Development of planar pixel sensors for the CMS Inner Tracker at the High-Luminosity LHC

Georg Steinbrück, Hamburg University for the CMS Tracker Group

HSTD12, 2019

Hiroshima, Japan Dec 14-18, 2019
Installation of CMS Phase-1 Pixels

Phase-2 TDRs

- Detectors are aging and suffering from radiation damage
- Increase in LHC luminosity requires detector improvements
CMS Tracker for Phase-2

Inner Tracker (IT, pixel) with extended coverage $|\eta| \approx 3.8$

- Subdivided in: Barrel (TBPX), Forward (TFPX), Endcap (TEPX)
- 1x2 and 2x2 chip modules
- Finer granularity $\Rightarrow$ IT: pixel size 25x100 or 50x50 $\mu$m$^2$
- Almost vertical incidence in forward pixel detector (TFPX)

3.8 T uniform B-field

42M Si-strips in 192 m$^2$

170M macro-pixels in 25m$^2$

10$^9$ pixels in 4.9 m$^2$

3D sensors option for innermost layer in TBPX and TFPX
Radiation Levels for CMS IT

Radiation level for layer 1 after 3000 fb⁻¹:
- $\Phi_{eq} \approx 2.3 \times 10^{16}$ cm⁻², dose $\approx 12$ MGy
- Option of replacement after $\frac{1}{2}$ lifetime

<table>
<thead>
<tr>
<th>Layer</th>
<th>$\Phi_{eq}$ [10^{16} cm⁻²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>2.3</td>
</tr>
<tr>
<td>L2</td>
<td>0.5</td>
</tr>
<tr>
<td>L3</td>
<td>0.2</td>
</tr>
<tr>
<td>L4</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Planar Sensors: Requirements & Specs.

- **n-in-p sensors with 150 µm active thickness** → HPK and FBK sensors covered in this talk

- **High voltage stability for \(\Phi_{eq} = 0-1 \times 10^{15} \text{ cm}^{-2}\):** At least 300 V required for optimal resolution

**Radiation hardness requirements**

- **Bias voltages** \((V_{bias})\) up to 800 V required after irradiation

- **L2-4:** Maintain efficiency > 99%* for \(V_{bias} < 800\) V up to \(\Phi_{eq} \approx 5 \times 10^{15} \text{ cm}^{-2}\)

- **L1 planar:** Maintain efficiency > 98%* for \(V_{bias} < 800\) V up to \(\Phi_{eq} \approx 1.2 \times 10^{16} \text{ cm}^{-2}\)

- Leakage current < 10 nA/pixel (ROC spec); < 45 µA cm\(^{-2}\) at 600 V for \(\Phi_{eq} = 5 \times 10^{15}\) (sensor spec)

* For high efficiency tracking with 4 layers (measured at vertical incidence)
New Pixel Readout Chip

Common development for ATLAS and CMS within RD53 collaboration

- RD53A prototype chip with three different analog front end (FE) designs
  - Linear Front end chosen by CMS for final ROC: Results shown here for linear FE
- 50x50 µm^2 pixels, 77k per chip (final CMS full size chip: 144k)
- 65 nm CMOS technology (TSMC), radiation hard design, serial powering

Final readout chips:

- ATLAS submission January 2020 (ITkPix) → CMS April 2020 (CROC)
- Slightly different sizes of the pixel matrix; differential FE (ATLAS), linear FE (CMS)
Sensor Layout Optimization: Bias Dot

HPK sensor with punch-through bias dot

\[ \Phi_{eq} = 5.6 \times 10^{15} \text{ cm}^{-2} \]

- At 800 V: Efficiency 97% at vertical \( \rightarrow \) 99.7% at 34°
- Efficiency loss at bias dot disappears only at large angles (27°)
- Almost vertical incidence in forward pixel detector (TFPX)

Next HPK submission:
- “No bias” default
- Impact on QC: No sensor test before bump bonding
- Wafer acceptance: small test sensors with bias dots
Hit efficiency after irradiation

- Layer 2 lifetime fluence for High luminosity LHC: $\Phi_{eq} = 5 \times 10^{15}$ cm$^{-2}$
- Efficiency of 99% reached with all design variants at 30° beam incidence
- Substantially lower voltage needed to reach 99% for sensors w/o punch through bias dot
Hit Efficiency: FBK Sensors

Planar sensors by FBK, Trento:

- Si-Si wafer bonded, 100 µm active thickness, 200 µm total
- 25x100 and 50x50 µm² pixel cells, for RD53A chip
- Versions with punch through bias and w/o:
  - temporary metal for testing
- Hit efficiency >99% (210 V, w/o punch through)
  >97.6% (390 V, with punch through)

![Pixel Cell Diagram](image)

![Efficiency Graph](image)

\[
\Phi_{eq} \approx 5 \times 10^{15} \text{ cm}^{-2}
\]

no-PT – threshold 1400 e
PT – threshold 1200 e

Vertical Beam Incidence
Efficiency maps for 2x2 pixel grid

- **Vertical** beam incidence
- Extended efficiency drop in bias dot region (80-85 %)
- Efficiency slowly increases with increasing bias voltage
FBK Sensors with Punch Through

$V_{bias} = 390$ V

Rotation = 0°

Rotation = 12°

Rotation = 20°

Same efficiency colour scales!

Efficiency quickly increases by rotating the module

- The efficiency in the bias dot region is > 90% at 12°
- At 20° the efficiency is almost uniform
- Global efficiency > 99% at 15° rotation
Efficiency maps for 2x2 pixel grid

- Vertical beam incidence
- Efficiency gets more uniform with increasing bias voltage
- Small efficiency drops at the intersection of four pixels
  - This effect reduces with increasing bias voltage...
  - ...or small rotations
Implant Size Optimization

100 x 25 μm² HPK sensors with p-stop isolation
- Sensors for ROC4sens* chip, standard and increased implant size
- No early breakdown observed for ca. 70 samples
- Larger implant → Higher efficiency: V(99%) reduced by ca. 100 V

*PSI, Switzerland chip for R&D

Max Eff. = 96.8% for P-Stop, enlarged implant (sample 1)

Efficiency vs. Bias Voltage graph

- Maximum Implant implemented for 2019 submission to HPK
- Reduce to 5 um standard implant
- Larger implant → Higher efficiency: V(99%) reduced by ca. 100 V

All: 100x25 μm², \( \phi_{eq} = 5.4 \times 10^{15} \text{cm}^{-2} \), protons

- P-Stop, enlarged implant (sample 1)
- P-Stop, enlarged implant (sample 2)
- P-Stop
**Cross talk in 25x100 µm² sensors**

**CMS baseline: 25x100 µm² pixel cells**
- O (10%) Xtalk due to metal-implant overlap: Even-odd pattern
- 72% first pixel in cluster even pixel number at 700 e threshold
- Partially curable with cutout-design: Inter-pixel C to coupled neighbor reduces from 21 to 14 fF (simulation), **implemented in 2019 Hamamatsu and FBK submissions**
- Evaluation of new design → choice of aspect ratio

**Lab measurement: S-curve with charge injection**

**Deep diffused FZ**
- Threshold tuned to 850 e
- Xtalk: ~850e/8500 e ~10%

**Implant metal**

**RDS3A preliminary**
- Chip S/N: 0x0529
- S-curves for 26112 pixel(s)

![Graph](image)
100x25 μm² pixel size, no punch through bias, non-irradiated

Increasing threshold to 1200 e reduces the impact of cross talk while keeping excellent spatial resolution

Measurement will be repeated with irradiated sensor

Spatial resolution degrades for thresholds > 1500 e
Spatial Resolution (HPK sensors)

- 100 x 25 µm² pixels
- No punch through bias dot

Excellent spatial resolution!

- 50 x 50 µm² pixels

- Bias-dot, wiggle line
- Proton-irradiated
- $\Phi_{eq} \approx 5.3 \times 10^{15}$ cm⁻²
- 800 V

Non bias dot, non-irradiated

- 120 V

Non-irradiated
Towards Ultimate Fluence

- Sensors bump bonded to **Roc4Sens** readout chip studied up to $\Phi_{eq} = 1.4 \times 10^{16} \text{ cm}^{-2}$
- **neutron irradiation** at JSI, Ljubljana
- 500V needed for 99% efficiency @ $1.4 \times 10^{16} \text{ cm}^{-2}$ for vertical beam incidence
- >50% layer 1 lifetime fluence
- Encouraging results, will be followed up by further proton irradiations in 2020

*PSI, Switzerland chip for R&D  
no punch through bias
Summary and Conclusion

- Upgrade of LHC accelerator complex for Phase-2: Up to 3000 or even 4000 fb\(^{-1}\)
- Major Detector Upgrade for CMS with entire new Tracking System
- Radiation hard fine pitch pixel sensors under development for CMS
  - Making planar sensors fit for high fluences
  - 3D sensors option for innermost layer ➔ Dedicated talk by Marco Meschini
- Planar sensors demonstrated beyond layer 2 lifetime fluence, more irradiations in 2020
- Optimized sensor designs
  - Submissions for dual and quad chip sensors to FBK and HPK ➔ bump bonding in 2020
  - CROC sensors included in 2019 HPK submission ➔ Ready when chip becomes available

Related contributions:
- Radiation Resistant Innovative 3D Pixel Sensors for the CMS Upgrade at the High Luminosity LHC (Marco Meschini)
- The Phase 2 Upgrade of the CMS Inner Tracker (Stella Orfanelli)
Backup
Sensor design

n-in-p sensors with:
1. Active thickness: 150 µm ➞ expected to deliver S/threshold > 3 beyond $5 \times 10^{15} \text{ cm}^{-2}$
2. Pixel size: 25x100 or 50x50 µm$^2$
3. Pixel cell design: Isolation, biasing scheme, layout details

Maximize efficiency by:
- implant width beyond design rules
- No bias dot or Poly-silicon
Study influence of metallization
Streamline plan focuses on **RD53A** compatible sensors

- 3 types of wafer: **FTH (150 µm)**, FDB (150+50 µm), FDD (150+50 µm)

- **In bold: sensors considered in high priority plan**

<table>
<thead>
<tr>
<th></th>
<th>25x100 µm²</th>
<th>50x50 µm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>no bias</td>
<td>5P1</td>
</tr>
<tr>
<td>P2</td>
<td>common punch through</td>
<td>5P2 (open p-stop)</td>
</tr>
<tr>
<td>P3</td>
<td>poly Si</td>
<td>5P3</td>
</tr>
<tr>
<td>P4</td>
<td>-</td>
<td>5P4</td>
</tr>
<tr>
<td>P5</td>
<td>poly Si</td>
<td>P5</td>
</tr>
<tr>
<td>P6</td>
<td>-</td>
<td>P6</td>
</tr>
</tbody>
</table>

- Similar sensors for p-spray, at this point not part of the plan for first irradiations

- Sensors compatible with other ROCs were also included in wafer layouts to minimize schedule risks as ROC picture less clear at time of production

- Details of HPK submission in backup slides