Edgeless semiconductor sensors for large-area pixel detectors

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Outline

• Introduction to Medipix detectors
• From single assembly to large-area detectors
• Edgeless sensors:
  – Active-edge
  – Slim-edge
Hybrid pixel detector

**Semiconductor sensor:**
Silicon, gallium arsenide, cadmium telluride

**Bump bonds:**
Copper/tin, Indium/tin

**Read-out chip:**
Medipix, Timepix, Medipix3

Photon or charged particle

Sensor pixel

Bump interconnect

Read-out pixel
Why Medipix?

- Photon counter
  - High signal-to-noise ratio
  - Noise rejection
- High functionality per pixel
  - Timepix: counting, ToT, ToA
  - Threshold equalisation
  - Dark current compensation
Medipix3 features ~1600 transistors per pixel:

- Charge summing circuitry
- Simultaneous counting and read-out → no dead time
- Energy dispersive mode: 7 energy bands
## Mono-crystalline sensors vs. amorphous selenium

### Energy [keV]

<table>
<thead>
<tr>
<th></th>
<th>a-Se</th>
<th>GaAs</th>
<th>CdTe</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Z</strong></td>
<td>34</td>
<td>31;33</td>
<td>48;52</td>
<td>14</td>
</tr>
<tr>
<td><strong>e⁻ mobility (cm²/Vs)</strong></td>
<td>$3 \times 10^{-3}$</td>
<td>8500</td>
<td>1100</td>
<td>1500</td>
</tr>
<tr>
<td><strong>h⁺ mobility (cm²/Vs)</strong></td>
<td>$1 \times 10^{-1}$</td>
<td>400</td>
<td>100</td>
<td>450</td>
</tr>
<tr>
<td><strong>Eh-pair creation energy (eV)</strong></td>
<td>20 – 50</td>
<td>4.26</td>
<td>4.43</td>
<td>3.6</td>
</tr>
</tbody>
</table>

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**Figure:**

- **Si**
- **GaAs**
- **CdTe**
- **a-Se**

**Y-axis:** Attenuation fraction

**X-axis:** Energy [keV]
Active detector area

- High-energy physics:
  - Close-to-beam/forward physics experiments (TOTEM, LHCb Velo) x200

- X-ray imaging:
  - Digital radiography detectors

Medipix quad module with Relaxd read-out
Tile-ability

Conventional

Sensor with guard ring

Medipix chip

Medipix chip

Carrier board

Edgeless

Edgeless high-Z sensor (1 mm)

Medipix chip

Medipix chip

Medipix chip

Redistribution layer

TSV

BGA

Carrier board
Wire bond → Through-silicon-via

Through-silicon-via

- Bond pad
- Di-electric
- Semiconductor
- Land
- Conductive pathway
Tile-ability: MPX3 pixel-to-edge distance

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Tile-ability: Sensor edges

Edge effects:
- Charge generation
- Surface currents
- High-field regions

Conventionally solved by guard rings

Rossi, “Pixel Detectors”
Active-edge silicon
Active-edge silicon: DRIE/ICP + edge doping

Edge implantation

\[ \nu \text{-type silicon} \]

50 μm

150 μm

Support wafer

\[ \text{phosphorus} \]

\[ \text{boron} \]
Reverse bias voltage [V]

Leakage-current density [A/cm²]

Blade dicing

Etching

Conventional

Active edge (pixel to edge: 30 µm)
Relaxd read-out interface:

- 4 detector assemblies in parallel
- up to 100 frames per second
Active-edge silicon: Flood-field image
Active-edge silicon: Laser setup

Focused laser beam
min. 1 μm steps

Physical edge
Sensitive edge

150 μm
50 μm

Pixel plane
Back face

- 40 V

λ
660 nm
980 nm
1060 nm
Effective size of Pixel 1 to 4: 4.62 pixels →

{physical width – effective width} = 256.5 \text{ μm} – 4.62/4 \times 220 \text{ μm} = 2.4 \text{ μm} \text{ insensitive edge}

Indicates VERY small insensitive edge  
(Spot radius = 20 \text{ μm})
Beam test setup - telescope

120 GeV/c muons and pions

Longitudinal

Courtesy of R. Plackett
Beam data: Long trails

~ 3 cm

Beam

LEFT  RIGHT
Beam data: Depth dependence of ToT

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Beam data: Depth dependence of ToT

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Slim-edge CdTe & GaAs
Detector: 9 slim-edge CdTe pieces

Detector readout: Medipix-MXR

Sensor specs (Acrorad):

- Quasi-Ohmic (Pt electrodes)
- $4.05 \times 4.05 \times 1 \text{ mm}^3$
- $36 \times 36$ pixels of $(110 \text{ m})^2$
- $65 \text{ m}$ pixel-to-edge distance
Laser data: charge collection efficiency

Fit function described by Hecht relation:

\[ Q(U) = Q_0 \frac{\mu \tau}{L^2} (U - U_0) \left[ 1 - \exp\left(\frac{dL}{\mu \tau (U - U_0)}\right) \right] \]

Centre pixel: \((\mu \tau)_e = 1.25 \times 10^{-4}\)

Edge pixel: \((\mu \tau)_e = 1.15 \times 10^{-4}\)
The leakage current as a function of time after voltage stepping (-200V → 200V → -200V). The current was monitored for one minute per voltage step of 40V.

Possibly caused by deep–level defects.
High-Z sensor issues

General:
• Material homogeneity and area
  • Grain boundaries – want single crystal
• Fluorescence
  • Degrades spatial and energy resolution above k-edge

CdTe:
• Only 3” wafers, even smaller dies
• tellurium inclusions
• hole trapping/polarisation

GaAs:
• Better single-crystal production (6”)
• Problem is defects!
  • Shallow defects prevent depletion
  • Carrier lifetimes
### Polarisation

**Schubweg:** \( \lambda_{e/h} = \mu_{e/h} \times \tau_{e/h} \times E \)

<table>
<thead>
<tr>
<th></th>
<th>Mobility ( \mu ) (cm(^2)/Vs)</th>
<th>Lifetime ( \tau ) (s)</th>
<th>( \mu \tau )-product (cm(^2)/V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td>1100</td>
<td>( \sim 3 \times 10^{-6} )</td>
<td>( 3 \times 10^{-3} )</td>
</tr>
<tr>
<td>Holes</td>
<td>100</td>
<td>( \sim 2 \times 10^{-6} )</td>
<td>( 2 \times 10^{-4} )</td>
</tr>
</tbody>
</table>

Silicon: \( \mu \tau_{e/h} \geq 1 \)

Polarising detector: \( \Phi_{\text{critical}} \approx 10^9 \text{ ph/mm}^2\text{s} \)

Non-polarising detector

\[
\lambda_{e/h} = \frac{\mu_{e/h}}{\tau_{e/h}} \times E
\]
Summary

Medipix + mono-crystalline high-Z sensors…

• … have great potential!

• However, limited active area… edgeless needed!

Active-edge silicon:

• Factor 10 decrease in pixel-to-edge distance.

• Sensitive edge very close to physical edge.

Slim edge high-Z:

• (Deep-level) defects and poor hole transport.

• First results indicate edges may not affect charge collection efficiency and noise performance
Thank you

High-energy nuclear interactions with Schottky CdTe. Multipixel-spread splashes, possibly due to polarisation or a cascade of fluorescence effects (?) Bias-voltage and interaction-depth dependence under study.