Optimisation of CMOS pixel sensors for high performance vertexing and tracking

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Late 90's
Native granularity & low material budget

Today
Beam telescope
STAR-PXL (RHIC)
ALICE-ITS
Hadrontherapy,...

Developments driven by ILC + Heavy Ion coll.
IPHC (Strasbourg) + IRFU (Saclay)
within typical analogue CMOS process

Ultimate speed & radiation tolerance

Limit sets by CMOS process
Outline

- Motivation for technology upgrade
- Prototypes in 0.18 μm technology
- Test beam characterisation
- Summary & outlooks to final detector
State-of-the-art

- **CMOS Pixel Sensor (CPS)**
  - Monolithic ↔ full detector system on sensor
  - Optimisation required / 3 functionalities

- **MIMOSA architecture**
  - In-pixel correlated double sampling (CDS)
    - Requires pre-amplification in pixel
  - Column parallel Rolling-shutter read-out
    - Integration time = matrix read-out time
      - $\# \text{ rows} \times \text{ row r.o. time}$
  - Limits power dissipation
    - Hence material budget
  - Allows high counting rate
    - Data compression ↔ zero-suppression
  - Preserves main CMOS pixel sensor advantages
    - Granularity ↔ small feature size
    - Small thickness ↔ sensitive layer 10-20 $\mu$m

Sensor: sensing node
FEE: analogue amplification
Acquisition board: digital treatment
**Current applications**

- **MIMOSA series: technology 0.35 μm OPTO process**
  - Epitaxial layer resistivity \( \sim 400 \ \Omega \cdot \text{cm} \)
  - Row read-out time \( \sim 200 \ \text{ns} \)

- **EUDET beam telescope**
  - MIMOSA 26: 100 μs integration time
  - Operating since 2008

- **STAR experiment PXL detector**
  - ULTIMATE sensor (400 needed)
  - Counting rate \( > 10^6 \ \text{part/cm}^2/\text{s} \)
  - **Power \( \leq 150 \ \text{mW/cm}^2 \)**
  - **Ladder material budget: 0.37 % \( \chi_0 \)**
    - sensors thinned to 50 μm
  - **Operating conditions @ 30°C**
    - Total Ionising Dose = 150 kRad,
    - Fluece = \( 3.10^{12} \ \text{n}_\text{eq}/\text{cm}^2 \)
  - Detector (1/3) commissioning in spring 201

**ULTIMATE/MIMOSA 28**
- 960x928 \( \sim 0.9 \ \text{Mpixels} \)
- Pitch 20.7 x 20.7 μm²
- Sensitive surface 19.7x19.2 cm²
- Readout time 200 μs
### Next frontier

<table>
<thead>
<tr>
<th></th>
<th>Single point res.</th>
<th>Integra. time</th>
<th>TID</th>
<th>Fluence (n_{eq}/cm^2)</th>
<th>Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>STAR - PXL</td>
<td>(\sim 5 \mu m)</td>
<td>(\leq 200 \mu s)</td>
<td>150 kRad</td>
<td>(3.10^{12})</td>
<td>30 °C</td>
</tr>
<tr>
<td>ALICE - ITS</td>
<td>(\sim 5 \mu m)</td>
<td>10-30 (\mu s)</td>
<td>700 kRad</td>
<td>(1.10^{13})</td>
<td>30 °C</td>
</tr>
<tr>
<td>CBM - MVD</td>
<td>(\sim 5 \mu m)</td>
<td>10-30 (\mu s)</td>
<td>(\leq 10) MRad</td>
<td>(1.10^{14})</td>
<td>(\ll 0 ) °C</td>
</tr>
<tr>
<td>ILD - VXD</td>
<td>(\leq 3 \mu m)</td>
<td>(\leq 10 \mu s)</td>
<td>(\mathcal{O}(100) kRad)</td>
<td>(\mathcal{O}(10^{11}))</td>
<td>(\leq 30 ) °C</td>
</tr>
<tr>
<td>Super Flavor Factory</td>
<td>(\leq 10 \mu m)</td>
<td>(\leq 2 \mu s)</td>
<td>5 Mrad/year x safety f.</td>
<td>5.10^{12} /year x safety f.</td>
<td>(\geq 10 ) °C</td>
</tr>
</tbody>
</table>

- **Accelerating the rolling-shutter read-out**
  - Less pixels for same surface → elongated pixel decreases #rows
  - Higher level of parallelisation → 2 to 4 rows read in parallel
  - Faster row read-out with binary signal transmission → In-pixel digitisation (discri or 3-bits ADC)

- **Enhancing radiation tolerance**
  - Ionising dose → small feature size
  - Non-ionising fluence → high resistive sensing layer

- **Preserve granularity & power budget**
  → limits pixel size & parallelisation

⇒ more complex \(\mu\)-circuits

⇒ CMOS technology upgrade & architecture optimisation
Upgrading the technology

- **Remark on CPS development**
  - q-collection properties poorly predictable
    - Frequent prototyping desirable
  - Choice of cost-effective technologies

- **TowerJazz® 0.18 μm process options**
  - CMOS Image Sensor (CIS) process
  - Up to 6 metal layers
  - Metal-Insulator-Metal (MIM) capacitor
  - Quadruple well
    - both NMOS & PMOS type transistors possible in pixel
  - Pinned collection diode
    - Decouple collection & transmission node
  - Highly resistive epitaxial layer: 1-5 kΩ·cm
    - thickness 18 μm standard (could reach 40 μm)
  - Stitching
Prototypes in 0.18 µm technology

**Common features**
- Same footprint
- 32 small matrices:
  - 16 × 16/32/64 pixels
  - Simple analogue readout (2MHz clock) → Integration time = 32 µs
  - Pixels without amplification & pixels with amplification
- Matrix combined with column-level discriminator (IRFU design)
- Matrix with in-pixel discriminator

**MIMOSA 32**
- Fabricated Q1/2012
- Sensing element
  - Pixel pitch: 20 × 20/40/80 µm
  - Collection diode: various area & numbers
- In-pixel amplification (for CDS)
  - NMOS and PMOS based
- First results presented at
  - RESMDD’12 (S.Senyukov)
  - NSS’12 (M.Winter)

**MIMOSA 32ter**
- Fabricated in Q4/2012
- Complements & corrections / Mimosa 32
  - Near ALICE-nominal pitch 20×33 µm²
Evaluation method

- **Irradiation**
  - Neutron fluence: $1/3/10 \times 10^{12} \text{ n}_{eq}/\text{cm}^2$
  - Total ionising dose: $0.3 / 1 / 3 \text{ MRad}$
  - Combinations
    - $\text{TID} = 0.3 \text{ MRad} + \text{fluence} = 3 \times 10^{12} \text{ n}_{eq}/\text{cm}^2$
    - $\text{TID} = 1 \text{ MRad} + \text{fluence} = 1 \times 10^{13} \text{ n}_{eq}/\text{cm}^2$

- **Operating conditions**
  - Coolant temperatures: $15 / 20 / 30^\circ \text{C}$
    - Sensor typically $+5^\circ \text{C}$ warmer

- **Beam (2012 campaigns)**
  - CERN-SPS: $\pi$ 20 to 120 GeV (mostly 80 & 120 GeV)
  - Beam telescope with either strip or pixel detectors
  - About 90 irradiation-temperature measurement points
    - 1500 to 3000 tracks per point
Detection efficiency > 99 % for all conditions
▶ Except 20x40 pixel at highest load and 30C (98 %)
▶ Validation of
  ▶ Radiation tolerance
  ▶ Elongated pixel
Basic feature: Noise

Noise level of $20 \times 20 \, \mu m^2$ with in-pixel amplification

- Noise increase with radiation level mainly explains SNR degradation
- Distribution of noise over pixels much larger

- non-yet optimised transistors geometry for 0.18 $\mu m$ process
Basic feature: cluster size

20 × 20 µm² with amplification

20 × 33 µm² staggered diode

Total cluster charge collected within ≲ 5 pixels

▶ Decrease of cluster size (SNR>5) related to increase of noise with irradiation load
▶ Impact of high resistive sensitive layer assessed

VCI 2013
Optimisation of CPS for high performances vertexing & tracking
Digitisation emulation

- **Apply same threshold to all pixels**
  - Binary output
  - Equivalent to zero-suppression in rolling-shutter read-out

- **Cluster characteristics**
  - Size = #pixels
  - Position = average (weight=1) over pixel positions

- **Fake hits**
  - Noise fluctuation of single pixels over threshold

[Image of pixel matrix with analogue signals and binary signals, illustrating the transformation process.]
MIMOSA 32ter, 0.18 µm process, 18 µm >1 kΩ.cm epi.
pitch 20x20 µm²

MIMOSA 28, 0.35 µm process, 20 µm <1 kΩ.cm epi.
pitch 20.7x20.7 µm², meas. binary+0-suppress output

- clear efficiency plateau near 100 % ➔ potential operating thresholds = 5-7 x noise
- fake hit rate high ➔ coherent with current noise performances
  ➔ will get down with transistors adapted to 0.18 µm process
- single point resolution in expected range (3.5 µm)
  ➔ detailed behaviour related to #pixels/cluster (average ranges from 3.5 ➔ 2)
Elements validated in the 0.18 µm process

- Baseline sensing node & in-pixel preamplifier
- Elongated pixel pitch (ALICE near-baseline: 20x33 µm²)
- Radiation tolerance with TID=1MRad & fluence 10^{13} n_{eq}/cm²

First successful step to go beyond state-of-the-art

Further steps

- Optimisation: noise (transistors), q-collection (diode)
- Complete read-out architectures on full-scale sensors
Outlooks...ALICE-ITS

- **Q1/2013**
  - MIMOSA-32/34: further optimisation of q-collection, noise, ampli.
  - MIMOSA-22-THR: pixel matrix + col-level discriminators
    - single and double rows read-out
  - SUZE-02: zero-suppression circuitry
  - AROM-0: matrix with in-pixel discriminator
  - MIMADC: matrix with in-pixel 3-bits ADC

- **Full Scale Basic Blocs (FSBB)**
  - = complete functionality over ~1 cm²
  - Q4/2013: col-level discrim. approach (↩MISTRAL)
  - Q4/2015: in-pixel discrim. approach (↩ASTRAL)

- **Final sensors**
  - Q4/2014: MISTRAL 22x33 µm² pitch
    with 30 µs integration time (15 µs possible)
  - Q4/2016: ASTRAL 15 µs integration time (2 µs possible)
  - 2015(?): AIDA large area (4 × 6 cm²) beam telescope sensor
ADDITIONAL SLIDES
Basic principle of CPS

Sensor with analogue output

Resolution (microns) vs pitch (microns)
High resistive layer and depletion

TCAD simulations for 0.35 \( \mu \text{m} \) process

Standard epitaxial layer

High Resistive layer (400 \( \Omega \cdot \text{cm} \))

Pixel width

Pixel depth

Depletion zone
Seed pixel SNR distributions

20 × 20 µm²

20 × 20 µm² with in-pixel PMOS transistor

20 × 40 µm² 1 diode staggered

20 × 20 µm² with in-pixel amplification
Number of significant pixels / cluster

Total charge in N pixels

- 20x20 µm² diode bias D
- 20x20 µm² diode bias T
- 20x20 µm² with PMOS
- 20x40 µm² staggered diode

# pixels ordered by decreasing charge collected

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