CHARACTERIZATION OF PLANAR AND 3D SILICON PIXEL SENSORS FOR THE HIGH LUMINOSITY UPGRADE OF THE CMS EXPERIMENT AT LHC

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On behalf of the CMS Tracker Upgrade Group
High Luminosity upgrade of the CERN-LHC

<table>
<thead>
<tr>
<th>Operation conditions</th>
<th>Sensor design constraints</th>
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</thead>
<tbody>
<tr>
<td>Luminosity $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, up to 200 collisions per 25 ns bunch crossing</td>
<td>Maintain occupancy at per mille level and increase the spatial resolution $\rightarrow$ pixel cell size reduced from $100 \times 150 \mu \text{m}^2$ to $25 \times 100 \mu \text{m}^2$ or $50 \times 50 \mu \text{m}^2$</td>
</tr>
<tr>
<td>Radiation level for first pixel layer after Run4+5 (2200 fb$^{-1}$): $1.9 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ $\rightarrow$ carrier lifetimes $\sim 0.3$ ns, mean free path $\sim 30$ $\mu \text{m}$ for electrons at saturation velocity</td>
<td>Reduce distance between electrodes to increase the signal $\rightarrow$ thin planar or 3D columnar technologies</td>
</tr>
</tbody>
</table>

[Diagram showing pixel cells and electron paths]
The CMS Inner Tracker (IT) for HL-LHC

- Upgrade of the CMS Tracker documented in this Technical Design Report

- 25 x 100 x 150 µm³ planar sensors baseline choice for the CMS IT
  - 3D sensors are investigated as an option for the first layer
  - 50 x 50 x 150 µm³ option discarded since marginal gain does not justify introduction of additional design
Planar sensors - generalities

- Floating zone $n^+$ on $p$ type
  - collect electrons, the faster carriers
  - avoid type inversion after irradiation
  - single sided process $\rightarrow$ much less expensive than double sided

- Fondazione Bruno Kessler (FBK) foundry employs Direct Wafer Bonding technology

![Diagram showing pixel cells and bonding process](image)

- Active layer (100 or 150 $\mu$m)
- Bonding using superficial short range forces
- Mechanical support and ohmic contact

Hamamatsu Photonics (HPK) design
3D sensors - generalities

Rectifying n+ columnar implant
Non rectifying p+ columnar implant

Single-sided DRIE process optimized by FBK → much less expensive than double-sided
The RD53A ROC

The RD53A ROC has a pitch of 50 x 50 μm² and can be operated at thresholds lower than 1000 electrons before irradiation and 1500 electrons after irradiation, depending on the fluence.

Sensors bonded to this ROC have been irradiated to fluences up to $24 \times 10^{15}$ n$_{eq}$/cm².

Only measurements on the Linear Front End will be shown.
FBK planar sensors - design

- DUT C → 25 x 100 Standard (100 µm thickness) → $7.5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$
- DUT E → 25 x 100 Bitten (150 µm thickness) → $11 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$
- DUT F → 25 x 100 Standard (150 µm thickness) → $18 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$
- DUT G → 25 x 100 Bitten (150 µm thickness) → $24 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$
- Bitten design introduced to reduce cross talk observed in previous measurements
FBK planar sensors - efficiency

Vbias for 99% detection efficiency:
350 V @ $7.5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$
550-650 V @ higher fluences

Uniform in-pixel detection efficiency observed at these bias voltages
Cluster size reaches ~ 1.5 at around 15 deg \(\rightarrow\) measured resolution around 6 \(\mu\)m

Resolution for fresh sensors is measured to be around 2 \(\mu\)m (at the optimal angle), compatible with simulation expectation
Bricked design introduced to increase resolution in the long pitch direction
Possible application in central part of the barrel detector

**Fresh sensors**

- $V_{bias} = 120$ V
- Online threshold 750-1100 electrons
- Bricked 25 x 100 same resolution of 50 x 50 for turn angles $> 15$ deg
HPK planar sensor - efficiency

Online threshold 1100-1300 electrons

Vbias for 99% detection efficiency:
- 400 V @ 8 x 10^{15} n_{eq}/cm^2
- 550 V @ 12 x 10^{15} n_{eq}/cm^2

Highest irradiated sensor reaches 98% efficiency at 650 V → reaches 99% when tilted

Compatible with FBK sensors
Sensors irradiated at $12 \times 10^{15}$ $n_{eq}/cm^2$ show a resolution of 5 $\mu$m at the expected angle (~9 deg)

- Bricked sensor features higher cluster size and hence better resolution than bitten sensors
- Improvement in resolution diluted after radiation
LFoundry planar sensors - design

- Passive CMOS sensor in 150 nm technology, 150 μm thickness
- Cost-effective and high-throughput commercial process
- Possible implementation of small on-pixel structures
  - multiple metal layers for signals routing → more freedom to optimize sensor design
  - high resistive poly-silicon used as bias resistors → better hit efficiency than with punch through structures
  - MIM-capacitors → AC-coupled sensors possible → leakage current not flowing in the chip
    → CMS will adopt DC-coupling since sensors’ leakage current can be tolerated by the ROC
Online threshold 1200-1300 electrons

Vbias for 99% detection efficiency:
450 V @ $10 \times 10^{15}$ neq/cm$^2$
compatible with HPK and FBK sensors

In pixel efficiency map, sensor at $1.2 \times 10^{16}$ neq.cm$^2$, 650 V

In-pixel efficiency is uniform at the highest bias voltage → reduced charge sharing leads to reduced efficiency in the corners
LFoundry planar sensors - resolution

Also in this case cluster size is < 2 at the highest irradiation fluences

- Rectangular sensor irradiated at $2 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ reaches 2 µm resolution at around 12 deg
- Rectangular sensor irradiated at $10 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ reaches 4 µm resolution at around 17 deg
- Reduced charge sharing $\rightarrow$ higher angle for optimal resolution
FBK 3D sensors - CERN TB

Efficiency vs bias

Irradiation fluence: $15 \times 10^{15}$ n$_{eq}$/cm$^2$ - normal incidence

In-pixel efficiency map @ 150 V - 1400 electrons threshold

In-pixel charge map @ 150 V - 1400 electrons threshold
FBK 3D sensors - CERN TB

Irradiation fluence: $15 \times 10^{15}$ n$_{eq}$/cm$^2$

99% detection efficiency reached a 8 deg tilt (no data acquired at smaller angles)

Measured resolution is $\sim 5 \mu m$, compatible with planar sensor
FBK 3D sensors - DESY TB

Sensors coming from newest FBK production → increased distance between n+ type column and low resistivity wafer

- $14 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$: 99% efficiency at $V_{\text{bias}}$ 130 V
- $18 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$: 98% efficiency at $V_{\text{bias}}$ 170 V

First measurements on irradiated sensors coming from this production → more sensors ready for irradiation and beam test in the next month(s)
Noise in 3D sensors

FBK - Stepper 2 - $14 \times 10^{15}$ $n_{eq}/cm^2$

- During test beam characterizations of 3D sensors at CERN and DESY in Autumn 2021 a sudden increase in the number of noisy pixel at high bias voltages was observed
- TID for irradiations with low energy protons (KIT, 23 MeV) 1.5 GRad per $10 \times 10^{15}$ $n_{eq}/cm^2$ higher than RD53A tolerance (1 Grad)
- Action items in progress
  - irradiate samples with higher energy protons (Fermilab ITA, 400 MeV)
  - measure noise in planar sensors to eventually rule-out ROC irradiation effects
  - measure IV curves to investigate possible correlation with breakdown

FBK - Stepper 2 - $18 \times 10^{15}$ $n_{eq}/cm^2$
Power dissipation simulation

- Barrel Layer 1
- Planar sensors: $T_{CO2}$ required to prevent thermal runaway is much lower than $-33 \, ^\circ C$ achievable
- 3D sensors: at least 4 $^\circ C$ margin if the power dissipated in the active volume of the sensor is less than 20 mW/cm$^2$ after $2 \times 10^{16}$ $n_{eq}$/cm$^2$
- Power dissipation $<20$ mW/cm$^2$ confirmed by lab measurements
Conclusions

■ Planar sensors
  - *Irradiation up to* $24 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2 \rightarrow$ *detection efficiency in line with specification*
    - 99% for $\text{Vbias} > 350$ (550) V @ $8 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ (12 $\times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$)
    - 98% for $\text{Vbias} > 650$ V for fluence $> 20 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$
  - *resolution of irradiated sensor in the range* $4 - 6 \mu m$ *depending on the fluence*

■ 3D sensors
  - *Irradiation up to* $15 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2 \rightarrow$ *99% detection efficiency for* $\text{Vbias} > 130$ V
  - *performance at higher fluence to be verified in next test beams (only one sample at the moment)*
  - *resolution compatible with planar sensor*

■ Choice to be made in the coming months
  - *3D sensors in barrel layer 1*
  - *bricked pixels only in the central* $\eta$ *region of TBPX L2-L3-L4*
  - *inputs from more test beam campaigns and simulation (tracking, vertexing, object reconstruction)*
Acknowledgements and Bibliography

- FBK: 10.1016/j.nima.2019.163222
- HPK: https://doi.org/10.1016/j.nima.2020.164438
- FBK Team: Maurizio Boscardin, Matteo Centis Vignali, Francesco Ficorella, Sabina Ronchin
Additional material
HL-LHC at a glance

![Graph showing luminosity and integrated luminosity over years with specific data points and labels for BPIX L1 and FPIX R1 runs.]

<table>
<thead>
<tr>
<th>Run</th>
<th>1E16 1 MeV n_eq</th>
<th>Grad</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPIX L1 Run 5</td>
<td>1.16</td>
<td>0.63</td>
</tr>
<tr>
<td>FPIX R1 Run 4+5</td>
<td>1.25</td>
<td>0.81</td>
</tr>
<tr>
<td>BPIX L1 Run 4+5</td>
<td>1.88</td>
<td>1.03</td>
</tr>
<tr>
<td>FPIX R1 Run 4+5+6</td>
<td>2.34</td>
<td>1.50</td>
</tr>
<tr>
<td>BPIX L1 Run 4+5+6</td>
<td>3.51</td>
<td>1.91</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ultimate</th>
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<tbody>
<tr>
<td>RUN 4</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Per run (fb⁻¹)</td>
</tr>
<tr>
<td>Accumulated (fb⁻¹)</td>
</tr>
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</table>
Fit two tracks using upstream and downstream triplets

Compute distance between the two impact points at the DUT (“sixdxc”)

The DUT residual is computed as the difference between the measured coordinate and the mean values of the track impact points coordinate predicted by the upstream and downstream triplets

The tracking error at the DUT is hence half the RMS of the distribution of sixdxc

A student-t function is used for the fit
• Telescope resolution computed using General Broken Lines (GBL) algorithm as function of $dz_{DUT}$ (distance between DUT and closest telescope plane)
• Verified measuring resolution of the same DUT inside and outside the cooling box
FBK fresh sensors - resolution

V bias ~70 V
Thr. 814 e-

Planar Bitten

V bias ~70 V
Thr. 793 e-

Planar Bitten FP

V bias ~30 V
Thr. 812 e-

3D

Position resolution well below the digital value

Sensor thickness = 150 um
HPK fresh sensors - resolution

\( \sigma_x \): Resolution along short axis (25 \( \mu \text{m} \))
Cross talk - test bench measurements

- Tested FBK modules:
  - Planar 25x100 Bitten Implant
  - Planar 25x100 Standard

- Injection in (0,0)

- Read only (0,0) and (0,1)

- Two S-Curves
  - First one is the true S-Curve
  - Second one is due to X-Talk
  - X-Talk = Thr1/(Thr1+Thr2)
# Cross talk - test bench measurements

<table>
<thead>
<tr>
<th>Bias Voltage</th>
<th>Main Threshold</th>
<th>Second Threshold</th>
<th>X-Talk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planar 25x100 Standard (SOI)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 V</td>
<td>1140 e</td>
<td>8140 e</td>
<td>12.3%</td>
</tr>
<tr>
<td>20 V</td>
<td>2050 e</td>
<td>15294 e</td>
<td>11.8%</td>
</tr>
</tbody>
</table>

| Planar 25x100 Bitten Implant | | |
| 40 V | 1114 e | 11388 e | 8.9% |
| 20 V | 2303 e | 22530 e | 9.3% |

`Bitten implant reduces the x-talk by few %`
Bricked sensors

- barrel: no advantage in using bricked for $\eta \geq 0.62$ (cotg $\beta = 100\text{um}/150\text{um}$)
- endcaps: small/no charge sharing $\Rightarrow$ no advantage in using bricked for $\eta \leq 1.8$
- Positioning of the modules with bricked pixels, especially in the endcaps, requires a lot of care $\Rightarrow$ barrel only studies
- bricked pixels option brings challenges in the offline reconstruction as it couples the two coordinates and therefore they are more difficult to model after irradiation