A study of the effects of ionizing radiation on CMOS pixel sensors
• ATLAS Inner Detector upgrade
• Introduction to Ionizing radiation damage
• X-ray irradiation facility at the University of Glasgow
• TowerJazz CMOS sensor development for the ATLAS ITk
• MALTA sensor irradiation campaign
• Mini-MALTA sensor irradiation campaign
  • Analog signal results
  • Threshold calibration results
  • Fluorescence measurements
• Conclusions
LHC upgrade on 2024 to increase luminosity (HL-LHC)

- Proposed option for the outermost Layer 4: Depleted Monolithic Active CMOS sensors (DMAPS)
- 45% of the outer barrel!

Radiation tolerance requirements:
- NIEL $1 \times 10^{15}$ neq/cm²
- **TID 80 Mrad**
- Hit rate 100 – 200 MHz/cm²
- Timing resolution 25 ns
Ionizing radiation damage

Material atoms

Photon

Radiation damage in Si bulk is reversible:

Units: Radiation Absorbed Dose (RAD)

1 rad = 0.01 J/kg = 8.1 x 10^{12} e-h/ cm^3 (SiO_2)

Lasting damage done on SiO_2:

Threshold voltage shift:
- Negative for pMOS
- From negative to positive for nMOS

Anneal from 400 °C
Anneal at room temperature

Number of traps increase linearly up to 1 MRad

Expect degradation of front-end functionality
Time between measurements has to be consistent
Fine steps to observe evolution


<table>
<thead>
<tr>
<th></th>
<th>nMOS</th>
<th>pMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxide traps</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Interface traps</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>
TJ CMOS DMAPS development

2015/2016

**TJ Investigator1**

Multiple pixel designs to determine optimal pixel performance

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2017/2018

**MALTA**

Full ATLAS size demonstrator with a novel asynchronous readout

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2019/Present

**Mini-MALTA**

Following the MALTA characterisation results, this chip implements features to improve radiation hardness

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TowerJazz 180 nm technology with process modification

Small electrode with high resistivity (>1kΩ cm) p-type epitaxial layer

Allow for reverse bias to improve charge collection and radiation hardness
1) X-ray tube operated at 50 kVp (6.3 mA)
2) Laser sample alignment system
3) 35x25x6 cm³ cold sample box (down to 0 °C with Silicone oil circulation)*
4) X-ray dosimetry done using a calibrated pin diode from RAL**
5) Gulmay MP1 integrated controller

* Lower temperatures are achieved with Peltier cooling based system
** Rutherford Appleton Laboratory, Oxfordshire (UK)
1) Dose rate measured at different positions by moving X-Y stages

- RAL diode mounted in X-Y stages
- Biased at -5V and current consumption read back
- Current $\propto$ intensity $\propto$ dose

2) At the beam position, vary the potential applied by Gulmay controller to tune the dose rate

<table>
<thead>
<tr>
<th>Z (cm)</th>
<th>Dose rate (Mrad/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3.1</td>
</tr>
<tr>
<td>20</td>
<td>1.3</td>
</tr>
<tr>
<td>40</td>
<td>0.45</td>
</tr>
</tbody>
</table>

X-ray tube
RAL2 pin diode

$y = 0.0296x$
Chip characteristics:

- Full ATLAS size demonstrator
- Size: 20 x 20 mm²
- Pixel size: 36 x 36 µm²
- 512 x 512 pixels (8 flavours)

- Asynchronous readout -> low power:
  - Analog power ≈ 1 µW per pixel (75 mW/cm²)
  - Digital power (Layer 4) ≈ 10 mW/cm²
Malta TID irradiation campaign

IRRADIATION SUMMARY:
- 2.5 Mrad
- 0.25 Mrad/h
- Monitored Noise, Threshold, Gain, analog waveforms and current consumption
- Chip powered during irradiation
- Cooled down to 0 °C

High noise in few pixels + no masking
Not able to operate the chip after 2.5 MRad

17/09/2019
Lluis Simon Argemi
The mini-MALTA sensor

**Chip characteristics:**
- Size: 1.7 x 5 mm²
- Pixel size: 36.4 x 36.4 um²
- 16 x 64 pixels (8 flavours)

**Improvements:**
- Larger transistors to reduce RTS noise
- Extra-deep p-well implant and n-gap sectors to improve collection efficiency

<table>
<thead>
<tr>
<th>Transistor</th>
<th>Standard ( W = 1 \ \mu m \ L = 0.18 \ \mu m )</th>
<th>Enlarged ( W = 1.22 \ \mu m \ L = 0.38 \ \mu m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M6</td>
<td>( W = 0.44 \ \mu m \ L = 0.18 \ \mu m )</td>
<td>( W = 0.88 \ \mu m \ L = 0.18 \ \mu m )</td>
</tr>
</tbody>
</table>

17/09/2019
Lluis Simon Argemi
Cold environment:
- Silicone oil flow: -40°C
- Dry air pump
- Humidity monitor
- PCB temperature monitored: 0°C

Irradiation parameters:
- 50 kVp X-rays
- 0.25 MRad/h
- Delivered 80 MRad

Electrical functionality tests:
- 0 – 2 Mrad: 0.125 Mrad step
- 2 – 10 Mrad: 1 Mrad step
- 10 – 80 Mrad: 5 Mrad step
• Send pulses of the same amplitude
• Record 128 waveforms on the analog output
• Compute parameters offline
Analog waveform output

Baseline | Amplitude
---|---
Std/ET (0 MRad) | 0.96 | 0.6
Std/ET (80 MRad) | 0.90 | 0.41
ET 80 / ET 0 | 0.996 | 0.93
Std 80 / Std 0 | 0.87 | 0.63
Threshold Scans

Error function fit:
Mean = threshold
Std = noise

V_high
V_low

150 dacs

1) 2) 3)

\( \chi^2 / \text{ndf} \) = 1.198 / 83
Prob = 1
\( \mu \) = 116.9 ± 0.1383
\( \sigma \) = 1.192 ± 0.1376

Lluis Simon Argemi
Threshold scans - Mean

<table>
<thead>
<tr>
<th></th>
<th>Threshold</th>
<th>Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std/ET (0 MRad)</td>
<td>1.81</td>
<td>0.87</td>
</tr>
<tr>
<td>Std/ET (80 MRad)</td>
<td>1.88</td>
<td>0.74</td>
</tr>
<tr>
<td>ET 80 / ET 0</td>
<td>0.74</td>
<td>2.4</td>
</tr>
<tr>
<td>Std 80 / Std 0</td>
<td>0.76</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Threshold mean vs TID

Noise mean vs TID

Preliminary
Threshold Scans - RMS

<table>
<thead>
<tr>
<th>Threshold</th>
<th>Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std/ET (0 MRad)</td>
<td>2.05</td>
</tr>
<tr>
<td>Std/ET (80 MRad)</td>
<td>2.3</td>
</tr>
<tr>
<td>ET 80 / ET 0</td>
<td>2.29</td>
</tr>
<tr>
<td>Std 80 / Std 0</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Fluorescence measurements

Fe (6.4 keV) / Ti (4.5 keV)

- Induce signal in the detector using a monochromatic x-ray beam from fluorescence
- Record amplitude on the analog output
Fluorescence measurements

<table>
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<tr>
<th></th>
<th>Fe (6.4 keV)</th>
<th>Ti (4.5 keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std/ET (0 MRad)</td>
<td>0.71</td>
<td>0.61</td>
</tr>
<tr>
<td>Std/ET (80 MRad)</td>
<td>0.38</td>
<td>0.30</td>
</tr>
<tr>
<td>ET 80 / ET 0</td>
<td>0.92</td>
<td>0.86</td>
</tr>
<tr>
<td>Std 80 / Std 0</td>
<td>0.49</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Conclusions

• CMOS DMAPS aiming the ATLAS ITk requirements are being developed in the TJ 180 nm technology
• A mini-MALTA chip has been successfully irradiated to 80 Mrad
• Threshold, noise, analog waveform and fluorescence has been measured at different stages of the irradiation
• Sectors with enlarged transistors show a better performance after irradiation:
  • Baseline drops ~0% after 80 Mrad vs ~15% in standard transistors
  • Amplitude of analog waveform drops ~10% after 80 Mrad vs ~45% in standard transistors
  • Gain 1.5x higher than in standard transistors
  • Noise 30% lower than in sector with standard transistors after 80 Mrad
  • Noise dispersion ~30% lower at 0 Mrad and ~40% at 80 Mrad
  • Threshold value 55% lower before and after 80 Mrad
  • Threshold dispersion 2.3x smaller after 80 Mrads
Thank you!
Backup
Threshold Scans distribution

Noise distribution

Threshold distribution
Threshold RMS over Mean vs TID

Preliminary

Enlarged transistors front end
Standard MALTA front end

TID dose [MRad]