Development of MISTRAL & ASTRAL Sensors for the Upgrade of the Inner Tracker System of the ALICE experiment at LHC

Christine Hu-Guo (on behalf of PICSEL-ALICE team of IPHC-Strasbourg)
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STAR Detector

Towards Higher Read-Out Speed and Radiation Tolerance

Next generation of experiments calls for improved sensor performances:

<table>
<thead>
<tr>
<th>Expt-System</th>
<th>$\sigma_t$</th>
<th>$\sigma_{sp}$</th>
<th>TID</th>
<th>Fluence</th>
<th>$T_{op}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>STAR-PXL</td>
<td>$&lt;~ 200 , \mu s$</td>
<td>$\sim 5 , \mu m$</td>
<td>150 kRad</td>
<td>$3 \times 10^{12} , n_{eq}/cm^2$</td>
<td>30 °C</td>
</tr>
<tr>
<td>ALICE-ITS</td>
<td>10-30 $\mu s$</td>
<td>$\sim 5 , \mu m$</td>
<td>700 kRad</td>
<td>$10^{13} , n_{eq}/cm^2$</td>
<td>30 °C</td>
</tr>
<tr>
<td>CBM-MVD</td>
<td>10-30 $\mu s$</td>
<td>$\sim 5 , \mu m$</td>
<td>$&lt;~10 , MRad$</td>
<td>$&lt;~10^{14} , n_{eq}/cm^2$</td>
<td>$&lt;0 , ^\circ C$</td>
</tr>
<tr>
<td>ILD-VXD</td>
<td>$&lt;~2 , \mu s$</td>
<td>$&lt;~3 , \mu m$</td>
<td>$O(100) , kRad$</td>
<td>$O(10^{11} , n_{eq}/cm^2)$</td>
<td>$&lt;~30 , ^\circ C$</td>
</tr>
</tbody>
</table>

Main improvements required while remaining inside the virtuous circle of spatial resolution, speed, material budget, radiation tolerance ➔ move to 0.18 $\mu m$ process

- For aim of higher radiation tolerance
  - High resistivity epitaxial layer
  - Smaller feature size process

- For aim of high readout speed
  - More parallelised read-out
  - Optimise number of pixels per column
  - New pixel array architectures
  - Smaller feature size process
Sensors R&D for the upgrade of the ITS: Our Strategy

- R&D of up- & down-stream of sensors performed in parallel at IPHC in order to match the ITS timescale

for 2 final sensors (~3x1 cm²)

- Mature architecture: MISTRAL = MIMOSA Sensor for the inner TRacker of ALICE
  - Relatively low readout speed (200 ns/ 2 rows)
    - ~ 200 mW/cm² for inner layers
- Promising architecture: ASTRAL = AROM Sensor for the inner TRacker of ALICE
  - Higher speed (100 ns/ 2 rows) + Lower power
    - ~ 85 mW/cm² for inner layers, ~ 30-60 mW/cm² for outer layers

- Modular design + reused parts → optimising R&D time

- Several groups involved in the ITS design
  → see T. Kugathasan's & H. Hillemanns' (CERN) talk in this conference
Upstream of MISTRAL Sensor

**Pixel level:**
- **Sensing node:** $N_{\text{well}}-P_{\text{EPI}}$ diode
  - Optimisation $f$ (diode size, shape, No. of diodes/pixel, pixel pitches, EPI)
- **In-pixel amplification and cDS:**
  - Limited dynamic range (supply 1.8 V) compared to the previous process (3.3 V)
  - Noise optimisation especially for random telegraph signal (RTS) noise
    - Sensing diode: avoid STI around N-well diode
    - RO circuit: avoid using minimum dimensions for key MOS & avoid STI interface
    - Trade off between diode size, input MOS size w.r.t. S/N before and after irradiation

**Column level:**
- **Discriminator:** similar schematic as in MIMOSA26 & 28
  - Offset compensated amplifier stage + DS (double sampling)
  - 200 ns per conversion
- Read out 2 rows simultaneously $\Rightarrow$ 2 discriminators per column (22 $\mu$m)

Layout of 2 discri. (1 columns)

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**Test Results of the Upstream of MISTRAL Sensor**

- **Lab test results @ 30 °C (MIMOSA22-THRA1 & 2, MIMOSA22-THRB)**:
  - Diode optimisation ➞ see M. Winter's talk in this conference
    - CCE optimisation: surface diode of 8-11 μm² (22x33 μm²)
  - In-pixel amplification optimisation
    - Reduction of RTS noise by a factor of 10 to 100
  - MISTRAL RO Architecture: (single & double raw RO)
    - 2-row RO increases FPN by ~1 e⁻ ENC ➞ negligible impact on ENC_{total}

  ➞ Design of the upstream of MISTRAL validated

- **Beam test results (DESY)**: ➞ see M. Winter's (IPHC) talk in this conference
  - SNR for MIMOSA-22THRA closed to 34
    - 8 μm² diode features nearly 20 % higher SNR (MPV)
  - Detection efficiency ≥ 99.8% while Fake hit ratio ≤ O(10⁻⁵)
  - 22×33 μm² binary pixel resolution: ~5 μm as expected from former studies
  - Ionisation radiation tolerance assessment under way
Upstream of ASTRAL sensor

- Thanks to the quadruple-well technology, discriminator integrated inside each pixel
  - Analogue buffer driving the long distance column line is no longer needed
    - Static current consumption reduced from ~120 µA to ~14 µA per pixel
  - Readout time per row can be halved down to 100 ns (2 rows at once) due to small local parasitic

- Sensing node & in-pixel pre-amplification as in MISTRAL sensors

- In-pixel discrimination
  - Topology selected among 3 topologies implemented in the 1st prototype AROM0
  - Test results in laboratory: total noise ~30 e⁻, ENC ~2 times higher than expected but phenomena understood
  - AROM0: Full functionality validated

- Further R&D will focus on large sensor integration along with power consumption and noise reduction
Downstream of Sensors: Zero Suppression Logic (SUZE02)

- **Identical both for MISTRAL & ASTRAL sensors**
  - AD conversion (pixel-level or column-level) outputs are connected to inputs of SUZE

  ![Diagram of SUZE02](image)

  **Window of 4x5 pixels**

- **Encoding: more efficient than SUZE01 implemented in MIMOSA28 sensor**
  - Sizable and suitable to process the binary information generated by a 1 cm long pixel array
    - Hit density of ~100 hits/collision/cm² + safety factor of 3-4
    - Compression factor: 1 to 4 order of magnitudes
  - Hit clusters identified in 4x5 pixel windows
  - Results stored in 4 SRAM blocks allowing either continuous or triggered readout
  - Sparsified data multiplex onto a serial LVDS output
    - Prototype data rate: 320 Mbit/s per channel (1 or 2 channels in SUZE02)

- **SUZE02 preliminary test results: functional and works well @ full speed**
  - Full sequence of signal processing steps validated using various types of patterns
  - SEU needed to be evaluated

- **MISTRAL / ASTRAL: 500 Mbits/s data rate required**
  - One channel output per sensor
    - INFN Torino is working on data transmission up to 2 Gbit/s
Conclusions

- 2 sensors being developed at IPHC for the ALICE ITS upgrade:
  - MISTRAL: validation of the upstream and downstream architectures confirmed
    - Spatial resolution (22x33 µm² pixel) ~5 µm
    - Detection efficiency > 99.8 % for fake hit rate ≤ O(10⁻⁵)
    - Integration time: ~30 µs
    - Power consumption ~200 mW/cm²
  - ASTRAL: architecture validation on going
    - ASTRAL pixel front-end amplification (same as MISTRAL part) validation confirmed
    - Downstream of ASTRAL (shares the same logic with MISTRAL) validation confirmed
    - Feasibility of the In-pixel discrimination validated ➔ fine optimisation on going
    - ASTRAL performs 2 x higher readout speed and lower power consumption than MISTRAL
      - Integration time: <~20 µs
      - Power consumption ~85 mW/cm² for inner layers & ~30-60 mW/cm² for outer layers

- At beginning of 2014, a large sensor about 1 cm² will be submitted to verify full chain and full functionalities