR) and region D are excellent, and are representative of the other fits over the contact area. The fits outside the contact area on the other hand are quite poor, leading to low mobility values. Such a fit is shown from region A in figure 7.15. This is by no means surprising, these regions (A, B and C) are all areas of damage, where the electric field is believed not to be constant, thus the assumptions used in producing mobility values (see section 2.2.2) are no longer valid.
Apart from the obvious scribed and scratched structures, the mobility map is featureless. This observation confirms the hypothesis that the structures observed in the $\mu_e\tau_e$ and CCE images (see figures 7.7 and 7.2 respectively) are due to lifetime effects. To quantify the variation in lifetime across the scanned region requires the production of a lifetime map. This is a trivial step as it only involves dividing the $\mu_e\tau_e$ map shown in figure 7.7 with the mobility map presented in figure 7.15. The resultant effective lifetime map is given in figure 7.16 above a y-projection taken along the white column indicated on the map.

The features that were not observed in the mobility map are obviously present in the lifetime map. The overall effective lifetime over the scanned area is approximately 6$\mu$s. This value appears in the literature and is an excellent electron lifetime for CdTe [30]. Unsurprisingly the areas of low CCE and low $\mu\tau$ correlate with areas of lower lifetime. What is striking is that these areas still have relatively long values of lifetime. Region D, for example, has a lifetime of approximately 2.5$\mu$s-3.0$\mu$s, however compared to the control region (CR) this is a decrease of 3.5$\mu$s. This difference is enough to cause lifetime limitations and therefore trapping at low bias where the charge drift time ranges between 2-4$\mu$s, but not at higher bias like -30V (the next experimental bias used) where the charge drift time ranges from 500ns to 1$\mu$s. Other areas, like the control region, have long enough lifetimes that lifetime limited trapping is not an issue, even at low bias. Thus the hypothesis stated previously that the trapping observed in the pre-amplifier pulses is due to lifetime limitations at low bias seems plausible.

Figure 7.17 shows the infrared and Lang topography image of region 15 of Eurd-1, compared to the lifetime map shown in figure 7.16. It is clear that the regions of contrast in the infra-red image do not relate to any features in the lifetime map. The opposite is also true, as apart from the scribed border regions, no structure in the lifetime map is visible on the infrared image. Thus the mechanism for the various differences in lifetime.
Figure 7.16: Effective electron lifetime map for Eurd-1, produced by dividing the mobility-lifetime map given in figure 7.7 by the mobility map given in figure 7.15. It is therefore an illustration of structures that are not visible in the mobility map. From this it can be argued that the structures visible in this figure are due to lifetime limitations of the electron transport.

Figure 7.17: Three different images taken with three different techniques of the same pixel (15) in sample Eurd-1.
is unclear. Effects on lifetime relate to increased trapping, therefore these regions have increased density of traps. Many processes can increase trap density, but one of the major trap forming processes is crystalline damage. It may be that these regions have been subject to mechanical damage that has altered the local crystalline structure and thus increased the number of traps, this would not be visible to infrared or Lang images. This process is a strong contender for the nucleation of the increased trapping near to the edges, as these regions have been mechanically scribed (or scratched) thus damage could have easily been introduced. It is less clear what has caused the reduced lifetime effect in regions D and E. These regions are surrounded by regions of excellent lifetime so it is less likely that they are caused by the same mechanical stress that caused the edge effects. The localised formation of traps could be a result of a host of processes: for example instability in growth parameters leading to bulk crystalline deformities or inhomogeneous dispersion of compensating material.

Conclusion

It has been shown that the IBIC method can produce useful spatial information on the efficiency and charge collection properties of a device. To fully utilise the quantitative power of the system both analogue and digital data should be used in conjunction. In this case the variation of the carrier lifetime was seen to vary over the scanned region, but no firm conclusions as to the origin of these variations could be made. It is thought that the variations are due to crystalline damage due to mechanical stress, especially around the edges where the sample was scribed. The variation of lifetime in the center regions is less likely to be due to the same mechanical damage, in this case the origins could have nucleated from numerous options. Overall sample Eurd-1 has excellent charge collection and transport properties, even though there is some variation in lifetime, even the lowest value is still within the range of good lifetime quoted in the literature [30]. As the operating
voltage of Eurd-1 is around -50v the charge trapping at low bias (-10v) is not an issue when operating as a radiation detector, and so overall the sample is of excellent uniformity.

7.4 Preparation and surface geography of sample 2-4

Although some interesting variations in lifetime were observed in Eurd-1 the observation of effects due to internal structures on the device charge transport was not so successful. Possibly due to the low density of observable inclusions. In order to study the effects of internal structures it was necessary to obtain samples with more observable inclusions and features.

From a batch of ten 5mm by 5mm CdTe samples supplied by EURORAD one sample was identified as having a large density of observable features from infrared images. It was thus decided that this sample should form the basis of further study.

7.4.1 Preparation of sample 2-4

To observe the effects of internal defects on charge transport it is necessary to match up structures observed in an IBIC image with optical images of the defect. For sample 2-4 a mask was laid down onto the sample which consisted of two 'L' shaped gold pieces that bounded an area equal to the maximum scan size of the IBIC system (2.5mm by 2.5mm). A sketch of the mask and its dimensions is shown in figure 7.18. This gold pattern was applied by evaporating 100nm of gold using a shadow mask.

Once the gold mask was deposited on both the front and back surface of the sample it was imaged using the infrared microscopy set-up described in section 4.1.1. The sample was then returned to the evaporator to deposit a metal contact onto the area bounded by the 'L' shaped mask. It was decided that this layer should be semitransparent (less than 15nm) so it could be used in laser time of flight experiments discussed in chapter 6.
one face was covered with a semitransparent layer and is termed the front contact. The back face was completely covered with 100nm of gold, in order to form a durable back contact able to be set onto a ceramic base using gold dag. Once the back contact was set onto ceramic the front contact was electrically connected using the same gold dag. In order to maintain the integrity of the thin semitransparent gold contact the electrical connection to the front surface was made to the thicker (100nm) 'L' shaped masks. The entire front contact structure can be seen in the photographs shown in figure 7.19. Gold dag was used instead of carbon dag (as is used with other samples) to produce a more durable bond able to withstand handling in the ion beam.

Once the sample was contacted, set onto ceramic and electrically connected, basic characterisation was carried out. The current-voltage investigations showed a manageable leakage current at high bias. Irradiation using 5.49MeV alpha particles from an $^{241}$Am source showed that the sample was able to generate good alpha spectra with an energy resolution of no more than 14%.

### 7.4.2 Surface geography of sample 2-4

On viewing the IBIC images from sample 2-4 and comparing them to the photographs of the sample surface given in figure 7.19 some correlation between the structures visible in
Figure 7.19: Photograph of sample 2-4. Marked on the image is the 'L' shaped mask (bordered in red), the semitransparent contact (bordered in blue) and the gold dag (bordered in green).

Figure 7.20: Part I shows a close up of the scan area (bordered in blue) and the outline of the contact extremities (marked in black) from a photograph of sample 2-4. Part II shows the same outline of the contact extremities (marked in black) transposed on top a suitably scaled electron Ebar IBIC image (-200V). Structures visible in the photograph (part I) and IBIC image (part II) are labeled A, B, C and D.
the IBIC images and surface photographs is obvious. Looking at figure 7.20 it is clear that the contact edge marked with the white line in the sample photograph gives rise to the shape marked with the white line visible in the IBIC image. Using this shape as a reference point it was possible to scale the IBIC image and transpose and correlate it over the sample photograph using image editing software. In this way it was possible to see that structures marked A, B, C, and D on the sample photograph in figure 7.20 give rise to the equivalent structures marked A, B, C, and D on the IBIC images. These structures are believed to be surface features which cause maximum absorption of the ion beam, thus produce regions of zero response in the IBIC image. The structures are also visible on the infrared images of sample 2-4 shown in figure 7.21 and are also marked A, B, C, and D. After the infrared images were taken and immediately before the last gold contacting procedure was done (the deposition of the semitransparent layer), sample 2-4 was washed, firstly in acetone for one minute then and in isopropanol for a further minute. If these surface structures were contaminants added during handling they would have been removed by this sequence wash and so would not be visible on the IBIC images or surface photographs. It is believed that the structures are features of the sample that may have been preferentially etched to the surface by a 5% bromine methanol etch performed before the 'L' shaped mask was laid down. It is also clear that the large circle of reduced response in the top right of the IBIC image shown in figure 7.20 is due to the gold dag that provides the top electrical contact to the device.

Due to small movements of the sample on the sample stage of the microbeam chamber caused by vibrations, each IBIC image taken had to be individually transposed and correlated with the surface photograph and infrared images. With regards to the hole IBIC images (figure 7.22), structures A, B, C, and D and the large circle in the top right of the IBIC image are the same structures present in the electron IBIC images. For reference the actual scan area and contact extremities are shown on all the surface photographs and
Figure 7.21: Part I shows a close up of the scan area (bordered in blue) and the outline of the contact extremities (marked in black) from an infrared image of sample 2-4. Part II shows the same outline of the contact extremities (marked in black) transposed on top a suitably scaled electron Ebar IBIC image (-200V). Structures visible in the infrared image (part I) and IBIC image (part II) are labeled A, B, C and D.

Figure 7.22: Part I shows a close up of the scan area (bordered in blue) and the outline of the contact extremities (marked in black) from a photograph of sample 2-4. Part II shows the same outline of the contact extremities (marked in black) transposed on top a suitably scaled hole Ebar IBIC image (+50V). Structures visible in the photograph (part I) and IBIC image (part II) are labeled A, B, C and D.
7.5 Spatially resolved charge transport of sample 2-4

Once the contacts were laid down on sample 2-4, electrical measurements were carried out to look at its bulk electrical properties. A manageable maximum leakage current density of $7.02 \times 10^{-7} \, A/cm^2$ was achieved at +300v in sample 2-4. Like Eurd-1, sample 2-4 was mounted into the microbeam chamber so that the proton beam would be incident orthogonal to the semitransparent gold layer. The beam fluence was lowered to 1kHz after it was focussed to approximately 4$\mu$m by 4$\mu$m and the beam was raster scanned over the sample surface.

7.5.1 Spatially resolved charge collection in Sample 2-4

With protons incident onto the cathode of sample 2-4 a sequence of IBIC scans was acquired at bias voltages of -10, -20, -50, -100, -200, and -250. With protons incident onto the anode a sequence of IBIC scans was taken at +50, +80, +100, +120, +150, and +200 volts. Like Eurd-1 the initial OMDAQ false colour maps (Ebar) where suitably normalised by application of a calibration (see section 4.2.3) to images of charge collection efficiency (CCE).

Electrons

Figure 7.23 shows the sequence of electron CCE images acquired from sample 2-4, along with the associated spectra. On the whole the charge collection efficiency and uniformity is excellent, it approaches values close to 100% even at relatively low bias. There are several things worthy of note; at low bias (-10V) the uniformity of CCE is poor compared to higher bias. From the spectra given in figure 7.23 there appears to be two peaks, which is evidence of two distinct regions of CCE. By gating over the two peaks separately it is easy
Figure 7.23: CCE images for electrons in sample 2-4 computed from the Ebar images produced by the ion beam control software (OMDAQ).
to illustrate the two regions. Figure 7.24 shows the Ebar image compiled using only events in the smaller peak (labelled X) and the Ebar image compiled using only events in the larger peak (labelled Y). There is clear evidence that low CCE regions exist close to the edge of the contact and around the surface features, where as the rest of the contact area has a better response. This discrepancy between the two regions disappears at high bias, as is illustrated for -200V in figure 7.25. Gating over the larger peak (labelled Z) and compiling an Ebar image shows that both regions have the same response at higher bias. Some low CCE events still exist and produce a shoulder (labelled S in figure 7.25) in the higher bias spectra but these events are in regions of the contact where lower CCE is expected, such as in the gold paint area and around the surface features. This CCE variation, that changes with bias voltage, could be due to variations in lifetime, but further analysis is required to prove this hypothesis.

Another point worthy of note is the increase of peak broadness with an increase of bias voltage. The low and intermediate bias voltages have a main peak resolution of approximately 8% some broadening is due to the electronics of the system and leakage current of the sample, which at -250V creates a wide peak with a resolution of approximately 24%. 
Figure 7.25: a) Shows a spectrum from sample 2-4 at -200V showing regions of interest. b) Is an Ebar image compiled from events just from the shoulder S and c) Is an Ebar image compiled from events just from the peak Z.

Holes

Figure 7.26 shows the sequence of hole CCE images acquired from sample 2-4. Due to the low mobility of holes in CdTe the CCE will not rise to 100% as seen in the electron data. Good hole collection efficiency is within the range 50-60%, which is achieved in sample 2-4 at high bias voltages. The hole CCE uniformity is excellent and the drastic fall in CCE observed near to the end of the contact in the electron images is not observed in the hole data.

Peak broadness however, unlike the electron data, decreases as one increases the bias voltage. The peak resolution at +50 volts is 14% where as the peak resolution at +120V is 9%. This decrease is possibly due to the variation in CCE across the device at low bias, which is not present at higher bias. This is illustrated in figure 7.27, which shows an x projection along the same line in a CCE image at +50V and +120V. The relative variation of CCE across the sample at +50V is approximately 23% where as the variation at +120v is approximately 9%, thus showing that the CCE uniformity improves with increasing bias. The poorer uniformity in CCE at low bias may be linked to charge transport variations present through out the entire sample, but more analysis is required before a firm conclusion.
Figure 7.26: CCE images for holes in sample 2-4 computed from the Ebar images produced by the ion beam control software (OMDAQ). The picket fence pattern in the pulse height spectra are artefacts of the OMDAQ MCA at long shaping times.
Figure 7.27: a) Shows a CCE image at +50v and an x projection along the white column shown in the image. b) Shows a CCE image at +120v and an x projection along the same line as the x projection in a.

Figure 7.28: a) Shows a spectrum from sample 2-4 at +100v showing regions of interest. b) Is an Ebar image compiled from events just from the shoulder S, c) Is an Ebar image compiled from events just from the peak X and c) Is an Ebar image compiled from events just from the peak N.
can be made.

Other details of the spectra in figure 7.26 worthy of note include the shoulder to the left of the main peak. Gating on this shoulder as in figure 7.28 shows that most of the events are due to the low CCE areas, such as on the gold 'dag' and events that are occur outside of the contact area. Gating on the main peak as in part c of figure 7.28 shows that most of the events on the contact area are present, again suggesting good hole uniformity. The noise marked N in figure 7.28 is an artifact produced by the electronics of the ion beam system and is just noise.

7.5.2 Spatially resolved $\mu \tau$ in Sample 2-4

Production of electron and hole $\mu \tau$ images in sample 2-4 proceeded in the same manner as electron and hole $\mu \tau$ image production in Eurd-1 (see section 7.2.2). The Levenberg-Marquardt algorithm was used to fit the single carrier Hecht equation (equation 2.23) to data showing the variation of CCE with bias voltage on a pixel by pixel basis.

Electrons

From the CCE images shown in figure 7.23 a mobility-lifetime map of electrons was produced and is presented in figure 7.29, along with two representative fits and an x projection along the white column shown in the image. As was previously discussed, the production of a mobility-lifetime map brings out greater contrast of weak features present in individual CCE images [76]. The variation of $\mu_e \tau_e$ in sample 2-4 can be discussed using three distinct regions, which encompass all the features visible. These regions are shown in figure 7.29. Region 1 (R1) defines an excellent region of $\mu_e \tau_e$, where the average is $5.8 \times 10^{-3} \text{cm}^2/\text{V}^{-1}$, a value for $\mu_e \tau_e$ in CdTe that appears in the range of good values elsewhere in the literature [18]. As one might expect R1 also encompasses areas of highly uniform CCE even at low bias voltages (see figure 7.23). The values of $\mu_e \tau_e$ vary from approximately
6.5 × 10^{-3} cm^2/V^{-1} to 5.5 × 10^{-3} cm^2/V^{-1} a variation of some 15%.

Region 2 (R2) on the other hand shows an area of poorer $\mu_e \tau_e$ with an average value of $3.5 \times 10^{-3} cm^2/V^{-1}$, this value is still in the range of good $\mu_e \tau_e$ values that appears in the literature [18], but it is a 40% reduction from the average value in R1. The transition between regions R1 and R2 is shown in the x projection given in figure 7.29. This shows that the $\mu_e \tau_e$ values fall from a value of approximately $5.0 \times 10^{-3} cm^2/V^{-1}$ at the beginning of R2 to a value of just $3.0 \times 10^{-3} cm^2/V^{-1}$ towards the end of the contact, a drop of approximately 40%. A similar drop (40%) in CCE is recorded in the same area at -10V. The poorer $\mu_e \tau_e$ is obviously because of the low CCE at low bias, which alters the fit, as can be seen in the representative fits of region 1 and 2 given in figure 7.29.

Region 3 (R3) defines the effect of the surface features discussed in section 7.4.2 on $\mu_e \tau_e$. It is obvious that the effect of the surface features extends beyond their physical size, which can be seen as the two areas of low response (black in colour) in the center of R3. The $\mu_e \tau_e$
values vary from $5.8 \times 10^{-3} \text{cm}^2/\text{V}^{-1}$ at the edge of R3 to as low as $1.3 \times 10^{-4} \text{cm}^2/\text{V}^{-1}$ near to the surface defects, nearly fifty times smaller than the maximum.

The origin of the poor $\mu_e \tau_e$ in R2 and the poorer $\mu_e \tau_e$ in R3 is unclear just from the data so far discussed. It does however seem plausible that the surface features are responsible for the lower $\mu_e \tau_e$ in R3, but the mechanism is still unclear. Similar results were found in the Eurd-1 (low CCE at low bias etc), so it may be that the features are due to lifetime variations. Of course to be certain the $\mu_e \tau_e$ needs to be de-convolved by division of a suitable mobility map.

Holes

From the CCE images shown in figure 7.26 a mobility-lifetime map of holes was produced and is presented in figure 7.30, along with two representative fits and an x projection along
the white column shown in the image. Also included in figure 7.30 are the three regions R1, R2 and R3 that were introduced previously. Looking at region 1 in the hole μτ image it seems that there is more variation than was observed in the μeτe over the same area. However by quantifying the variation using the x projection there is a 15% variation in hole μτ which is similar to the variation in electron μτ along the same region. Thus both electron and hole μτ have the same distribution in region 1.

Region 2 however is comparatively quite different from its election counterpart, in that the reduction of over 40% percent of μhτh does not occur as it does in the same region in the electron μτ image. Instead there is a variation in region 2 of only 15% for μhτh. This is a result of a constant CCE at low bias, which does not alter the fit.

Region 3 in the hole μhτh image is also different to its electron counterpart, in that the effect of the surface features do not seem to extend into the same area for the μhτh as they did for μeτe. The μhτh value in region 3 varies from a maximum of $2.5 \times 10^{-4} \text{cm}^2/V^{-1}$ to a minimum, ten times less, at $2.6 \times 10^{-4} \text{cm}^2/V^{-1}$. This reduction is smaller than the reduction seen in the same area for electron μτ data which shows a reduction of fifty times the maximum.

Conclusion

Overall the charge collection efficiency and μτ values observed for holes and electrons in sample 2-4 have been excellent. All values for μeτe and μhτh have been published elsewhere in the literature as good values for μτ in CdTe [18]. Although there has been excellent values measured, a large spatial variation of effects and large differences between the hole and electron data has been observed. The hole data seems to have less spatial variation compared to the electron data and the effect of surface features at low CCE, leading to a large variation in μτ for electrons, has been seen in region three but not in the same region for hole data. The origin of these differences in the data is thus far unclear. More processing
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Figure 7.31: A typical rise time map from sample 2-4 taken with a bias voltage of -20v. Also shown is an x projection along the white column shown in the rise time image.

of the data is required to better understand the mechanisms causing the differences. To proceed, mobility maps will be constructed to de-convolve the electron and hole $\mu T$ data.

7.5.3 Drift, mobility and lifetime of charge carriers in sample 2-4

Electrons

Using the digital data that was collected simultaneously alongside the analogue data, the spatial variation of drift time was calculated (see section 7.3 for details). A typical drift time map from sample 2-4 is shown in figure 7.31, this shows that the drift time in R1 is very uniform with an average of $1.90 \times 10^{-6}$s at -20v and a distribution of only 28% around this mean value. Region R3 apart, from the presence of the surface features, is also very uniform with an average drift time at -20v of $1.85 \times 10^{-6}$s and a similar distribution as R1 of 30%. The variation seen at R3 in the $\mu e\tau_e$ image given in figure 7.30, is obviously
Figure 7.32: Drift time spectra compiled using events from the entire area of the equivalent drift time map. Shows the progressive decrease of the charge drift time as the bias is increased.

not present in the drift time images. This would suggest that R3 shows lifetime limiting behavior similar to that observed in the Eurd-1 sample. Region 2 however does show a steep increase in drift time, the average in this region climbs almost 70% to $2.73 \times 10^{-6}$s and has a distribution of almost 65% about the mean. The increase of drift time from region 1 to region 2 can easily be seen in the projection given in figure 7.31. This increase in region 2 is seen in all drift time maps from sample 2-4.

Obviously as one increases the bias on the sample the drift time of the charge decreases as the velocity of the charge carriers increase. This is shown in the sequence of drift time spectra given in figure 7.32. The mean drift time increases from $4 \times 10^{-6}$s at -10v to approximately $2 \times 10^{-7}$s at -250v.

From the drift time maps a mobility map was produced via the same method as previously discussed (see section 7.3.3) and is shown in figure 7.33. Like the drift time data, R1 is very uniform with an average mobility value of $962 \text{cm}^2/\text{Vs}$. R3 like R1 is also uni-
Figure 7.33: An electron mobility map of sample 2-4. Uniform mobility is visible over most of the active area. This Mobility map was produced from drift time maps at different bias. Also shown are two representative fits from R1 and R2 as well as an x projection along the white column shown in the image.

form with a similar mean mobility value of $942 \text{cm}^2/\text{Vs}$. Like in the drift time images, the variation seen at R3 in the $\mu_e \tau_e$ image is not present in the mobility image. This leads to the conclusion that R3 is lifetime limited in a similar manner to Eurad-1. The lifetime map for sample 2-4 is given in figure 7.34.

Region R3 shows a variation in effective lifetime, which is not seen in the corresponding mobility map. The average lifetime in R3 is calculated as being $2.4 \times 10^{-6}$s where as the average calculated in R1 is $6.0 \times 10^{-6}$s. At low bias (-10v) where the drift time vary between $3.0 \times 10^{-6}$s to $5.0 \times 10^{-6}$s (see figure 7.32) the reduced lifetime in R3 restricts the charge carriers by causing increased trapping. At higher bias this lower lifetime becomes progressively less of an issue. At -20v for example the average rise time is $2.0 \times 10^{-5}$s, which is equivalent to the calculated lifetime in R3, so less charge carriers are lifetime limited but as there is a distribution in the drift time leading to a maximum of up to $3.0 \times 10^{-6}$s so
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Figure 7.34: An electron lifetime map of sample 2-4, showing three regions of interest and an x projection taken along the white column in the image.

there is still an effect at higher bias. At very high bias (-250v) the drift time decreases to 1.0 – 3.0 \times 10^{-7}s (see figure 7.32) and so these charges carriers are no longer effected by the reduced lifetime in R3.

The lateral extent of the surface regions with increasing bias is shown in figure 7.35 which shows two CCE images, one at -10v and one at -250v, along with a profile along the y-axis. The FWHM of this profile defines the extent of the lifetime effects caused by the surface features. It is clear that the FWHM of the profile reduces with increasing bias (and decreasing transit time) until a minimum value is reached, equivalent to the effective physical size of the surface feature.

The lifetime limited effect of the surface feature can be further corroborated by looking at the pulse shapes in much the same was as was done for Eurd-1. From the data thus far presented region R1 has been shown to have excellent charge collection and transport properties, even at low bias, and as such is defined as a control region. By comparing
Figure 7.35: Shows two CCE images, one at -10v and one at -250v, along with a y projection along the white column indicated in the CCE image. Both illustrate the decreasing effect of the surface regions with increasing bias. The plot of FWHM of the y projection with increasing bias is also shown.

Pulses from region R3 to pulses from region R1 it is possible to see lifetime limited pulse shapes, as defined in section 2.2 and references [2, 17]. Figure 7.36 shows pulses from R1 compared to pulses from R3 taken at -10v. As can be seen, there is a distinct curvature in the rise time, suggesting that the charge carriers are lifetime limited in R2. However at higher bias, also shown in figure 7.36, there is no evidence of similar pulse shapes. Thus it can be concluded that the surface features reduce the lifetime in their near region, but only by an amount that effects low bias charge collection, in this case -10v to approximately -50v.

The mobility map in figure 7.33 shows that there is a drop in the mobility in region 2 (R2). Looking at the pulse shapes from this region it seems that there is evidence for processes that can be attributed to the effect of extended defects. As such this discussion is postponed until section 7.6.
Figure 7.36: Pulse shapes taken from the control region R1 compared to pulse shapes from R3 at two different bias voltages, namely -10v and -250v.

Holes

A similar analysis was performed on the drift time data collected for hole transit in sample 2-4. One of the drift time maps that was produced is shown in figure 7.37. From these maps, spectra showing the decrease of drift time with increasing bias (see figure 7.38) were produced, which shows the drift time starting at $1.2 \times 10^{-5}$s at +50v and ending at approximately $3 \times 10^{-6}$s at +200v.

From the drift time maps a mobility map was produced and is shown in figure 7.39. From this it is clear that the region R1 has a uniform response, with an average value of $78 cm^2/Vs$ a maximum value of $100 cm^2/Vs$ and a minimum value of $60 cm^2/Vs$ all values that are published elsewhere as accepted values for hole mobility [18]. In region R3 the mean, maximum and minimum values are also very similar. As with the electron data no variation of hole mobility was observed in R3. Thus it is suggested that the variation in hole $\mu \tau$ is due exclusively to variations in lifetime around the surface features. To verify this a lifetime map was produced and is shown in figure 7.40.

From the lifetime map (figure 7.40) the mean lifetime in R3 is $2.5 \times 10^{-6}$s, compared to the mean lifetime in R1 of $3.8 \times 10^{-6}$s. So as with the electron data there is a shorter lifetime in region 3 compared with region 1. However the surface feature has less of an
Figure 7.37: A typical drift time map from sample 2-4 taken with a bias voltage of +120v. Also shown is an x projection along the white column shown in the rise time image.

Figure 7.38: A Hole drift time spectra compiled using events from the entire area of the equivalent hole rise time map. Shows the progressive decrease of the charge rise time as the bias is increased.
Figure 7.39: A hole mobility map of sample 2-4. Uniform mobility is visible over most of the active area. This Mobility map was produced from drift time maps at different bias. Also shown are two representative fits from R1 and R2 as well as an x projection along the white column shown in the image.

Figure 7.40: A hole lifetime map of sample 2-4, showing three regions of interest and an x projection taken along the white column in the image.
Figure 7.41: Shows two CCE images, one at +80v and one at +200v, along with a y projection along the white column indicated in the CCE image. Both illustrate the static effect of the surface regions with increasing bias. The plot of FWHM of the y projection with increasing bias is also shown.
effect on the hole charge collection and transport compared to the electron data as can be seen in figure 7.41. The variation of the size of the effect of the surface region, measured using the FWHM along a y projection, also stays constant with increasing bias voltage. Like the electron data these effects can be attributed to the lifetime of the material. The hole lifetime in R1 and R3, although different from each other, are both lower than the drift time of the charge for all but the highest investigated bias (figure 7.38). As a result the entire sample is a lifetime limited. Close to the surface feature in R3 the lifetime is further reduced due to the effects of the feature but further away from the feature the lifetime becomes limited by the sample. Thus it appears that the lifetime effect of the surface feature does not change with bias voltage. However at the highest bias voltage investigated the drift time of the charge becomes faster than the lifetime of the sample. As a result the effect of the surface feature is reduced, as can be seen by the small but statistically significant fall in FWHM of the surface feature y projection shown in figure 7.41.

This effect can be shown by looking at the shape of the pre amplifier pulses in R1 and R3. Figure 7.42 shows pulses from R3 compared with pulses from R2 at two different bias voltages. At the lowest bias voltage shown (+50v) both pulses show lifetime limited transport, as predicted by comparing the drift time to the lifetime map. At this voltage the full extent of the effect of the surface feature cannot be seen as it is swamped by lifetime effects of the sample. Figure 7.42 also shows pulses from region R1 and R3 at +200v, which not lifetime limited at this bias voltage.

The mobility map in figure 7.39 shows that there is a drop in the mobility in region 2 (R2). looking at the pulse shapes from this region it seems that there is evidence for processes that can be attributed to the effect of extended defects. Again this discussion is postponed until section 7.6.


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Figure 7.42: Pulse shapes taken from the control region R1 compared to pulse shapes from R3 at two different bias voltages, namely +50v and +200v.

7.6 Effect of extended defects on charge transport in CdTe

The region R2, unlike R3, showed pulse shapes that can be explained by the interaction of drifting charge carriers with bulk defects [2]. In sample 2-4 these pulses were observed in a region with a high concentration of observable defects, and it is likely that these defects are interacting with the drifting charge.

Electrons

Looking at the electron mobility map in figure 7.33, region 2 shows reduced mobility which is attributed to an increase in the pulse drift time. Figure 7.43 shows the pulse drift time for the three regions at four different bias voltages. It is clear that regions 1 (the control region) and region 3 have very similar drift time (leading to similar mobility) where as region 2 has pulses with two distinct drift times. One pulse shows a drift time similar to the other regions where as the other pulse shows a much longer drift time. This bi-polar drift time spectrum can be attributed to the two different pulse shapes that are present only in this region.

Figure 7.44 shows the two different types of pulses that are present in region 2. The
Figure 7.43: Shows the variation of electron drift time with increasing bias for three distinct regions in sample 2-4.

Figure 7.44: Shows the variation of pulses from region 2 at four different bias voltages. Kinked pulses and non-kinked pulses are observed.
prompt pulse is similar to pulses from region 1 and as such has a similar drift time. The kinked pulse by contrast has a longer rise time and is not seen in other regions. This kinked pulse shape is attributed in the literature to the interaction of drifting charge carriers with defects in the bulk, specifically tellurium inclusions. The model proposed by Amman et al [2] involves increased trapping near to an inclusion. If an electron moves through a region of the device free of inclusions it will experience normal uniform electron trapping and will produce a pulse similar to the prompt pulses in figure 7.44. If however it drifts through a region which is initially free of inclusions but at a depth enters a region of increased trapping as a result of the presence of inclusions, it will produce a pulse shape similar to the kinked pulses shown in figure 7.44. Thus it is proposed that the kinked pulses observed in region 2 are due to enhanced electron trapping due to the presence of inclusions. Unfortunately it was not possible to localise these diverted pulses to individual inclusions due to the limitations of the experimental apparatus. Charge carriers created by the ion beam are subject to lateral diffusion as they drift through the bulk of the device. Thus as one gets deeper into the device the initial resolution of the collimated proton beam is lost. The lateral diffusion of charge carriers in an electric field is a thermal process and as such can be described as a Gaussian distribution whose standard deviation $\sigma$ is given by [37] and is reproduced in equation 7.1 where $x$ represents the drift distance, $E$ the electric field, $e$ the electronic charge, $k$ Boltzmann’s constant and $T$ the temperature.

$$\sigma = \sqrt{\frac{2kT}{aeE}} \quad (7.1)$$

For example in CdTe at -50v the laterally diffused distribution of charge carriers near to the back of the device (2.4mm in thickness) is estimated to be 73$\mu$m where as at -250v the laterally diffused distribution of charge carriers is estimated to be 33$\mu$m. Thus the lateral size of the charge cloud as it drifts through the device is not good enough to measure
Figure 7.45: A zoom of the contact edge in a CCE image taken at -20v in sample 2-4. Clearly visible outside the contact area, earmarked by a white dotted line, is the signal recorded off the contact area.

individual inclusions which are no more than 10μm in diameter and located towards the back contact.

7.7 Lateral diffusion in sample 2-4

One observation that has so far not been discussed involves the presence of a signal from outside the contact area. An example is shown in an electron CCE image in figure 7.45.

The response that can be seen outside the contact area is thought to be due to lateral diffusion of charge carriers. A model for this process is described in figure 7.46. If the detector is at position A a signal is recorded at C due to moving charge carriers response to the field. If the ion beam then moves to B it is outside the contact area, no signal should be produced as charge carriers are created in a region of the sample with no field and so do not induce charge. However because of diffusion the charge carriers created at B are able to move. Some diffuse laterally into the field region, where they drift in response to the field and induce a charge of measurable amplitude which is recorded by the listmode file as originally from position B. Thus a signal outside the contact area is produced. Since
Figure 7.46: Shows a planar detector with the ion beam in two separate positions, A and B. When the ion beam is at A the charge induced is recorded at C and the signal is written to the list mode file as being from the position A. When the ion beam reaches position B, it is outside the contact, but still creates charge carriers. These carriers laterally diffuse with some reaching the edge of the contact and thus a field region, where they move and induce charge at C. The listmode file records that a signal (a diffusion signal) was produced at B.
only a fraction of the generated charge will diffuse into the high-field region, the recorded response will be less than 100%.

7.8 Summary

Over the preceding chapter it has been shown that the ion beam can be used as a useful tool to investigate the charge transport in CdTe. Its most useful feature is that it can deliver spatial information regarding the charge transport, and so changes can be observed over the device. This was done using two samples, Eurd-1, a large (2.5cm in diameter) device grown and contacted by EURORAD and sample 2-4, a smaller device (5mm x 5mm) grown by EURORAD but contacted at the University of Surrey. Both devices showed good bulk \( \mu \tau \) values when investigated using alpha particle irradiation using an \(^{241}\)Am source and both had similar current density at high voltage that lead to manageable leakage current.

With regards to Eurd-1 the spatial electron and hole \( \mu \tau \) values obtained were equivalent to excellent \( \mu \tau \) values shown in the literature \cite{18}. It was shown that there were subtle variations of electron \( \mu \tau \) over the scanned area. These variations were only observed due to investigation at low bias namely -10v. Using the digital data obtained simultaneously with the spatial pulse height data it was possible to produce mobility maps. When used in conjunction with \( \mu \tau \) maps the mobility map made it possible to produce lifetime maps of the scanned area. From this data it was shown that there were similar variations of lifetime and that the lower \( \mu \tau \) coincided with shorter lifetime. It was concluded that there was a lifetime limiting effect at low bias, which would have no detrimental effect on the normal operation of the device, as the operation bias was several times greater than the bias where lifetime effects were observed.

The lifetime limiting nature at low bias was also confirmed by looking at the pulse shapes. At low bias a curved shape indicative of lifetime limitations was observed. At
higher bias this same shape was not observed. Overall it was shown that the charge drift was not effected by objects seen in infrared images of the scanned area nor by changes in the crystalline structure observed by Lang topography images. Overall the spatial distribution of the charge drift and collection was excellent in Eurd-1.

Sample 2-4 shows some features that were not observed in Eurd-1. The sample was chosen, unlike Eurd-1, because it had a large number of observable defects in the infrared images taken of it. These defects were most likely tellurium inclusions as the were areas of contrast no more than 10µm in diameter and existed at various depths through out the bulk.

For simplicity the charge collection and charge drift images were divided into three regions which encompassed the entire spectrum of observable effects. Region 1 (R1) was termed the control region as it benefited from uniform and high electron and hole $\mu\tau$ as well as uniform mobility. Region 3 (R3) in contrast covered the effect of a surface defect on the charge collection and drift and Region 2 (R2) covered the effect of a high density of inclusions on the charge drift.

The effect of a surface defect on the spatial charge collection was observed and it was concluded that at low bias there was lifetime limited effects caused by the presence of the surface defect. This was confirmed by the pulse shapes from this region which showed curved pulses that were indicative of increased charge trapping.

Region 2 by contrast had lower electron and hole $\mu\tau$ and unlike regions 1 and 3 had a decreased mobility. This region had an increased number of inclusions observable in the infra red images. By looking at the pulse shapes from this region pulses that were kinked part way through there rise were observed. These were contrasted to pulses from the control region where no kinked pulses were observed. These kinked pulses were consistent with the interaction of drifting charge with the inclusions part way through the device. Unfortunately due to the lateral diffusion of charge carriers along the drift length the
resolution of the beam became too large to observe and localise the effect of individual inclusions.

As a final observation a response outside the contact area in a region of the device with no field was recorded. In the electron data this was attributed to the lateral diffusion of electrons from the no-field region drifting into a region with field, thus forming an induced pulse.
8 Conclusion and further work

8.1 Conclusion

A high atomic number and large band gap make CdTe ideal for use as a room temperature radiation detector. Over the years it has proved useful as a radiation detection medium, with several companies offering medical imaging systems based around the technology. This potential was only realised once single crystal material was available, before that point the uses for CdTe were mainly in solar cell applications. As the CdTe growth technology progressed so too has the quality and size of the material. However it is still the growth processes that needs to be further refined if even larger crystals are to be produced. The problem that exists with CdTe material at present is still the low hole mobility, a problem which requires segmented detectors or post processing, and thus sophisticated contacting and read out electronics. The benefits of CdTe with regards to charge transport is the high electron mobility but charge trapping for both electrons and holes is still a problem and limits the spectroscopic capability.

One of the aims of this work was to quantitatively assess the quality of EURORAD CdTe by using infrared, X-ray imaging techniques and electrical characterisation. This showed that the material can be grown on a large scale with a minimum of observable defects and obtain high $\mu T$ values, equivalent to literature values. Other samples in contrast had a higher density of observable defects, which did not hinder the bulk $\mu T$ values, as they
were equivalent to the larger clearer sample. It was also shown that all samples produced current voltage characteristics that were heavily effected by leakage currents. The type of metal did not seem to be an issue for creating a reasonable planar contact as all maximum current density values reported were within the same order. In all it was concluded that the performance of EURORAD CdTe was equivalent to other CdTe material presented in the literature.

The second major topic to be discussed within this work was regarding the underlying electron mobility limiting processes in EURORAD CdTe. It was found that the mobility was controlled in part by optical phonon scatter. This mechanism dominated until lower temperatures were reached and it was found that the effect of ionised impurity scattering increased. This is in corroboration with the experimental and theoretical work given by [82]. However the model we present shows that there may be some effect due to deformation potential scatter and neutral impurity scatter, especially at room temperature. Unfortunately our mobility data was limited by the observation of space charge build up due to trapping events at temperatures below 200K. Thus beyond this temperature no mobility values were calculated. An algorithm was designed that could measure the tail of the transit current which was attributed to trapping events. If the carrier lifetime is much smaller than the de-trapping time and the transit time then under these conditions trapped charge carriers are not re-emitted more than once. Unfortunately calculation of the trapping energy did not yield a physical value attributable to any known defect in CdTe. Thus it was concluded that the assumption under pinning the method (a non zero current is produced after the transit time, which follows an exponential decay that is proportional to \( \exp(-t/\tau^*) \)) was incorrect and that there may have been multiple trapping and de-trapping events present. The time of flight method was then extended to include the derivation of the electric field profile from room temperature current pulses. Once the bandwidth limitations were taken into account the electric field was seen to fall from the
illuminated cathode to the anode. A qualitative result that is in agreement with several other authors [12, 24].

The final chapter of this thesis was concerned with spatial assessment of charge transport variations in several EURORAD samples. This involved the use of a proton beam with micrometer resolution provided by the University of Surrey microbeam facility. The first sample investigated was Eurd-1 the sample identified as having the smallest inhomogeneity concentration. An area with some visibility identifiable defects was scanned and the electron and hole \( \mu \tau \) was mapped. This showed that there were spatial variations of \( \mu \tau \) but due primarily to field variations near the edge of the contact. No variations could be localised to the defects identified by Lang topography or infrared images. This study was extended to a sample that was identified to have more visibly observable defects. Large variations in the electron and hole charge transport were identified and by cross referencing these features with maps of charge drift it was concluded that most variations were due to localised variations in lifetime. Where there were areas of variation in the mobility a large number of kinked pre-amplifier pulses were located. This formation can be modeled by a sudden variation in the charge trapping and is synonymous with the interruption of charge carriers by tellurium inclusions [2]. Although these kinked pulses were not correlated to individual inclusions, their presence was concentrated in an area that had a large concentration of inclusions. Ultimately the quality of the charge transport imaging was limited by the spatial resolution of the IBIC technique, which is controlled by diffusion of the charge carriers in the CdTe.

8.2 Further work

With regards to the laser time of flight system, as the method proved to be successful in measuring mobility and an obvious extension to improve the system would be the ability
to take spatially localised data. This would require suitable software to control both an X-Y stage and the ToF equipment, which would be relatively simple within the LabVIEW environment. Spatially localised laser mobility information from the laser time of flight system would provide a complementary technique to spatially localised ion beam data as samples could be preferentially selected for interesting spatial variations in charge transport before one is committed to a more expensive ion beam run.

This work has shown that THM CdTe has excellent electron transport properties in regions of the material free of inclusions. Further improvements in material quality are anticipated that will produce large area, single crystal, inclusion-free CdTe. This new high quality CdTe is now becoming available by Kromek using the multi-tube vapour phase transport (MTVPT) method.
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