Planar pixel sensor development for the CMS Phase II upgrade

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High-Luminosity LHC:
- Luminosity of $5-7.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, up to 200 events/25 ns bunch crossing
- Maintain occupancy at the permille level and increase the spatial resolution
  ➡ Pixel size $\sim 25 \times 100 \mu\text{m}^2$ or $50 \times 50 \mu\text{m}^2$ (currently $100 \times 150 \mu\text{m}^2$)

Pixel layout:

Radiation tolerance for the 1st pixel layer after 3000 $\text{fb}^{-1}$:
- $\Phi_{eq} \approx 2.3 \times 10^{16} \text{cm}^{-2}$, dose $\approx 12 \text{MGy}$

3D or planar pixel sensors for the 1st layer?
- R&D in parallel. Both options described and costed in TDR.
**OPERATIONAL VOLTAGE:**

- Before irradiation and for fluences up to $1 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ for an optimal resolution in a 3.8 T B-Field with low threshold

  ➡ $300 - 400 \text{ V}$ are required for 150 $\mu\text{m}$ thick sensors

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**Simulation by J. S.**

Cluster size vs bias voltage @ $B = 3.8 \text{ T}$, $T = 253 \text{ K}$

- Thickness 150 $\mu\text{m}$, threshold 1200 e

**Pixelav with HPTM**

- For 100 $\mu\text{m} \times 25 \mu\text{m}$

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**I-V of HPK RD53A sensors**

- For $100 \times 25 \mu\text{m}$

  ➡ Breakdown voltage > 600 V
  ➡ No problem for HPK sensors
**SENSOR REQUIREMENTS**

**Efficiency after irradiation for track reconstruction with 3 out of 4 hits should be > 99.9%:**
- Maintain efficiency > 99% for voltages < 800 V at $\Phi_{eq} \approx 5 \times 10^{15} \text{ cm}^{-2}$ (Layer 2)
- Maintain efficiency > 97% for voltages < 800 V at $\Phi_{eq} \approx 1.2 \times 10^{16} \text{ cm}^{-2}$ (0.5x Layer 1)

High bias voltages (~800 V) required to maintain high efficiency at larger fluences

Irradiation study with **ROC4SENS** chip + sensor w/o bias dot
Thin, small pitch planar pixel sensors:
- HPK submission (n+-p): 150 µm active thickness
- INFN - FBK R&D program, together with ATLAS (see talk from M. Meschini at HSTD10 (2015))
  - 6” n+-p, > 3 kΩ·cm, direct wafer bond
  - 100 µm and 130 µm active thickness
  - p-spray isolation
  - temporary metal for sensor testing
  - active edge / slim edge designs

Readout chip available for R&D with pixel size 50 µm x 50 µm and 100 µm x 25 µm
- ROC4Sens (PSI R&D chip available since summer 2017)
- RD53A

**Expected threshold of the CMS ROC**

→ expected to deliver S/threshold > 3 at up to \( \Phi_{eq} \approx 8 \times 10^{15} \text{cm}^{-2} \)

Simulation by J. S.

Pixelav with HPTM for 100 µm x 25 µm
**Sensor order:**
- 35 wafer 6” n+-p FZ
  - 10 wafer with 150 µm thickness (FTH150)
  - 20 wafer with 150 µm + 50 µm handle wafer (FDB150)
  - 5 wafer with 150 µm deep diffused (FDD150)
- Resistivity: 1 kΩ·cm - 5 kΩ·cm
- Isolation: 25 with p-stop (P) and 10 with p-spray (Y)
- Biasing schema: none, common punch-through, polysilicon resistor
- Backside grid for laser test

**Bump-bonding:**
- 8 wafers (2xFDB150P, 2xFTH150P, 2xFDD150P, 2xFTH150Y) have been processed at IZM
- 2 wafers (2x FDB150P) have been processed at RTI
- approx. 130 ROC4Sens modules received
- approx. 70 RD53A modules received
- + test structures (diodes, MOSFETs, MOS-C, GCDs etc.)
• Streamline plan focuses on **RD53A** compatible sensors
• 3 wafer types -> 2 wafer types: FTH150, FDB150, **FDD150** (no deep diffused)
• In bold: sensors considered in high priority plan

<table>
<thead>
<tr>
<th></th>
<th>25x100 mm²</th>
<th>50x50 mm²</th>
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<tbody>
<tr>
<td>P1</td>
<td>no bias</td>
<td>5P1</td>
</tr>
<tr>
<td>P2</td>
<td>common punch through</td>
<td>5P2</td>
</tr>
<tr>
<td></td>
<td>(open p-stop)</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>poly Si</td>
<td>5P3</td>
</tr>
<tr>
<td></td>
<td>common punch through, straight</td>
<td></td>
</tr>
<tr>
<td>P4</td>
<td>-</td>
<td>5P4</td>
</tr>
<tr>
<td></td>
<td>common punch through, wiggle</td>
<td></td>
</tr>
<tr>
<td>P5</td>
<td>poly Si</td>
<td>P5</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>P6</td>
<td>-</td>
<td>P6</td>
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<tr>
<td></td>
<td>poly Si</td>
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• Similar sensors for **p-spray**, evaluated with somewhat lower priority
• Designs with polysilicon resistors showed problems for the ROC4Sens
  ➔ Not considered in the streamline plan for the RD53A
DEFINE PIXEL CELL

Irradiation and measurement program on small pitch sensor modules
- Irradiate small-pitch hybrids at CERN (24 GeV/c p)\(^1\), LANL, KIT (23 MeV p)\(^1\) and JSI (n, only ROC4Sens)\(^1\)
  - RD53A \(\rightarrow\) O(80) SCMs available, highest priority
  - ROC4Sens \(\rightarrow\) available earlier, first measurements of small-pitch pixel sensors
- Perform Test Beam measurements at different facilities: SPS(2018), DESY, FNAL

Performance comparison of design variants based on:
- Hit efficiency and spatial resolution (versus incident angle)
- Bias voltage scans
- Threshold scans for inter-pixel coupling (cross-talk)
- Power dissipation (\(V_{\text{bias}} \times I_{\text{leak}}\)) per unit area (at -20°C)

Based on measured sensor+ROC performance, choose:
- Layer 1: planar vs 3D
- Sensor thickness (active and total)
- Cell size: 50x50 vs 25x100 \(\mu\text{m}^2\)
- Pixel cell design (bias scheme, pixel isolation, ...)

\(^1\) This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 654158
BIAS DOT

Efficiency maps for bias dot design
- RD53A HPK single chip module
- Beam at vertical incidence (as in Forward pixel, TFPX)

Higher efficiency with bias dot floating
Bias dot design

Cluster size maps for bias dot design
- RD53A HPK single chip module
- Beam at vertical incidence (as in Forward pixel, TFPX)

Bias Grid Floating
Bias Grid Grounded
Higher (better) charge sharing between pixels with bias dot floating
Excellent spatial resolution confirmed before irradiation

- 50x50 μm² RD53A HPK single chip module
- $\sigma_{\text{hit}} = 4.6 \, \mu\text{m}$ (unfolded)

- Optimal turn angle ($p$: pixel size, $d$: thickness)
  - $\alpha = \arctan(p/d) = 16.7^\circ$
- Calibration of analog front ends ongoing
*Efficiency*

- **RD53A SCM**: 150 µm thick “FTH”
- **25x100 µm² pixel cell, no bias scheme**
- **Fluence** $5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$
- **Linear FE**, threshold trimmed to 1.3 ke
- **101 masked pixels**
- **vertical incidence**

- *Caveat*: Irradiation non-uniform and dosimetry not well-known
ToT

**IRRADIATED RD53A**

- **RD53A SCM**: 150 µm thick “FTH”
- **25x100 µm² pixel cell, no bias scheme**
- **Fluence** $5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$
- **Linear FE**, threshold trimmed to 1.3 ke
- **101 masked pixels**
- **vertical incidence**

- **400 V needed for 99%, 250 V for 97%**
- **Caveat**: Irradiation non-uniform and dosimetry not well-known

**Sync e>iciency map**

- **RD53A 509**: 
  - $8 \cdot 10^{15} \text{p/cm}^2$
  - 800 V bias
  - Sync section
  - threshold 1.6 ke
  - auto-zero pulse: 1.6 µs every 240 µs
  - 4 masked pixels
  - turn 34°

**Gducial region**: 96.8%
IRRADIATED RD53A

Cluster size

- RD53A SCM: 150 µm thick “FTH”
- 25x100 µm² pixel cell, no bias scheme
- Fluence $5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$
- Linear FE, threshold trimmed to 1.3 ke
- 101 masked pixels
- vertical incidence
- Metal pattern visible?
IRRADIATED RD53A

Sync FE

- **Same module as before** (25x100 µm, no bias)
- Fluence $5 \times 10^{15} \text{neq/cm}^2$, 800 V bias
- Sync FE, threshold trimmed to 1.6 keV
- Varying auto-zero repetition
  - best compromise: auto-zero pulse 1.6 µs, every 240 µs (4 kHz)
  - **Next test beam**: block triggers during auto-zero with NIM hardware chain
- Efficiency 96.8% in fiducial region (34° turn)

Differential FE too noisy on this module!
NIEL VIOLATION?

• Bias voltage for 99% efficiency
  ‣ less than 400 V < 7.2x10^{15} n_{eq}/cm^2

• What is the ultimate reach for planar sensors?

• Next measurements:
  ‣ 1.6x10^{16} p/cm^2
  ‣ 1.6x10^{16} n/cm^2

• Protons vs neutrons
  ‣ NIEL breaking?
**EDGE-ON I**

**PSI ROC4SENS Chip**
- 24800 pixels (155 columns x 160 rows)
- No zero suppression
- Analog readout
- Low rate (120 Hz)

**Edge on beam test**
- At DESY II beam test facility using the EUDET DATURA telescope
- Beam in 100 µm direction parallel to sensor surface
- Track reconstruction using upstream triplet and time reference module

➡️ Measure charge collection as function of depth + distance to pixel center
➡️ Allows detailed studies of trapping effects
Samples and conditions
• 100x25 p-stop default
• Irradiated with neutrons to $4 \times 10^{15}$ cm$^{-2}$
• $T \approx -24^\circ$C
• No additional annealing

Column charge vs depth

Charge collection tomography
• Reconstruct height (y) and $x$ with telescope
• Plot pulse height vs $y$ and pixel-track distance

Complete charge collection and charge sharing information only possible with the ROC4SENS
Multi-RD53A

- **Quad RD53A** sensor batch for CMS TK common project running at FBK
- Sensor list:
  - **6 doublets (3 quads) No PT 25x100** pixels and no punch through bias. Temporary metal will be used for measurements at FBK premises
  - **14 doublets (7 quads) PT 50x50** pixels with punch through bias
  - **15 singlets with 25x100 or 50x50** pixels
- Wafer material (Icemos)
  - **6” Float Zone Si-Si DBW** (Direct Bonded Wafer) 150 µm thick active device, on 500 µm handle
  - P type, FZ Sensor resistivity > 5 kΩ·cm
  - Handle wafer: CZ 0.1-1 Ohm cm resistivity
- Three singlets with **slim edge**!
  - Distance last pixel implant to dicing line: **230, 180 and 130 µm** (real distance will be smaller after dicing)
SUMMARY

- Intense IT planar sensor R&D campaign with HPK, FBK
- Test beam results:
  - **Before irradiation:** Only small differences observed in efficiency between pixel cell designs, in particular between common punch through vs. no bias
  - Planar sensors **tested to Layer 2 lifetime fluence (5x10^{15} n_{eq}/cm^2):**
    - 400 V bias needed for 99% hit efficiency,
    - 99.6% at 800 V (HPK sensor without bias grid)
- Detailed performance comparison of cell designs after irradiation, and determination of ultimate reach of planar pixels: Ongoing