Development of inner tracking systems equipped with CMOS pixel sensors for future colliders

Outline:
- Introduction
- The state-of-the-art CMOS sensors and their applications
- Evolution of the technology
- New prototype performances
- Conclusion and outlook
**Pixellated inner trackers**

- **Added value of designing fully pixellated inner trackers.**
  cf. ALICE-ITS upgrade. Experimental environment: \( B=0.5 \) T, high hit rate, low momentum tracks.

- **Constraints when designing sensors for an inner tracker:**
  - Performances: spatial resolution, read-out speed, radiation hardness, material budget (power dissipation).
  - Cost.

  But also: flexibility to choose the best suited performances to each detection layer:
  - Low radius layers: specifications governed by occupancy rate.
  - High radius layers: spec. governed by power consumption.

- **CMOS pixel sensors present attractive performances for inner trackers**
MIMOSA 0.35 µm CMOS pixel sensors

- CMOS pixel sensor (CPS) features:
  - Monolithic: signal sensing and analogue processing in pixel array.
  - Very thin: sensitive layer 10-20 µm, total thickness < 50 µm.
  - High granularity: square or elongated pixels.
- The state-of-the-art in HEP: MIMOSA series
  - 0.35 µm OPTO process.
  - Partially undepleted.

- Architecture:
  - In-pixel pre-amplification and CDS.
  - End-of-column discrimination, binary charge encoding and 0 suppression.
  - Column parallel rolling shutter read-out
    integration time = # rows × row read-out time (100-200 ns).

  ➤ corresponds to one possible optimisation with emphasis on the particle rate to be read out and the power dissipation.

- Advantages and performances:
  - Industrial mass production: excellent manufacturing yields, low costs, technology evolution.
  - Detection efficiency ~ 100 % with very low fake rate ~10^{-5}.
  - Read-out time: 0(100 µs), suited to > 10^6 particles/cm²/s.
  - Running conditions: from ≪0 °C to 40 °C.
  - Low power consumption: 150-250 mW/cm² ➤ further allows low material budget.
  - Low material budget: 0.2 % - 0.5 % X₀.
  - Radiation tolerance: 0.1-1 MRad + 10^{12}-10^{14} n_{eq}/cm² depending on T°, read-out time, pitch.
Current applications

- MIMOSA sensors have already been chosen by several projects:
  - EUDET Beam Telescope of the FP6 project: operating since 2008.
  - Hadrontherapy: FIRST (GSI), dose monitoring (Lyon, Strasbourg).
  - STAR @ RHIC: PXL detector ➔ ~1/3 installed in May 2013.
    One month commissioning run completed.
    First vertex detector equipped with CMOS pixel sensors.

- ULTIMATE sensor features:
  - Active area: 960 columns of 928 pixels
    19.9×19.2 mm², ≈ 0.9 million pixels.
  - Pitch: 20.7×20.7 µm².
  - Binary output.
  - Power consumption ~ 150 mW/cm².
  - Air flow cooling.
  - t_r.o. ~ 200 µs.
  ➔ Measured performances:
    - N ~ 15 e- ENC at Tº= 35 ºC.
    - σ_s.p. ≥ 3.5 µm.
    - Radiation tolerance validated:
      3×10^{12} n_{eq}/cm² + 150 kRad at 35 ºC.
Future experiments

- Now CPS are also being considered by forthcoming projects (e^+e^-, heavy ions collisions):
  - ALICE @ LHC: baseline to equip the entire upgraded ITS (~10 m^2).
  - CBM @ FAIR: data taking > 2016 (SIS-100).
  - ILD @ ILC: option to equip the VD.
  - BES-3 @ BEPC: option to equip an inner tracker.

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{\text{single point}}$</th>
<th>read-out time</th>
<th>TID</th>
<th>Fluence n_{eq}/cm^2</th>
<th>$T_{\text{coolant}}$ °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>STAR-PXL</td>
<td>5 µm</td>
<td>~200 µs</td>
<td>150 kRad</td>
<td>$3 \times 10^{12}$</td>
<td>30</td>
</tr>
<tr>
<td>future projects</td>
<td>3-5 µm</td>
<td>1-30 µs</td>
<td>up to 10 MRad</td>
<td>up to $10^{14}$</td>
<td>&lt; 0 - 30</td>
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Considering: hit rate, data flow and trigger rate:
Correlation between all specifications + strong dependence on the extrapolated track quality
→ a global design of the inner tracking system geometry enables to go beyond current technology limits.

- Next generation of experiments call for higher read-out speed and radiation tolerance:
  - Smaller feature size technology: switch to 0.18 µm.
  - Higher epitaxial layer resistivity.
Evolution of the technology

- Performances of monolithic planar technology: global optimisation of all functionalities: sensing, analogue amplification, digital treatment. Specifications are not driven by HEP but by commercial concerns.
  - full potential of CPS for HEP not reached yet.

- Path defined to improve radiation hardness and to accelerate read-out speed while keeping low power consumption:
  - Parallelised rolling shutter: sensor divided in sub-arrays read out in //, and several rows read out in //.
  - Elongated pixels: thanks to excellent charge collection.
  - Smarter pixels: row read-out fasten to 100 ns with in-pixel digitization thanks to smaller feature size.
  - Binary signal transmission: to maintain power consumption low.
  - High resistivity epitaxial layer.

- Pixel dimension increased in that direction ↑:
  - less rows to be read.
  - r.o. time = # rows × row read-out time (100 ns)
  - higher read-out speed.

- Pixel dimension increased in that direction ↓:
  - less pixels in a row.
  - limited power consumption.
0.18 μm sensor prototypes

- **TowerJazz® CIS 0.18 μm process:**
  - Epitaxy: 18 μm thick, high resistivity 1-5 kΩ.cm.
  - Quadruple well.
  - Up to 6 metal layers.

- **Different prototypes submitted and tested in 2012:**
  - Explore pixel sizes: 20x20, 20x40 and 20x80 μm².
  - Explore charge amplification and collection system:
    - diode sizes ~9-15 μm², NMOS and PMOS transistor based amplifiers.
  - Explore discrimination: 1 discriminator at each column end, in-pixel discrimination.
  - Integration time = 32 μs (per sub-matrix).

- **Tests performed with $^{55}$Fe source and with CERN SPS T4-H6 beam line, 60-120 GeV π⁻:**
  - $T_{\text{coolant}} = 15, 20$ and $30$ °C.
  - Total Ionising Doses: 1 and 3 MRad.
  - Non-ionising fluences: $0.3 - 1.0 - 3.0 \times 10^{13}$ $n_{\text{eq}}$/cm².
  - Combined irradiations: up to 1 MRad + $10^{13}$ $n_{\text{eq}}$/cm².

► First evaluation of this technology:
  - Validation of the charge collection performances, before and after irradiation.
  - Validate the different steps required for a final sensor: enlarged pixels, in-pixel discri, parallelised rolling-shutter.
0.18 µm sensor test results

- Charge collection:
  - High resistivity confirmed, limited thermal diffusion and total charge collected within 4 pixels.
  - Deep P-well does not parasite charge collection.

- Radiation hardness:
  - Irradiation has no impact on charge collection even at 30 ºC. Signal not degraded by traps induced by bulk damages after NI rad.
  - Evolution of noise with fluence is a typical effect of leakage current.

- Impact of pixel dimension:
  - Square pixels: detection $\varepsilon \sim 100\%$ even at 30 ºC and after combined I+NI irradiation.
  - Elongated 20x40 µm$^2$ pixels: still detection $\varepsilon \geq 99\%$ at 15 ºC ($\sim 98\%$ at 30 ºC) after combined I+NI irradiation.
Conclusion and outlook

- CMOS pixel sensors (CPS) are a mature technology to equip high performances inner trackers whose specifications are governed by spatial resolution, material budget, power dissipation and cost.

- The STAR-PXL detector is the first operating vertex detector equipped with CMOS pixel sensors: CPS well suited for tracker innermost layers.
The ALICE-ITS upgrade is based on CPS: CPS also well suited to equip a complete inner tracker.

- Exploration of 0.18 mm technology, to design CPS aiming at equipping future inner trackers (upgrade of ALICE-ITS, CBM-MVD, etc.):
  - 2011-12: Charge collection performances and radiation hardness validation.
  - 2014-16: MISTRAL (30 µs read-out time) and ASTRAL (15 µs r.o. time).

- CPS new 2D-technologies, with deep sub-micronic feature size, thicker epitaxy and higher resistivity offer conditions of a potential breakthrough in performances:
  - integration time ~ 1 µs.
  - radiation hardness up to 10 MRad + \(10^{14}\) n_{eq}/cm^2.

  ➔ open the door to future possible applications: X-ray imaging.
  and motivate further performance improvement: applications to HL-LHC with t_{r.o.} << 1 µs.

thank you for your attention