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

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**

**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**
Precision scans: Efficiency

Full efficiency, $99.8\pm0.5\%$, reached at an angle of $10^\circ$ to the incident beam.
**Timepix Telescope**

**Binary resolution** = \( \frac{55\mu m}{\sqrt{12}} = 15.9\mu m \)

| 3D | Planar * |
|----|----------|
| Degrees | 0° | 10° | 0° | 10° |
| Spatial resolution | 15.8±0.1 | 9.18±0.1 | 10.15±0.1 | 5.86±0.1 |

* Resolutions shown can be and have been improved with eta corrections and the removal of track extrapolation error

- 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° *
59% of incident particles multiple pixel hits in the **planar** sensor.
14% of incident particles multiple pixel hits in the **3D** sensor.
Electrical measurements

| Fluence (1x10^{15} 1MeV n_{eq} cm^{-2}) | Lateral depletion voltage (V) |
|---------------------------------------|-------------------------------|
| 0                                    | 4                             |
| 0.5                                  | 15 ± 5                        |
| 5                                    | 100 ± 10                      |
| 10                                   | 145 ± 10                      |

Strip devices

3D devices

P-stop isolation before and after irradiation to 10x10^{15}

Inter-strip resistance 100MΩ

Leakage current scales as expected

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

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

Planar

3D

80 µm

285 µm

80 µm

74.5 µm

320 µm
Silicon Beam Telescope

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

3D binary resolution = $74.5\mu m / \sqrt{12} = 23.1\mu m$

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 $Q_0$ at $10^{16}$ 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 $Q_0$ at $10^{16}$ fluence at 1000V

Charge collection studies and electrical measurements of heavily irradiated 3D Double-Sided sensors and comparison to planar strip detectors. R. Bates et al., submitted to IEEE
Charge collection efficiencies (~250-300V)

Sr-90 electrons

Charge multiplication through impact ionisation

- 52% of $Q_o$ collected at $20 \times 10^{15}$ $1\text{ MeV n}_{eq}\text{ cm}^{-1}$
- Charge Multiplication when bias $>150\text{V}$ ($10^{15}$)
- Noise $\sim$ constant until $> 250\text{V}$
- 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)

Laser scanning

- 3D un-irradiated @ 77V
- p+ column evident
- Uniform charge collection outside of column position
**Laser scanning**

**Bias:** 260V  
**Fluence:** $2 \times 10^{15}$ 1 MeV $n_{eq} \text{ cm}^{-2}$  
**Sr-90** measured $\sim 137\%$ of $Q_o$ 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
Charge Multiplication - simulations

**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

**3D silicon strip detector**

- Fluence \(10^{15} \text{ MeV } n_{eq} \text{ cm}^{-1}\)
- Collected charge (electrons)

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 35\(\mu\)m active Si above column
- High efficiency across pixel matrix
  - 93.0±0.5% @ 0\(^\circ\), **Full pixel efficiency, 99.8±0.5%**, at an angle of 10\(^\circ\)
- 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 100M\(\Omega\)
- Higher collected charge at modest voltages for 3D
  - 47% of \(Q_o\) 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
Mapped CCE with scanned laser

Laser scanning

Bias: 150V
Fluence: $1 \times 10^{15}\,\text{MeV}\,\text{n}_{\text{eq}}\,\text{cm}^{-2}$
Sr-90 measured ~100% of $Q_0$ collected

- 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

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

### P-Type Radiation Damage Model

| Defect’s energy (eV) | Introduction rate ($cm^{-1}$) | Electron capture cross-section ($cm^{-2}$) | Hole capture cross-section ($cm^{-2}$) |
|----------------------|-------------------------------|------------------------------------------|---------------------------------------|
| $E_c - 0.42$         | 1.613                         | 2.e-15                                   | 2e-14                                 |
| $E_c - 0.46$         | 0.9                           | 5e-15                                    | 5e-14                                 |
| $E_c - 0.10$         | 100                           | 2e-15                                    | 2.5e-15                               |
| $E_v + 0.36$         | 0.9                           | 2.5e-14                                  | 2.5e-15                               |

J.P. Balbuena et al., 6th Trento Workshop 2011
Precision scans of the Pixel cell response of double sided 3D Pixel detectors to pion and X-ray beams. 2011 JINST 6 P05002
**SI Beam Telescope**

**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 $10 \times 10^{15} \text{ cm}^{-2}$ 1 MeV $n_{eq}$. The four curves are labeled on the figure.