Time-Resolved Ion Beam Induced Charge Imaging at the Surrey Microbeam

P.J. Sellin¹, A. Simon², A. Lohstroh¹, D. Hoxley¹

¹Department of Physics
²Surrey Centre for Ion Beam Analysis
   University of Surrey
   Guildford, UK

p.sellin@surrey.ac.uk
Introduction

- Ion Beam Induced Imaging (IBIC) - applications to semiconductor detector physics
- The new IBIC facility at the Surrey Tandetron
- IBIC imaging of charge transport in new semiconductor materials for radiation detectors:
  - polycrystalline CVD diamond
  - single crystal CdTe/CdZnTe
- Digital IBIC - a new technique for time resolved imaging and spectroscopy
- Conclusions
New semiconductor materials for radiation imaging detectors

The development of new compound semiconductor materials for radiation imaging detectors, for use in:

- medical X-ray imaging (high Z semiconductors: CdTe, HgI$_2$)
- particle physics tracking (high radiation hardness: GaN, SiC)
- medical dosimetry (tissue equivalence: diamond)

Characterisation of material and devices uses ion beam induced imaging (IBIC) for micron-resolution imaging of:

- Material uniformity
  - monocrystalline vs polycrystalline
  - mechanical defects, distribution of electrical traps

- Electrical properties
  - Electric field profile and uniformity

- Charge transport and trapping
  - Mobility-Lifetime products (µt) for electrons and holes
  - Charge Collection Efficiency: CCE $\Rightarrow$ energy resolution
The Surrey microbeam

- ion beam
- scanning unit
- quadrupole triplet
- chamber with temperature-controlled sample stage
The microbeam chamber

beam axis

RBS detector

microscope port

X-ray detector

port for IBIL optical fibre

Faraday cup
Charge (IBIC) and luminescence (IBIL) data can be acquired simultaneously:

- high spatial resolution
- single event detection (~1 kHz event rate on sample)
- true bulk measurement

Incident ion beam can be orthogonal or lateral:
- orthogonal: for uniformity and single carrier CCE
- lateral: for electric field probing
Ion Beam imaging of polycrystalline materials

Charge transport uniformity is particularly important for polycrystalline materials, eg. 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

Ground

Negative Bias

Signal Output
IBIC imaging of diamond with 2 MeV protons

The Surrey University microprobe performs Ion Beam Induced Charge (IBIC) imaging with a 2 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 ~120µm wide by ~150µm 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.
Pulse height spectra vs. bias voltage

Single crystallite spectrum

Channel Number

Counts

Charge Collection Efficiency (%)

- 50 V
- 100 V
- 200 V
- 370 V

100% CCE is observed within a single large crystallite that lies between two electrodes.

We see no evidence for gain mechanisms giving >100% CCE.
IBIC studies of CdTe and CdZnTe

CdTe and CdZnTe are high Z compound semiconductors, of interest for X-ray imaging detector applications.

Poor hole transport causes position-dependent charge collection efficiency

⇒ ‘hole tailing’ characteristic of higher energy gamma rays in CdZnTe

CdTe suffers from Te precipitates in the bulk causing local trapping centres

‘monocrystalline’ CdZnTe

\[ \text{\( ^{241}\text{Am} \) (gain=100)} \]

\[ \text{\( ^{57}\text{Co} \) 122 keV (gain=200)} \]

\[ \text{\( 14 \text{ keV} \)} \]

\[ \text{\( 136 \text{ keV} \)} \]
IBIC of monocrystalline CdZnTe

Orthogonal imaging of charge amplitude in a CdZnTe detector:

Detector is 2 mm thick, with irradiation of the cathode
⇒ signal is due only to electron transport

Mean pulse height:
-250 V, 250 K

Selected channels
(1726-1768)
-250 V, 250 K

Selected channels
(1789-1827)
-250 V, 296 K
Lateral IBIC on CdZnTe

Pulse height spectra as a function of depth

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Digital IBIC techniques

Conventional analogue pulse processing measures signal amplitude only, to obtain the event energy:

In digital IBIC, measuring the preamplifier pulse shape gives charge drift times, and hence mobility, carrier lifetimes etc.

8 bit, 500MS/s, 2ns resolution
Time resolved digital IBIC

An 8-bit 500 MS/s waveform digitiser replaces a conventional peak sensing ADC - dedicated software captures the complete pulse of each event and analyses the pulse amplitude and risetime (2ns resolution).

Analysis of ion-beam induced pulses in CdZnTe allows separation of electron and hole components.

Time resolved IBIC imaging produces maps of electron and hole lifetimes, mobilities, and amplitudes without ballistic deficit.
Energy resolution of digital IBIC

Energy resolution measurement of 8-bit flash ADC, using a triple-alpha peak and a silicon surface barrier detector

FWHM = 1.5%
IBIC pulses from CdZnTe

2 typical pulse shapes from CdZnTe data file:

(a) close to cathode: fast signal from electrons, risetime ~0.5 µs.

(b) further from cathode: slower signal with a visible hole component, risetime ~1.5 µs.
Comparison of digital and analogue IBIC

Lateral IBIC maps, showing CCE variation from the cathode

- Digital IBIC map
  - 350k events in file, 560 MB

- Analogue IBIC map, with a shaping time of 0.5 µs.

P.J. Sellin et al., “Digital IBIC - new spectroscopic modalities for Ion Beam Induced Charge imaging”, submitted to NIM A.

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Digital IBIC risetime from CdZnTe

Digital amplitude and risetime maps from one IBIC data file:

The 10-90% risetime is displayed in $\mu$s.

X-projection slices at $Y=14$ of amplitude and risetime show a clear anti-correlation. Analysis is still ongoing to determine carrier lifetime and mobility values.
Conclusions

Micrometer resolution IBIC imaging is a powerful technique for the evaluation of electrical and charge transport properties in bulk semiconductor materials.

IBIC at Surrey has concentrated on new materials for radiation imaging detectors:

- high resolution studies of intra-crystallite charge trapping and material structure in CVD diamond
- correlation of mechanical defects and precipitates in CdTe with electrical properties
- lateral IBIC of electron and hole signals in CdZnTe

Time resolved digital IBIC is a new technique developed at Surrey:

- spectroscopic imaging of pulse risetime and amplitude to produce maps of mobility and carrier lifetime
- low temperature effects - trap activation energies

Time resolved digital luminescence imaging is currently under development.