Effect of thermal donors induced in bulk and variation in p-stop dose on the no-gain distance measurements of LGADs

- Shudhashil Bharthuar

on behalf of the CMS collaboration
Motivation:

**BTL: L(Y)SO bars + SiPM readout:**
- TK/ECAL interface ~ 45 mm thick
- $|\eta|<1.45$ and $p_T>0.7 \text{ GeV}$
- Active area ~38 m$^2$; 332k channels
- Fluence at 3 ab$^{-1}$: $2\times10^{14}$ n$_{eq}$/cm$^2$

**ETL: Si with internal gain (LGAD):**
- On the HGC nose ~ 65 mm thick
- $1.6<|\eta|<3.0$
- Active area ~14 m$^2$; ~8.5M channels
- Fluence at 3 ab$^{-1}$: up to $2\times10^{15}$ n$_{eq}$/cm$^2$
- Thin layer between tracker and calorimeter
- MIP sensitivity with time resolution of ~30 ps
- Hermetic coverage for $|\eta|<3$

Figure showing FBK UFSD3.1 production 2x2 sensor with optical opening running across adjacent pads
Samples measured: FBK UFSD3.1 2x2 sensors

- Sensors with 11 different interpad termination strategies
- Identical gain layer dose: equivalent to FBK scale factor - 1.02
- Samples from 3 wafers:
  - W13, W14 and W18 with 3 different p-stop dose such that:
    
    \[
    \text{p-stop dose W13} < \text{p-stop dose W14} < \text{p-stop dose W18}
    \]

Objective behind this production:
Optimise the interplay between the no-gain region width and the p-stop doping dose

<table>
<thead>
<tr>
<th>Type</th>
<th>Nominal width [µm]</th>
<th>Inter-pad design</th>
<th>Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>grid + extra grid</td>
<td>Aggressive</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>grid</td>
<td>Medium</td>
</tr>
<tr>
<td>3</td>
<td>21</td>
<td>grid</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>grid</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>grid</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>28</td>
<td>grid + extra grid</td>
<td>Safe</td>
</tr>
<tr>
<td>7</td>
<td>28</td>
<td>grid + extra grid</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>28</td>
<td>grid + extra grid</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>38</td>
<td>2 p-stop</td>
<td>Super safe</td>
</tr>
<tr>
<td>10</td>
<td>49</td>
<td>2 p-stop + bias grid</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>21</td>
<td>grid</td>
<td>Medium</td>
</tr>
</tbody>
</table>
**IV measurements**:

Breakdown voltage for sensors with varying nominal no-gain distance strategies:

- For supersafe sensors: breakdown voltage does not depend on p-stop dose and electrical configuration of the pads.

- The inter-pad configuration does not affect the break-down voltage at low p-stop doses.

- At increasing p-stop doses, the inter-pad terminal strategy affects the electrical behaviour of the sensor.

- Aggressive configuration: the p-stop dose plays a role in the breakdown voltage; even when the remaining pads are grounded.

- **Note**: the ETL plan is to use the conservative designs with larger interpad gaps, where the breakdown voltage is robust even with missing bump bonds.
V vs 1/C² plots for sensors from W13, W14 and W18:

- Measured at 1 kHz.

Uncertainties observed in the measured capacitance values for W13 and W14 sensors until the gain layer is depleted completely --- shift in the capacitance value changes the slope in extrapolation of gain-layer depletion voltage as well as full-depletion voltage of the bulk (by ±2V) ---- uncertainties in capacitance values measured for the sensors depends on the ‘type’ of the sensor.

No such anomaly is observed when the gain layer begins to deplete for sensors from W18.
Reason for anomaly observed in CV measurements for W13 and W14:

- UFSD3.1: bulk is intrinsic (almost); very slightly p doped
  In processing: due to thermal donors a small n⁺ doping layer is created. So the bulk for UFSD3 & UFSD3.1 sensors from W13 and W14 is n⁺.
  Therefore, depletion starts from the bottom. As a result of which CV is different.
- Sort of ‘space charge inversion’ -----> polarity of bias does not change
- Since depletion begins from bottom --------> no interpad isolation. So active area is dependent on the nominal interpad-gap value and majorly on the area outside the sensor ----> both affecting the capacitance measurements.

**Note:** thermal donors in the bulk is an anomaly of this production due to unusually high purity silicon and not the nominal design.

**Active cross-sectional area**

W18 (UFSD3.1)  
Depletion begins from top

W13 and W14 (UFSD3.1)  
Depletion begins from bottom

**Possible explanation for shift in CV while the gain layer is depleting**

Observed as a significant shift in doping profile and is strongly dependent on the nominal interpad value!
Type-6 (measured also for Type 9 & 10 - shown in back up slides)

- Offset observed in Measured no-gain distance and nominal interpad-gap value:
  ----> 10.65 ± 2.20 μm for W13 sensors
  ----> 6.27 ± 1.10 μm for W18 sensors
- Difference in measured no-gain distance between W13 and W18 : ~ 3-7 μm (with measured distance for W13 at a higher value)

Interpad profiles for : Nominal value - 28 μm

W13/W14 sensors (suspected n-bulk due to thermal donors) and W18 (p⁺ implant in p-bulk)
- Voltage scans show at RT (at same laser intensity) : behaviour is identical for sensors from W13 and W18. However, at 248K (-25°C) ----> the voltage scan plot for W13 gets steeper and Collected charge at 300V is ~2-3 higher for W13 sensors.
- With variation in temperature from 25°C to -25°C, The change in the measured no-gain distance decreases with an increase in the nominal interpad value.
- Change in the the measured no-gain distance with decreasing temperature is slightly higher for W13 sensors ----> even though the fill factor does not vary significantly with change in temperature for both W13 and W14 sensors.

**CMS Phase-2 Preliminary**

<table>
<thead>
<tr>
<th>Type</th>
<th>W13</th>
<th>W18</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nominal no-gain distance value</td>
<td>Measured no-gain distance @</td>
</tr>
<tr>
<td></td>
<td>25°C</td>
<td>0°C</td>
</tr>
<tr>
<td>Type 6 (285 V)</td>
<td>28</td>
<td>40.50 ± 0.21</td>
</tr>
<tr>
<td>Type 9 (300 V)</td>
<td>38</td>
<td>46.38 ± 0.25</td>
</tr>
<tr>
<td>Type 10 (295 V)</td>
<td>49</td>
<td>60.90 ± 0.09</td>
</tr>
</tbody>
</table>

*Note: Uncertainties are statistical only. The bias voltage is changed to keep the collected charge constant for measurements taken at different temperatures.*
Thank you!
Summary

- Decrease in the p-stop dose improves the breakdown behaviour of the sensors; independent of the interpad termination strategy ---> observed in IV measurements

- Uncertainties in capacitance values, until the depletion of the gain layer, is observed for sensors with thermal donors induced in the bulk. As a result of this space charge inversion of the bulk, the active cross-sectional area, majorly the area lying outside the sensors, affects the C-V measurements.

- Scanning TCT measurements performed with IR laser show no significant difference in the charge collection values when measured at RT.
  - At lower temperatures: the voltage scan curves gets steeper for sensors with thermal donors induced in the bulk ---> collected charge increases by a value of ~2-3 @ high voltages (close to BDV)
  - Decrease in the measured no-gain distance is slightly higher for sensors with thermal donors induced in the bulk (as well as measured value at a given temperature is higher in comparison to those without thermal donors in the bulk) ---> The % decrease does not affect the change in Fill factor significantly with variation in temperature.
Back-up Slides
Doping profile extraction from CV measurements: **on W18 - as expected**

- No significant shift in the depth of the gain-layer as well as of the thickness of the bulk for sensors without any thermal donors induced in the bulk.

\[
\eta(x) = \frac{C^3}{q\varepsilon_S A^2} \left( \frac{dC}{dV} \right)^{-1} = -\frac{2}{q\varepsilon_S A^2} \left( \frac{d\frac{1}{C^2}}{dV} \right)^{-1}
\]

**Note:**
In the doping profile extraction we consider the active cross-sectional area of each pad as a constant value \( \sim 1.3 \times 1.3 \text{ mm}^2 \)
**TCT scans**: comparison study of **Type 6, 9 and 10 sensors from W13 and W18 sensors**.

* Based on: Voltage scans + interpad profiles (with varying temperature @ 285V, 295V and 300V for Type-6, Type-10 and Type-9 sensors, respectively)

**Focus Scan- FBK UFSD3.1 W13 type-6 (Safe)**

**Measured with IR laser: low laser intensity (62.5 %, 1kHz) - equivalent to 5 MIPs**

- Size of gaussian spot - 10 μm
- Focused optical positioning - 950 μm
Interpad profiles for:

W13/W14 sensors (suspected n- bulk due to thermal donors) and W18 (p⁺ implant in p-bulk)

Voltage scan comparison at different temperatures for W13 and W18 sensors
Interpad profiles for:

W13/W14 sensors (suspected n- bulk due to thermal donors) and W18 (p⁺ implant in p-bulk)

Voltage scan comparison at different temperatures for W13 and W18 sensors
**Results on Electrical Characterisation**

**I-V measurements:**
- The sensors have a breakdown voltage above \( \sim 350 \text{ V} \).
- For SuperSafe sensors breakdown voltage does not depend on p-stop dose and electrical configuration of the pads.
- For Aggressive configuration: The p-stop dose plays a role in the breakdown voltage, even when the remaining pads are grounded.
- The inter-pad configuration does not affect the breakdown voltage at low p-stop doses. At increasing p-stop doses, the inter-pad design strategy affects the electrical behaviour of the sensor.

**C-V measurements:**
- Gain-layer and bulk depletion voltage from C-V:
  - For W13 and W14 sensors, the full depletion voltage of the bulk and gain-layer are 25 V and 23 V, respectively.
  - Table 2 shows the measured no-gain distance with temperature variation for W13 and W18 sensors. Note: Uncertainties are statistical only. The bias voltage is changed to keep the collected charge constant for measurements taken at different temperatures.

**Conclusion**
- Decrease in the p-stop dose improves the breakdown behaviour of the sensors, independent of the interpad termination strategy.
- Thermal donors induced in the p-type bulk creates uncertainties corresponding to the capacitance values measured till the depletion of the gain layer. Due to space charge inversion of the bulk, the active cross-sectional area, majority the area lying outside the sensors, affects their C-V measurements.
- Decrease in the measured no-gain distance value with decreasing temperature is slightly higher for sensors with thermal donors induced in the bulk. The decrease in no-gain distance value does not affect the fill factor significantly.

**Special Acknowledgments**

**Figure 1:** CMS-MTD Design showing the positioning of the ETL and BTL.

**Figure 2:** I-V characterisation of sensors from three different wafers with varying p-stop dose and different electrical configurations.

**Figure 3:** a) Measured no-gain distance is the width between the mid-point of the S-curves corresponding to the adjacent pads. b) FWHM vs optical distance of IR laser from sensor.

**Figure 4:** Doping profile (doping concentration vs. depth) extracted from C-V measurements for sensors from W18 with different inter-pad strategies.

**Figure 5:** Voltage scan on temperature variation for W13 and W18 sensors.