Charge transport and mobility mapping in CdTe

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Introduction

Motivation for this Work:
- THM-grown CdTe supplied by Eurorad - investigation of uniformity of: mobility, $\mu \tau$, and lifetime
- What is the role of Te precipitates in degrading signal response?
- Pulse shape analysis can identify regions of trapping or reduced mobility
- Does CdTe exhibit non-uniformity in the same way as CdZnTe?
- Alpha particle TOF measurements are used to characterise CdTe mobility and $\mu \tau$ as a function of temperature
- High resolution ion beam (IBIC) studies map charge transport processes close to precipitates
- Digital time-resolved IBIC produces maps of mobility

Mechanisms for reduced signal amplitude:
- Reduced electron lifetime
- Reduced mobility or field
- Reduced initial charge
- Partial trapping
Electron and Hole Mobility in CdTe

Poor signal amplitude and low resolution is caused by low electron and hole mobility-lifetime ($\mu\tau$) products:

**Typical mobility and lifetime values for CdTe:**

<table>
<thead>
<tr>
<th>$\mu_e$ (300K)</th>
<th>$\mu_h$ (300K)</th>
<th>$\tau_e$</th>
<th>$\tau_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>800-1100 cm$^2$/Vs</td>
<td>60-90 cm$^2$/Vs</td>
<td>$\sim$1 µs</td>
<td>$\sim$1 µs</td>
</tr>
</tbody>
</table>

Temperature dependent mobility $\Rightarrow \mu_e$ increases at lower temperature, $\mu_h$ decreases.

Scattering mechanisms alone cannot describe the temperature variations – need a trap-controlled mobility model:

$$\mu = \mu_0 \left(1 + \frac{N_T}{N_C} \exp \left( \frac{E_T}{kT} \right) \right)^{-1}$$

$\mu_0$ – scattering-limited mobility

$E_T, N_T$ – trap energy and concentration

$N_C$ – effective density of states at bend edge

**Electron trapping** normally associated with a complex defect:
2 Cl donors on Te site + Cd vacancy $[V_{Cd} 2Cl_{Te}]^0$

**Hole trapping** often associated with shallow Cd-vacancies ($V_{Cd}$) and **A-Centers** ($V_{Cd}^{-}$ donor complex), acting as single and double acceptors.
IR microscopy – imaging Te precipitates

IR imaging used to identify the distribution of Te precipitates:

☐ are Te precipitates a cause of non-uniform signal response in CdTe, as seen in CdZnTe?

25mm diameter CdTe wafer, scribed with locating grid lines prior to metal deposition

2nd sample shows very low precipitate concentration away from the wafer edges
IR imaging and X-ray topography

Lang X-ray topography is an imaging method that identifies changes in the near-surface crystalline orientation – scribed sample allows correlation to IR image:
Alpha particle electron and hole $\mu\tau$ in CdTe

Alpha particle $\mu\tau_e$ and $\mu\tau_h$ data were obtained as a function of temperature:

- CCE pulse height spectra at various bias voltages
- the single-carrier Hecht equation:

$$ CCE = \frac{Q(x)}{Q_0} = \frac{\mu_e \tau_e V}{d^2} \left[ 1 - e^{\left(-\frac{d^2}{\mu_e \tau_e V}\right)} \right] $$

Holes at 295K:
$\mu\tau_h = 7.3 \times 10^{-5} \text{ cm}^2/\text{V}$

Electrons @ 295K:
$\mu\tau_e = 7.8 \times 10^{-4} \text{ cm}^2/\text{V}$

- Sample thickness 1.3mm
- Electron and hole drift times <1$\mu$s – amplifier shaping time was 2 $\mu$s
- Electron pulse amplitude saturates at $-50V$
- Hole pulse amplitude is almost linear, up to +150V
Electron and Hole mobility vs Temperature

Alpha particle time-of-flight (TOF) was used to measure electron and hole drift mobility in our sample.

Drift mobility $\mu$ is calculated from the carrier drift time $t_{dr}$:

$$\mu = \frac{v}{E} = \frac{d^2}{V t_{dr}}$$

where $d$ is the device thickness, $v$ is the drift velocity.
Drift mobility in Acrorad CdTe

Similar data previously reported for Acrorad THM-grown CdTe:

Electron mobility saturates at low temperature – maximum \( \mu_e = 2000 \text{ cm}^2/\text{V}s \)

Trap-controlled mobility gives \( E_T = 28 \text{ meV} \) below CB,
\( N_T = 1 \times 10^{16} \text{ cm}^{-3} \)

Consistent with \( [V_{Cd}, 2Cl_{Te}]^0 \) complex

Hole mobility has exponential decrease at temperatures below 220 K.

Trap-controlled mobility gives:
\( E_T = 140 \text{ meV} \) above the VB,
\( N_T = 3.3 \times 10^{15} \text{ cm}^{-3} \)

Consistent with A-Centres
Knowing $\mu \tau$ and $\mu$, the effective carrier lifetime $\tau$ can be calculated:

Hole lifetime is 0.7 $\mu$s at RT, increasing slightly at low temperature – similar to hole drift time.

$\Rightarrow$ Lifetime limits hole drift lengths at typical device field strengths.
**Digital IBIC - ion beam TOF mapping**

IBIC uses the nuclear microbeam at the Surrey Tandetron accelerator:

- 2 MeV protons or alpha particles:
- high spatial resolution (<3 µm)
- single event detection (~1 kHz rate on sample)

**Planar geometry:** ion beam images onto the cathode or anode – induced signal is due to either electrons or holes

**Time Resolved IBIC for TOF mapping:**

- A fast waveform digitiser acquires pulse shapes on an event-by-event basis:
  ⇒ 200 samples per pulse @ >1.5 kHz event rate
  ⇒ waveform sampling down to 1ns per point
- Quantitative images of carrier drift time, mobility, and lifetime.

*PJ. Sellin et al, NIM A521 (2004) 600-607*
Ion Beam Induced Charge (IBIC) imaging was performed with a 2.05 MeV scanning proton beam, focussed to <3 µm diameter.

A large surface scratch is clearly shown – under the metal contact, not visible by eye.

Cathode irradiation – amplitude maps show electron drift length.

Local regions of reduced signal amplitude – possibly due to precipitates in the material bulk.
Uniformity of electron $\mu\tau$ in CdTe

Map of electron $\mu\tau_e$ in CdTe shows $\mu\tau_e \sim 4.2 \times 10^{-4} \text{ cm}^2/\text{Vs}$ at $T=295\text{K}$

- Good uniformity across the majority of the area
- Local regions show “25% reduction in $\mu\tau$” - may be due to reduced field or reduced $\mu\tau$
  - Requires pulse shape information
Time resolved IBIC maps

Time resolved IBIC captures complete pulse shapes for every pixel:

⇒ maps of electron drift time

No sign of ‘slow’ pulses in the precipitate region

Drift time ~150 ns at -50V
Uniformity of electron mobility

Second CdTe sample, 8mm thick:

$V = 150V, d = 8\text{mm}, \Rightarrow \mu_e \sim 850 \text{cm}^2/\text{Vs}$
Zoom into precipitate region

Pulses from the precipitate region:

Extract amplitude and risetime data from the same data set

Pulses from a ‘normal’ region:

Drift times remain unaffected: cannot be reduced μ or E.

Pulse shapes require further study – at higher waveform resolution
Conclusions

- Temperature dependent alpha particle TOF measurements show a defect-limited mobility for electrons and holes in CdTe.
- THM-grown CdTe has a very low concentration of bulk precipitates, except for regions close to the wafer edge.
- Hole drift lengths are severely restricted, due to the short hole lifetime and low mobility.
- IBIC $\mu \tau$ maps demonstrate excellent uniformity of electron transport over a micrometer length scale.
- Time resolved IBIC used to produce maps of electron mobility, showing good uniformity.
- Bulk precipitates reduce $\mu \tau$ as an analogous way to CdZnTe - further work is required to identify the exact trapping mechanism.