Rad damage in CMOS

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Outline

○ **VXD in Belle II**
  • Limits of the current system
  • Requirements for an upgraded system

○ **Depleted CMOS**
  • Requirements for high radiation tolerance
  • Commercial vendors
  • Radiation tolerance performance of recent demonstrators
  • Possible improvements

○ **Conclusion**
VXD in Belle II

- **Limits of the current VXD system**

<table>
<thead>
<tr>
<th>layer</th>
<th>PXD1</th>
<th>PXD2</th>
<th>SVD3</th>
<th>SVD4</th>
<th>SVD5</th>
<th>SVD6</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius (mm)</td>
<td>14</td>
<td>22</td>
<td>39</td>
<td>80</td>
<td>104</td>
<td>135</td>
</tr>
<tr>
<td>trigger rate (kHz)</td>
<td>30</td>
<td>30 with 6 APV25 samples</td>
<td>70 with 3 APV25 samples</td>
<td>52.2</td>
<td>33.9</td>
<td>2.8</td>
</tr>
<tr>
<td>occupancy (%)</td>
<td>3</td>
<td>2.6</td>
<td>0.8</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>hit rate (MHz/cm²)</td>
<td>52.2</td>
<td>33.9</td>
<td>2.8</td>
<td>0.9</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>TID (MRad)</td>
<td>&gt; 20</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>NIEL x10¹² (cm⁻²)</td>
<td>100</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

- **Requirements for an upgraded VXD system**

<table>
<thead>
<tr>
<th>layer</th>
<th>radius (mm)</th>
<th>hit rate (MHz/cm²)</th>
<th>TID (MRad/smy)</th>
<th>NIEL x10¹² (cm⁻²/smy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PXD1</td>
<td>14</td>
<td>22.6</td>
<td>2</td>
<td>10.0</td>
</tr>
<tr>
<td>PXD2</td>
<td>22</td>
<td>11.3</td>
<td>0.6</td>
<td>5.0</td>
</tr>
<tr>
<td>SVD3</td>
<td>39</td>
<td>1.41</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>SVD4</td>
<td>80</td>
<td>0.29</td>
<td>0.02</td>
<td>0.1</td>
</tr>
<tr>
<td>SVD5</td>
<td>104</td>
<td>0.22</td>
<td>0.01</td>
<td>0.1</td>
</tr>
<tr>
<td>SVD6</td>
<td>135</td>
<td>0.15</td>
<td>0.01</td>
<td>0.1</td>
</tr>
</tbody>
</table>

  - TID (PXD1) → 50 MRad/smy * 10 years lifetime = 500 MRad
  - NIEL (PXD1) → 250x10¹² cm⁻²/smy * 10 years lifetime = 2.5x10¹⁵ cm⁻²
Requirements for high radiation tolerance

What’s needed?

- **High substrate biasing**
  - Larger signal due to larger depletion region
  - Faster charge collection

- **High resistivity substrates**
  - Convergence of $N_{\text{eff}}$ after high fluence ($> 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$)

- **Sensor thinning**
  - Improved charge collection efficiency

- **Backside substrate biasing**
  - More uniform electric field lines and depletion region
  - Improved charge collection efficiency

- **Multiple nested wells**
  - In-pixel low-voltage CMOS readout electronics
  - Isolated from substrate biasing

- **Suitable technology design rules**
  - Eg circular transistors

- In the long run, access to processes with smaller feature sizes
Demonstrator chips for ATLAS/Mu3e

- **MuPix8**
  - 180 nm HV-CMOS ams/TSI
  - Standard process
  - 20 – 200 Ω·cm wafers (≤ 1k Ω·cm possible)
  - Fully monolithic
  - Large fill-factor pixels
  - ≈ 60 V breakdown voltage
  - Thinned to 60 μm
  - Backside biasing being investigated

- **ATLASPix1**
  - Standard process
  - 2k Ω·cm substrate (10 – 3k Ω·cm possible)
  - Fully monolithic
  - Large fill-factor pixels
  - > 250 V breakdown voltage
  - Thinned to 200 μm
  - Backside biasing being investigated

- **LF-MonoPix1**
  - 150 nm HV-CMOS LFoundry
  - Standard process
  - 20 – 200 Ω·cm wafers (≤ 1k Ω·cm possible)
  - Fully monolithic
  - Large fill-factor pixels
  - ≈ 60 V breakdown voltage
  - Thinned to 60 μm
  - Backside biasing being investigated

- **MuPix8**
  - 180 nm CMOS TowerJazz
  - Modified process
  - 1k Ω·cm substrate (≤ 8k Ω·cm possible)
  - Fully monolithic
  - Small fill-factor pixels
  - 15 V substrate bias voltage
  - 25 μm epitaxial layer
  - Backside biasing
Before irradiation
- $I_{\text{LEAK}} \leq 1 \mu \text{A/cm}^2$
- $V_{\text{BD}} \geq 60 \text{ V}$
- Studies with guard rings to improve situation

After irradiation ($2 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$)
- $I_{\text{LEAK}} = 100 \mu \text{A/cm}^2$
- Highest p-fluence:
  - Trigger $\rightarrow V_{\text{BD}}$ decreases (earlier impact ionization due to peripheral current)
  - Simple $\rightarrow V_{\text{BD}}$ increases
- Highest n-fluence:
  - Trigger $\rightarrow V_{\text{BD}}$ remains the same
  - Simple $\rightarrow V_{\text{BD}}$ increases
- $V_{\text{BD}} \approx 36 \text{ V (p, trigger)}$
- $V_{\text{BD}} \approx 62 \text{ V (n, trigger)}$
- $V_{\text{BD}} \geq 90 \text{ V (p and n, simple)}$
Studies of **sensor depletion depth** with e-TCT measurements of test structure

- Test structure is a 3 x 3 matrix of passive pixels with dedicated I/O pads
- Measurements shown here correspond to central pixel
- High substrate resistivity of 80 Ω·cm
- Chip standard thickness (750 μm) and topside biasing
- Before and after irradiation ($\geq 2 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$, $\leq 1 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$)

$\frac{W}{2e} = W_0 + \sqrt{\frac{2e_{\text{Si}}}{qN_{\text{eff}}}} \cdot V_{\text{sub}}$

$N_{\text{eff}} = N_{\text{eff0}} - N_c \left(1 - \exp(c \cdot \Phi_{\text{eq}})\right) + g_c \cdot \Phi_{\text{eq}}$

- Measurements with irradiated backside processed samples (300 μm thinning + backside contacts) will start soon

M. Franks, 2019
Test beam campaign at Fermilab and CERN (before/after irradiation)

- 200 Ω·cm
- 60 μm thin
- 60 V bias voltage

Residuals
- 60 μm thin
- 65 V bias voltage
- Good alignment

Simple matrix > 99% track reconstruction efficiency (before irradiation)

M. Benoit, PIXEL2018

M. Kiehn, 2019
180 nm ams (aH18) – ATLASPix1

- **Test beam campaign** at Fermilab and CERN (before/after irradiation)
  - 80 Ω·cm samples
  - 60 μm thin
  - 60 V bias voltage
  - 10° C temperature

- **Very high efficiency after** $10^{15}$ n$_{eq}$/cm$^2$ fluences (threshold dependent)
- Low noise (dominated by single pixels)
- **Test beam campaign** at Fermilab and CERN (before/after irradiation)

- Measurements with prototypes in 180 nm TSI are on-going
Time resolution (before/after irradiation)

- Results shown here correspond to MuPix7
- Standard substrate resistivity (20 $\Omega \cdot \text{cm}$)
- Standard thickness (750 $\mu\text{m}$)

- Time resolution $\approx 15$ ns before irradiation
- $\approx$ constant $\leq 1.5 \times 10^{15}$ $n_{\text{eq}}/\text{cm}^2$ fluences significantly worse for higher fluences
- Best time resolution achieved so far is $\approx 6$ ns (MuPix8)
Before irradiation
- $I_{\text{LEAK}} \approx 0.1 \mu\text{A}$
- $I_{\text{LEAK}} = 18 \text{ nA (V}_{\text{bias}} = 100 \text{ V)}$
- $V_{\text{BD}} \approx 280 \text{ V}$

After irradiation (protons, $2 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$)
- $I_{\text{LEAK}} \approx 3 \text{ orders of magnitude increase}$
- $I_{\text{LEAK}} = 25 \mu\text{A (V}_{\text{bias}} = 100 \text{ V)} \rightarrow 5.3 \text{ nA/pixel}$
- $V_{\text{BD}} > 300 \text{ V}$

Before irradiation
- $W > 250 \mu\text{m (V}_{\text{bias}} = 250 \text{ V)}$

After irradiation ($n, 2 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$)
- $W > 50 \mu\text{m (V}_{\text{bias}} = 250 \text{ V)}$
- 2k $\Omega \cdot \text{cm samples}$
- 750 $\mu\text{m thin}$
Test beam campaign at ELSA with 2.5 GeV electron beam (before/after irradiation)

- 2k Ω·cm samples
- 750 μm thin
- MPV decreases after $10^{15} \text{n}_{eq}/\text{cm}^2$ fluences, but very high efficiency

$V_{bias} = 200 \text{ V}$

non-irradiated

$V_{bias} = 130 \text{ V}$

$1 \times 10^{15} \text{n}_{eq}/\text{cm}^2, n > 98\%$

T. Hirono, 2018

T. Wang, 2018
- **Total Ionizing Dose (TID)** measurements after X-ray irradiation

- **LF-CPIX (≤ 50 MRad)**
  - Normalized gain vs. TID [rad]
  - Normalized noise vs. TID [rad]

- **LF-MonoPix1 (≤ 160 MRad)**
  - Tuned
    - Mean = 2861 e⁻
    - Sigma = 156 e⁻
  - Un-Tuned
    - Mean = 4822 e⁻
    - Sigma = 1525 e⁻

- **Threshold distribution**
  - 40 V bias voltage
  - -12⁰ C temperature
  - Threshold dispersion tuned to ≈ 150 e⁻
  - Noise ≈ 250 e⁻

- Room temperature
- Gain decreases ≈ 5%
- Noise increases ≈ 50%
180 nm TowerJazz – Investigator

Standard TowerJazz process

Modified TowerJazz process

Signal amplitude

Sr-90 source tests

W. Snoeys, 2017

Signal rise time

I. Berdalovic, 2018

W = 155 μm

Unirradiated MPV = 18.937 ± 0.122 mV
1e14 neq MPV = 19.499 ± 0.147 mV
1e15 neq MPV = 15.904 ± 0.124 mV

Unirradiated Peak = 16.67 sigma 1.96 ns -
sigma/peak = 11.76 %
1e14 neq Peak = 16.03 sigma 2.10 ns -
sigma/peak = 13.10 %
1e15 neq Peak = 18.98 sigma 2.78 ns -
sigma/peak = 14.63 %
Test beam campaign at CERN with 180 GeV pion beam (before/after irradiation)

- Before irradiation → average efficiency 96% (less in corners)
- After $1 \times 10^{15}$ n$_{eq}$/cm$^2$ irradiation → average efficiency 74% (less in corners)

Inefficiencies due to high noise levels

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Before irradiation

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$1 \times 10^{15}$ n$_{eq}$/cm$^2$ neutron irradiated sample

 avg eff. 74 %
Both fixes target increasing the lateral electric field to improve charge collection.

98-99% efficiency after $1 \times 10^{15} \text{ neq/cm}^2$

Test beam at DESY and ELSA
Depletion depth

Charge collection efficiency

**Not thinned without BP and thinned with BP:**
- Very similar behaviour
- Depletion depth grows with $V_{\text{bias}}$ (until full depletion of thinned devices is reached)

**Not thinned without BP:**
- Large drop of collected charge even at low fluences (due to lower electric field)

**Thinned with BP:**
- Collected charge follows e-TCT results (15% smaller than expected)
- Devices have smaller depletion depth (than not thinned), they collect more charge
Conclusion

- **Strong requirements on radiation tolerance for the innermost layers at Belle II:**
  - TID (PXD1) → 50 Mrad/smy * 10 years lifetime = 500 MRad
  - NIEL (PXD1) → 250x10^{12} cm^{-2}/smy * 10 years lifetime = 2.5x10^{15} cm^{-2}

- **Radiation tolerance depends on:**
  - Substrate biasing
  - Substrate resistivity
  - Backside processing
  - Small technology node

- **I have shown the radiation tolerance performance of recent demonstrators:**
  - 180 nm ams/TSI + large fill-factor → MuPix8/ATLASPix1
  - 150 nm LFoundry + large fill-factor → LF-MonoPix1
  - 180 nm TowerJazz + small fill-factor → MALTA, TJ-MonoPix, Mini-MALTA

- **and possible improvements with backside processing**

- **Best radiation tolerance achieved so far:**
  - TID → measured several hundred MRad with fully functional circuits (not shown in these slides)
  - NIEL → \( \approx 2x10^{15} \text{n}_{eq}/\text{cm}^2 \)