Beam Test Measurements on Planar Pixel Sensors for CMS Phase 2

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Introduction – CMS Phase-2 Upgrade

High-Luminosity LHC

- Luminosity of up to $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Up to an average of 200 events per 25 ns bunch crossing

To keep occupancy low and improve spatial resolution ⇒ reduce pixel size

- $25 \times 100 \mu \text{m}^2$ or
- $50 \times 50 \mu \text{m}^2$ compared to $150 \times 100 \mu \text{m}^2$

To face radiation damage up to a dose of 12 MGy and $\Phi_{eq} \approx 2.3 \times 10^{16} \text{n}_{eq}/\text{cm}^2$

- 100 - 150 $\mu$ m planar sensors compared to 285 $\mu$m
- Or 3D sensors (layer 1)
Introduction – Investigated Samples

CMS Phase-2 Prototype Design Variations

- $n^+p$-pixel sensors with $p^+$ backside
- Different thicknesses
- Geometry, $100 \times 25 \mu m^2$ and $50 \times 50 \mu m^2$
- Pixel isolation schemes
- With and without biasing scheme

Readout Chip – PSI ROC4SENS

- All samples are bump bonded to a PSI ROC4SENS analogue readout chip
- No zero suppression but low rate (120 Hz)
- Region of interest based data taking

Irradiation with neutrons in Ljubljana (TRIGA)
Introduction – Investigated Samples

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Irradiation with neutrons in Ljubljana (TRIGA)
DESY II Beam Test Facility
- Radius $r = 46.6 \text{ m}$
- Electron/positron synchrotron beam
- Conversion $e^-(e^+) \rightarrow \gamma \rightarrow e^-(e^+)$
- Energies from 1 to 6 GeV
- Peak rates around 10 kHz

Beam Telescope
- EUDET DATURA Telescope for tracking
- Scintillators for triggering
- 6 MIMOSA 26 planes ($t_{int} = 115 \mu\text{s}$)
- Time REFerence module
- Device UNDER TEST
Glued single chip module

Telescope upstream part
Telescope Resolution – Upstream Triplet Resolution

Telescope-only study to measure triplet track resolution at different DUT positions

**Technique**

- Extrapolate upstream triplet to 4th telescope plane
- Fit residual distribution with Student’s t
- Subtract 3.3 µm intrinsic plane resolution

\[
\sigma_{\text{track}} = \sqrt{\sigma_{\text{meas}}^2 - \sigma_{\text{intr}}^2}
\]

Using only the upstream triplet mitigates the effect of multiple scattering in copper cooling block

![Resolution vs dz](image_url)
Efficiency – Efficiency Definition

Hit Efficiency

- Efficiency = \( \frac{N(\text{hit on track})}{N(\text{track})} \)

- Track definition:
  - Get upstream and downstream triplets
  - Match triplets using 0.1 mm cut
  - Demand REF-link; 0.15 mm cut
  - Demand 0.6 mm isolation at time REF

- Hit on track definition:
  - Extrapolate upstream-track to DUT
  - Demand DUT-link (pixel); 0.2 mm cut
  - Pixel ∆PH cut
    - Significance cut of 4
      (RMS ≈ 7 ADC)
  - Fiducial region 0.2 mm to sensor edges
Efficiency – Results on Neutron Irradiated Samples

Comments

- Final selection \( \approx 60 \) k for 160 k triggers
- \( 4 \times 10^{15} \) n/cm\(^2\) noise RMS \( \approx 4 \) ADC
- \( 8 \times 10^{15} \) n/cm\(^2\) noise RMS \( \approx 7 \) ADC
- At \( \approx -24^\circ \text{C} \); no additional annealing
- Error calculation: Efficiency \( \epsilon = k/N \) 
  \[ \sigma_{\epsilon} = \left( \frac{1}{\sqrt{N}} \right) \cdot \sqrt{\epsilon(1 - \epsilon)} \]

Observations

- Efficiency above 99% for all samples above 300 V
- Max imp - highest efficiency at 8E15
- Effect of 19° tilt is smaller then 0.5%
Efficiency – In Pixel x-Dependence

Where do we lose efficiency?

Sample and Conditions
- P-spray max imp
- Irradiated with $8 \times 10^{15}$ n/cm$^2$
- At $\approx -24^\circ$C; no additional annealing

Observations
- Lower voltages: Efficiency drop 1 - 2% on the pixel edges
- In pixel features can be resolved even in direction of the small pitch (25 µm)
Edge-On – Picture I
Edge-On – Picture II
Edge-On – Setup

Setup
- Beam in 100 µm direction
- Track reconstruction using upstream triplet
- Time REF module upstream

The Idea
- Measure charge collection as a function of depth
- Allows detailed studies of trapping effects
Edge-On – Charge Collection Profile

Sample and Conditions

- 100x25 p-stop default
- Irradiated with $4 \times 10^{15}$ n/cm$^2$
- At $\approx -24^\circ$C
- No additional annealing

- Very sensitive measurements for model tuning
- But we can do even better...

![Graph showing edge-on charge collection profile with bias voltage conditions (800V, 600V, 400V, 200V) and Electron Drift indicated.]
Edge-On – Data Storage

- Take pixel above significance cut of 4 – hit
- Define Region Of Interest (ROI)
  - E.g. field of $7 \times 7$ (column $\times$ row) pixels
  - Centered around each hit
- Store hit position (column, row) and trigger number
- Store position (column, row) and PH
  - Of all pixel in ROI
  - IF not stored in any previous hit of the same trigger number (no double counting)
- Thereby store $\leq n \times 3 \times 49$ instead of 24800 numbers per event
- But we maintain quasi threshold less readout

Example storage pattern

Finn Feindt (University of Hamburg)
Edge-On – Charge Collection Tomography

Sample and Conditions
- 100x25 p-stop default
- Irradiated with $4 \times 10^{15}$ n/cm$^2$
- At $\approx -24^\circ$C; 150 V, 800 V
- No additional annealing

Observation
- Direct charge collection and charge sharing information
- Negative signal induced in neighboring pixels for low voltages
- Only possible with this chip

- Reconstruct height (y) and x with the telescope
- Plot pulse height vs y and pixel-track distance
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Conclusion and Outlook

Conclusion

- Results on neutron irradiated ROC4SENS sensor assemblies (up to $8 \times 10^{15} \text{n/cm}^2$)
  - Efficiency above 99% for all samples and above 300 V
  - Highest efficiency for sensors with p-spray isolation and enlarged implants
    - next test beam: Sensors with biasing scheme

- Despite the low energy of DESY II we are able to resolve in-pixel features for vertical incidence and edge-on measurements to study details of charge collection

Outlook

- Due to the high efficiency at $8 \times 10^{15} \text{n/cm}^2$ we will measure new irradiated samples with fluences up to $1.6 \times 10^{16} \text{n/cm}^2$
- Use charge collection tomography for model tuning, simulations and template generation
Backup – Hit Finding Method

Method

- \( Dph_j = PH_j - PH_{j-1} \)
- \( Sph_j = \frac{Dph_j}{\sigma(Dph_j)} \) (significance)
- Set a threshold of 4
- Pixel \( j \) marked as hit if \( Sph_j < 4 \)
- Pixel \( j - 1 \) marked as hit if \( Sph_j > -4 \)
Backup – Clustering Algorithm

Before Clustering – DUT
- Common mode correction is applied
- Gain equalization is applied
- ROC coordinates $\Rightarrow$ sensor coordinates

Center of Gravity Clustering – All Planes
- Take any not yet clustered pixel over threshold
- Add all neighbors to cluster
- Charge weighted average position of all pixels in the cluster $\Rightarrow$ Cluster position
- Start next cluster

- DUT: Threshold $\approx 4$ signi. cut on $\Delta PH$
- Telescope: Binary, skip hot pixels
Backup – Common Mode Correction

**Online**
- Perform pedestal correction
- Take difference of neighboring pixels $Dph_j$
- Calculate significance $Sph_j$
- Use threshold of ± 4
- Store region of interest (ROI)
- Not suitable in offline analysis

**Offline**
- ROI-based data
- Perform column wise correction
- Find first and last pixel of the column
  - Subtract average PH from those in between

*If the first and the last pixel have the same distance we correct by the last.*
Backup – ROC4SENS

- Geometry: 50 x 50 µm pitch
- 155 x 160 pixels
- Analogue readout chain:
  - Preamplifier
  - Shaper
  - Sample and hold
  - Output Amplifier
- No discriminator, no zero suppressio, no ADC: 50 kB/event
- \( \approx 0.7 \text{ ms} \) for a readout cycle (at 40 MHz)
- Operated with Pixel Digital Test Board

Schematic of the analogue readout chain
Backup – Gain Equalization

Take Gain Calibration

- Use internal calibrations pulses ($V_{cal}$) of the ROC4SENS
- Draw $PH - ped$ vs $V_{cal}$
- Fit by Fermi function for every pixel
  \[ PH - ped = p_3 + \frac{p_2}{1 + \exp(-u)}; \quad u = \frac{V_{cal} - p_0}{p_1} \]
- Use inverse function to get the charge
  \[ Q(PH - ped) = V_{cal} \]
- Correction for relative gain variations of the pixels!
- Source calibration missing
  \[ \Rightarrow \text{Abs. calibration to expected charge} \]
The clusters in each plane are combined to get tracks

**Building Telescope Triplets Tracks**
- Build all combinations of P0 and P2
- Cut angle 0.005 rad
- Interpolate to P1
- Calculate $dx = x_{int} - x_{cl}$
- Reject tracks with $\|dx\| > 0.05$ mm
- Same procedure in y
- And for the downstream triplet (cut 0.10 mm)