Performance of Capacitively Coupled Active Pixel Sensors in 180nm HV-CMOS Technology after Irradiation to HL-LHC Fluences

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Simon Feigl\(^{[1]}\) – CERN, University of Oslo (PhD student)

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on behalf of the ATLAS upgrade HV-CMOS collaboration:

Bonn University, CERN, CPPM Marseille, Geneva University, Göttingen University, Glasgow University, Heidelberg University, LBNL

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HEP detector challenges

- requirements on silicon detectors for future colliders are challenging
- environment/specs for HL-LHC tracker detectors:
  - high radiation levels: $\approx 2 \times 10^{16}$ neq/cm$^2$, $\approx 1$ GRad (pixel layers)
  - large surface at reasonable cost (strip layers: $\approx 200$ m$^2$)
  - fast (40MHz readout)
  - high spatial granularity ($\approx 50$-100 $\mu$m)
**HV-CMOS process**\(^2\) properties and sensor ideas

- CMOS electronics inside deep n-well (NMOS inside additional p-well): “Smart Diode Array” (SDA)
- low substrate resistivity, high \(N_{\text{eff}}\)
- negative biasing creates depletion zone around n-wells
- charge collection by drift
- signal amplification on sensor chip
- capacitive coupling to readout chip (gluing!)
- small pixel size

<table>
<thead>
<tr>
<th>Technology</th>
<th>Austria Microsystems (AMS) + IBM 350 nm / 180 nm</th>
</tr>
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<tbody>
<tr>
<td>Substrate Resistivity</td>
<td>&gt; 10 Ωcm</td>
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<tr>
<td>Pixel Size</td>
<td>down to 20 µm</td>
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<tr>
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<tr>
<td>Reverse Bias Voltage</td>
<td>down to (\approx -100) V</td>
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<td>MIP Signal Charge</td>
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[2] AMS H18 / IBM CMOS 7HV Process
### Suitability for future tracker detectors

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**HV-CMOS Active Pixel Sensors**

Simon Feigl
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Prototype Sensors

- First prototypes in 350nm technology yielded promising results (see backup slides)
- 180nm Prototype sensors: HV2FEI4v1 (1\textsuperscript{st} generation, rad-soft electronics design) HV2FEI4v2 (2\textsuperscript{nd} gen, rad-hard)
  - designed by Ivan Perić (University of Heidelberg)
  - 60 columns x 24 rows
  - pixel size 33x125 μm\(^2\)
  - ASIC designed to fit FEI4 readout chip
    → use of highly optimized readout electronics
  - on-pixel electronics: amplifier, discriminator, TuneDACs etc.
  - IO bond pads for different operation modes

![Prototype Sensor Diagram]
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    - IO bond pads for different operation modes
- Standalone measurements
  - investigation of performance of sensor electronics
  - irradiation effects
- CCPD: \textbf{Capacitively Coupled Pixel Detector}
  - HV2FEI4 glued onto ATLAS pixel front-end chip (FE-I4)
  - proof of principle
  - irradiation effects
- Strip-Readout
HV2FEI4v1 (1st Generation)

- electronic elements from standard library (not radiation hard)
- physics events clearly visible
- $^{90}$Sr and $^{55}$Fe-spectra recorded

Discriminator Output

Sr-90 spectrum

entries

Fe-55 spectrum

entries

ToT

ToT

ATLAS CERN
HV2FEI4v1 – Ionizing Radiation Effects

- $^{90}$Sr-spectrum still visible after 80 Mrad proton irradiation (but visible effects)
- particle signals observed up to 200 Mrad
- preamp worked after 200Mrad, discriminator died
- reasons for signal loss:
  - large amplifier gain drop
  - large leakage current
HV2FEI4v2 (2\textsuperscript{nd} Generation)

- rad-hard design
- different pixel types:
  - “normal”: guard rings implemented
  - “rad-hard”: circular transistors (→ larger capacitance → lower gain)
- $^{55}$Fe- and $^{90}$Sr-spectra measured
HV2FEI4v2 (2nd Generation)

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![Threshold dispersion graph]

- threshold tuning implemented

![Signal vs. Counts graph]
HV2FEI4v2 (2nd Generation)

- rad-hard design
- different pixel types:
  - “normal”: guard rings implemented
  - “rad-hard”: circular transistors (→ larger capacitance → lower gain)
- $^{55}$Fe- and $^{90}$Sr-spectra measured

- threshold tuning implemented
- noise ≈ 75e
• X-ray irradiation to 862 Mrad, 2 hours of annealing at 70°C after each 100Mrad, powered on during irradiation
• amplifier gain loss in rad-hard pixels fully recovered after optimizing chip settings

Radiation effects on preamplifier gain

rad-hard pixels

simple pixels

annealing

re-optimization of settings (irradiation stopped at 862Mrad)
• X-ray irradiation to 862 Mrad, 2 hours of annealing at 70°C after each 100Mrad, powered on during irradiation
• amplifier gain loss in rad-hard pixels fully recovered after optimizing chip settings
• noise increase on partially rad-hard pixel: 90e → 150e (at room temperature)
• amplifiers work with reduced bias current (2µA instead of 5µA)

Radiation effect on noise level

Before irradiation

- Noise before irradiation: 90e

After irradiation

- Noise after irradiation: 150e
• on-sensor signal amplification
  – capacitive coupling possible
  – gluing instead of bump-bonding
    → fast & cheap production
CCPD – Capacitively Coupled Pixel Detector

- on-sensor signal amplification
  - capacitive coupling possible
  - gluing instead of bump-bonding
    → fast & cheap production

- readout with FE-I4 / sub-pixel structure
  - three sub-pixels connected to one readout pad
  - position encoding in signal height
    → improves spatial resolution with respect to standard FE-I4 cell
CCPD Setup

HV-CMOS Active Pixel Sensors

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CCPD (HV2FEI4v1 on FEI4) – It Works

- $^{90}\text{Sr}$-source
- Readout by FEI4 (STcontrol)
- w/o source: 0 rate
- w/ source: kHz rate
• ionizing radiation (protons, X-ray) → affects mainly electronics
• non-ionizing radiation (neutrons) → affects mainly bulk silicon
HV2FEI4v1 – Non-Ionizing Radiation Effects (Bulk Damage)

- Ionizing radiation (protons, X-ray) → affects mainly electronics
- Non-ionizing radiation (neutrons) → affects mainly bulk silicon
- Presumably radiation hard

- Irradiation of HV2FEI4v1 to $1 \times 10^{15}$ and $1 \times 10^{16}$ neq/cm$^2$ in Ljubljana
- Leakage current behaves as expected

Leakage current at room temperature

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<tr>
<td>0</td>
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</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
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- Neutrons
- Room temperature
ionizing radiation (protons, X-ray) → affects mainly electronics
non-ionizing radiation (neutrons) → affects mainly bulk silicon
presumably radiation hard

irradiation of HV2FEI4v1 to 1e15 and 1e16 neq/cm² in Ljubljana
leakage current behaves as expected
sensor works even at room temperature!
CCPD – Particle Detection

- first measurements with scintillator trigger
- LVL1-distribution clearly show that we really see physics
- rate goes up with -HV, saturation still to be seen
- further measurements will include higher bias voltage

after $1e16$ neq/cm$^2$!
CCPD – Sub-Pixel Encoding

- sub-pixel encoding works on single pixel cells
- individual sub-pixels well separated in ToT-spectrum
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- sub-pixel encoding works on single pixel cells
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FE-I4 pixels

HVCNOMS pixels

Signal transmitted capacitively

Bias A

Bias B

Bias C

Sub-Pixel 1

Sub-Pixel 2

Sub-Pixel 3

unirradiated sensor!
CCPD – Test Beam

- data taken, but problems with reconstruction (DUT data stream sync problems during data taking)
- HV-CMOS worked in test beam!
- no cooling!
- next studies: efficiency comparison unirrad./irrad, spatial resolution

stay tuned!
CCPD - Outlook

- performance of sensors has to be measured systematically:
  - cooled sensors
  - rate and leakage current vs. bias voltage
  - efficiency
  - spatial resolution

- 2nd generation sensors ready → CCPDs to be tested

- neutron irradiation of 2nd generation sensors
• performance of sensors has to be measured systematically:
  – cooled sensors
  – rate and leakage current vs. bias voltage
  – efficiency
  – spatial resolution

• 2nd generation sensors ready → CCPDs to be tested

• neutron irradiation of 2nd generation sensors

• optimization of pixel electronics and geometry

• engineering run (full size sensors suitable for large scale HEP detectors)
Strip Readout

- Pixels are summed to “virtual strips”
- Readout with analogue or digital readout chips
- Hit position encoded again in pulse height
Strip Readout

- Pixels are summed to “virtual strips”
- Readout with analogue or digital readout chips
- Hit position encoded again in pulse height

- pixel hitmap reconstructed from strip information (here: shadow of a wire)

cheap pixel sensor used as strip detector → 200m² affordable!
Outlook on HV-CMOS technology for sensors

- HV-CMOS processes enable the fabrication of active sensors with many advantageous properties needed for HL-LHC application and beyond:
  - cheap & fast production
  - rad-hard
  - high spatial resolution
  - fast
  - thin
  - low bias voltage
- first results look promising with regard to withstanding $1 \times 10^{16}$ neq/cm$^2$!
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  - ideas to use 65 and 130nm
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- final goal: full-size detector for large scale HEP tracking detectors
Thank you!
Backup Slides
Development in 350nm Technology

- used AMS 0.35µm technology
- Several prototypes have been designed
- Three detector types:
  - A) Monolithic detector with intelligent CMOS pixels
  - Pixel electronic is rather complex – CMOS based charge sensitive amplifier, usually discriminator, threshold tune…
  - B) Monolithic detector with 4-PMOS-transistor pixel and rolling shutter RO
  - C) Capacitively coupled hybrid detectors
  - Good results, >98% efficiency in test-beam, high radiation tolerance
Pixel Schematics

normal pixel

HV-CMOS Active Pixel Sensors

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