Radiationhard monolithic CMOS sensors with small electrodes for HL-LHC

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Monolithic Silicon Pixel Detectors

Depleted Monolithic Active Pixel Sensors for ATLAS

- Thin detector with high granularity
- **Low cost** cf hybrid pixel due to large-scale CMOS production without bump-bonding
- Allows very thin sensors to achieve ultimate **low mass trackers** (0.3% $X/X_0$)

MAPS in HEP & Heavy Ion Physics:
- E.g. STAR HFT, ALICE ITS ALPIDE chip from TJ 180 nm to be installed during ALICE tracker upgrade in LS2
- Typically collect charge via diffusion, but need depletion to go above $1 \times 10^{13} n_{eq}/cm^2$

**For ATLAS ITk L4: Rad hardness: NIEL $1 \times 10^{15} n_{eq}/cm^2$, TID $>80$ MRad & Hit rate $>100$ Mhz/cm$^2$** based on original specs for ITK outermost pixel layer
- **Innermost layers: CMOS** interesting option for future upgrades ($>LS3$) for biggest physics gain: small pixel ($\sim 25 \mu m$) & thin ($\sim 50 \mu m$?) - tough specifications will require strong R&D
Towards radiation hard MAPS... 

...there were several obstacles to overcome:

**Depletion is key:**

- At high radiation levels ($>10^{16}$ $n_{eq}/\text{cm}^2$) the ionization charge is trapped in the non-depleted part.
- Diffusion makes signal collection slower than typical requirements for pp-colliders for pixel pitches around typical 50$\mu$m.

Readout architectures are low power but not designed for high hit-rates of pp experiments at LHC or future pp colliders.
ATLAS CMOS Pixel Collaboration

- Collaboration of ~25 institutions

For ATLAS Prototypes from LFoundry 150 nm, AMS 180 nm, and Tower Jazz 180 nm designed for ATLAS radiation specifications
The STREAM Project

- The STREAM Project is the Marie Skłodowska Curie Innovative Training Network for CMOS Sensor Development in the context of LHC experiments and for selected industrial applications.

- The STREAM research and training program focuses on the development of radiation hard CMOS sensor technologies for innovative scientific and industrial instruments.

- STREAM offers 17 fellowships for the Early-stage researchers to participate in the design and test of novel radiation hard CMOS sensors.

- Parts of the ATLAS CMOS RD on CMOS sensors are supported through the STREAM MC fellows.

- STREAM Website: http://stream.web.cern.ch/
Small electrode designs

- Small electrode design allows for **small pixel size, low capacitance and low power** but require **special measures for full radiation hardness**

  - Electrode separated from circuitry
    - No analog-digital cross-talk
    - Smaller pixels
  - Allows for **small pixels** and **high spatial resolution** (<50x50µm²)
  - **Small diameter electrode** (3µm diameters) to achieve **minimal capacitance** (<3fF)
  - **Low power** due to low capacitance: bias current 500nA/pixel or <70mW/cm²
MALTA & MonoPix – Depleted CMOS sensors with small electrodes

- Design of two large scale demonstrators to match ATLAS specifications for outer pixel layers

The “MALTA” chip (2 x 2 cm²)
- Asynchronous readout architecture

The “TJ-Monopix” chip (2 x 1 cm²)
- Synchronous readout architecture.

The ATLAS “MALTA” and “MonoPix” chips for high hit rate suitable for HL-LHC pp-collisions
- Radiation hard to >10^{15} n/cm² & Shaping time 25ns (BC = 25ns)
- MALTA: Asynchronous readout architecture for high hit rates and fast signal response
- MonoPix: Synchronous Column drain readout architecture with ToT measurement

See poster L. Flores, P. Riedler
See talk C. Bespin
Novel CMOS Depleted MAPS with small electrodes

- Small collection electrode (few um²)
- Small input capacitance (<3fF) allows for fast & low-noise Front-end (ENC<10e⁻)
- High S/N for a depletion depth of >20um
- To ensure full lateral depletion, uniform n-implant in the epi layer (modified process with initial tests on Alice Investigator, then ATLAS MALTA, MiniMALTA, MonoPIX)

H. Pernegger et al 2017 JINST 12 P06008
MALTA after irradiation

- Good analog performance for ENC and timing
- But not sufficient efficiency after $10^{15} n_{eq}/cm^2$

Shared signal from neigb. Pixel hits

Leading hits
Efficiency with small electrodes

- Due to small collection electrode, the field configuration and charge collection under DPW in pixel corner is critical
  - Require full depletion under the DPW
  - Operating at low threshold is essential
  - Transversal field components in corner is needed for radiation hardness

Unirradiated @ 250e- threshold
2x2 pixel at 36µm pitch

Irradiated $10^{15}$n/cm$^2$ @ 350e- threshold
2x2 pixel at 36µm pitch
The MiniMALTA sensor

- MPW/TJ180nm run in 2019 to prototype further improvements in implant structure and front-end
  - Matrix with 64x16 pixels in 8 sectors
  - 36.4\(\mu\)m pixel pitch
  - Asynchronous column design (MALTA)
  - synchronization memory at EoC (end-of-column) to synchronize with 320/640Mhz clk
Optimization for radiation hardness
The MiniMALTA sensor

- Special layouts for deep p and n wells to optimize field configuration and charge collection
- Increase lateral field near pixel edge to “focus” charge to electrode
- Also can improve time-resolution and charge sharing (see poster by T. Kugathasan on FastPix & presentation by M. Munker on CLIC)

Common development with CLICTD (presentation M. Munker)
Optimized Front-End

- MALTA/MonoPix Front-End improvements prototyped in MiniMALTA to increase gain and reduce noise

Increased $C_s$ & Transistor sizes:

- Increased gain
- Reduce ENC noise & threshold dispersion
- Reduce RTS noise (observed in MALTA and MonoPix)
The MiniMALTA Sensor – improved radiation hardness

64x16 pixels in 8 sectors to investigate different implant structures and FE transistors

Modified Process with gap in n-layer

Modified Process plus additional DPW

Modified Process

M. Dyndal et al., arXiv:1909.11987
MiniMALTA analog

Threshold reduced by factor $\sim x2$ over original front-end design (300e- to 570e- at same setting). Threshold dispersion was 30-50e- now 22-30e-. Gain increased by factor 1.7

ENC noise similar mean (10e- pre-irrad, 20e- after irradiation) but substantially less RTS noise.
Efficiency before/after $10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ irradiation

Beam test results show that >98% efficiency is reached after $10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ through the combination of FE improvement and charge collection improvement in pixel corners on high resistivity epitaxial p-type substrate (25-30\(\mu\)m)

**MiniMALTA**

TJ180nm 
36x36\(\mu\)m

98% efficiency after $10^{15} \text{n}_{\text{eq}}/\text{cm}^2$

M. Dyndal et al., arXiv: 1909.11987
**γ-irradiation to 100Mrad**

- Irradiated MiniMALTA to 100Mrad
- Measured analog performance during irradiation
  - No substantial annealing carried out, always use pre-irrad setting (no optimization)
  - ENC increase from 10e⁻ to 20e⁻ @100Mrad, Gain unchanged to 100Mrad
    - Some “bump” between 1 to 10Mrad – under investigation

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**Graphs**

- **Noise mean vs TID**
  - New front-end
  - Original front-end

- **Amplitude of FE target as a function of TID**
  - New front-end
  - Original front-end

*See L. Simon Argemi / Uni Glasgow TWEPP 2019*
Efficiency vs threshold

For **full efficiency after irradiation** on epitaxial substrate need improved **front-end plus implant modification**

- Implant modified
- PLUS Improved Front-end

**Implant modified**

**PLUS Improved Front-end**

- Large trans.
- Large trans. + extra p-well
- Large trans. + n' gap
- Std trans.
- Std trans. + extra p-well
- Std trans. + n' gap

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H. Pernegger/CERN Dec 16, 2019

HSTD2019 Hiroshima
New MALTA on HR Cz substrate

- Original MALTA & MonoPix matrix reprocessed on high resistivity Cz substrate material
- Allows for significant larger depletion and signal -> prospects for even higher radiation hardness and possible improved time-resolution with O(1ns)

### MALTA-Cz main features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Pitch</td>
<td>36.4x36.4 µm²</td>
</tr>
<tr>
<td>Matrix size / active area</td>
<td>512x512 /18.3x18mm²</td>
</tr>
<tr>
<td>Hit rate capability</td>
<td>&gt;&gt; 100MHz/cm²</td>
</tr>
<tr>
<td>Time resolution</td>
<td>&lt;10ns (under test)</td>
</tr>
<tr>
<td>TID radiation hardness</td>
<td>&gt;100Mrad</td>
</tr>
<tr>
<td>NIEL radiation hardness</td>
<td>&gt;10^{15} n_{eq}/cm²</td>
</tr>
</tbody>
</table>
Key objectives for MALTA-Cz

- **Objective: improve radiation hardness**
  - n-layer gap and 2\textsuperscript{nd} DPW as already implemented in MiniMalta
  - Enlarge signal through thick substrate (100 to 300\,\mu m p-type high resistivity Cz substrate biased to \sim 50V)

- **Objective: cluster size / better timing**
  - Better slew rate with thin pCz 100\,um operating at \sim 50V
  - Cluster size: EPI vs Cz – if clusters are larger on Cz due to different drift path we can improve spatial resolution through charge weighting
  - Must avoid punch-through on Cz to allow higher operation voltage $V_{\text{sub}} \gg V_{\text{pwell}}$

### Produced Summer 2019 – First irradiation and beam test results now

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Implant configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPI (30,\mu m)</td>
<td>N- gap and 2\textsuperscript{nd} DPW</td>
</tr>
<tr>
<td>Cz HR</td>
<td>Continuous n- layer, n- gap and 2\textsuperscript{nd} DPW</td>
</tr>
</tbody>
</table>
Operation voltage MALTA-Cz

- Received **MALTA-Cz** August 2019 - neutron irradiated full-size MALTA-Cz (2x2cm²) at Triga reactor IJS/Slovenia
- **Breakdown voltage > 50V**, even on sensor with gap in n-layer
  - TCAD predicts lower $V_{bd}$ - under investigation
- Good prospects for high depletion depth (larger than EPI – substrates)

**High operation voltage achieved**

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**Cz Std MALTA**

- **W7R0Cz**
  - $1 \times 10^{15}$ $n_{eq}/cm^2$
  - Preliminary

**Cz n-gap**

- **W9R1Cz**
  - $1 \times 10^{15}$ $n_{eq}/cm^2$
  - Preliminary
Efficiency MALTA-Cz

- n-irradiated (IJS) to $2 \times 10^{15}$ \(n_{eq}/\text{cm}^2\) followed by DESY beam test
- Full-size MALTA sensor with original front-end design on HR pCz
- Preliminary Efficiency (shown as 2x2 pixel x-y dependency) compared unirradiated – $1 \times 10^{15} n_{eq}/\text{cm}^2$ - $2 \times 10^{15} n_{eq}/\text{cm}^2$

<table>
<thead>
<tr>
<th>MALTA Cz unirradiated</th>
<th>MALTA Cz n-gap $1 \times 10^{15} n_{eq}/\text{cm}^2$</th>
<th>MALTA Cz n-gap $2 \times 10^{15} n_{eq}/\text{cm}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon = 98.5% )</td>
<td>( \varepsilon = 97.0% )</td>
<td>( \varepsilon = 95.4% )</td>
</tr>
<tr>
<td>Sector 2, (&lt;\text{eff}&gt; = 98.5\pm0.0 % )</td>
<td>Sector 2, (&lt;\text{eff}&gt; = 97.0\pm0.0 % )</td>
<td>Sector 2, (&lt;\text{eff}&gt; = 95.4\pm0.0 % )</td>
</tr>
</tbody>
</table>

- Thres = 427 e\(^{-}\)  
  ENC = 9.8 e\(^{-}\)
- Thres = 260 e\(^{-}\)  
  ENC = 12.7 e\(^{-}\)
- Thres = 226 e\(^{-}\)  
  ENC = 14 e\(^{-}\)
Cluster size MALTA-Cz vs EPI

- **Unirradiated MALTA sensor substrate comparison**

- Substantially *more charge sharing in Cz material*
- **Cluster size increases with substrate voltage** as depletion depth & drift path length increases in Cz substrate
- Expect better spatial resolution in Cz due to charge interpolation -> to verify in high energy beam test
Next in TJ180: MALTA & MonoPix Version 2

- Based on recent 2 years R&D on radiation hard high-granularity monolithic sensors with small electrodes in TJ180nm

Improved implant layout

Cz & EPI Substrate Choice

Better Pixel and Front-end designs
Next in TJ180: MALTA & MonoPix
Version 2

- New Front-End design for ~x2-x3 higher gain, less noise
- Threshold adjustment on pixel level
- New implant designs, reset optimization
- New HR pCz substrate as well as EPI substrate

Increased Cs & Transistor sizes (now minimum length)

Increased gain, reduced threshold dispersion & reduced RTS noise

Diode reset for increased TID robustness
MALTA & MonoPix Version 2

- New Matrix designs 512x512 and 512x226 for MonoPix V2 and MALTA V2
- 7-bit ToT for analog measurements (MonoPix)
- Reduced column latency (~4ns) and timewalk for best time resolution (MALTA)
- Submission: Q1/2020 – Tests & Results Q2- Q3/2020

HSTD 2019 See Presentation and Poster by Christian Bespin & Leyre Flores
Summary & Outlook

• The development of new **depleted monolithic CMOS sensors** in HR/HV CMOS process progresses rapidly

• **Small electrode designs** like TJ180nm produced MALTA and MonoPix sensor matrices offer **low capacitance, low noise and low power** solutions for fine-pitch (<50µm) pixel sensors

• For the first time we have achieved **full radiation hardness** to 100Mrad & \(10^{15}\) n_{eq}/cm\(^2\) with **small electrodes** on MALTA sensors
  • Significant improvement in front-end performance
  • Substantially larger signal on pCz substrate - High substrate bias voltage of 50V

• We are now implementing all knowledge in **next generation sensors** designs of MALTA & MonoPix Version 2 in two large-size matrices for submission in Q1/2020
DMAPS/CMOS for Future Trackers

<table>
<thead>
<tr>
<th></th>
<th>RHIC STAR</th>
<th>LHC - ALICE ITS</th>
<th>CLIC</th>
<th>HL-LHC Outer Pixel</th>
<th>HL-LHC Inner Pixel</th>
<th>FCC pp</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIEL [n_{eq}/cm^2]</td>
<td>10^{12}</td>
<td>10^{13}</td>
<td>&lt;10^{12}</td>
<td>10^{15}</td>
<td>10^{16}</td>
<td>10^{15-17}</td>
</tr>
<tr>
<td>TID</td>
<td>0.2 Mrad</td>
<td>&lt;3 Mrad</td>
<td>&lt;1 Mrad</td>
<td>80 Mrad</td>
<td>2x500 Mrad</td>
<td>&gt;1 Grad</td>
</tr>
<tr>
<td>Hit rate [MHz/cm^2]</td>
<td>0.4</td>
<td>10</td>
<td>&lt;0.3</td>
<td>100-200</td>
<td>2000</td>
<td>200-20000</td>
</tr>
</tbody>
</table>

- **Strong interest for R&D to fully exploit potential of MAPS in future Trackers**
  - High granularity, Low material budget and power, Large area at reduced cost (cf hybrid)
  - CMOS foundries offer substantial processing power to enable significant performance gains

H. Pernegger/CERN Dec 16, 2019
CMOS sensor designs

- Purse different design approaches for optimal performance

- Large electrodes
  - Electronics in collection well
  - No or little low field regions
  - Short drift path for high radiation hardness
  - Large(r) sensor capacitance \((dpw/dnw)\) -> higher noise and slower @ given pwr
  - Potential cross talk between digital and analog section

- Small electrodes
  - Electronics outside collection well
  - Small capacitance for high SNR and fast signals
  - Separate analog and digital electronics
  - Large drift path -> need process modification to usual CMOS processes for radiation hardness

- “Burried” electrodes (SOI)
  - Electronics and sensor in separate layer
  - Can use thick or thin high resistivity material and HV (>200V)
  - Special design/processing to overcome radiation induced charge up of oxides
Initial results on small electrodes

2018 MALTA & TJMonoPix measurements
- Both chips work – same FE design, different readout architecture
- Tests ongoing (lab, beam tests, irradiations) show excellent ENC ~ 8e-

H. Pernegger et al 2017 JINST 12 P06008
H. Pernegger/CERN Dec 16, 2019
MALTA readout architecture

- Matrix design optimize **for very high hit-rate** (in circuit simulation 1 GHz/cm²)
- **Each pixel hit** is generates a LE signal (0.5 to 2ns) on its line of the pixel bus
- **Group number** encoded on 5-bit group address bus
- **One fast “HitOR”** generated for blue and red groups
- All signals are transmitted **asynchronously** at the time of the discriminator output (plus gate delays)