Characterisation of Glasgow/CNM double-sided 3D sensors

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TIPP, Chicago, June 2011.
Motivation for radiation hard sensors

- Fact of 10 luminosity upgrade of LHC to HL-LHC to extend physics programme
- Radiation damage increase in proportion to integrated luminosity
- Need to optimise silicon detector design to survive

#203: Silicon Detectors for High Luminosity Colliders. RD50 Status Report. Ulrich Parzefall

- Radiation hardness requirements (including safety factor of 2)
  - \(2 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2\) for the innermost pixel layers
  - \(1 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2\) for the innermost strip layers
3D sensors

- **Greater signal charge** due to faster collection time (less trapping)
- **Reduced power consumption** due to lower depletion voltages
- **Reduced charge sharing**
- Active edge technology: large-area tiled ‘edge-less’ detectors

**Drawbacks**
- increased complexity, **yield** issues
- areas of **inefficiency**
Double sided 3D sensors

- Reduce fabrication complexity
- Increase yield
- All regions of sensor have active Silicon

Double depletion
Lateral depletion ~4V
Full depletion ~40V
Precision scans of a 3D pixel cell

Timepix Telescope

- TimePix/Medipix chips: 256*256 55µm square pixels
- Energy deposition provided by Time over Threshold in TimePix
- 120 GeV pion beam from SPS
- Device under test (DUT): double sided 3D N-type pixel sensor
- DUT on high resolution rotational and translational stage

For more details on telescope see
- # 147 - The LHCb VELO upgrade. Daniel Hynds
- Charged Particle Tracking with the Timepix ASIC. arXiv:1103.2739
Precision scans: Charge deposition

Timepix Telescope

Mean energy deposited mapped onto pixel cell

- Area removed from columns exhibits standard Landau shape
- Charge deposition full/column ration = 35/285µm ratio
- Full cluster energy reconstruction
Full efficiency, \(99.8 \pm 0.5\%\), reached at an angle of \(10^\circ\) to the incident beam.
Precision scans: Spatial resolution

Timepix Telescope

Binary resolution = 55µm / √12 = 15.9µm

<table>
<thead>
<tr>
<th>Degrees</th>
<th>3D</th>
<th>Planar *</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>15.8±0.1</td>
<td>10.15±0.1</td>
</tr>
<tr>
<td>10°</td>
<td>9.18±0.1</td>
<td>5.86±0.1</td>
</tr>
</tbody>
</table>

**Spatial resolution**

- Hits that only affect one pixel have limited resolution
- Tilting the sensor means all tracks charge share
- Can use ToT information in centroid, CoG calculations
- Maximum spatial resolution at 10° *

*Charged Particle Tracking with the Timepix ASIC. arXiv:1103.2739*
Timepix Telescope

Precision scans: Charge sharing

59% of incident particles multiple pixel hits in the planar sensor.
14% of incident particles multiple pixel hits in the 3D sensor.
Strip devices

**Electrical measurements**

<table>
<thead>
<tr>
<th>Fluence (1x10^{15} 1MeV n_{eq} cm^{-2})</th>
<th>Lateral depletion voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>0.5</td>
<td>15 ± 5</td>
</tr>
<tr>
<td>5</td>
<td>100 ± 10</td>
</tr>
<tr>
<td>10</td>
<td>145 ± 10</td>
</tr>
</tbody>
</table>

0.5 1,2,5,10,20 \times 10^{15} 1 \text{ MeV } n_{eq} \text{ cm}^{-2} (±20%)  

Karlsruhe Institute of Technology, -20°C, 26 MeV protons

3D devices
P-stop isolation before and after irradiation to 10x10^{15}
Inter-strip resistance 100MΩ
Leakage current scales as expected
Spatial resolution

Silicon Beam Telescope

- Resolution before and after irradiation close to binary resolution
- Summer 2011 – highly irradiated sensors in TimePix Telescope

3D binary resolution = \( \frac{74.5 \mu m}{\sqrt{12}} = 23.1 \mu m \)

The spatial resolutions contain telescope alignment error
**Sr-90 electrons**

- Large charge collection at high fluences and modest voltages
- 3D charge collection of 47% of $Q_0$ @ $10^{16}$ fluence at 150V
- This has been simulated using TCAD without any high field effects present and shows very good agreement
- Noise is constant giving a signal to noise value of >10 @ $10^{16}$ fluence at 150V
- Compared to planar sensor higher charge collected
- Planar charge collection, 30% of $Q_0$ @ $10^{16}$ fluence at 1000V
Charge collection efficiencies (~250-300V)

Sr-90 electrons

Charge multiplication through impact ionisation

Expected charge deposition = $Q_o$

- 52% of $Q_o$ collected at $20 \times 10^{15}$ 1MeV $n_{eq}$ cm$^{-1}$
- Charge Multiplication when bias >150V ($10^{15}$)
- Noise ~ constant until > 250V
- 3D Signal >> Planar Signal (higher voltage)

* M. Koehler et al., 6th Trento Workshop 2011
Experimental setup:
- Space-resolved relative signal
- Motorised x-y stages, 4μm laser spot scanned in 2μm steps
- IR laser, 974 nm wavelength, absorption length: ~90μm (in Si, T=-20°C)

- 3D un-irradiated @ 77V
- p+ column evident
- Uniform charge collection outside of column position
Mapped CCE with scanned laser

Laser scanning

Bias: 260V
Fluence: $2 \times 10^{15}$ 1 MeV $n_{eq}$ cm$^{-2}$
Sr-90 measured ~137% of $Q_0$ collected

- p+ column evident
- Non-uniform charge collection outside of column position
- Area of low charge collection between the n+ contacts were a low field is present, greater probability of charge trapping
TCAD

\[ V_{\text{bias}} = 300 \text{ V} \mid \text{Fluence} = 2 \cdot 10^{15} \text{ n/cm}^2 \mid T = -10^\circ \text{C} \]

- Charge multiplication occurs along column length
- Work on-going on low field region

NSS 2011 - "Simulations of charge multiplication effect in 3D-DDTC silicon strip detectors"
Conclusions

- Precision scans of the pixel performed, charge deposition mapped
  - Full charge collection from 35µm active Si above column
- High efficiency across pixel matrix
  - 93.0±0.5% @ 0°, **Full pixel efficiency, 99.8±0.5%**, at an angle of 10°
- Large decrease in charge sharing compared to planar
  - MIPs that create clusters in sensor: 59% in planar, 14% in 3D
- Good electrical performance after irradiation
  - inter-strip resistance of 100MΩ
- Higher collected charge at modest voltages for 3D
  - 47% of Qc, collected in 3D @150V, 30% in planar @1,000V
- Charge multiplication in 3D irradiation device.
- Spatially resolved laser scanning uniform charge collection after irradiation
- Simulations can predict charge multiplication in irradiated devices
Laser scanning

- Two p+ columns evident
- Non-uniform charge collection outside of column position
- Area of low charge collection between the n+ contacts were a low field is present
- Low field areas have greater probability of charge trapping
X-ray test beam: Pixel Maps

- 77.5 $\mu$m square scans
- 2.5 $\mu$m steps
- Background subtracted
- Interpolated
TCAD model physics used

<table>
<thead>
<tr>
<th>Physics</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility</td>
<td>Doping dependance, High Electric field saturation</td>
</tr>
<tr>
<td>Generation and Recombination</td>
<td>Doping dependant Shockley-Read-Hall Generation recombination, Surface recombination model</td>
</tr>
<tr>
<td>Impact ionization</td>
<td>University of Bologna impact ionization model</td>
</tr>
<tr>
<td>Tunneling</td>
<td>Band-to-band tunneling, Hurkx trap-assisted tunneling</td>
</tr>
<tr>
<td>Oxide physics</td>
<td>Oxide as a wide band gap semiconductor for mips (irradiated), interface charge accumulation</td>
</tr>
<tr>
<td>Radiation model</td>
<td>Acceptor/Donor states in the band gap (traps)</td>
</tr>
</tbody>
</table>

### P-Type Radiation Damage Model

<table>
<thead>
<tr>
<th>Defect’s energy (eV)</th>
<th>Introduction rate (cm(^{-1}))</th>
<th>Electron capture cross-section (cm(^{-2}))</th>
<th>Hole capture cross-section (cm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_c - 0.42)</td>
<td>1.613</td>
<td>2.0e-15</td>
<td>2.0e-14</td>
</tr>
<tr>
<td>(E_c - 0.46)</td>
<td>0.9</td>
<td>5.0e-15</td>
<td>5.0e-14</td>
</tr>
<tr>
<td>(E_c - 0.10)</td>
<td>100</td>
<td>2.0e-15</td>
<td>2.5e-15</td>
</tr>
<tr>
<td>(E_v + 0.36)</td>
<td>0.9</td>
<td>2.5e-14</td>
<td>2.5e-15</td>
</tr>
</tbody>
</table>
Precision scans of the Pixel cell response of double sided 3D Pixel detectors to pion and X-ray beams. 2011 JINST 6 P05002
Fig. 2. Normalized signal distributions for different irradiation fluences (a) measured with planar detectors and (b) measured with 3D detectors. The fit superimposed is a convolution of a Landau function and a Gaussian.

Fig. 3. Signal as a function of the applied bias voltage for different irradiation fluences (a) measured with the planar sensors and (b) measured with the 3D sensors. The errors are dominated by a systematic contribution due to the calibration uncertainty.
Irradiated devices: double depletion

Fig. 6. Strip to back plane capacitance as a function of bias voltage measured after four different irradiation levels, namely: 0, 0.5, 5 and $10 \times 10^{15}$ cm$^{-2}$. The four curves are labeled on the figure.