Characterisation of charge transport in compound semiconductor detectors

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Issues for new detector materials

- Material uniformity
  - monocrystalline vs polycrystalline
  - mechanical defects, eg. pipes and twins
  - distribution of electrical traps

- Metal - Semiconductor contacts
  - contact technologies
  - ohmic vs blocking contacts
  - Electric field profile and I-V characteristics

- Charge Transport
  - Mu-tau products for electrons and holes ⇒ CCE
  - MIPS S/N ratio

- Radiation Hardness
  - effect on trap concentrations, IV, CCE

Contact-less mapping techniques:
- photoluminescence,
- cathodoluminescence, resistivity

Nuclear microbeam (IBIC) imaging

I-V, barrier heights

Field mapping: IR, Franz-Keldysh imaging

Radioisotopes

Irradiation measurements

Transient spectroscopy - PICTS, DLTS
Whole wafer photoluminescence mapping

Material uniformity can be characterised using room temperature photo-luminescence mapping - a contact-less, whole wafer technique:

- A 25 mW 633 nm HeNe laser is focussed to ~50 µm on the wafer
- the wafer is mounted on an XY stage, and scanned
- PL intensity maps at peak the band edge emission wavelength (eg. 870nm for GaAs) are acquired
PL maps of GaAs

Photoluminescence mapping clearly shows the uniformity of epitaxial GaAs compared to semi-insulating VGF material:

Epitaxial GaAs

Bulk GaAs


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Resistivity mapping of GaAs wafers

Contact-less resistivity mapping using the Time Dependent Charge Method has been pioneered at Freiburg.

The wafer forms a capacitor dielectric where the time dependence of the discharge depends on the resistivity.

Mu-tau products in new materials

Compound semiconductors often exhibit low mobilities - particularly holes - and short carrier lifetimes.

In order to maximise the induced signal (CCE), both the field strength $E$ and the mu-tau product $\mu \tau$ must be maximised:

$$CCE = \frac{Q}{Q_0} = \frac{\lambda}{d}$$

$$\lambda = \mu \tau E$$

Semi-insulating materials are often compensated by doping.

Requirements for new materials are typically:

- **high purity material**, to minimise residual impurity concentration
- **minimal** doping to avoid over compensation and maximise lifetimes
- well-controlled doping, **uniform** over the wafer surface

Radioisotope spectroscopy routinely gives CCE - *spatially resolved methods give CCE imaging*

$\Rightarrow$ Correlation with CCE imaging and material uniformity/properties
Poor hole transport affects gamma ray spectroscopy

Low hole mu-tau values cause depth-dependent charge collection efficiency

⇒ ‘hole tailing’ in CdZnTe shows characteristic asymmetric gamma ray peaks

For MIPs, severely reduced hole transport causes:
⇒ reduced S/N ratio
⇒ depth-dependent signals could degrade position resolution
Mobility-Lifetime products

Mobility-lifetime products are normally measured from alpha particle spectra - cathode (anode) irradiation is sensitive to electron (hole) transport.

Generally:

\[
\text{CCE} = \frac{Q}{Q_0} = (\mu_e \tau_e + \mu_h \tau_h)E
\]

The Hecht equation is used, eg. for cathode irradiation with alphas:

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

Hence fitting relative peak position as a function of electric field extracts \( \mu_e(h) \tau_e(h) \) for cathode and anode irradiation respectively.
Alpha particle CCE in InP detectors

Temperature dependent CCE was measured for electrons and holes in InP detectors

AXT material
Hole CCE

electron mobility
hole mobility

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Different InP samples show variations in $\mu\tau$ values over a 50x range - reflecting the material purity and Fe doping concentration.
Polycrystalline Materials

Some promising materials are truly polycrystalline, and have the potential for large area sensors:

- CVD diamond, supplied as free-standing films with thickness of typically 50 - 300 μm
- Polycrystalline amorphous silicon, CdTe and HgI₂

CVD diamond has been studied extensively by the HEP community:
- excellent radiation hardness
- minimal leakage currents, low noise
- robust technologies for contacts and bonding
- charge signal per MIP is low
- charge trapping can cause CCE <100%
- cost for large area detectors
Ion Beam imaging of polycrystalline materials

Charge transport uniformity is particularly important for polycrystalline materials, eg. a-Si and CVD diamond. Ion Beam imaging provides micron resolution imaging of CCE, allowing correlation of detector performance to material properties.

Unbiased substrate

Inter-electrode gap $L \approx 100 \mu m$

Typical $\lambda \approx 20-100 \mu m$

Charge drift

Negative Bias Signal Output

Ground
The Surrey Ion Beam Microprobe

3 MeV protons or 6 MeV alpha particles, with event rates on the sample of 100 Hz - 1 kHz

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Scanning of CCE vs depth using lateral Ion-beam induced charge microscopy

Image of CCE using 1µm resolution 2MeV scanning proton beam

Pulse height spectra as a function of depth

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IBIC imaging of diamond with 2 MeV protons

The Surrey University microprobe performs Ion Beam Induced Charge (IBIC) imaging with a 1 micron resolution 6 MeV proton beam.

IBIC maps show ‘hot spots’ at electrode tips due to concentration of the electric field.
Simultaneous SEM and CL images show the morphology of a small region of a diamond strip detector.

The large crystallite is \(~120\mu m\) wide by \(~150\mu m\) high, and is positioned centrally between two electrodes.

The IBIC data clearly follows the morphology of the grain and shows charge transport terminating at the grain edges.
Intra-crystallite charge collection efficiency

IBIC system records a full pulse height spectrum at each pixel in the image.
100% CCE is observed within a single large crystallite that lies between two electrodes.

We see no evidence for gain mechanisms giving >100% CCE.
For 50 - 100 µm spatial resolution, laser scanning provides a convenient mechanism to map CCE and E-field profiles. Sub-bandgap IR probes the bulk, red lasers tend to probe the surface.

In this study, charge transport in partially-depleted GaAs detectors used lateral IR laser scanning.
Scanning optical bench

- Imaging camera
- Cryostat
- XY scanning table
- 850nm laser
- 300ns pulse

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Laser pulse shapes

T=273K, 20V

At 60µm from cathode:
no slow component to signal

At 180µm from cathode:
charge drift times are ~350µs

IR laser spot appears to have significant beam waist
Pulse risetime and amplitude vs bias

T=223K, V=90V

Position from Schottky (µm)

Amplitude

Signal Risetime (µs)

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5

0.0 0.5 1.0 1.5 2.0

0 20 40 60 80 100 120 140 160 180 200 220
Interaction close to the anode - inside depletion region
Interaction close to n+ substrate - in low field region
Conclusions

A range of optical, electrical and radiation techniques can be used to characterise new materials, specifically:

- material uniformity
- mu-tau products and CCE
- radiation hardness and characterisation of radiation-induced traps
- robust contact technologies

In the framework of RD50 materials such as SiC, a-Si and GaN are of particular interest.

Supply of high quality semi-insulating material from commercial vendors needs to be developed (e.g., SiC from Cree, GaN from Kymatech).

Fabrication of standard test structures and protocols for characterisation will allow direct comparison between institutes.

Collaboration with the ‘material characterisation’ sub-group will be vital.
Facilities in the Group

**Semiconductor detector laboratories:**
- Optical and electrical characterisation (PICTS, DLTS, PL, Raman)
- Detector mapping systems using microfocus lasers and collimated radioisotopes

**Ion Beam accelerator lab:**
- new 6 MeV proton, 3 MeV alpha particle accelerator
- sub micron resolution nuclear microprobe for detector imaging
- implantation and damage studies

**Device Fabrication:** semiconductor clean room, photolithography

**Device simulation:** 3D device modelling (Silvaco), MCNP, EGS4, Geant

**X-ray laboratory:** X-ray sources 50-200 keV, Philips Fluorex monoenergetic X-ray source, image intensifiers, X-ray μ–CT

**Radiation Physics:** >130 sources including:
- Am:Be neutron sources (up to 18 GBq)
- $^{60}\text{Co}$ ‘hot spot’ irradiator (1.9 TBq), ~2.5 kGy per day
Polycrystalline Mercuric Iodide Hgl₂

Single crystal Hgl₂ is attractive for gamma ray imaging due to high atomic number (80, 53) with ρ ~10¹³ Ωcm
Electron µτ ~10⁻⁴ cm²/V, but hole µτ is ~10⁻⁶ cm²/V

Polycrystalline Hgl₂ offers a low cost large area detector material, fabricated by screen printing of ceramic:
- electron µτ ~ 10⁻⁷ cm²/V
  (cf. diamond µτ ~ 10⁻⁶ cm²/V, selenium µτ ~ 10⁻⁵ cm²/V)

Evaporated material gives better charge transport, and shows columnar growth similar to CVD diamond

Other single crystal materials

Other bulk materials show promise for single element radiation detectors, but are not yet ready for commercial use:

**Gallium Nitride**

Single crystals of GaN have been developed in Warsaw

Grown in liquid Ga with N₂ over pressure: 20 kbar and 1700 ºC

Undoped
⇒ n-type at 10¹⁹ cm⁻³, p ~ 10⁻³-10⁻² Ωcm

Grown with 0.5% Mg
⇒ semi insulating, p ~ 10⁴-10⁶ Ωcm

SI material has residual concentration of ~10¹⁶ cm⁻³ - very poor charge transport

S. Porowski, J Cryst Growth 189/190 (1998) 153-158