RADIATION EFFECTS IN THE CMS PHASE-1 PIXEL DETECTOR

Danyyl Brzhechko on behalf of the CMS collaboration

TREDI2020: 15th "Trento" Workshop on Advanced Silicon Radiation Detectors
INTRODUCTION
CMS Pixel detector consists of two main parts: Barrel Pixel and Forward Pixel.

An upgraded Pixel detector was installed in 2017 and operated (up to now) until the end of 2018:

- Barrel Pixel (BPix): four layers, 4 hit coverage and high-rate capability
- Forward Pixel (FPix): 2 rings x 3 disks, turbine-like structure for forward disks for optimal resolution
- CO₂ cooling
- Leakage current and depletion voltage studies are done for 2017-2018 years of operation for full CMS pixel detector.
Leakage current change for BPix is simulated using the following expression:

$$\Delta I_{\text{leak}}(t, T; \Phi_{eq}) = \alpha(t, T) \Phi_{eq}(r, z) V$$

- $V$ is the **volume** of the sensor module.
- $\Phi_{eq}$ is **1-MeV neutron equivalent fluence** of all the particles, calculated using FLUKA. $\Phi_{eq} \sim r^{-1.5}$ and almost flat vs $z$.
- $\alpha(t, T) = \alpha_0 + \alpha_i \exp \left( -\frac{t}{\tau_i(T)} \right) - \beta \ln(t \Theta(T))$ is a current related damage rate.

For FPix, we need to **integrate over** the module volume (modules cover wide radius range):

$$\Delta I_{\text{leak}}(t, T; \Phi_{eq}) = \alpha(t, T) \int \Phi_{eq}(r, z) dV = \alpha < \Phi_{eq} > V,$$

$k_{eq}$ is the average fluence over a module volume.

- **Leakage current** at the end is **scaled to** a reference temperature $T_{\text{ref}}$ using:

$$I_{\text{leak}}(T_{\text{ref}}) = I_{\text{leak}}(T) \cdot \left( \frac{T_{\text{ref}}}{T} \right)^2 \exp \left( -\frac{E_g^*}{2k_B} \left( \frac{1}{T_{\text{ref}}} - \frac{1}{T} \right) \right)$$

DEPLETION VOLTAGE

- Number of effective doping concentration:
  \[ N_{\text{eff}} = N_{c}^{dr} + N_{c}^{a} + N_{r}^{a,1} + N_{r}^{a,2} \]
  
  \[ N_{c}^{dr}(t; \Phi_{eq}) \] – initial donor removal

- \[ N_{c}^{a}(\Phi_{eq}) = g_{c}\Phi_{eq} \] – constant damage

- \[ N_{r}^{a,1}(t, T; \Phi_{eq}) \sim g_{A} \] – beneficial annealing

- \[ N_{r}^{a,2}(t, T; \Phi_{eq}) \sim g_{Y} \] – reverse annealing

- Two parameter sets are considered (oxygenated silicon): RD48-oxy and CB-oxy

- Fit of the depletion voltage data for FPix is performed to find optimal value of \( g_{C} \) constant (\( g_{A} \) and \( g_{Y} \) fixed)

- In addition, log-dependence of the constant damage rate was tested for FPix using \( N_{c}^{a}(\Phi_{eq}) = g_{c}^{\log} \ln(\Phi_{eq}) \) as an empiric model

- Depletion voltage data is determined from the cluster charge (for BPix also from cluster size) vs bias voltage data

- In order to fully deplete a sensor, the fluence of the innermost part (\( r \sim 4.5 \) for ring 1, \( r \sim 9.5 \) cm for ring 2) of the module is taken in the depletion voltage simulation

---

BARREL PIXEL RESULTS
LEAKAGE CURRENT RESULTS: BARREL PIXEL, LAYER 1

- Simulated leakage current per module scaled to measured temperature
- Satisfactory agreement for Layer 1
- **Temperature** is measured on top of CO$_2$ cooling pipe:
  - added +3°C during operation as a correction of module temperature

![Graph showing leakage current results for Layer 1 with simulation data and experimental data.](image)

**Barrel pixel detector**

Layer 4
Layer 3
Layer 2
Layer 1

<table>
<thead>
<tr>
<th>Layer</th>
<th>$r$ (cm)</th>
<th>Density $n$ (n$_{pp}$/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>2.9</td>
<td>$7 \times 10^{14}$</td>
</tr>
<tr>
<td>Layer 2</td>
<td>6.6</td>
<td>$1.8 \times 10^{14}$</td>
</tr>
<tr>
<td>Layer 3</td>
<td>10.9</td>
<td>$9 \times 10^{14}$</td>
</tr>
<tr>
<td>Layer 4</td>
<td>16.0</td>
<td>$0.5 \times 10^{14}$</td>
</tr>
</tbody>
</table>

**Simulation for $z = 0$ cm, scaled to silicon temperature**

- Leakage current simulation $\times 1.0$
- Temperature spread $\pm$ 2 K (from laboratory studies)
- Mean leakage current data
LEAKAGE CURRENT RESULTS: BARREL PIXEL, LAYERS 2,3,4

- Simulated leakage current per module scaled to measured temperature
- Underestimation by about a factor of 2 for Layer 2, 3 and 4. Scale factor is needed.
- **Temperature** is measured on top of CO₂ cooling pipe:
  - added +3°C (+4°C for layer 4) during operation as a correction of module temperature
  - Discrepancy in Layer 2, 3 and 4 might be caused by temperature mismodeling
DEPLETION VOLTAGE RESULTS: BARREL PIXEL

- Use $N_{\text{eff}}$ as calculated from the Hamburg model. CB-oxy parameter set is considered for the simulation.

- Full depletion Voltage:
  
  $$V_{\text{depl}} = |N_{\text{eff}}| \frac{qd^2}{2\varepsilon_0}$$

- Data obtained from HV scan during operation:
  
  - Avg. cluster charge and size are determined as a function of bias voltage
  
  - The full depletion voltage is estimated from the kink in the respective distributions

- Layer 1 to be replaced during LS2. Layer 2 depletion voltage to be expected at 650V at the end of Run 3
FORWARD PIXEL RESULTS
LEAKAGE CURRENT RESULTS: FORWARD PIXEL, RING 1

- Leakage current per volume scaled to 0°C
- Good agreement between data and simulation for Ring 1:
  - No scale factor required
  - Temperature reading on module, T-sensor on top of the HDI
- FLUKA prediction reliable in full z range
- Discrepancy at the start of run periods in 2017 and 2018 probably due to temperature underestimation

\[ \Phi_{eq/Disk} \]
\[
\text{Final fluence (} L_{\text{int}} = 120 \text{ fb}^{-1}) \]

<table>
<thead>
<tr>
<th>Disk</th>
<th>Disk 1</th>
<th>Disk 2</th>
<th>Disk 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_{eq}$</td>
<td>$1.71 \cdot 10^{14} \text{ } n_{eq}/\text{cm}^3$</td>
<td>$1.62 \cdot 10^{14} \text{ } n_{eq}/\text{cm}^3$</td>
<td>$1.56 \cdot 10^{14} \text{ } n_{eq}/\text{cm}^3$</td>
</tr>
</tbody>
</table>

\[ z = 32 \text{ cm} \]

\[ z = 40 \text{ cm} \]

\[ z = 50 \text{ cm} \]
LEAKAGE CURRENT RESULTS: FORWARD PIXEL, RING 2

- Leakage current per volume scaled to 0°C
- Good agreement between data and simulation for Ring 2:
  - No scale factor required
  - Temperature reading on module, T-sensor on top of the HDI
- FLUKA prediction reliable in full z range
- Discrepancy at the start of run periods in 2017 and 2018 probably due to temperature underestimation

<table>
<thead>
<tr>
<th>Φ_{eq}</th>
<th>Disk 1</th>
<th>Disk 2</th>
<th>Disk 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final fluence (L_{int}=120 fb^{-1})</td>
<td>0.81 \cdot 10^{14} n_{eq}/cm^{3}</td>
<td>0.78 \cdot 10^{14} n_{eq}/cm^{3}</td>
<td>0.76 \cdot 10^{14} n_{eq}/cm^{3}</td>
</tr>
</tbody>
</table>
Depletion voltage results for Ring 1, Disk 1.

- Fit $g_C$ parameter, assuming linear model, with $g_A = 1.4 \times 10^{-2}$ cm$^{-1}$, and $g_Y = 7 \times 10^{-2}$ cm$^{-1}$ fixed.
- Data is obtained from the average cluster charge distribution vs. bias voltage – kink of the distribution.
- Fit is done only for 2018 data points.
- Logarithmic model for $N_C$ tested – try to find an effective empiric model.
- Final fluence assumed for the innermost slice of Ring 1, Disk 1: $3.32 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$.

**Final fluence of the innermost slice of the module for Run 2 ($10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$), $L_{\text{int}}=120 \text{ fb}^{-1}$**

<table>
<thead>
<tr>
<th>Ring/Disk</th>
<th>Disk 1</th>
<th>Disk 2</th>
<th>Disk 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1</td>
<td>3.32</td>
<td>2.99</td>
<td>2.92</td>
</tr>
<tr>
<td>Ring 2</td>
<td>1.15</td>
<td>1.11</td>
<td>1.09</td>
</tr>
</tbody>
</table>
**DEPLETION VOLTAGE: RING 1, DISK 3**

- Depletion voltage results for Ring 1, Disk 3.
- Fit $g_C$ parameter, assuming linear model, with $g_A = 1.4 \times 10^{-2}$ cm$^{-1}$, and $g_Y = 7 \times 10^{-2}$ cm$^{-1}$ fixed.
- Data is obtained from the average cluster charge distribution vs. bias voltage – kink of the distribution.
- Fit is done only for 2018 data points.
- Logarithmic model for $N_C$ tested – try to find an effective empiric model.
- Final fluence assumed for the innermost slice of Ring 1, Disk 3: $2.92 \cdot 10^{14}$ $n_{eq}/cm^2$.

<table>
<thead>
<tr>
<th>Ring/Disk</th>
<th>Disk 1</th>
<th>Disk 2</th>
<th>Disk 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1</td>
<td>3.32</td>
<td>2.99</td>
<td>2.92</td>
</tr>
<tr>
<td>Ring 2</td>
<td>1.15</td>
<td>1.11</td>
<td>1.09</td>
</tr>
</tbody>
</table>

**Final fluence of the innermost slice of the module for Run 2 ($10^{14} n_{eq}/cm^2$), $L_{int}=120$ fb$^{-1}$**
CONCLUSIONS
Leakage current studies:
• Good agreement for Layer 1, scale factor of ~2 is needed for Layer 2-4
• Good agreement for FPix (no need for scale factors, better knowledge of the temperature)

Depletion voltage studies:
• BPix: underestimation for Layers 2-4, underestimation in 2017 and overestimation at the end of 2018 for Layer 1
• FPix: fit results for \( g_C \) parameter is close to “oxy” models.
• Logarithmic dependence of \( N_C \) on fluence was tested. Better agreement in 2017 and at the end 2018 data.
BACK UP
Leakage current depends on the accumulated fluence, $\alpha(t, T)$ function responsible for the annealing and volume of the sensor.

1. **Handles the annealing process**
2. **Volume of the sensor (cm$^3$)**
3. **Accumulated 1MeV-neutron equivalent fluence (cm$^{-2}$)**

$I_{\text{leak}}(t, T) = \alpha(t, T) \cdot \Phi_{eq} \cdot V$

Leakage current

Dividing whole run period by $N$ chunks, we define leakage current density $G_i = G_i^{\text{exp}} + G_i^{\text{log}}$ for step $i$, using accumulated fluence and temperature information from previous steps $k (= 1 \text{ to } i)$ of duration $t_k$ (might be different for different steps).

1. These parts corresponds to annealing
2. Accumulated fluence per time $t_j$, $\Phi_{eq,j} = \Phi_{eq} \cdot t_j$
3. Leakage current for each step is calculated by multiplying the current density by volume of the sensor. The last equation is used to scale the simulated (measured) leakage current from the temperature $T_{\text{ref}}$ it is simulated (performing the measurement) at to the specified temperature $T$. $E_g^* = 1.21 \text{ eV}$, $k_B$ is the Boltzmann constant.

$G_i^\text{exp} = \xi_i \sum_{j=1}^{i} \Phi_{eq,j} \cdot e^{-\sum_{k=j}^{i} t_k \theta(T_k)}$

$G_i^\text{log} = \sum_{j=1}^{i} \Phi_{eq,j} \cdot (\alpha - \xi \cdot \ln \left( \sum_{k=j}^{i} t_k \theta(T_k) \right))$

$I_{\text{leak}} = (G_i^{\text{exp}} + G_i^{\text{log}}) \cdot V$

$I_{\text{leak}}(T) = I_{\text{leak}}(T_{\text{ref}}) \cdot \left( \frac{T}{T_{\text{ref}}} \right)^{2} \exp \left( -\frac{E_g^*}{2k_B} \left( 1 - \frac{1}{T} \right) \right)$

DEPLETION VOLTAGE: SIM AND DATA

- \( N_{eff}(t, T; \phi_{eq}) = N^d(t; \phi_{eq}) + N^a(t; \phi_{eq}) + N^{a,1}(t, T; \phi_{eq}) + N^{a,2}(t, T; \phi_{eq}) \) - number of effective doping concentration

- \( V_{depl} = \frac{e \cdot d^2}{2 \epsilon_r \epsilon_0} \left| N_{eff}(t, T; \phi_{eq}(r_0 - \Delta r/2)) \right| \) - depletion voltage as a function of effective doping concentration. \( \phi_{eq}(r_0 - \Delta r/2) \) is a fluence/time (flux) for the nearest slice of a FPix module.

- Reverse annealing: \( N^{a,2}(t, T; \phi_{eq}) = g_Y \frac{\phi_{eq}}{k_Y} (k_Y t + e^{-k_Y t} - 1) + N_0^{nd} (1 - e^{-k_Y t}) \)

- Initial donor removal: \( N^d(t; \phi_{eq}) = N_{eff}^{0,1} + N_{c,0} \cdot (1 - e^{-c\phi_{eq}(t)t}) \)

- Constant damage: \( N^a(t; \phi_{eq}) = g_C \phi_{eq}(t)t \)

- Beneficial annealing: \( N^{a,1}(t, T; \phi_{eq}) = \frac{g_A \phi_{eq}}{k_A} (1 - e^{-k_A t}) + N_0^{a,1} \cdot e^{-k_A t} \)
<table>
<thead>
<tr>
<th>Function, relation or constant</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time/temperature scaling function</td>
<td>$\Theta(T; T_{\text{ref}}) = \exp \left( -\frac{E_i^+}{k_B} \left( \frac{1}{T} - \frac{1}{T_{\text{ref}}} \right) \right)$</td>
</tr>
<tr>
<td>Arrhenius law</td>
<td>$\frac{1}{\tau_i} = k_{0i} \cdot \exp \left( -\frac{E_i}{k_B T} \right)$</td>
</tr>
<tr>
<td>$\alpha_i$</td>
<td>$(1.23 \pm 0.06) \cdot 10^{-17} [A \text{ cm}^{-1}]$</td>
</tr>
<tr>
<td>$k_{0i}$</td>
<td>$(1.23^{+5.3}_{-1.0}) \cdot 10^{13} [s^{-1}]$</td>
</tr>
<tr>
<td>$E_i$</td>
<td>$1.11 \pm 0.05 [eV]$</td>
</tr>
<tr>
<td>$\alpha^*_0$</td>
<td>$7.07 \cdot 10^{-17} [A \text{ cm}^{-1}]$</td>
</tr>
<tr>
<td>$\xi$</td>
<td>$3.07 \cdot 10^{-18} [A \text{ cm}^{-1}]$</td>
</tr>
<tr>
<td>$E^*_i$</td>
<td>$1.30 \pm 0.14 [eV]$</td>
</tr>
<tr>
<td>$E^*_g$</td>
<td>$1.21 [eV]$</td>
</tr>
<tr>
<td>$k_B$</td>
<td>$8.6173303 \cdot 10^{-5} [eV \text{ K}^{-1}]$</td>
</tr>
</tbody>
</table>
## PARAMETER SETS

<table>
<thead>
<tr>
<th>Parameter set name</th>
<th>Constants ($10^{-2} \text{ cm}^{-1}$)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Neutrons</td>
<td>Protons</td>
</tr>
<tr>
<td></td>
<td>$g_A$</td>
<td>$g_Y$</td>
</tr>
<tr>
<td>CB-oxy</td>
<td>1.4</td>
<td>5.7</td>
</tr>
</tbody>
</table>