Fully depleted CMOS Pixel Sensor (CPS) development and potential applications

Jérôme Baudot, Maciej Kachel, Barbara Bensimon and Wojciech Dulinski†
For the PICSEL group

CPS assets & properties
Options for fully depleted CPS
Prototypes of HR-CPS
Conclusion & outlooks

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Lisboa
CMOS Pixel Sensors assets

- **A digital camera for cell phone**
  - Low power, μm-size pixel, low cost, smart
  - Ultra-dominant application → drives industry development

- **Scientific CMOS**
  - Very sensitive & fast (100-1000 fps) camera
  - Exploit in-pixel amplification & embedded treatment

- **Radiation sensors**
  - Charge particle counters
  - Trackers for High Energy Physics
    - high granularity, sparse r-o, low power
    - easy integration, lower cost
  - Dosimeters

→ **Other applications ?**
First CPS for HEP

- **Requirements from Heavy Ion Collisions**
  - low material budget, include low power dissipation
  - granularity beyond strip
  - moderate radiation tolerance
  - In-line with ILC-spec (except for \( \sigma_{s.p.} \))

- **The STAR PXL (operating since 2014)**
  - Ultimate/MIMOSA-28 sensor from IPHC
    - Binary rolling-shutter read-out
    - AMS 0.35 \( \mu \)m CMOS technology
  - 400 sensors \( \rightarrow \) 360x10^6 pixels
  - Air flow cooling Top \( \leq 35 \) °C
  - \( \sigma_{s.p.} \approx 4 \) \( \mu \)m
  - mat. budget = 0.39 % \( X_0 \) / layer
  - 2 layers: \( r = 2.5 \) & 8 cm

+ CPS in dev. for ALICE-ITS upgrade (10 m²)
Charge collection properties

- **The basic working principle**
  - Secondary charges generated in epitaxial layer
    - For ionizing part. → signal ∝ epi-thickness
  - Charges transport driven by 3 potentials
    - P-well / collection node / P++ substrate
    - Usually ground / few Volts / ground
  - Transport = mix of diffusion and drift
    - Ratio depends on electric fields

- **Electric fields in epi-layer?**
  - Front depleted area depends on
    - $\sqrt{V_{N\text{-well}} \times \text{epi-resistivity}}$
    - Pixel pitch (= density of coll. nodes)
  - Back-side field extension depends on
    - Doping gradient from substrate to epi
  - Note: if epi thick enough
    - Middle region with no field

- **Typical epi thickness**
  - 10 to 40 µm

- **Low resistivity epi**
  - resistivity < 100 Ω.cm

- **High resistivity epi**
  - 100 Ω.cm ≪ resistivity
  - Few kΩ.cm available
Sensor global properties 1/2

- **A hit = cluster of fired pixels**
  - Cluster extension ➔ with depletion ➔

- **Detection efficiency**
  - Driven by largest pixel-SNR
  - Benefit from small cluster

- **Single point resolution**
  - Driven by pixel pitch
  - Benefits from large cluster
    - Exploit Q center of gravity

![MIMOSA-26 sensors](image)

**MIMOSA-26 sensors (forerunner of MIMOSA-28)**

**Mimosa resolution vs pitch**

-Maryland Sensors [2015]

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Sensor global properties 2/2

- **Non-ionizing radiation tolerance**
  - Limited by signal collection time
    - Prob. Trapping by crystal defects $\propto$ time
  - Benefits from high diode density (pixel-SNR)

- **Energy resolution**
  - Poor with cluster $> 1$ pixel
    - Noise $\propto \sqrt{\text{#pixels}}$
    - Pixel-to-pixel gain variation

- **Back-side illumination**
  - Industrial process
  - Thinning down to epi-layer
  - Passivation to re-create substrate effect

- **Single particle sensitivity**
  - Minimum ionizing particle
    - 80 e-h/µm
  - Low energy particles + Photons (stopping in few µm of Si)
    - Total charge OK $\sim$ E
    - Reaching the epi layer?
Motivation for depleted CPS

- **High energy physics trend**
  - Tolerate high non-ionizing part. Fluences $10^{15} \text{n}_{eq}/\text{cm}^2$ (tracker / vertex)
  - Integration time $\ll \mu$s

- **X-rays detection**
  - Require thickness (Beer-Lambert attenuation law)
  - Require equivalent collection properties all over epi-layer

- **Fully depleting the sensitive layer is a key**
  - However situation different / sensors for hybrid-systems (CERN-RD50)
    - Same substrate embed sensitive and first amplification layer

- **Open questions**
  - Which structure to enforce depletion?
    - Depth & uniformity on chip area
  - impact on in-pixel treatment $\mu$-circuits?
    - Noise, transistor behavior
Way 1: High Voltage

- **Experiments**
  - ATLAS, µ2e, CLIC
  - Groups in Bonn, CERN, Genève, Heidelberg, Karlsruhe, Marseille...
  - new collab. ➔ CERN-RD53

- **Concept**
  - Low resistivity (10-20 Ω.cm)
  - High Voltage applied few 10s V
  - HV-compliant CMOS technologies

- **HV-CMOS**
  - Deleted depth demonstrated 5 to 15 µm with 60-70V
  - Fast amplification ~ 1 µs
  - Only 30% signal loss after $10^{15}$ n$_{eq}$/cm$^2$

- **HV-SOI**
  - Depleted depth demonstrated 40-50 µm with 150-200 V
  - Hint of tolerance beyond $10^{14}$ n$_{eq}$/cm$^2$

! Prototypes area 10 mm$^2$

S. Feigl et al., PoS (TIPP2014) 280

T. Hemperek et al., arXiv:1412.3973

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Way 2: High Resistivity

- **Experiments**
  - ALICE, CBM
  - soft X-rays detection
  - Groups in Bonn, CERN, RAL, Strasbourg

- **Concept**
  - High Resistivity thin epi-layer
  - moderate voltage $\lesssim 10$ V

⇒ See next slides for IPHC developments
Depleted-CPS prototypes

- **2 Technologies explored**

  - **Tower Jazz 0.18 µm ➔ Pegasus-1/2**
    - Various sensitive layers
      - epi with >1 kΩ·cm, 18, 30, 40 µm thick
      - Czochralski substrate-thick
    - Main architecture tested
      - Analogue readout with 10 µs integration time
      - Collection node AC-coupled to amplificator
    - Small matrix: 32 columns x 56 rows
    - Pixel size 25x25 µm²

  - **EPC-ESPROSS 0.15 µm ➔ MIMOSA-33**
    - high resistivity 50 µm thinned + passivated substrate
    - Main architecture tested
      - Analogue read-out with 11 µs integration time
      - Back-side biasing through IP structure
    - Small matrix: 8 columns x 44 rows
    - Pixel size 25x25 µm²

Ready for back-side illumination!

M. Havranek et al., JINST 10 (2015) 02, P02013
Reported measurements

- **X-ray from $^{55}$Fe illumination**
  - monochromatic rays (5.9 & 6.4 keV)
  - Energy calibration (5.9 keV = 1640 e- in Si)

- **$\beta$ from $^{90}$Sr illumination**
  - MIP-like e- (~80 e-h/µm)
  - Probe the sensitive volume in depth

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**Room temperature measurements**

<table>
<thead>
<tr>
<th>Vbias</th>
<th>Number of Entries</th>
<th>$Q_{seed}$ (ADC Counts)</th>
</tr>
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<tbody>
<tr>
<td>1V</td>
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Equivalent capacitance
- From 55Fe peak:
  \[ C_{eq} = \frac{Q(1640e-)}{V_{mes}(peak)} \times g_{Ampli} \]
  \( g_{Ampli} \) poorly known \( \Rightarrow \) no absolute measure
- Expected behavior \( C_{eq} \propto \frac{1}{\sqrt{V_{bias}}} \)

Equivalent noise charge
- Interplay \( C_{eq} \) & leakage current
View on depletion 1/4

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- Expected behavior \( C_{eq} \propto \frac{1}{\sqrt{V_{bias}}} \)

- Depletion-like behavior observed
  - Saturation of effect \( \lesssim 10 \text{ V} \) (~ \( V_{dep} \) ?)
  - Reasonable noise for PEGASUS
    - ENC \~ 30 e-
  - Large noise for MIMOSA-33
    - ENC \~ 75 e-
  - Poorly tuned \( \mu \)-circuits parameters

Equivalent noise charge
- Interplay \( C_{eq} \& \) leakage current

\[ C_{eq} = (7 + 10 / \sqrt{V_{bias}}) \times 10^{-15} \]
**View on depletion 2/4**

- **Equivalent charge collection thickness**
  - From $^{90}$Sr-\(\beta\):

  \[
d_{eq} = \frac{\text{Max.Prob.}(Q_{\text{cluster}}) \times \text{conv.}(e/adc)}{80(e/\mu m)}
  \]

- **Expectation:** \(d_{eq} \propto \sqrt{V_{bias}}\)
  - **No change with bias voltage**
  - even if not fully depleted, diffusion complete charge collection
  - Method useless to evaluate depletion depth (with epi layer)
Cluster size is impacted by depletion → ratio $Q_{\text{seed}} / Q_{\text{cluster}}$

- Clear evolution with bias voltage
  - Method Saturation effects ≤ 8 V
  - However not quantitative for depletion depth
Another look at cluster size
- # significant pixel contributing in average to the cluster charge

PEGASUS – epi 18 µm @ 1 V

# significant pixels

Full charge in 5x5 pixels

Same charge with 4 highest pixels

Repeated over all $V_{bias}$

⇒ Same qualitative effect observable
Some global property

- **Energy resolution**
  - Pegasus-18µm @ $V_{bias} = 12$V
  - $\sigma_{charge} = 36 \pm 3$ e-
Ongoing prototypes design

- Submission to Tower-Jazz 0.18 µm technology (June 2015)

- **MIMOSA - 22 SX**
  - Forerunner of sensors dedicated to X-rays with energy < 5 keV
    - Pixel pitch ≤ 25x25 µm² and ≃ 10⁴ photons/pixel/sec
  - Developed with the detector group of SOLEIL
  - "Not so small" matrix: 5.6x 4.4 mm²
  - combine:
    - AC coupled collection diode from PEGASUS
    - read-out architecture developed for ALICE
  - Binary output:
    - From 2 discriminators/column → energy window selection
    - Photons detected individually → counting & spatial resolution

- **Small analogue prototype**
  - Faster amplification → target 10⁶ photons/pixel/sec
  - Mitigation of noise
Conclusions & Outlooks

- **Fully depleted CPS promises**
  - Spectroscopic measurements
  - Tolerance to non-ionizing particle fluence ($\leq 10^{15}\, n_{eq}/cm^2$ range ?)

- **Active field**
  - Large collaboration in the game (HL-LHC) around HV-CMOS
  - Other developments for specific applications (SOLEIL)

- **Still only “promising”**
  - Concept validated on small prototypes
  - Next step to be validated = cm$^2$ sensor (requires final r-o archi. + uniformity)

- **More to learn on prototypes**
  - Depletion depth? → Chochralsky substrate
  - Depletion uniformity? → laser scan of surface area
  - Non-ionizing tolerance (Pitch-depletion correlation?)