Pixel Detectors Development for CMS Phase-2 Upgrade

A. Messineo, Università & INFN sez. di Pisa

On behalf of the INFN-R&D Phase-2 and CMS Tracker collaborations
Sensor R&D programs in CMS

• R&D projects plan: *design of thin, radiation tolerant, small pitch pixel sensors*

  – **Phase-2 (High-Luminosity LHC) challenges:**
    • Luminosity of $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$, up to 200 events/25 ns bunch crossing
    • Maintain occupancy at $\approx\%$ level and increase the spatial resolution
      – Pixel size $\sim 25 \times 100 \ \mu$m$^2$ or $50 \times 50 \ \mu$m$^2$ (currently $100 \times 150 \ \mu$m$^2$)
    • Radiation level for the 1$^{st}$ pixel layer after 3000 fb$^{-1}$
      – $\Phi_{eq} \approx 2 \times 10^{16}$ cm$^{-2}$, dose $\approx 10$ Mgy

  – **Two technology approaches**
    • *Planar Pixel*
      i. INFN – FBK R&D program, ATLAS & CMS common ($n^+-p$)
      ii. CMS tracker collaboration, HPK submission ($n^+-p$)
    • *3D columnar Pixel*
      i. INFN – FBK R&D program, ATLAS & CMS common ($n^+-p$)
      ii. CNM Barcelona  *(see Gomez talk)*
INFN-FBK R&D pixel Phase-2 Project

- **R&D aim:** *Design and production of pixel detectors for innermost layers of HL-LHC trackers*
  - Partnership: Fondazione Bruno Kessler-FBK (Trento, Italy)

- **Device technologies:**
  - Planar n-in-p *(see S. Ronchin poster)*
    - Process Options: p-spray and/or p-stop
    - Periphery design: standard and A/T-Edge.
  - 3D Columnar n-in-p *(see R. Mendicino talk)*
  - Devices are designed in collaboration with FBK, Single Sided processing optimized by FBK.

- **Prototypes assembly main features:**
  - Hybridization on chip via Bump Bonding: SnAg\(^{(1)}\) and Indium\(^{(2)}\)
  - Thinning after processing: *smallest total sensor thickness 180 \(\mu\text{m}\)\(^{(1)}\)*
  - Spark protection: on Sensor (periphery) and ROC (periphery or whole area) by a patterned BCB (Benzo-Cyclo-Butene) layer \(\sim 2 \mu\text{m}\) thick\(^{(1)}\)

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(1) IZM Fraunhofer, Berlin
(2) Leonardo Finmeccanica, Roma
**Production and tests:**
- Two Planar and one 3D columnar pixel batches produced in collaboration with FBK
- Prototypes qualified in laboratory and in three beam test sessions
- One neutron and proton irradiation done

**Team:**

**Design, processing, qualification, assembly…**
- M. Boscardin, G. Giacomini\(^{(1)}\), S. Ronchin (FBK Trento)
- G.F. Dalla Betta, D.M.S. Sultan (Trento)
- M. Meschini, (Firenze)
- A. Messineo, R. Dell’Orso (Pisa)
- F. Ravera, A. Solano (Torino)

\(^{(1)}\) Now at BNL

**Test Beam and Data Analysis**
- M. Dinardo, L. Moroni, D. Zuolo (Milano B.)
- C. Civinini, M. Meschini, G. Sguazzoni, L. Viliani, I. Zoi\(^{(1)}\) (Firenze)
- L. Uplegger, C. Vernieri (FNAL)

\(^{(1)}\) Now at Hamburg Univ.
Material features (Planar and 3D)

- **Material:**
  - Silicon wafers, 6-inch, FZ p-type resistivity > 3 kOhm cm, wafers Si-Si Direct Wafer Bond and SoI\(^{(1)}\)
    - Thin active bulk: 100 µm and 130 µm

\(\text{Doping concentration (cm}^{-3}\)\)

- dE/dx reduced for thin silicon layer
  - Down to ~60% of most probable energy loss (388 eV/µm)
- Charge collection reduced by Boron diffusion
  - At Beam test ~6000 (100 µm) ~8000 (130 µm) electrons expected
    - Measured by the CMS pixel Phase-1 ROC PSI45dig: threshold ~1500 e + dispersion ~120 e

\((1)\text{Icemos Technology, Belfast}\)
**INFN-FBK R&D: Planar Pixel Devices**

- **Device design details, standard pixel:**
  - CMS/ATLAS standard ROC pitch pixel devices, assembled in prototypes using ROCs available today

- **Standard Pixel prototype (CMS)**
  - CMS Phase-0 design
  - 100 µm X 150 µm pitch (4160 Cells)
  - Can be Readout by
    - PSI46dig ROC (Phase-1) Rad.-Qual.: 2.5 MGy
    - PROC600 R-Q: 5 MGy

- **Device design details, small pitch pixel:**
  - Phase-2 pitch pixel devices adapted to standard ROC,
  - Phase-2 pitch pixel devices for new ROC chip.

- Design includes devices to be assembled with next generation ROCs
  - ROC4sens (PSI)
    - IBM 250 nm, 50 x 50 µm², 155 x 160 pixels, no charge threshold, rad hard > 5 MGy, operated with CMS pixel test board, **staggered BB pattern**, available since summer 2016 (on PROC600 wafer)
  - RD53A (RD53 collaboration):
    - 65nm, 50 x 50 µm², 400 x 192 pixels, min. threshold: 600 e-, rad hard up to 10 MGy **non-staggered BB pattern**, availability later 2017
**Beam Test experiment**

- Beam test done at the MTest test beam facility in Fermilab (US)
  - Beam: 120 GeV protons from Main Injector

- Tracking pixel telescope
  - 8 CMS pixel planes (pixel cell: 100x150 μm²)
  - Readout by PSI46 analog chip
    - Tracking performance: ~8 μm resolution for the extrapolated track on each coordinate

- DUT fixed to an optical bench with step rotation, HV, FNAL-Captan DAQ and active cooling at −20°C

- Typical prototype
  - Assembled on PCB
  - Connector to DAQ board
Beam Test: charge collection

- **Standard** pixel prototype
- Require single pixel clusters
- Tracking pixel telescope selection:
  - the predicted track impact point should be located ± 20 µm far from pixel cell edges (two sides)
- **Standard** quality cuts on tracks
  - Fit with Landau convoluted with Gaussian

Averaging over full sample the Ratio MPV@130um / MPV@100 is ~1.38 , expected [1.2-1.44]
Beam test: charge sharing neighboring pixels

- **Standard** pixel prototype
- Tracking pixel telescope selection:
  - the predicted track impact point should be located ± 20μm far from pixel cell edges (one side)
- **Standard** quality cuts on tracks

  \[ V_{\text{bias}} = 40V \]

- Hit of pointed pixel
- Hit of pointed pixel or hit in closest pixel on same row

- Standard thin detectors fully efficient in both views: long pitch (row direction) and short pitch (column direction)
Device Irradiation

- Irradiations:
  - Los Alamos 800 MeV protons
  - Neutron irradiated Ljubljana-reactor \(^{(1)}\)
  - CERN proton irradiation 24 GeV protons

- Irradiation done after Flip Chip assembly
  - Constraints from radiation tolerance of PSI46 Digital ROC ~250 Mrad

- Results affected by
  - Non uniform irradiation in case of charged particle beam
    - Non uniform radiation damage on ROC Pixel Unit cells
  - Different activation of damage on ROC for charged particles vs neutron

- Radiation level measured by in situ dosimetry and corrected (normally scaled down) by simulation predictions
  - Effective Fluences (today) between \(~2 \times 10^{14} \text{ n}_{eq} / \text{ cm}^2\) and \(~2.7 \times 10^{15} \text{ n}_{eq} / \text{ cm}^2\)

- Planned irradiation for non bump bonded pixel sensor
  - post irradiation low-T Flip Chip assembly (Indium)

\(^{(1)}\) Irradiations at JSI (Ljubljana) were supported by the H2020 project AIDA-2020, GA no. 654168, TNA. Thanks to V. Cindro and colleagues.
**Radiation damage: planar pixel**

- **Standard** pixel prototype
  - 100 µm active thickness

- Neutron irradiation
  - $1 \times 10^{15} \text{n}_{\text{eq}}/ \text{cm}^2$
    - ~20% of charge loss observed at 280V (safer operation)
    - Temperature -20 °C

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**Before irradiation**

- $\chi^2 / \text{ndf}$: 81.01 / 48
- Width: 611.4 ± 5.2
- MPV: 6142 ± 7.2
- Noise: 916.4 ± 8.9

**After irradiation ~1x10^{15} \text{n}_{\text{eq}}/ \text{cm}^2**

- $\chi^2 / \text{ndf}$: 464.8 / 220
- Width: 266.3 ± 6.1
- MPV: 4929 ± 8.9
- Noise: 519.1 ± 10.2
Radiation damage: proton irradiation

- **Standard** pixel prototype
  - Fluence Corrected for non-uniformity of the beam spot on device
  - Charge collected at the highest available voltage, Temperature -20 °C
  - New beam test on going

<table>
<thead>
<tr>
<th>Dev. Thick. (µm)</th>
<th>Fluence (10^{15})</th>
<th>(V_{bias}(V))</th>
<th>Charge loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.2±0.03</td>
<td>400</td>
<td>4.4%</td>
</tr>
<tr>
<td>100</td>
<td>0.9±0.14</td>
<td>280</td>
<td>19.7%</td>
</tr>
<tr>
<td>130</td>
<td>1.15±0.17</td>
<td>300</td>
<td>25.9%</td>
</tr>
</tbody>
</table>

- Apparently thin detector seems to be more radiation tolerant, however the thick detector should be at under-depletion at the highest \(V_{bias} = 300V\)
Pixel cell design details

• Tracks detection efficiency is affected by the pixel bias structure

• **Standard** Pixel prototype

![](image1)

Pixel Unit Cell efficiency

<table>
<thead>
<tr>
<th>Dev. 45B</th>
<th>Pixel Unit Cell efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi \sim 0$</td>
<td>$\Phi \sim 2 \times 10^{14} \text{n}_{\text{eq}} / \text{cm}^2$</td>
</tr>
</tbody>
</table>

• Geometry of the bias structure or moderated p-spray mitigate the inefficiency before irradiation
  • Observed however after irradiation
    – Simulation study to optimize geometry/process of bias structure
  • For small pitch pixel design can be critical (i.e. common 4-fold bias dot)
INFN-FBK R&D project Submission on 6” $n^+\text{-}p$ wafers

- Batch designed and produced  
  - Now at qualification step
- Material  
  - SiSi DWB and SoI 100 μm and 130 μm thick on carrier wafer
- Layout includes  
  - Thin/Active edge periphery design
  - Standard ROC pixel 100 μm X 150 μm PSI46dig
  - Small pitch pixel adapted to standard ROC\(^{(1)}\)
  - New ROCs: RD53A and Roc4sens FE-I4, CHIPIX65, FCP130

\(^{(1)}\)Device design example

- Adapt small pitch to standard ROC pitch  
  - All ROC readout channels are connected

Adapt 50 μm X 50 μm: 4-fold readout cells
Adapt 25 μm X 100 μm: three columns readout cells
Aims of the R&D submission:
- Evaluate pixel geometry: 25x100 vs. 50x50 μm²
- Study and optimize sensor design
  - Pixel isolation: p-stop vs p-spray (rad-hardness)
  - Bias scheme for small pixels
    - no bias, common punch through, poly-silicon bias
  - Metal overhang to mitigate E-field
  - Signal routing

Pixel sensors for these r/o chips:
- PSI46/PROC600, ROC4sens, RD53a, FCP130, CHIPIX65, (FE-I4)

Design in collaboration with HPK, wafers expected back April 2017
• Devices Single Sided processed: can be thinned
• Pixel Unit Cell design with variety of collecting electrodes
• Location of pad for bump bonding optimized

- **Standard** pixel prototype
  - 100 µm X 150 µm pitch
  - Readout by PSI46dig ROC (Phase-1)
  - 130 µm active thickness

- **Small pitch** pixel prototype
  - 50 µm X 50 µm and 25 µm X 100 µm pitch
  - Readout cell adapted for PSI46dig ROC (Phase-1)
Beam test: Charge collected 3D compared to planar

- **Standard** pixel prototype
  - 3D: cells with 3E or 2E junction column

- Planar and 3D prototypes used on the same beam test session

- Charge collection performance on 3D columnar thin prototype comparable to planar thin one (@ higher $V_{bias}$)
Beam test Charge collection summary

- **Standard** pixel prototype
- Tracks orthogonal to the detector
  - Standard track quality selection
  - Tracking telescope predicted track impact on the selected cell

**Charge collected vs $V_{bias}$ 3D pixels**

- 3D 2E
- 3D 3E

**Charge collected vs $V_{bias}$ planar pixels**

- Systematic uncertainties are not taken into account: 5%-10% expected
- Absolute calibration not applied: small variation ROC by ROC expected
  - Plan to measure the charge calibration factor by X-ray fluorescence (standard procedure)
  - New beam test measurement in order to improve statistic
Pixel 3D detector: hit reconstruction efficiency

- **Standard** pixel prototype
- Orthogonal tracks
  - Standard track quality selection
  - Tracking telescope predicted track impact on the selected cell or in the 8 neighborhood

Hit efficiency: 2D map

Efficiency is very high and uniform

- **Inefficiency from columns**
  - 3E column eff. 0.9927±0.0002
    - Fraction of column area ~0.8%
  - 2E column eff. 0.9943±0.0002
    - Fraction of column area ~0.5%

Efficiency is very high and uniform

High efficiency also at low $V_{bias}$

Device 56B – 2E @40V

Bias voltage (V)

<table>
<thead>
<tr>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>0.91</td>
<td>0.92</td>
<td>0.93</td>
<td>0.94</td>
<td>0.95</td>
<td>0.96</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Bias voltage distribution: 2D efficiency

Efficiency is very high and uniform

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**Pixel Unit Cell: hit reconstruction efficiency**

- **Standard** pixel prototype
- Different cell column design: 2 and 3 electrodes
- Orthogonal tracks
  - All Pixel Unit Cells (4160) overlapped on a single cell: hit efficiency 2D map

- Visible effect of columns (non collecting) volume
  - Smaller charge collection efficiency for tracks pointing to Junction columns
  - Lowest charge collection efficiency values located on tracks pointing to Ohmic columns (E\text{field} \sim 0)
**Pixel Unit Cell hit reconstruction efficiency: tilted**

Prototype 56D-3E @ 30V

Orthogonal tracks

Detector 5 degree tilted

Detector 10 degree tilted

<table>
<thead>
<tr>
<th>Angle (degrees)</th>
<th>Efficiency 3E</th>
<th>Efficiency 2E</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>99.27%</td>
<td>99.45%</td>
</tr>
<tr>
<td>5</td>
<td>99.77%</td>
<td>99.85%</td>
</tr>
<tr>
<td>10</td>
<td>99.88%</td>
<td>99.87%</td>
</tr>
</tbody>
</table>

max $\Delta$ Efficiency 0.62% 0.43%

- **Almost full geometrical factor recovered**
  - 3E Detector Efficiency by +0.6%
    - Fraction of column area $\sim$0.8%
  - 2E Detector Efficiency by +0.4%
    - Fraction of column area $\sim$0.5%

- Efficiency improved for non orthogonal tracks

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Beam test Small pitch 3D Pixel: 50 x 50 µm²

Charge shared with not readout adjacent pixels. Effect over 3/4 cell sides

Dev. 130µm thick, $V_{\text{bias}}=30$ V

- $\chi^2 / \text{ndf} = 233.4 / 180$
- MPV $= 8799 \pm 15.8$
- Noise $= 1117 \pm 23.4$

Two adjacent double columns pixel readout ROC (PSI46dig) fully connected
Sensitive area readout: 1/6

MPV vs Bias Voltage
Beam test Small pitch 3D Pixel: 25 x 100 μm²

Dev. 130 μm thick Vbias=30V

Charge shared with not readout adjacent pixels. Effect over 2(long)/4 cell sides

One full column readout
ROC (PSI46dig) fully connected
Sensitive area readout: 1/6
Conclusion

- R&D programs to develop thin, radiation tolerant, fine pitch sensors and address pixel design/assembly issues
  - A few research programs on going in parallel within CMS
    - Planar: CMS/HPK submission, INFN/FBK (together with ATLAS)
    - 3D: INFN/FBK (together with ATLAS), CNM
  - Design and Radiation hardness study
    - Efficient and precise tracking at high rates
    - Material, Pixel Bias scheme, ....
  - Prototype assembly: fine pitch bump bonding of thin sensors/ROCs challenging and a major cost driver for small pitch

- Preliminary results on prototype show good data quality for planar and on 3D pixels, detailed analysis on smallest pitch devices still ongoing
  - Thin 3D pixels, n-in-p, are working as expected, both for standard pitch and new 50x50 μm² 25x100 μm² pitch (preliminary results)
  - Qualification and Irradiations campaign to be completed
    - Today constraint from PSI46dig ROC performance
  - New Beam test experiments planned in order to fulfill this program

- Activity on going: new wafers submission at process or qualification step
  - New ROC (PROC600, RD53, ROC4sens,..) for Phase-2 pitch pixel assembly.
Back Up
Tracker radiation dose

1 Gy = 100 Rad

Layer 1: 100 MRad
Layer 2: 40 MRad
Layer 3: 20 MRad
Layer 4: 13 MRad

Fluence:
1 MRad $\approx 3 \times 10^{13}$/cm$^2$ pions
• Threshold: in time 1800-2000 e The difference, $\Delta Q$, between absolute and in-time threshold 100-200 e

• Radiation hardness
• Desy dice soglia 1.8 ke

Table 4.1: List of the applied target materials presenting their $K_\alpha$ transition energies as well as the expected number of electrons $N_{el}$ created via the photoelectric effect [NIS13].

<table>
<thead>
<tr>
<th>Target</th>
<th>$E_{K_\alpha}$ [eV]</th>
<th>$N_{el}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>6403.13</td>
<td>1779</td>
</tr>
<tr>
<td>Cu</td>
<td>8048.11</td>
<td>2236</td>
</tr>
<tr>
<td>Zn</td>
<td>8639.10</td>
<td>2400</td>
</tr>
<tr>
<td>Rb</td>
<td>13 375.05</td>
<td>3721</td>
</tr>
<tr>
<td>Mo</td>
<td>17 479.10</td>
<td>4855</td>
</tr>
<tr>
<td>Ag</td>
<td>22 162.99</td>
<td>6156</td>
</tr>
<tr>
<td>In</td>
<td>24 209.78</td>
<td>6725</td>
</tr>
<tr>
<td>Sn</td>
<td>25 271.34</td>
<td>7020</td>
</tr>
<tr>
<td>Ba</td>
<td>32 192.87</td>
<td>8942</td>
</tr>
<tr>
<td>Nd</td>
<td>37 361.40</td>
<td>10 378</td>
</tr>
<tr>
<td>Tb</td>
<td>44 485.90</td>
<td>12 356</td>
</tr>
</tbody>
</table>
Radiation hardness

CMS
• Sensors are used for the present BPIX.
• Performance fully satisfactory
• Radiation level is still low but above the point of space charge sign ("type") inversion

Radiation hardness studies
• $\sim 1.2 \times 10^{15} \text{N}_{\text{eq}}/\text{cm}^2$:
  Several test beam studies in the years 2002-06
  NIM A 583 (2008) 25-41
• Summer 2013: $1.5$ and $3 \times 10^{15} \text{N}_{\text{eq}}/\text{cm}^2$
  Irradiation at KIT and testbeam at DESY

Signal height and detection efficiency fully sufficient for the targeted radiation level of $1.5 \times 10^{15} \text{N}_{\text{eq}}/\text{cm}^2$ ($\sim 250 \text{fb}^{-1}$ in layer 1 at 3cm)
6.1. Silicon sensor requirements

Figure 6.4: Charge collection in non-irradiated and irradiated sensors with different doses and different particle types (sensors of 285±15 μm thickness.)

PSI46dig digital version:
Charge threshold: >1.5ke-
Charge resolution: ~120e-
   (pixel-by-pixel calibration needed)
Rad hardness: >250 Mrad
Operation: triggered only
SiSi DWB substrate qualification
Planar sensor test batch, 2014

G.-F. Dalla Betta, NIMA 824 (2016) 388

Circular diode, 4 mm², two GRs

Doping concentration profiles:
• Active layer doping $1 - 3 \times 10^{12}$ cm$^{-3}$
• Thicknesses about 10 $\mu$m lower than the nominal values, due to Boron diffusion from support wafer

$J_{\text{leak}}$ distribution on 135 diodes

$\Rightarrow$ Different material quality?
Test diode: C-V measurements

Depletion voltages:
• $V_{\text{depl}} \sim 16\,\text{V}$ for $100\,\mu\text{m}$ thick.
• $V_{\text{depl}} \sim 20\,\text{V}$ for $130\,\mu\text{m}$ thick.

$\Rightarrow$ Different resistivities …

Concentration profiles
• Doping $1 - 3 \times 10^{12}\,\text{cm}^{-3}$
• Thicknesses about $10\,\mu\text{m}$ lower than the nominal values, compatible with Boron diffusion from support wafer and measurement limit ($L_{\text{debye}}$)
31.9: Most probable energy loss in silicon, scaled to the mean 1 ionizing particle, 388 eV/µm (1.66 MeV g⁻¹ cm²).
Beam test: charge sharing neighboring pixels

- Charge collected proportional to "on pixel" projected track length
  - \( \frac{w}{2} \cdot \tan(\theta) + x \sim \text{charge}_L \)
  - \( \frac{w}{2} \cdot \tan(\theta) - x \sim \text{charge}_R \)

  \[
  \text{Asymmetry} = \frac{\text{charge}_L - \text{charge}_R}{\text{charge}_L + \text{charge}_R}
  \]

- \( \text{Asymmetry} = 2x / (w \cdot \tan(\theta)) \)
- \( \text{Slope} = \frac{x}{\text{Asymmetry}} = \frac{w}{2} \cdot \tan(\theta) \)

  \( w = 100 \, \mu m \rightarrow \) Slope = 18.2 \( \mu m/\text{asymmetry} \)

  \( w = 130 \, \mu m \rightarrow \) Slope = 23.7 \( \mu m/\text{asymmetry} \)

- Standard Pixel prototype

  - 130\( \mu m \) thick; slope 22.3
  - 100\( \mu m \) thick; slope 16.2
• Charge increases (~0.6%) with track angle and track length

• Cluster width increases by ~10% for 2E and 3E
• Efficiency is high: charge collected is far beyond the measurement threshold