Monolithic Active Pixel Sensors for High-Energy Physics applications

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Outline

• **Monolithic Active Pixel Sensor** technology

• Successful experiences: **STAR HFT** and **ALICE ITS2**

• The future: **ALICE ITS3** and further plans
High-precision tracking in High-Energy Physics

The ingredients for the recipe …

• Low material budget

• Large number of track-points

• Small distance from interaction point
High-precision tracking in High-Energy Physics

The ingredients for the recipe … pose technological challenges

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The ingredients for the recipe … pose technological challenges

• Low material budget
• Reduce unnecessary material
• Minimize sensitive thickness with acceptable signal

• Large number of track-points

• Small distance from interaction point
High-precision tracking in High-Energy Physics

The ingredients for the recipe … pose technological challenges:

- Low material budget
- Large number of track-points
- Small distance from interaction point
- Reduce unnecessary material
- Minimize sensitive thickness with acceptable signal
- Equip large areas (scales with $r^2$)
- Limit power, data, costs
High-precision tracking in High-Energy Physics

The ingredients for the recipe … pose technological challenges

- Low material budget
  - Reduce unnecessary material
  - Minimize sensitive thickness with acceptable signal
- Large number of track-points
  - Equip large areas (scales with $r^2$)
  - Limit power, data, costs
- Small distance from interaction point
  - Improve radiation tolerance
  - Explore novel layouts
Monolithic Active Pixel Sensor technology

- Combines sensitive volume and front-end readout CMOS logic in the same piece of silicon

Minimizes the material budget + simplifies the construction

Front-end logic ~ 10 µm
High resitivity epi-layer ~ 20 µm
Substrate: can be thinned!
MAPS: the origins

• Invented in the ’90s for the detection of visible light
  • Soon became leader technology for cameras
  • Later reached performance required by scientific imaging applications
  • Active area is just a fraction of the pixel; the standard substrate has low resistivity

• Only in the early 2000s proposed for charged particle tracking in HEP
  • Need larger fill factor and better charge collection (higher resistivity substrate)
### First MAPS for collider experiment: STAR HFT

#### Requirements for the MAPS layers

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<th>Specification</th>
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<td>20 to 90 kRad / year 2*10^{11} to 10^{12} 1MeV n eq/cm²</td>
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<td>DCA pointing resolution</td>
<td>≤ 30 µm for 750 MeV/c kaons</td>
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<td>Installation and maintenance</td>
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The STAR Experiment at RHIC (BNL)

Goal: Detect charm decays with small $c\tau$ in Au-Au collisions at 200 GeV
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A new Heavy Flavor Tracker (HFT)

Two vertexing layers based on thin, low-power, small-pitch MAPS sensors
The MIMOSA *Ultimate*-2 sensor for STAR HFT

MIMOSA-family sensor developed for HFT at IPHC, Strasbourg

- AMS 0.35 µm CMOS, Twin-well process
  - Only NMOS transistors to avoid competition in charge collection
- ‘High’ resistivity (≥ 400 Ω⋅cm) p-epi layer (~ 15 µm)
  - Reduced charge collection time and improved radiation hardness
- Charge collection mostly by **diffusion**
  - Shallow depletion region formed between n-well and p-epi
  - High-potential difference between epi and substrate acts as a mirror
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  - High-potential difference between epi and substrate acts as a mirror
- Rolling-shutter readout architecture
- 185.6 µs integration time
- ~170 mW/cm² power dissipation
  - Clock distributed across the matrix
- Pixel matrix
  - 20.7 µm pitch
  - 928 rows * 960 columns = ~1M pixel
  - In-pixel amplifier
  - In-pixel Correlated Double Sampling (CDS)
- Digital section
  - Ping-pong memory
  - 160 MHz LVDS data output
The STAR HFT PXL Layers

Ladder with 10 MAPS sensors (~ 2×2 cm each)

Mechanical support with kinematic mounts (insertion side)

Cantilevered support

Highly parallel system
10 sectors total
5 sectors / half
4 ladders / sector
10 sensors / ladder

~356 M pixels over ~0.16 m²

carbon fiber sector tubes

Untested technology in a collider environment
• Plan for a way to quickly replace malfunctioning components
• Produce spare replica and components ready to plug in

See G. Contin @ iWoRiD 2014

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HFT Production, Assembly and QA workflow

Production processes:
- Sensor probe testing
- Ladder assembly
- Ladder testing
- Sector assembly
- Detector-half assembly

Production goals:
- 2 detector copies
- 40 additional spare ladders for refurbishment
- 120 high quality ladders

Production processes:
- Probe tested sensors
- Electrically tested low mass cables
- Electrically tested driver boards
- Dimensionally checked composite backer

Ladder assembly
- Ladder wirebonding
- Full functionality test
- Wire bond encapsulation
- Quick test

Tested Ladders
- Sized Sector Tubes
- machined Dovetail/D-tube
- Elect. tested MTB/cables/insertion

Sector assembly
- Quick test
- Sector metrology

Half detector head assembly
- Half detector head metrology

Quick test

Full functionality test

% HFT PXL
Production goals:
- 2 detector copies
- 40 additional spare ladders for refurbishment
- 120 high quality ladders

Production processes:
- Sensor probe testing
- Ladder assembly
- Ladder testing
- Sector assembly
- Detector-half assembly

- Semi-automated sensor probe testing
- Manual ladder assembly
- Manual sector assembly
- Detector-half assembly & survey

- Sector metrology survey
• **2013 Engineering Run** (3 sectors in actual STAR environment) crucial to solve:
  - Electrical shorts, mechanical interference, missing functionalities
  - Power control, monitoring and overcurrent thresholds were made available

• **2014-2016 Physics Runs** operations: up to 1000 hits/sensor; Trigger rate: 0.8-1 kHz
HFT PXL timeline and operations

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• **SEL (Single Event Latch-up) induced damage**
  • Current limited latch-up states (typically ~300 mA) permanently damaging the thin sensor
  • Affected mostly high-density logic in the digital section: local power dissipation melting the metal layers
  • Mitigated with latch-up detection and automatic power cycling: dead time up to ~6%

Operational sensor % trend
HFT PXL timeline and operations

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- **MAPS technology proved to be suitable for a collider experiment!**
ALICE ITS2: first large-area MAPS-based tracker

- **ITS1**: three silicon technologies
  - Hybrid pixels
  - Drift chambers
  - Micro-strips

- **ITS1**: operated for 10 years in ALICE
  - Secondary vertex reconstruction: essential ingredient for its physics output

- **ITS2**: a large-scale MAPS detector

- **Goal**: a dramatic improvement in the detector performance, especially at low $p_T$

- **ITS2**: a large-scale MAPS detector

- **Single technology**: MAPS sensor developed within the Collaboration in TowerJazz 180nm CMOS process
ALICE ITS2: 12.5 Gpixels on ~10 m² of silicon

- Monolithic Active Pixel Sensor
- Pixel pitch: ~30 µm
- 7 cylinders covering ~10 m²
- Innermost radius: 23 mm
- ~0.35% $X_0$ material budget
- ~24k chips = 12.5G pixels

"Technical Design Report for the Upgrade of the ALICE Inner Tracking System"
The ALPIDE sensor for ALICE ITS2

MAPS produced using TowerJazz 0.18\(\mu\)m CMOS Imaging Process

- Deep P-well allows in-pixel **full CMOS**
- Low-power (~40mW/cm\(^2\))
- ~30 \(\mu\)m pitch \(\rightarrow\) high granularity
- 50 \(\mu\)m thickness \(\rightarrow\) low material budget
- >1 k\(\Omega\)\cdot\)cm p-type epitaxial layer (25 \(\mu\)m)
- Possibility of **reverse biasing** to expand drift region
- TID \(\sim\) 0.3 Mrad
- NIEL \(\sim\) 3 \(\cdot\) 10\(^{12}\) 1 MeV n\(_{eq}\)/cm\(^2\)

- 27x29x25 \(\mu\)m\(^3\)
- 1024 x 512 pixels
- Spatial resolution: ~5 \(\mu\)m
- Priority Encoder Readout

- Integration time: < 20 \(\mu\)s
- Read out up to 1.2 Gbit/s
- Continuous or triggered read-out
- Final testing yield: 64%
Assembly and Quality Assurance workflow

**Assembly:**
- HICs → Half-staves → Staves

**QA:**
- Functional test at each step + HIC Endurance

**Metrology:**
- Align components and map the sensitive volume positions

Concurring processes:
- HIC wire bonding
- FPC gluing
- Chip alignment
- Reception test

Rework procedures:
- HIC: repeat wire bonding
- Half-Stave: replace HIC
- Stave: Disconnect and rework Half-Stave

Final validation test → Stave delivered to CERN

~4 days

- Probe tested Chips
- Tested and sized Flexible Printed Circuits
- Interconnection soldering
- Half-Stave metrology
- Functional test
- Endurance test

~2 weeks

- Tested Power Bus and Filter Board
- Sized Carbon Fiber Space Frame
- Stave assembly
- Stave metrology
- Power Bus soldering

ALICE ITS2
Custom-made module assembly machine for **automated** placing, alignment, inspection, gluing.
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Manual gluing on carbon fiber plate

Manual module connection soldering

Surveyed manual stave assembly

Manual power-bus application and folding

More than 10 Institutes for a few years!
1-year commissioning at the surface

- ITS2 included in ALICE Data Taking since 2022:
  - Extremely quiet (<10^{-7} hits/event/pixel), meeting performance expectations

See J. Liu’s poster @ this conference!
ITS2 technology transfer to other projects

ALICE ITS2

sPHENIX MVTX @RHIC

• Detector replicas for new experiments

ITS2 ALPIDE sensor

• Modified process developed and prototyped within ALPIDE R&D for better timing and radiation hardness
• Now adopted or considered by future experiments...
  • HADES, CBM, PANDA, NUSTAR, NA61, CSES2-Limadou, iMPACT, COMPASS++/AMBER, pCT, ePIC ...
• & chip developments:
  • MALTA,
  • CLICpix,
  • FastPix, ...

MPD Inner Tracker @NICA

1024 x 512 pixels
30 x 15 mm
50 or 100 μm thick
> 99% efficient
fake hit rate < 10⁻⁴/pixel/event – difficult to estimate due to radiation background consumption: ~100 mA @ 1.8V
The next MAPS development for HEP

STAR HFT
(2014-2016)

ALICE ITS2
Inner Barrel
(2021 - 2025?)

Material: 0.4%\(X_0\)
Minimum radius: 2.8 cm
Pixel pitch: \(~21\ \mu\text{m}\)

Material: 0.3%\(X_0\)
Minimum radius: 2.3 cm
Pixel pitch: \(~30\ \mu\text{m}\)

How can we do better than this?
The next MAPS development for HEP

A truly-cylindrical, ‘silicon-only’ detector to achieve unprecedented tracking performance at low transverse momenta.

ALICE ITS3
(2027 - ?)

Material: < 0.05%X₀
Minimum radius: ~ 1.8 cm
Pixel pitch: < 25 µm

Material: 0.4%X₀
Minimum radius: 2.8 cm
Pixel pitch: ~ 21 µm

Material: 0.3%X₀
Minimum radius: 2.3 cm
Pixel pitch: ~ 30 µm

See M. Suljic’s talk @ this conference!

STAR HFT
(2014-2016)

ALICE ITS2
Inner Barrel
(2021 - 2025?)
ITS3 silicon-only layers

- **Curved geometry**
  - Silicon becomes flexible below 50 µm thickness

- **Large area** chips to reduce segmentation and interconnections
  - 30 cm wafers
  - Stitched design:
    - abutting identical but functionally independent units
    - connect metal traces for power distribution and long range on-chip interconnect busses
    - repeat in vertical direction to match layer size

- **TPSCo 65 nm CMOS process** exploration
  - First submission containing test structures now characterised
  - Performance meeting ITS3 requirements

- **30 cm wafers (vs 20 cm in 180 nm)**
- **2D stitching experience**
- **Smaller feature size → smaller pixels**
Bent silicon validation

Bent ALPIDE

Bent silicon works!


Unchanged efficiency

Bent ALPIDE mini-tracker
Bent silicon validation

65 nm CMOS modified process with gap

M. Buckland’s poster @ this conference!

Bent ALPIDE

Bent ALPIDE mini-tracker

Unchanged efficiency

Bent silicon works!


doi:10.48550/arXiv.2212.08621

65 nm CMOS meets ITS3 requirements!

65 nm CMOS meets ITS3 requirements!
Manual bending and assembly

Manually wrapping a 50 µm thick dummy sensor, ~10 x 28 cm² around the 3 cm radius assembly mandrel

See M. Mager @ LCWS 2023

Total active area: ~0.12 m²
Manual bending and assembly

Manually wrapping a 50 µm thick dummy sensor, ~10 x 28 cm² around the 3 cm radius assembly mandrel

Bent sensor manually glued to the low-mass carbon foam supports and stuck on top of each other

Total active area: ~0.12 m²
Future challenges for MAPS-based trackers - 1

• Improve radiation tolerance and develop mechanics to place the detector directly ‘in the beam’

→ **ALICE 3 Experiment,** proposed for LHC LS4 (2034)

• **ALICE 3 Vertex Layers:** curved sensors at 5 mm from the interaction point
  
  • Expected **NIEL:** $10^{16}$ 1MeV $n_{eq}$ / cm$^2$ ~ $1000 \times$ ITS3 level  
    • Improve doping profiles in modified process
  
  • Expected **TID:** 300 Mrad ~ $300 \times$ ITS3 level  
    • Extend tests to understand limitations

• **Retractable mechanics** inside the beam pipe

• **Vacuum-compatible** services and interconnections

See M. Mager @ *FCC Week 2023*
Future challenges for MAPS-based trackers - 2

- **Cover extra-large areas** on barrel and disk layers
  
- **ALICE 3 Outer Tracker** ~60 m²
  - Industrialisation of the production
    - Module layout complying with industrial standards
  - Specific sensor development
    - Extremely low power consumption (≈ 20 mW/cm²)
    - Larger pixel pitch to reduce data and power

  **See M. Mager @ FCC Week 2023**

- **ePIC Silicon Vertex Tracker, proposed for EIC (2034)**
  - Based on ALICE ITS3 sensor
  - Stitched sensor size adapted for yield optimisation

  **See X. Li @ Vertex 2022**

See X. Li @ Vertex 2022
Summary: the sensor

**MIMOSA Ultimate-2**
- AMS 350 nm CMOS
- Twin-well process
- In-pixel NMOS transistors only
- Rolling-shutter readout
- \((\rho > 0.4k\Omega\cdot cm)\) p-type epitaxial
- Collection mostly by diffusion + drift in the built-in depletion

**ALPIDE**
- TowerJazz 180 nm CMOS
- Quadrupole-well technology
- Deep-pwell for in-pixel **full CMOS**
- Hit-driven readout
- \((\rho > 1k\Omega\cdot cm)\) p-type epitaxial (~25µm) on p-type substrate
- Depleted drift region expanded through reverse bias (0-6V)

**ITS3 sensor**
- TPSCo 65 nm CMOS
- Deep-pwell for in-pixel **full CMOS**
- Hit-driven readout
- Modified process for planar depletion + gaps for efficient collection from the edges
- Uniformly and fully depleted epitaxial
Summary: the sensor

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**27/06/2023**

24th iWoRiD, Oslo - giacomo.contin@ts.infn.it
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- **Uniformly and fully depleted epi-layer**
Summary: the apparatus

STAR HFT Pixel
- 2 vertexing layers
- ~356 Mpixel on 0.16 m²
- Traditional stave layout in turbo-like geometry
- 50 µm sensors on carbon fiber supports + FPC
- Air cooled
- Inner layer X/X₀ = 0.39%

ALICE ITS2
- 7-layer tracker – Inner(-Outer) layers
- ~12.5 Gpixels on 10 m²
- Traditional (module-)stave layout in turbo-like or staggered geometry
- 50(/100) µm sensors on carbon fiber + FPC (+ power bus)
- Water cooled
- Inner layer X/X₀ = 0.35%

ALICE ITS3
- 3 vertexing layers (~0.12 m²) integrated in ITS2 tracker
- Truly-cylindrical layer layout
- ~40 µm sensors on minimal carbon foam supports
- No in-acceptance data/power bus
- Air cooled
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Final considerations

• The HEP experiment requirements **pushed the sensor technology** to the current specifications and performance

• Innovative solutions for sensor, layout and mechanics developed for HEP goals are now **enabling new detector concepts**, made available for any application

• The **construction approach** depends on detector area and layout complexity:
  • From manual to semi-automated, to fully industrialised procedure as the area increases

• **Novel technologies**, fresh from R&D, quickly embedded in operating detectors, need risk mitigation strategies:
  • Engineering run (HFT), long-period commissioning (ITS2), spare detector copies for relatively quick replacement in case of failure

• **Higher radiation tolerance** and **larger areas** are the next challenges for MAPS
Thank you for your attention!