Characterisation of planar and 3D Silicon pixel sensors for the High Luminosity upgrade of the CMS experiment at LHC

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### 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 $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, up to 200 events per 25 ns bunch crossing</td>
<td>Maintain occupancy at per mille level and increase the spatial resolution → pixel cell size reduced from 100 x 150 $\mu\text{m}^2$ to 25 x 100 $\mu\text{m}^2$ or 50 x 50 $\mu\text{m}^2$</td>
</tr>
<tr>
<td>Radiation level for first pixel layer after 10 years (3000 fb$^{-1}$): $2.3 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$ → carriers lifetime $\sim 0.3$ ns, mean free path $\sim 30 \mu\text{m}$ for electrons at saturation velocity</td>
<td>Reduce distance between electrodes to increase the signal → thin planar or 3D columnar technologies</td>
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</tbody>
</table>

[Diagram of detector layers and particle interactions]

Radiation level for first pixel layer after 10 years (3000 fb$^{-1}$): $2.3 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$ → carriers lifetime $\sim 0.3$ ns, mean free path $\sim 30 \mu\text{m}$ for electrons at saturation velocity.
The CMS Inner Tracker (IT) for HL-LHC

- Upgrade of the CMS Tracker documented in this Technical Design Report
- 150 μm thick planar sensors are baseline for the CMS IT, 3D sensors are investigated as an option for the first layer
INFN – FBK Sensors

• New thin Silicon pixel sensors developed by CMS-ATLAS INFN collaboration with Fondazione Bruno Kessler (FBK, Trento, Italy)
• Floating zone n+ on p type
• Direct Wafer Bonding Technology (DWB)

Planar sensor sketch

Active layer (100 or 130 μm)
Bonding using superficial short range forces
Mechanical support and ohmic contact
3D Sensors

![Diagram of 3D Sensors]

Rectifying n+ columnar implant
Non rectifying p+ columnar implant
The RD53A ROC

The RD53A ROC has a pitch of 50 x 50 $\mu$m$^2$ and can be operated at thresholds lower than 1000 electrons before irradiation and 1500 electrons after irradiation. Sensors bonded to this ROC have been irradiated to fluences up to $1 \times 10^{16}$ $n_{eq}/cm^2$.

Only measurement on the Linear FE will be shown.
Test beam facilities:

- Fermilab test beam facility (120 GeV protons)
- Desy test beam facility (5.2 GeV electrons)
- Cern test beam facility (24 GeV protons)

Test beam measurements using orthogonal tracks show that punch through structures and columnar implants determine efficiency losses that are recovered once the module is tilted.
Planar – 50 x 50 – Not Irrad (FNAL TB)

Detection efficiency of this module is greater than 99% already at 20 V bias voltage

Charge distribution for size 1 clusters pointed by a track in a fiducial window of the cell (20 x 20 μm²)

Distribution of the charge collected by the pixel pointed by a track (Vbias = 60 V)

- Vbias = 60 V
- Active thickness: 100 μm
- Threshold: 1000 e⁻
- MPV: 7285 e⁻
Planar – 50 x 50 – Not Irrad (FNAL TB)

Landau MPV as a function of the applied bias voltage. Error bars represent a systematic uncertainty of 5% coming from the calibration of the analog gain of the ROC.

Collected charge MPV reaches a maximum at $V_{bias} < 40$ V
Planar – 50 x 50 – Irrad (DESY TB)

- No Punch Through module
  - Efficiency > 99% at Vbias = 200 V
- Punch Through module
  - Efficiency starts saturating around Vbias = 200 V
  - Efficiency max value is 97.6% at Vbias = 390 V, limited by the presence of the PT structure
  - Full efficiency can be recovered tilting the module (see next slide)

Planar 50 x 50 noPT
- Active thickness: 100 μm
- Threshold: 1400 e-
- Irradiation fluence: $5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$

Planar 50 x 50 PT
- Active thickness: 100 μm
- Threshold: 1200 e-
- Irradiation fluence $5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$
Planar PT – 50 x 50 – Irrad (DESY TB)

Efficiency distribution on four pixel cells – Irradiation fluence: $5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ – $V_{bias} = 390 \text{ V}$

- **No tilt**: Detection efficiency: **97.6%**
- **12 deg tilt**: Detection efficiency: **98.8%**
- **20 deg tilt**: Detection efficiency: **99.4%**

![Graph showing efficiency distribution](image-url)
Charge distribution for size 1 clusters pointed by a track in a fiducial window of the cell (20 x 20 μm²)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$/ndf</td>
<td>198.8 / 83</td>
</tr>
<tr>
<td>Width</td>
<td>583.8 ± 17.4</td>
</tr>
<tr>
<td>MPV</td>
<td>6415 ± 12.9</td>
</tr>
<tr>
<td>Area</td>
<td>8.46e+06 ± 4.46e+04</td>
</tr>
<tr>
<td>GSigma</td>
<td>1507 ± 21.6</td>
</tr>
<tr>
<td>$p4$</td>
<td>413.5 ± 1.4</td>
</tr>
<tr>
<td>$p5$</td>
<td>2132 ± 1.4</td>
</tr>
</tbody>
</table>

Vbias = 130 V
Active thickness: 130 μm
Threshold: 1500 e⁻
Irradiation fluence: $1 \times 10^{16}$ n$_{eq}$/cm²
MPV: 6415 e⁻
Landau MPV and detection efficiency as a function of the bias voltage (Irradiation fluence: $1 \times 10^{16}$ $n_{eq}/cm^2$)

98% detection efficiency reached at $V_{bias}$ 130 V
• Irradiation profile is visible in the efficiency map of the sensor at low bias voltages
• Two small regions of the linear FE corresponding to the center of the irradiation spot were analysed at the highest bias voltage (180 V)
• Detection efficiency resulted 97.4% (black region) and 97.8% (blue region)
• This is a good news because the irradiation fluence in these regions is the closest to $1 \times 10^{16}$ $n_{eq}/cm^2$
3D – Irrad (CERN TB)

Efficiency distribution on four pixel cells

3D 50 x 50
Active thickness: 130 μm
Threshold: 1300 e-
Irradiation fluence: $1 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$

3D 25 x 100
Active thickness: 130 μm
Threshold: 1300 e-
Irradiation fluence $1 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$

Vbias = 149 V
Vbias = 123 V
Conclusions

- Planar and 3D Silicon pixel sensors developed by FBK have been characterised on beam both before and after irradiation up to $5 \times 10^{15}$ and $1 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$, respectively.

- Their performance in terms of detection efficiency is very encouraging ($> 98\%$ for 3D sensors irradiated @ $1 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$ and $> 99\%$ for planar sensors irradiated @ $5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$).

- Next batches of planar and 3D sensors for RD53A ROC with target active thickness (150 µm) are available.

- Bump bonding, irradiation and test on beam will take place in the second half of 2019.

- Dual and quad modules for RD53A will be available later in 2019.
Many thanks to...

Backup
Material features: active thickness

- \( dE/dx \) reduced for "thin silicon"
  - Down to \( \sim 60\% \) of most probable energy loss (388 eV/\( \mu \)m)

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

\[ \beta \gamma \]

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

Charge collected from theory
Pixel planes are not used in track reconstruction but each reconstructed track is required to have hits on the pixel telescope.
FNAL TB: Gain calibrations

- RD53A modules were read out using the YARR system
- Using this system we have been able to perform gain calibrations
- All calibrations have been taken with the modules mounted on the test beam and in the same temperature conditions of the data taking
- Enabling the three FE simultaneously the whole system was extremely noisy → we took all the data with the sync FE and the autozero disabled in order to get rid of this noise

Linear FE looks really linear!!!
3D – Not Irrad (CERN)

- Active thickness: 130 μm
- Columnar implants are not visible once the module is tilted
Irradiation of modules

- 3D modules have been irradiated at the CERN IRRAD facility
- Requested fluence was $1 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$. The corresponding dose is 6 MGy
- Sensors were tilted by 55 degrees to have more uniform irradiation
- Irradiation was done without cooling
- No LV or HV was applied to the module
- Irradiation ended out to be non-homogeneous -> evalutation of the effective fluence is in progress but modules were well centered on the beam
- Planar modules were irradiated at KIT: requested fluence was $5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$, irradiation was uniform
Efficiency at 250 V: All FE 86.2%; Lin FE 90.0%; Diff FE 75.0%

Efficiency distribution at Vbias ~ 70 V in the picture

The pattern of this distribution on the diff FE is due to the killed cells

The module was defective: current at 250 V was ~ 1 mA.

Irradiation spot is clearly visible