Charged particle detection performances of CMOS pixel sensors produced in a 0.18 μm process with a high resistivity epitaxial layer

Serhiy Senyukov on behalf of the PICSEL group
(IPHC-CNRS Strasbourg, France)
Outline

• ALICE Inner Tracking System (ITS) upgrade
• Candidate technology: CMOS pixel sensors
• CMOS pixel sensors at IPHC
• TowerJazz 0.18 μm CMOS process
• First prototype chip: MIMOSA 32
• Test program
• Test results
• Conclusions
ALICE Inner Tracking System (ITS) upgrade

- ALICE ITS upgrade is an essential part of the general ALICE upgrade in 2017-18 aiming to enhance sensitivity to rare particles (D and B mesons and baryons).

- Requirements to the new ITS:
  - Increase spatial resolution:
    - closer to the vertex $39 \rightarrow 22$ mm
    - more layers
    - smaller pixel size
    - reduced material budget
  - Withstand higher interaction rate (8 -> 50 kHz)

Two upgrade scenarios under consideration:
- 7 layers of pixel detectors
- 3 pixel layers + 4 strip layers

More info: CERN-LHCC-2012-013
### Candidate technology: CMOS pixel sensors

<table>
<thead>
<tr>
<th>Advantages:</th>
<th>Challenges:</th>
<th>Solutions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High granularity: pixel size ~ 20x20 µm²</td>
<td>• High event rate: ~ 50 kHz</td>
<td>• Our developments show that integration time ~ 20 µs is feasible</td>
</tr>
<tr>
<td>• Low material budget: ~ 0.3% $X_0$ per layer</td>
<td>• High radiation load:</td>
<td>• Modern CMOS processes with reduced feature size and high resistivity epitaxial layer should be more radiation hard</td>
</tr>
<tr>
<td>• Low power consumption: ~ 0.3 W/cm²</td>
<td>– TID = 700 kRad</td>
<td></td>
</tr>
<tr>
<td>• Low production cost</td>
<td>– NIEL = $10^{13}$ $n_{eq}/cm^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(innermost layer (r=22 mm), per year, safety factor = 4 included)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Operating temperature: 30 °C</td>
<td></td>
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</tbody>
</table>
CMOS pixel sensors at IPHC

From Ultimate (STAR)

- First CMOS sensor validated for the HEP experiment
- Pixel pitch: 20.7 μm
- Chip thickness: 50 μm
- Rolling shutter readout
- Integration time: 200 μs
- TID = 150 kRad
- NIEL = 3*10^{12} n_{eq}/cm^2 @ 30 °C
- 0.35 μm process (AMS)

To MISTRAL (ALICE)

- Rolling shutter readout with reduced integration time: 10 – 30 μs:
  - rectangular pixels: 22 x 33 μm^2
  - 2 or 4 column parallel readout
  - In-pixel discrimination
- 0.18 μm process
TowerJazz® 0.18 µm CMOS process

- Feature size: 0.18 µm
- Six metal layers
- Thick epitaxial layer: ~18 µm, ρ>1 kΩ*cm
- Deep P-well option: P-layer underneath N-well protecting from parasitic charge collection. Gives possibility to use PMOS transistors.
First prototype chip: MIMOSA 32

- Chip consists of several blocks aimed to study different aspects of CMOS sensors
- Central part under study contains 22 sub-matrices of simple pixels (diode + source follower) with different diode sizes and transistors implementations and 10 sub-matrices with in-pixel amplification
- Pixel pitches: 20x20, 20x40, 20x80 µm²
- Integration time: 32 µs at 2 MHz clock
- Overall chip size: 3.3x13=43 mm²
Test program

• Irradiation of sub-sample of chips:
  – TID: 1, 3 and 10 MRad (X-rays at CERN)
  – NIEL: 0.3, 1, 3 x 10^{13} n_{eq}/cm^2 (FRM II, Munich)
  – TID+NIEL: 1 MRad + 10^{13} n_{eq}/cm^2

• 1st stage: tests with Fe^{55} source in the laboratory
  – All sub-matrices were tested. Noise and CCE were assessed at 15 °C and 30 °C

• 2nd stage: tests of selected sub-matrices with π⁻ of 60 and 120 GeV/c at CERN SPS:
  – Telescope: 8 strip planes
  – Trigger: 2x2 mm² scintillator
  – ~1500 - 3000 tracks per measurement:
    • Cluster characteristics
    • SNR distribution
    • Particle detection efficiency (SNR cut on seed pixel = 5)
Beam test results:

simple reference pixel (20x20 µm²)

<table>
<thead>
<tr>
<th>Irradiation</th>
<th>SNR (MPV) 15 °C</th>
<th>SNR (MPV) 30 °C</th>
<th>Detection efficiency [%] 15 °C</th>
<th>Detection efficiency [%] 30 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>32.3 ± 0.4</td>
<td>31.4 ± 0.6</td>
<td>99.84 ± 0.07</td>
<td>99.64 ± 0.16</td>
</tr>
<tr>
<td>1 MRad + 10¹³ n_eq/cm²</td>
<td>22.3 ± 0.3</td>
<td>16.2 ± 0.3</td>
<td>99.87 ± 0.08</td>
<td>99.77 ± 0.11</td>
</tr>
</tbody>
</table>
Beam test results: pixel with deep P-well (20x20 µm²)

<table>
<thead>
<tr>
<th>Irradiation</th>
<th>SNR (MPV)</th>
<th>Detection efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30.9 ± 0.4</td>
<td>99.91 ± 0.06</td>
</tr>
<tr>
<td>1 MRad + 10^{13} n_{eq}/cm²</td>
<td>22.6 ± 0.4</td>
<td>99.92 ± 0.08</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>15 °C</th>
<th>30 °C</th>
<th>15 °C</th>
<th>30 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF@30C</td>
<td>30.9</td>
<td>29.7</td>
<td>99.91</td>
<td>99.7</td>
</tr>
<tr>
<td>REF@15C</td>
<td>30.85</td>
<td>30.85</td>
<td>99.92</td>
<td>99.87</td>
</tr>
<tr>
<td>1MRad+10^{13}@30C - MPV=19.29±0.22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1MRad+10^{13}@15C - MPV=22.6±0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Irradiation SNR (MPV) Detection efficiency [%]
Beam test results:
Simple elongated pixel (20x40 µm²)

<table>
<thead>
<tr>
<th>Irradiation</th>
<th>SNR (MPV) 15 °C</th>
<th>SNR (MPV) 30 °C</th>
<th>Detection efficiency [%] 15 °C</th>
<th>Detection efficiency [%] 30 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>22.6 ± 0.2</td>
<td>21.8 ± 0.3</td>
<td>99.86 ± 0.06</td>
<td>99.78 ± 0.08</td>
</tr>
<tr>
<td>1 MRad + $10^{13}$ n$_{eq}$/cm$^2$</td>
<td>13.9 ± 0.3</td>
<td>10.9 ± 0.1</td>
<td>99.51 ± 0.25</td>
<td>97.99 ± 0.25</td>
</tr>
</tbody>
</table>
## Summary table of beam test results

<table>
<thead>
<tr>
<th>Pixel</th>
<th>Irradiation</th>
<th>SNR (MPV)</th>
<th>Detection efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>15 °C</td>
<td>30 °C</td>
</tr>
<tr>
<td>Simple</td>
<td>0</td>
<td>32.3 ± 0.4</td>
<td>31.4 ± 0.6</td>
</tr>
<tr>
<td>20x20 μm²</td>
<td>1 MRad + 10^{13} n_{eq}/cm²</td>
<td>22.3 ± 0.3</td>
<td>16.2 ± 0.3</td>
</tr>
<tr>
<td>Deep P-well</td>
<td>0</td>
<td>30.9 ± 0.4</td>
<td>29.7 ± 0.4</td>
</tr>
<tr>
<td>20x20 μm²</td>
<td>1 MRad + 10^{13} n_{eq}/cm²</td>
<td>22.6 ± 0.4</td>
<td>19.3 ± 0.2</td>
</tr>
<tr>
<td>Simple</td>
<td>0</td>
<td>22.6 ± 0.2</td>
<td>21.8 ± 0.3</td>
</tr>
<tr>
<td>elongated</td>
<td>1 MRad + 10^{13} n_{eq}/cm²</td>
<td>13.9 ± 0.3</td>
<td>10.9 ± 0.1</td>
</tr>
</tbody>
</table>
Conclusions

• **TowerJazz 0.18 µm** CMOS process provides very **promising results** for charged particle detection.

• **Deep P-well** option **works well** giving more flexibility for in-pixel circuitry design.

• **Performance** of the elongated pixels **satisfies** the requirements of the **ALICE ITS upgrade program**: 
  \[ \text{TID} = 700 \text{ kRad} \times \text{NIEL} = 10^{13} \text{n}_{eq}/\text{cm}^2 \text{ at } T=30 \, ^\circ\text{C} \]

  What’s next? – see next slide

• Technology is of great interest for **CBM, SuperB, AIDA** and **ILD** and other future detectors.
ALICE ITS upgrade: what is next?

- MIMOSA 32 results allow to validate the charge collection part of the chip and its radiation hardness
- More chips are coming to check other building blocks:
  - MIMOSA 32ter (back from the foundry at the end of October): in-pixel amplification
  - MIMOSA 22THR (submission by the end of the year): integration of pixel array, column-level discrimination
  - AROM1: in-pixel discrimination
  - SUZE02: zero suppression logic
Thank you for your attention!
Backup slides
Cluster multiplicities

- Average cluster multiplicities (RMS):
  - Simple square pixel: 3.3 (1.3)
  - Square pixel with deep P-well: 3.2 (1.2)
  - Simple elongated pixel: 3.9 (1.8)
Deep P-well: signal and noise

Charge of the seed pixel for P9

Noise of the seed pixel for P9

Charge of the seed pixel for P9

Noise of the seed pixel for P9
Laboratory tests with Fe$^{55}$ source

- Very good charge collection: seed pixel collects $\sim$50% of cluster charge
- Noise: 15 – 20 e$^-$
Mimosa32:

Diodes&Ampli area: SF pixels
- 3T readout $\rightarrow$ (2T like readout)
- 2T readout

Diagram showing the connection of Vdiode (Vclamp), Vdd, Pixel SF-3T, Pixel SF-2T, reset (or LineReset) plus Global Reset, and Pixel Array Periphery.