R&D for new high radiation tolerant pixel sensors for the high-luminosity phase of the CMS experiment at LHC

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On behalf of the CMS – Pixel R&D INFN Collaboration

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## High Luminosity upgrade of the CERN-LHC: operation conditions

| Luminosity 5x10^{34}/(cm^2\cdot s), up to 200 events/25 ns bunch crossing | Maintain occupancy at % level and increase the spatial resolution \(\rightarrow\) pixel cell size \(\sim 25\times100 \ \mu m^2\) or 50x50 \(\mu m^2\) currently 100x150 \(\mu m^2\) CMS |
| Radiation level for first pixel layer at 3000 fb^{-1} \(\sim2\times10^{16} \ \text{n}_{eq}/cm^2\) \(\sim 10\) years \(\rightarrow\) carriers lifetime \(\sim0.3\) ns, mean free path \(\sim30 \ \mu m\) for electrons at saturation velocity | Reduce electrodes distance to increase electric field and thus the signal \(\rightarrow\) thin planar or 3D columnar technologies |
New thin n-in-p planar sensors have been designed by an FBK-INFN collaboration exploiting the Direct Wafer Bonding (DWB) technology, with different active thicknesses (100 and 130 μm) and total thicknesses (180, 200 and 285 μm).

**Wafers produced by IceMOS Technology**
Test Beam Facility

• Planar sensors bonded to the PSI46dig Read-Out Chip (PbSn Bump Bonds @IZM) have been tested at the Fermilab Test Beam Facility using 120 GeV protons.

• Track reconstruction is based on a telescope composed by 8 pixel planes. Resolution on both transverse coordinates at the Devices Under Test is approximately 9 μm.
In this talk...

<table>
<thead>
<tr>
<th>ID Chip</th>
<th>Active Thickness ($\mu$m)</th>
<th>P-stop (around cell)</th>
<th>n.GR/P-stop between GR</th>
<th>Punch-Through</th>
<th>BCB mask</th>
<th>Irradation Dose (neq/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>62D</td>
<td>100</td>
<td>yes</td>
<td>1/no</td>
<td>no</td>
<td>frame</td>
<td>3.10E+15</td>
</tr>
<tr>
<td>31D</td>
<td>100</td>
<td>no</td>
<td>1/no</td>
<td>yes</td>
<td>frame</td>
<td>5.02E+15</td>
</tr>
<tr>
<td>11C</td>
<td>130</td>
<td>yes</td>
<td>10/yes</td>
<td>yes</td>
<td>frame</td>
<td>3.10E+15</td>
</tr>
<tr>
<td>53B</td>
<td>130</td>
<td>yes</td>
<td>10/yes</td>
<td>none</td>
<td>none</td>
<td>1.19E+15</td>
</tr>
<tr>
<td>43A</td>
<td>100</td>
<td>no</td>
<td>1/yes</td>
<td>yes</td>
<td>full</td>
<td>5.02E+15</td>
</tr>
</tbody>
</table>

We’ll refer to the detectors using this ID

“Frame” in column “BCB mask” means that an insulating layer is applied both on sensor (frame from guard ring to cutting edge) and on ROC everywhere excluding bump bond area and wire bond pads.

“Full” means that the insulating layer is applied on both sensor and ROC everywhere but on bump bond pads.
Performance before irradiation:
MPV vs. Vbias

Thickness 130 μm
Expected Values
Active thickness reduced by
Boron diffusion of about 10 μm
Thickness 100 μm

N.B. Detection efficiency is close to 100% ( > 99.8%)
Detector thickness 100 μm/31D: Punch Through (Before Irradiation)

Map of the efficiency as a function of the impact point of the reconstructed tracks on the cell of this sensor shows losses in the region where punch through and its bias grid are present: detection efficiency reaches 96.8% at 150V.
Performance after irradiation:
Efficiency vs. Vbias

Thresholds have been chosen in order to minimize the out-of-time noise of the DUT
Performance after irradiation: MPV vs. Vbias

Landau MPV values have been corrected to account for the band-gap reference voltage variation as a function of irradiation dose.

Gain of the chip is affected by sensor leakage current (165 μA @ 650V)
Detector thickness 130 μm/1.2E15: Collected charge

Vbias = 40 V
Fluence = 0

\[ \text{Corrected MPV: } 6809 \text{ e- (**)} \]

Vbias = 500 V
Fluence = 1.2 \times 10^{15} n_{eq}/cm^2 (protons - 800 MeV/c)

(*) See slide 9
Detector thickness 130 μm/1.2E15: Efficiency

Vbias = 500 V - Fluence = 1.2 x 10^{15} \text{n}_{eq}/\text{cm}^2 \text{ (protons - 800 MeV/c)}

Efficiency: (98.60 ± 0.03)\% - after irradiation

Even columns

Odd columns
Detector thickness 130 μm/3.1E15: Collected Charge

Not tested before irradiation!

Assuming 8000 e-, as measured for the other 130 μm sensor before irradiation, charge loss is 34%
Detector thickness 130 μm/3.1E15:
Efficiency

Vbias = 700 V - Fluence = 3.1 x 10^{15} n_{eq}/cm^2 (protons - 24 GeV/c) – Threshold: 3300 e

Efficiency: (97.33 ± 0.03)% - after irradiation

Even columns
Odd columns
Detector thickness 100 μm/3.1E15: Collected charge

Vbias = 40 V  
Fluence = 0

\[ V_{bias} = 800 \text{ V} \]
\[ \text{Fluence} = 3.1 \times 10^{15} n_{eq}/\text{cm}^2 \]
(protons - 24 GeV/c)
Threshold: 2200 e-

Corrected MPV: 6326 e-(*)

Full charge collection after irradiation!!!

(*) See slide 9
Detector thickness 100 μm/3.1E15: Efficiency

Vbias = 800 V - Fluence = 3.1 x 10^{15} n_{eq}/cm^2 (protons - 24 GeV/c) – Threshold: 2200 e-
Sensor without punch through

Efficiency: (98.82 ± 0.03)% - after irradiation

Even columns  Odd columns
Detector thickness 100 μm/5E15/31D: Collected charge

Vbias = 150 V
Fluence = 0

Vbias = 650 V
Fluence = 5 x 10^{15} \text{n}_{eq}/\text{cm}^2
(protons - 24 GeV/c)
Threshold: 2600 e-

Corrected MPV: 5199 e-

Difference: 13%

(*) See slide 9
Detector thickness 100 μm/5E15/31D: Efficiency

Vbias = 650 V - Fluence = $5 \times 10^{15}$ n$_{eq}$/cm$^2$ (protons - 24 GeV/c) – Threshold: 2600 e-

Efficiency: $(90.32 \pm 0.17)\%$ - after irradiation

Even columns

Odd columns
Detector thickness 100 μm/5E15/43A: Efficiency

Vbias = 600 V - Fluence = 5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2 (\text{protons} - 24 \text{ GeV}/c) – Threshold: 2450 e-

Efficiency: (91.85 \pm 0.06)\% - after irradiation

Even columns

Odd columns
To Summarize...

- Expected value of collected charge before irradiation: 6300 e- and 8400 e- for 100 and 130 µm active thickness sensors respectively → sensor 62D collects the same charge before and after irradiation
- Lower efficiency for irradiation dose of 5.02E15 n_{eq}/cm^2 is determined both by losses due to the punch through bias grid and by the relatively high threshold

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<thead>
<tr>
<th>ID Chip</th>
<th>Active Thickness (µm)</th>
<th>Punch-Through</th>
<th>Irradiation Dose (neq/cm²)</th>
<th>Collected Charge (e-)</th>
<th>Detection Efficiency (%)</th>
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</thead>
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<tr>
<td>62D</td>
<td>100</td>
<td>no</td>
<td>3.10E+15</td>
<td>6326 @800 V</td>
<td>98.82 @800 V</td>
</tr>
<tr>
<td>31D</td>
<td>100</td>
<td>yes</td>
<td>5.02E+15</td>
<td>5189 @650 V</td>
<td>91.85 @650 V</td>
</tr>
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<td>5313 @700 V</td>
<td>97.33 @700 V</td>
</tr>
</tbody>
</table>
Conclusions

• Results on irradiated planar sensors produced in collaboration with FBK using the new DWB technology are very promising for the realization of thin high radiation-hard sensors

• Use of punch through structures should be questioned on the base of its effect on the cell efficiency, as showed in this presentation

• Irradiation of these sensors bonded to the PSI46dig ROC is limited to $5\times 10^{15}\, n_{eq}/cm^2$ by the ROC radiation hardness

• We look forward to bonding our sensors to the new RD53 ROC in order to exploit it’s higher radiation hardness and lower thresholds
Many thanks to...
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M. Boscardin (FBK & TIFPA–INFN Trento)
T. Zoi (Univ. Hamburg)
R. Rivera, L. Uplegger (FNAL)
Backup
**Material features: active thickness**

- dE/dx reduced for “thin silicon”
  - Down to ~60% of most probable energy loss (388 eV/µm)

- Charge collection reduced by Boron diffusion
  - At Beam test 6000-8000 electrons expected
    - Measure by ROC PSI45dig: threshold 1500 e + dispersion 120 e

- Doping concentration profile measurement
  - Effective thickness reduced by the Boron diffusion (for SiSi) from wafer carrier deep about 10 µm.

\[
\begin{array}{|c|c|c|}
\hline
\beta & 100 (~90) & 130 (~120) \\
\hline
3 & 5919 & 8068 \\
1000 & 6535 & 8885 \\
\hline
\end{array}
\]

Charge collected from theory
Resolution

Selecting tracks with double hits on all the telescope planes (best resolution), we measured the residuals with respect to the double hits coordinate on the DUT, reconstructed from the measured charge division characteristic.

Subtracting the expected telescope resolution of 7.3 μm we measured a resolution of 4.3 μm on both transverse coordinates for this DUT.
Tilted Sensors Before Rad

Ratio Slope@130µm / Slope@100µm is ~1.4

Back of an envelope calculations for Slope at non-zero incidence angle:

\[ \frac{w}{2} \tan(\theta) + x \sim \text{charge}_L \]
\[ \frac{w}{2} \tan(\theta) - x \sim \text{charge}_R \]

Asymmetry = \[ x / (w \tan(\theta)) \]

**Slope** = \[ x / \text{Asymmetry} = \frac{w}{2} \tan(\theta) \]

- \( w = 100 \, \mu m \Rightarrow \text{Slope} = 18.2 \, \mu m/\text{asymmetry} \)
- \( w = 130 \, \mu m \Rightarrow \text{Slope} = 23.7 \, \mu m/\text{asymmetry} \)

Amazingly close to our measurements
Tilted Sensors After Rad Efficiency Maps

Even Columns

5°

10°

20°

Odd Columns
PSI46dig was designed for operations with 300 μm sensors, collecting approximately 22500 e⁻. New sensors reach 100 μm thickness, hence lowest collected charge is 6000 e⁻. Lower values are reached once detectors are irradiated.

Now we are operating with this ROC in a heavily non linear region of the gain curve. Determination of the collected charge is very hard!!
Comparison with other results

ATLAS results obtained at higher irradiation fluences are in agreement with our results in terms of efficiency.

From T. Bisanz presentation at PSD11
Band-gap reference voltage variation

Variation of band gap reference voltage with irradiation → ADC to electron conversion must be corrected

[Hoß, Jan Hendrik doctoral thesis: https://doi.org/10.3929/ethz-b-000182698]
Chip gain variation

- PSI46 digital chip with same sensors as those installed right now in CMS (300 µm active thickness)
- Irradiated with 23 MeV proton beam at Zyklotron AG Karlsruhe
- 120 Mrad corresponds to \( \sim 0.8 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2 \)
- 60 Mrad corresponds to \( \sim 0.4 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2 \)

[many thanks to Malle B. and ETH team for providing the sample and the setup]

1. Fit all gain curves (i.e. ADC output vs injected charge) with a second degree polynomial
2. For every ROC and for every voltage (i.e. leakage current), histogram the ADCs for an injected charge of 6 000 electrons

The mean of such an histogram is what is shown in the plot versus leakage current

The gain of the PSI46 digital chip is affected by the leakage current of the sensor