Spectroscopic performance of High-Z Sensor Materials

Paul Sellin
Department of Physics
University of Surrey, Guildford, GU2 7XH, UK

p.sellin@surrey.ac.uk
Contents

Overview of High-Z detector materials

Charge transport and spectroscopy

Signal formation in pixel detectors

Current status of key materials:

- CZT and CdTe
- GaAs
- TlBr
- Other materials
High-Z materials for gamma and X-ray detection

For gammas and X-rays, the detection efficiency is highly dependent on the atomic number ‘Z’ of the detecting material.

```
<table>
<thead>
<tr>
<th>Photon energy (keV)</th>
<th>Detection Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>200</td>
<td>Si</td>
</tr>
<tr>
<td>250</td>
<td>GaAs</td>
</tr>
<tr>
<td>300</td>
<td>CdTe</td>
</tr>
<tr>
<td>350</td>
<td>HgI₂</td>
</tr>
<tr>
<td>400</td>
<td>TlBr</td>
</tr>
<tr>
<td>450</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
</tr>
</tbody>
</table>
```

Calculated for 500 μm thick material

Compound semiconductors (e.g. GaAs or CdTe) have been increasingly developed for use as X-ray detectors.

These compounds provide moderately high-Z detector materials, eg. CdTe with $Z_{Cd} = 48$ and $Z_{Te} = 52$.

The ternary alloy CdZnTe (CZT) has almost identical detection efficiency.

As we have heard this morning, germanium is also a high-Z semiconductor which has unique requirements for cryogenic cooling.
Detection efficiency in thin detectors

For pixel detector applications at lower energies thin detectors provide sufficient detection efficiency. For example, CdTe is normally obtained with 0.5mm or 1mm thickness and has good efficiency for energies up to 50 keV:

The mean free path lengths of the Cd and Te K\(_\alpha\) and K\(_\beta\) fluorescence are long:
- 119\(\mu\)m and 62\(\mu\)m respectively
- High yields: 84.3% and 87.7%

This reduces the spatial and spectroscopic resolution of small pixel detectors with CdTe sensors

New sensor materials

The Klein chart shows the relationship between electron-hole pair creation energy (often called the ‘W value’) and bandgap:

There are many interesting candidate sensor materials, beyond CdTe/CZT and GaAs, eg:

- TlBr
- CdMnTe
- GaN
- Diamond

Resolution limits in real detectors

To optimise detector performance we should understand the various factors that limit spectroscopic resolution in real detectors:

- **Detection Efficiency**
  Photoelectric quantum efficiency is strongly dependent on Z. Compton Scatter reduces photopeak efficiency.

- **Fano Factor**
  Charge generation statistics limit detector resolution, defined by the Electron-Hole Pair creation energy and Fano factor.

- **Sensor polarisation**
  Time dependent changes in bulk electric field cause spectral degradation.

- **Fluorescence X-rays**
  Characteristic X-rays emitted from the detector material can cause escape events.

- **Charge Trapping**
  Incomplete charge transport reduces the signal amplitude and degrades resolution.

<table>
<thead>
<tr>
<th>Element</th>
<th>Z</th>
<th>K-edge [keV]</th>
<th>L1-edge [keV]</th>
<th>L2-edge [keV]</th>
<th>L3-edge [keV]</th>
<th>$\alpha_1$ [keV]</th>
<th>$\alpha_2$ [keV]</th>
<th>$d_{\alpha 1}$ [\mu m]</th>
<th>$d_{\alpha 2}$ [\mu m]</th>
<th>$\omega_K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>14</td>
<td>1.839</td>
<td>0.150</td>
<td>0.100</td>
<td>0.100</td>
<td>1.74</td>
<td>1.739</td>
<td>11.86</td>
<td>11.86</td>
<td>0.041</td>
</tr>
<tr>
<td>Ga</td>
<td>31</td>
<td>10.367</td>
<td>1.298</td>
<td>1.142</td>
<td>1.115</td>
<td>9.25</td>
<td>9.225</td>
<td>40.62</td>
<td>40.28</td>
<td>0.505</td>
</tr>
<tr>
<td>Ge</td>
<td>32</td>
<td>11.110</td>
<td>1.426</td>
<td>1.259</td>
<td>1.228</td>
<td>9.89</td>
<td>9.856</td>
<td>50.85</td>
<td>50.40</td>
<td>0.548</td>
</tr>
<tr>
<td>As</td>
<td>33</td>
<td>11.867</td>
<td>1.527</td>
<td>1.359</td>
<td>1.323</td>
<td>10.54</td>
<td>10.508</td>
<td>15.62</td>
<td>15.47</td>
<td>0.566</td>
</tr>
<tr>
<td>Cd</td>
<td>48</td>
<td>26.711</td>
<td>4.018</td>
<td>3.727</td>
<td>3.538</td>
<td>23.17</td>
<td>22.984</td>
<td>113.2</td>
<td>110.7</td>
<td>0.836</td>
</tr>
<tr>
<td>Te</td>
<td>52</td>
<td>31.814</td>
<td>4.939</td>
<td>4.612</td>
<td>4.341</td>
<td>27.44</td>
<td>27.202</td>
<td>59.32</td>
<td>57.85</td>
<td>0.873</td>
</tr>
</tbody>
</table>

R. Ballabriga, JINST 11 (2016) P01007
A radiation interaction creates carriers which are either free and/or excitonically bound, determined by the exciton binding energy ($E_B$), sample temperature and carrier density.

Free carriers can either diffuse or drift, depending on the presence of an electric field, with associated mobilities $\mu_n$ and $\mu_p$.

Carriers have an average recombination lifetime $\tau$ before they recombine, during which they drift or diffuse.

The lifetime is determined by the recombination rate, a result of radiative and non-radiative processes.
Time of Flight (TOF)

To directly measure drift mobility $\mu$ the Time of Flight (TOF) method is used:
- the drift time of the electrons and/or holes are directly measured from the pulse shape induced in the external circuit
- either current pulses or charge pulses can be used

Drift velocity is related to $\mu$, such that:

$$v_{dr} = \mu E = \frac{d}{t_{dr}}$$

Electrons and holes are generated using a fast laser pulse (or alpha particles).

TOF relies on two assumptions:
- The measured carrier drift time is not limited by trapping, ie. at least some of the carriers reach the electrodes, so the drift distance is known.
- The field strength is uniform through the device.

For single carrier transport, the mobility is given by:

$$\mu = \frac{d^2}{\tau_{dr} V}$$
In its general form, a laser pulse is used to excite charge carriers

Electrons and hole drift under the influence of an applied field

A photocurrent pulse is measured in an external circuit

The form of the current pulse:

**Plateau region**, as the carriers drift through the semiconductor with a drift time $t$

**Tail region**, there can be a range of drift times across the semiconductor, with a mean drift time $t$
Room temperature mobility in CdTe

Mobility is extracted from drift time data as a function of field strength. This can be graphed in many different forms:

- velocity vs field, gradient is $\mu$
- drift time vs $1/V$, gradient is $d^2/\mu$

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

Drift mobility of electrons and holes measured in CdTe

Z. Burshtein et al, APL 63 (1993) 102-104
Mobility and Trapping

Both electron and hole mobility can be affected by the presence of traps in the material.

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

- \( \mu_e (300K) \)
- \( \mu_h (300K) \)
- \( \tau_e \)
- \( \tau_h \)

800-1100 cm\(^2\)/Vs 60-90 cm\(^2\)/Vs  \( \sim 1 \) \( \mu \)s  \( \sim 1 \) \( \mu \)s

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

In CdTe electron trapping is associated with a complex defect: \( [V_{Cd} 2Cl_{Te}]^0 \)

2 Cl donors on Te site + Cd vacancy

Hole trapping is associated with shallow Cd-vacancies (\( V_{Cd} \)) and A-Centers (\( V_{Cd-donor} \) complex), acting as single and double acceptors.
Drift mobility in CdTe

TOF mobility measurements of CdTe vs Temperature show the dominant conduction mechanisms:

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

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

**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

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

Consistent with complex

\[ [V_{Cd}2Cl_{Te}]^0 \]

Drift mobility at high charge injection

At high charge injection carrier mobility drops due to increased scattering between electrons and holes.

This effect has been observed in X-ray detectors used in high beam fluxes, such as at synchrotrons.

The effective mobility $\mu$ is a combination of:

- the carrier-carrier limited mobility $\mu_{cc}$
- the mobility due to conventional scattering mechanisms such as phonon and impurity scattering, $\mu_0$:

Using Mathiessen’s rule, these contributions are combined as:

$$\frac{1}{\mu} = \frac{1}{\mu_0} + \frac{1}{\mu_{cc}}$$

The data shows a significant decrease in effective mobility in diamond for charge densities above $10^{15}$ cm$^{-3}$.
Mobility-Lifetime product

For a detector the charge drift distance $\lambda$ is a fundamental measure of material quality, often measured by the mobility-lifetime product $\mu \tau$, where:

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

The Hecht plot shows the increase in the mean pulse height as a function of bias voltage.

For a single carrier type (either electrons or holes) we fit the Hecht plot using:

$$\eta = \frac{\mu \tau \cdot V}{d^2} \left[1 - \exp\left(-\frac{d^2}{\mu \tau \cdot V}\right)\right]$$

and hence obtain effective $\mu \tau$ value for the material.

In a pixel detector the Hecht equation is not accurate and corrections are required.
Induced signals – planar detector

In a planar detector, where $N_0$ electron-hole pairs are generated per event, the induced charge $dQ$ is expressed in terms of electron and hole drift lengths ($dx_e$ and $dx_h$) respectively:

$$dQ = \frac{qN_0}{d}(dx_e + dx_h)$$

Ramo’s theorem:

The separate contributions from holes and electrons are combined - both carrier types travel completely across the detector.

⇒ for a point interaction at a depth half-way through a detector, the electrons and holes contribute equally to the total induced charge.

In a planar detector the same induced signal is generated at either electrode (but inverted).
Pixel Detectors and Weighting Field

For pixel detectors the signal induced in any particular pixel is not the same as the signal induced on the planar contact. We need to consider how the drifting charges induce a current in all the electrodes. The Weighting Field $E_W$ describes the electrostatic coupling between a moving charge and the sensing electrode.

The induced current is given by:

$$i = -q E_W \cdot v$$

where $v$ is the drift velocity of the moving charge.
Pixel weighting fields (1)

Consider a pixel detector: the weighting field $E_W$ is highly non-uniform

Here the charge is drifting away from the pixel:

- charge $q$ drifts in the physical field
- the current pulse decreases, due to reducing $E_W$
- assumes that the drift velocity is constant

If the charge drifts the complete distance, the total induced charge is $\int i(t) dt = q$

* The Weighting Field $E_W$ is the gradient of $\Phi_W$ - not related to the physical field

Pixel weighting fields (2)

In the neighbouring pixel the induced current pulse is complex:

Since:

\[ i = -q E_w \cdot v \]

- the current pulse changes sign as the charge drifts across the device
- if the charge crosses the complete device, the induced charge is zero, i.e.

\[ q = \int i(t) dt = 0 \]

but there is a measurable current pulse!

These induced neighbour signals can produce 2nd order effects in pixel detectors.
Hecht plot for small pixels

In a small pixel detector, the weighting field introduces a significant correction to how the induced signal couples to the pixel electrode.

In this case the classical Hecht equation is not applicable, and a modified expression must be used:

\[
Q(U) = Q_0 \cdot \frac{d}{\mu \tau \cdot (U - U_0)} \cdot \int_0^d w(x) \cdot e^{-\frac{x-d}{\mu \tau (U-U_0)}} dx + e^{-\frac{d^2}{\mu \tau (U-U_0)}}
\]

where:
- \(Q_0\) is the charge generated
- \(d\) is the detector thickness
- \(U_0\) is a bias offset threshold
- \(w(x)\) is the pixel weighting potential as a function of distance \(x\) from the cathode

The modified Hecht expression tends towards a “S shape” at small pixel sizes.

At low voltage a significant amount of charge is trapped before nearing the pixel, and the induced charge is less.

P. Smolyanskiy et al, Properties of GaAs:Cr Timepix detectors, 13 (2018) T02005

Fano limited energy resolution

For the highest quality detector materials, the detector resolution can approach the intrinsic limit imposed by the Fano resolution.

The total measured energy resolution \( \Delta E \) has the form:

\[
\Delta E = 2.35 \sqrt{\sigma_F^2 + \sigma_N^2 + \sigma_C^2}
\]

where:
- \( \sigma_F^2 \) is variance due to Fano noise \((\sigma_F^2 = FEw)\)
- \( \sigma_N^2 \) is variance due to Electronic noise from the leakage current and preamplifier \((\sigma_N \text{ is independent of } E)\)
- \( \sigma_C^2 \) is variance due to trapping and incomplete charge collection \((\sigma_C \propto E)\)

Data taken from a GaAs detector pixel with a resolution of 700 eV at 98 keV

A. Owens et al, JAP 90 (2001) 5376
Fano limited energy resolution (2)

At high detector resolution, small affects can be observed as a function of bias voltage:

At 100V: resolution at -40C is 375 eV FWHM. At room temperature, 660 eV FWHM

A. Owens et al, JAP 90 (2001) 5376
Overview of CZT and CdTe

CZT is the dominant “high Z” detector materials, and the commercial availability of high quality “single crystal” material has improved significantly

CZT crystal growth is complex! Generally crystal growers require:

- Radial uniformity through the crystal (wafer)
- Low impurity & defect concentrations
- No grain boundaries or mechanical defects

In this poor quality crystal, the “last-to-freeze” region is at the top of the crystal.

The material in this region is highly polycrystalline, and contains voids.

It is useless for electronic devices.
CZT crystal growth & yield

Early results in CZT crystal growth struggled to produce large-volume high quality material. Issues include:

- Impurities limit good charge transport
- Material is polycrystalline; the desired single-crystal regions must be cut from each wafer
- High defect concentration such as dislocations, “twins” and tellurium precipitates

IR microscopy used to assess Te inclusions, formed from Te-rich melt:

- Mainly triangular or polyhedron shape
- Often located along grain boundaries
- Te inclusions act as trapping sites, over a large range

Pixel detectors fabricated from CZT

Some of the best quality CZT crystal is produced for use in pixellated gamma ray imaging detectors – uses include medical imaging and security detection. Excellent charge transport is now available, e.g. resistivity $\rho=3\times10^{11}\Omega\text{cm}$, and $\mu\tau_e=1.8\times10^{-2}\text{ cm}^2/\text{V}$.

4x4 pixellated devices have shown very good resolution $\Rightarrow 1.35\%$ FWHM at 662 keV.

CZT pixel detectors for space imaging

SWIFT CZT detector array:

- Contains 32768 elements of 4x4x2mm CZT, forming an array detector 1.2 x 0.6 m
- The coded aperture mask is ~54,000 lead tiles

The INTEGRAL project used a similar CdTe detector array with 16384 CdTe pixels,

The typical performance of a single CZT module is 3.3 keV FWHM at 60 keV (5.5% FWHM):
Current status of CdTe and CZT

Commercial availability of high quality CdTe and CZT remains with a small number of manufactures. The leading supplier of CdTe remains Acrorad (Japan) and the 2 dominant CZT suppliers are Redlen (Canada) and eV Products/Kromek (USA).

CdTe is normally used at only 0.5mm thickness to avoid field instability issues. Spectra show pixel energy resolution of 1.6 keV at 122 keV and 5.0 keV at 511 keV.

CZT is now mainly commercially grown by the Travelling Heater Method (THM) which was pioneered by Redlen.

Whole wafer material is increasingly becoming available, compatible with conventional industrial processing.

3 inch diameter CZT wafer grown using THM growth and fabricated using wafer level processing (WLP).
CZT spectroscopy at low rates

Various groups have reported good photon resolution from thin CZT, typically optimised for energies below 150 keV.

The HEXITEC collaboration have demonstrated spectroscopic pixel detectors on 2mm thick Redlen CZT with a 250μm pitch. The typical single pixel resolution is 1.8 keV FWHM:

CZT performance at high flux

Redlen offer a variant of their THM grown CZT for use in high flux environments which has reduced impurity and defect concentrations. The objective is to minimise charge trapping and so reduce polarisation effects at high flux.

The main improvement has been in hole transport, with hole \( \mu T \) improving from \( \sim 10^{-5} \) to \( \sim 10^{-4} \) cm\(^2\)/Vs. Stable performance is seen at count rates of 200 Mcps/mm\(^2\).

<table>
<thead>
<tr>
<th>High Flux CdZnTe</th>
<th>( \mu_e \tau_e ) (( \times 10^{-4} ) cm(^2)/V)</th>
<th>( \mu_e ) (cm(^2)/V/s)</th>
<th>( \tau_e ) (( \times 10^{-6} ) s)</th>
<th>( \mu_h \tau_h ) (( \times 10^{-4} ) cm(^2)/V)</th>
<th>( \mu_h ) (cm(^2)/V/s)</th>
<th>( \tau_h ) (( \times 10^{-6} ) s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdZnTe Standard</td>
<td>11 ± 6</td>
<td>940 ± 190</td>
<td>1.2 ± 0.8</td>
<td>2.9 ± 1.4</td>
<td>114 ± 22</td>
<td>2.5 ± 1.4</td>
</tr>
</tbody>
</table>

Direct beam tests using a tungsten X-ray tube at 60kvp and 3mm Al filter.

Photon counting pixel detector with 1mm pixel pitch, at up to 4 Mcps/pixel.

Germanium as the ‘gold standard’

Germanium pixel detectors remain the ‘gold standard’ for high resolution imaging. Resolution near to the Fano limit is obtained by:

- Cryogenic cooling to suppress dark currents
- A small W value => creation of many electron/hole pairs per MeV
- Extremely high purity material with excellent energy resolution

\[
\begin{align*}
\text{18 keV photons incident on a Ge pixel, showing the } & \text{k}_\alpha \text{ and } \text{k}_\beta \text{ escape peaks at } E_{\text{PK}} = 9.8 \text{ keV and } E_{\text{PK}} = 11.0 \text{ keV} \\
\end{align*}
\]
Early work on GaAs detectors

- High resolution performance was demonstrated in epitaxial GaAs, developed by ESTEC (ESA) in 2001
- Fano-limited performance was achieved, with full depletion of \(~40\mu\text{m}\) of GaAs
- This material had some availability through Metorex (Finland)

A. Owens et al, JAP 90 (2001) 5376
Recent results from GaAs

The conventional method of growing semi-insulating GaAs wafer is by Liquid Encapsulated Czochralski (LEC) growth. This materials has several problems:

- High leakage currents
- Short carrier lifetimes, due to deep level traps such as “EL2”
- Non-uniform electric field distributions.

Over the last 20 years the group at Tomsk have developed a chromium-compensated method to produce SI GaAs with good charge transport properties. The sensitive thickness of these wafers is ~1mm.

Energy response function of 500 μm thick GaAs:Cr coupled to Medipix3 at 55μm pixel pitch.

The escape peak at ~15 keV is just visible in the 25 keV data.

Charge transport properties of GaAs:Cr

GaAs:Cr was bonded to Timepix to assess the material performance. At 20°C the material resistivity is ~10^8 Ωcm (equivalent to 0.05 nA per pixel).

Electron μτ was measured using 15.7 keV photons from zirconium, with an average range of 25 μm from the cathode contact.

The electron μτ distribution from all pixels was well defined, with a mean μτ value of 1.1x10^{-4} cm^2/V

P. Smolyanskiy et al, JINST 13 (2018) T02005
Comparison of GaAs with other materials

The spectroscopic HEXITEC pixel detector has produced a direct comparison of the spectroscopic performance GaAs:Cr against CdTe

Room temperature $^{241}\text{Am}$ single pixel spectra from 250um pitch HEXITEC detectors after charge sharing discrimination.

The 0.5mm GaAs:Cr sensor performs very well at energies <30keV. It also has reduced escape peaks due to the lower energy of the Ga and As fluorescence X-rays.

At higher energies depth of interaction effects have a negative effect on the spectroscopic performance due to the increased contribution of holes.
Early TlBr spectroscopy

TlBr is an interesting detector material at very high Z (81 and 35) and with high density. It’s a specialist material with very limited current commercial availability.

Cooling is necessary to ensure field stability. Figure shows charge collection efficiency vs inverse bias voltage at -8°C. Electron $\mu\tau = 1.9 \times 10^{-4}$ cm$^2$V$^{-1}$

Energy spectrum acquired from 20 keV photons. The escape peaks are from Br $K_\alpha$, $K_\beta$ and from Tl $L_\alpha$, $L_\beta$ and $L_\gamma$.
Russian-grown TiBr material

TiBr ingots grown by Bridgeman-Stockbarger method. TiBr planar detector, thickness 2mm, at T=-40°C

Fe-55

ΔE = 840 eV

Am-241

ΔE = 1.4 keV

Co-57

ΔE = 2.1 keV

Cs-137

ΔE = 7.1 keV

TLBr detectors from RMD

<table>
<thead>
<tr>
<th>Detector</th>
<th>Date</th>
<th>Overall Resolution</th>
<th>Best Pixel Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>58A3R</td>
<td>June 2010</td>
<td>1.32%</td>
<td>0.93%</td>
</tr>
<tr>
<td>58A4L</td>
<td>May 2010</td>
<td>1.98%</td>
<td>1.04%</td>
</tr>
<tr>
<td>48A2R</td>
<td>March 2011</td>
<td>4.26%</td>
<td>3.16%</td>
</tr>
<tr>
<td>935-16B1R</td>
<td>May 2011</td>
<td>0.97%</td>
<td>0.73%</td>
</tr>
<tr>
<td>935-16B1L</td>
<td>June 2011</td>
<td>1.45%</td>
<td>1.07%</td>
</tr>
<tr>
<td>44B2L</td>
<td>September 2011</td>
<td>2.64%</td>
<td>1.81%</td>
</tr>
<tr>
<td>70BA1L</td>
<td>December 2011</td>
<td>1.76%</td>
<td>1.22%</td>
</tr>
<tr>
<td>70BA1R</td>
<td>December 2011</td>
<td>1.19%</td>
<td>1.05%</td>
</tr>
<tr>
<td>47AR</td>
<td>April 2012</td>
<td>1.89%</td>
<td>1.09%</td>
</tr>
<tr>
<td>44A12R</td>
<td>June 2012</td>
<td>4.28%</td>
<td>2.94%</td>
</tr>
<tr>
<td>43A4R</td>
<td>September 2012</td>
<td>3.87%</td>
<td>2.89%</td>
</tr>
<tr>
<td>70BA2R</td>
<td>September 2012</td>
<td>2.98%</td>
<td>2.04%</td>
</tr>
<tr>
<td>44AB1R</td>
<td>September 2012</td>
<td>1.82%</td>
<td>1.37%</td>
</tr>
</tbody>
</table>

More recently TLBr has been extensively developed by RMD.

Results from TLBr pixel detectors have been reported, e.g., 3x3 pixel arrays on a 5mm pixel pitch.

High bias voltage of 1000V is used to maximise electron transport.

5mm thick pixel detectors operated at -20°C to minimise field polarisation.

Depth-corrected, pixel-by-pixel energy spectra for detector.

The energy resolution in the best pixel is 0.77% FWHM at 662 keV.

W. Koehler et al, NSS/MIC Conference Record 2012, R11-3
Other Materials: High-Z polycrystalline

Polycrystalline thick film high-Z (Z≥80) materials have been extensively studied for X-ray imaging applications. Their main potential is for large areas.

<table>
<thead>
<tr>
<th>Material</th>
<th>Z</th>
<th>density</th>
<th>mobility</th>
<th>$E_G$</th>
<th>resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Iodides:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hgl$_2$</td>
<td>80/53</td>
<td>6.4</td>
<td>50</td>
<td>2.1</td>
<td>$10^{13}$</td>
</tr>
<tr>
<td>PbI$_2$</td>
<td>82/53</td>
<td>6.2</td>
<td>53</td>
<td>2.5</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>BiI$_3$</td>
<td>83/53</td>
<td>5.8</td>
<td>48</td>
<td>1.7</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td><strong>Bromides:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TlBr</td>
<td>81/35</td>
<td>7.6</td>
<td>75</td>
<td>2.7</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>PbBr</td>
<td>82/35</td>
<td>-</td>
<td>-</td>
<td>2.5-3.1</td>
<td>-</td>
</tr>
<tr>
<td><strong>Oxides:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PbO</td>
<td>82/8</td>
<td>9.5</td>
<td>-</td>
<td>1.9</td>
<td>-</td>
</tr>
</tbody>
</table>

The iodide and bromide families have many suitable candidates:
- Detailed studies of Hgl$_2$ and PbI$_2$ have been carried out
- Hgl$_2$ shows superior dark current and charge transport properties
- Promising results from polycrystalline TlBr
Large-area epitaxial CdTe grown by MOVPE

Metal-organic vapor-phase epitaxy (MOVPE) is capable of growing large-area epitaxial thick films, eg. up to 200 μm thick

- MOVPE growth of CdTe or CZT on GaAs or Si substrates, produces uniform mono-crystals
- GaAs substrates provide a good lattice match and strong adhesion

- Iodine-doped buffer layer grown onto substrate (10^{17} \text{ cm}^{-3})
  Prevents Ga diffusion into epitaxial CdTe layer
- undoped p-type epitaxial CdTe layer grown at 415-560 °C
- rectifying p-n junction formed at the CdTe/GaAs interface

M. Niraulla et al, J. Elec Mat 34 (2005) 1-5
Epitaxial CdTe pixel sensor

First prototypes have been reported for large area MOVPE CdTe pixel detectors

8 x 8 pixel array on 1.27mm pixel pitch, with mechanical grooves to define each pixel. The CdTe sensor lay is 100 - 260 μm thick.

Leakage current are high for this device, ~150nA/cm$^2$ at 150V bias.

Modest spectral performance with a broad 59 keV photopeak at room temperature
Conclusion

Detector materials are one essential part of our “fishing kit” for synchrotron detectors.

In materials development that is always a compromise between performance, cost, and timescale.

Driven by the medical imaging market, CZT material has now started to deliver real detectors with “good enough” energy resolution.

Operation of CZT at high rates continues to be a challenge, which must be solved by the medical and security markets.

Other high-Z materials are now providing niche solutions, eg: germanium, GaAs, and perhaps vapour phase materials.