Testbeam and laboratory test results of irradiated 3D CMS pixel detectors

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Outline

- The CMS experiment
- The CMS pixel detector
- 3D vs planar technology
- 3D detectors @ CERN LHC
- CMS 3D sensors
- Pre-irradiation
  - laboratory tests
  - beam test results
- Irradiation
- Post-irradiation
  - laboratory results
  - beam test results
- New improved 3D sensors
- Summary & outlook
The CMS experiment

- magnetic field
  4T (in solenoid)
  2T (in muon detector)

- 12.5 kton weight
- 21.6 m height
- 15 m diameter
The CMS Pixel Detector

- Barrel layers at $r$ of 4.3, 7.3, 10.4 cm
- Forward disks at $z$ of $\pm 34.5$, $\pm 46.5$ cm (modules tilted 20° for better resolution)
- High granularity: 66 MPix camera
  - 100 $\mu$m x 150 $\mu$m pixel dimensions
- Low mass occupancy
- 1 m$^2$ silicon coverage
3D vs planar technology

- p+ and n+ electrodes are arrays of columns that penetrate into the bulk
- Lateral depletion and charge collection is sideways
- Superior radiation hardness due to smaller electrode spacing:
  - smaller carrier drift distance
  - faster charge collection
  - less carrier trapping
  - lower depletion voltage

Disadvantages:
- Higher noise
- Complex, non-standard processing

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3D @ CERN LHC

3Ds are promising tracking detector candidates for future upgrades at LHC

25% of ATLAS IBL will be 3D sensors at phase I upgrade in 2015

- New rad-hard sensor candidates for the HL-LHC CMS vertex detector ($L = 10^{35} \text{cm}^{-2}\text{s}^{-1}$)
- Equivalent dose $\sim 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$ @ $r = 5 \text{ cm}$
- Current CMS pixel detector can collect 50% charge at the fluence of $\sim 1 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ at $\geq 600\text{V}$
  (doi:10.1016/j.nima.2010.03.157)

- HPS (near beam proton spectrometer - under approval for CMS)
  Crucial requirement for this application: radiation hardness and active edges

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3D layouts (200 µm substrate thickness)

2E Configuration
- 7.5 µm
- 64 µm
- 100 µm
- 150 µm

4E Configuration
- n+ (readout)
- p+ (bias)
- 46 µm

1E Configuration

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3D sensor assembly

- 3D sensors bump-bonded to CMS PSI46v2 readout chip
  - At IZM for SINTEF 3Ds (PbSn)
  - At SELEX for FBK 3Ds (In)
  - At IZM for CNM 3Ds (PbSn)
- CMS sensor dimensions 52(col)x80(row) (100 µm x 150 µm)
- Wire bonding and assembly done at Purdue, FNAL, and Torino
- *Purdue flip-chip bonder* fully functional for next 3D sensors

Lab testing:
- ROC calibration
- Leakage current
- Noise
- Radioactive source testing
CMS 3D sensor assembly

Testboard assembly

Plaquette assembly

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Leakage current measurements

SINTEF 3D

2E Vbreakdown ~120 V
4E Vbreakdown ~100 V

FBK 3D (ATLAS09 batch)

All 1E type

Vbreakdown ~45 V

CNM 3D

Vbreakdown ~100 V

FBK 3D (ATLAS08 batch)

Vbreakdown 25-40 V

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Noise measurements

**SINTEF 3D**

Unable to measure 4E noise at $V_{bias} < 40$V

**FBK 3D (ATLAS08 batch)**

-20 °C

**FBK 3D (ATLAS09 batch)**

20 °C

- Higher number of electrodes, larger capacitance $\rightarrow$ larger noise
- CMS planar sensor noise 100-150 electrons

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Source charge collection

- Sr-90 source: 1 mCi, $E_\beta = 0.546$ MeV
- Random trigger used

Slight difference between measured and simulated collected charges:
- combined effect of charge sharing and readout chip threshold (~3.9 ke-)
- Lower chip gain calibration due to high noise of 3D sensors
- wafer thickness uncertainty (200±20) µm
Irradiation

• Irradiation at the Los Alamos Neutron Science Center (LANSCE) with 800 MeV protons/cm²
  – Fluences: 5E14, 1E15, and 5E15 p/cm² (FBK)
  – Fluences: 1E15, and 5E15 p/cm² (SINTEF)
  – Fluences: 1E14, 3E14, 5E14, and 1E15 p/cm² (CNM)
• Post-irradiation lab (@ Purdue) and beam tests (@ FNAL) performed for SINTEF and FBK 3D sensors
  – CNM sensors only tested in testbeams
• Most of the readout chips work after irradiation
  – Except SINTEF case: 1 out of 6 ROCs worked, and CNM sensors had calibration problems
• Post-irradiation lab measurements carried out in the thermal chamber running at -20 °C
  – Sensor temp estimated by an IR camera to be -7 °C

*800 MeV proton to 1 MeV neutron equivalent conversion factor is 0.7*
Post-irradiation charge collection

- Sr-90 source: 1 mCi, $E_\beta = 0.546$ MeV
- Random trigger used

Signal **LOSS in FBK 3D** (@ -30V, 3900 electrons threshold):

- 1E 43% after 1E15 p/cm$^2$ (0.7E15 n$_{eq}$/cm$^2$)
- 1E 50% after 5E15 p/cm$^2$ (3.5E15 n$_{eq}$/cm$^2$)
- 2E 14% after 1E15 p/cm$^2$ (0.7E15 n$_{eq}$/cm$^2$)
- 4E 14% after 1E15 p/cm$^2$ (0.7E15 n$_{eq}$/cm$^2$)

**CMS pixel 50% after 1E15 n$_{eq}$/cm$^2$ at 600V**

(doi:10.1016/j.nima.2010.03.157)

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Fermilab testbeam setup

Geometrical layout of the telescope

- Four 2x3 and four 2x4 CMS pixel modules rotated at 25° w.r.t. beam to improve tracking resolution
- Pixel pitch: 100 µm along the rotated axis (150 µm in the other direction)
- Alignment done with a software developed at Milano Bicocca
- Telescope resolution on DUT: 6 µm
Beam test: pre-irradiation

**CNM 3D, 1E**

- $V_{\text{bias}} = -15\,\text{V}$
- $20^\circ$ tilt
- Hitmap
- 93.4% efficiency

**FBK 3D, 1E**

- $V_{\text{bias}} = -15\,\text{V}$
- $20^\circ$ tilt
- ATLAS08 batch
- Hitmap
- 98.5% efficiency

**FBK 3D, 2E**

- $V_{\text{bias}} = -5\,\text{V}$
- $20^\circ$ tilt
- ATLAS08 batch
- Hitmap
- 94.6% efficiency

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Beam tests: pre-irradiation

FBK (ATLAS09 batch, slim edge), 1E

1E configuration

Charge collection

\[ V_{\text{bias}}: -20 \text{ V} \]

MPV: 17 ke- 200 ± 20 µm

Efficiency vs bias

Efficiency vs tilt

\[ V_{\text{bias}} = -20 \text{ V} \]

0° tilt

20° tilt

Residuals for 2 pixel clusters

\[ \sigma_x = 14.4 \text{ µm} \]

\[ \sigma_y = 12.8 \text{ µm} \]

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Beam test: post-irradiation

- Measured at -20 °C
- No tilt (0° degree) wrt beam
- Electrodes are less sensitive: observed lower efficiency in electrode regions
- Simulations ongoing to understand post-irradiation sensor efficiencies
- Track efficiency decreases after irradiation. 1E sensors more affected
- Efficiency increases with bias, due to larger electric field in the bulk, up to breakdown where it falls off
- Not all sensors tested up to breakdown

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Pre-irradiation</th>
<th>Post-irradiation</th>
<th>Fluence ([\text{n}_{\text{eq}}/\text{cm}^2])</th>
</tr>
</thead>
<tbody>
<tr>
<td>1E_1</td>
<td>97.7</td>
<td>37.9</td>
<td>(3.5 \times 10^{15})</td>
</tr>
<tr>
<td>1E_2</td>
<td>81.1</td>
<td>59.2</td>
<td>(0.7 \times 10^{15})</td>
</tr>
<tr>
<td>2E</td>
<td>97.1</td>
<td>91.1</td>
<td>(0.7 \times 10^{15})</td>
</tr>
</tbody>
</table>
New improved 3D sensors

- **WAFFER LAYOUT:**
  - ATLAS10 batch
  - CMS-1E diode only
  - Diodes are highlighted (RED)
  - The shipped test structures are also highlighted (ORANGE)

- **Test structures (TestPad):**
  - Gate controlled diode
  - MOS capacitor
  - Planar diode
  - Capacitor

- **CM 1E diodes:**
  - 3.5x3.8 mm²
  - 200 ± 20 um thickness
  - 19x29 pixel arrays

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Diodes pre- and post-cut IV measurements

- Diodes irradiated while actively biased (-10V)
- Breakdown improved from -40 V to -80 V

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Capacitance measurements

- Full depletion ~ -7 V at 20 °C
- ~200 pF at -10 V

2.26 MRad (Gamma irradiation facility at Purdue)

- Post-irradiation full depletion
  ~ -20 V at -20 °C
- ~200 pF at -10 V
Summary & outlook

- 3D sensors have several features outperform planar sensors
- Sensors received from SINTEF (Norway), FBK (Ital), and CNM (Spain)-
  - Breakdown voltage: SINTEF > 100V, CNM > 100V, and FBK <= 40V
- 3D sensors have higher noises
- Pre-irradiation beam test results show efficiencies higher than 90%
- Irradiated fluences are between 1E14 and 3.5x10^{15} n_{eq}/cm^2 (800 MeV protons)
- Beam tests at Fermilab
  - > 90% tracking efficiency before irradiation
  - Low tracking efficiency after irradiation due
    - High readout threshold
    - Low electric field (lower post-irradiation breakdown voltage)
  - Good charge collection after heavy irradiation wrt planar
  - 2E configuration outperforms 1E and 4E after irradiation
- Expecting more 3Ds from SINTEF, FBK and CNM
- Ongoing simulation to develop understanding FBK beam test results
- New irradiation fluences up to 1E16 n_{eq}/cm^2

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CMS 3D collaboration

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