MOS and Diode irradiation studies for Phase 2 CMS Tracker Upgrade

Outline:

- Phase II, Tracker, Samples
- Irradiation Facility
- Irradiation Protocol
- MOS CV measurements
- Diode CV, IV measurements
- Annealing Problems
- Summary

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Expected Total Dose for various CMS Phase II Tracker Sets

<table>
<thead>
<tr>
<th>Set</th>
<th>Dose (kGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low outer</td>
<td>38</td>
</tr>
<tr>
<td>Nom. outer</td>
<td>77.5</td>
</tr>
<tr>
<td>Max outer</td>
<td>155</td>
</tr>
<tr>
<td>Low inner</td>
<td>300</td>
</tr>
<tr>
<td>Nom. inner</td>
<td>900</td>
</tr>
<tr>
<td>Max inner</td>
<td>1500</td>
</tr>
</tbody>
</table>

2 types of Outer Tracker:
- **2S (Strip-Strip sensor modules)**
- **PS (macro-Pixel Strip sensor modules)**

2 types of Inner Tracker modules:
- **2x2 Pixel Chip modules**
- **2x1 Pixel Chip modules**
Outer Tracker 8’’ wafer

Used for Irradiation Studies

Package Label Name
1 Main Sensor
2 D 1PS 2GR etc (Upper)
3 Sensor PS light etc
4 VDP Flute etc (Upper Left)
5 Sensor No Pstop
6 Sensor Baby
7 VDP Flute etc (Upper Right)
8 VDP Flute etc (Lower Left)
9 Sensor Center Bias Contact
10 Sensor KIT test
11 Sensor Seg Area
12 VDP Flute etc (Lower Right)
13 D 1PS 2GR etc (Lower)
14 Sensor Irradiation
15 MOS & Diode
16 SIMS etc (Left)
17 Sensor PStop Geo
18 HMSet (Left)
19 HMSet (Right)
20 Sensor PCommon
21 SIMS etc (Right)
Irradiation was performed at the secondary standard ionizing radiation laboratory of the Greek Atomic Energy Commission (GAEC), accredited according to ISO 17025 among others in calibration in the field of radiotherapy, and the relevant CMCs (calibration and measurement capabilities) are published in the BIPM database (https://www.bipm.org/en/about-us/).

\[ {\text{60}}^{\text{Co}} \text{ source: Picker therapy unit 30 TBq (March 2012) horizontal orientation (~11 TBq October 2019)} \]
Calculated dose rate (in air) at irradiation point (40 cm from the source): 0.96kGy/h using FC65-P Ionization Chambers from IBA Dosimetry.

Peltier element/thermoelectric cooler with glue protection to withstand radiation, fan, microcontroller for stabilization of temperature, power Supplies.

Charged particle equilibrium (CPE) → box of 2 mm-thick Pb and 0.8 mm of inner lining Al sheet → lead-aluminum container for absorption of low energy photons and secondary electrons (ESCC Basic Specification No. 22900)
60Co energy spectrum

Energy spectrum taken from our source Inside CPE box

X-ray Fluorescence at 75 keV to 80 keV
Back Scatter Peak at 209.8 keV
Back Scatter Peak at 214.4 keV

Compton Edge at 903.4 keV
Compton Edge at 1118.1 keV

Co60 at 1173.24 keV
Co60 at 1332.5 keV

Max: 39.137.00 cp
For γ-rays of energy 200 keV to 2 MeV, converting from Gray in Air to Gray in Silicon is easy: we multiply by 1.0.

https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients
Irradiation Protocol

- Irradiation procedure was split in slots of 6 hours of irradiation
- During irradiation temperature kept at $(20.0 \pm 0.2) \, ^\circ C$
- After every 6 hours of irradiation:
  - Annealing in the climate test chamber at $60 \, ^\circ C$ for 10 min (corresponding to 4 days of annealing at room temperature)
  - Electrical tests after annealing performed using our experimental setup
  - Electrical measurements:
    1) Oscillation level = 250 mV
    2) Various frequencies: 100 Hz, 1 kHz, 10 kHz, 100 kHz, 1 MHz
- Between irradiation slots: samples stored in freezer at -28 °C
MOS Structures: CV Measurement

Float zone oxygenated silicon n-in-p MOS test structures: Thinned 240 μm produced by Hamamatsu

- Clear evidence of positive charge induced in the oxide of the MOS structures after exposure to gamma photons
- Initial shift of the flatband voltage ($V_{fb}$) i.e. the voltage where the MOS behavior changes from accumulation to depletion, to higher absolute values
- The above trend is reversed after an irradiation dose of ~ 50kGy
- Similar behavior observed by other teams that irradiated with X-rays
- Effect not very well understood, A possible explanation could be that the positive charge in the oxide created by irradiation is strong enough to start attracting negative charges from the surrounding material
MOS features from CV (I)

MOS accumulation capacitance within 4%

MOS inversion capacitance within 10%

Oxide thickness not affected because it is a geometric characteristic of the device

Reverse of flatband voltage increase
MOS features from CV (II)

**MOS Flatband Capacitance**

- Flatband increases after irradiation but remains almost stable afterwards.

**MOS N\text{eff}**

- Reverse of N\text{eff} initial increase after ~50kGy.
CV taken from measurements (left) and TCAD simulation (right) for Non-irradiated MOS structures
Diode CV Curves (I)

Diode Capacitance vs Voltage ($f = 100$ kHz)

Diode Capacitance ($C$) vs Bias Voltage before and after irradiation

Diode $1/C^2$ vs Bias Voltage before and after irradiation
Depletion voltage remains almost unchanged after irradiation as a result of the oxygenated structures.
I(20°C) = I(T) \cdot (293/T)^2 \cdot \exp[-E_g/(2k_B)(1/293 - 1/T)], E_g = 1.21\text{eV}, T \text{ in K}, \text{ RD50 TN 2011-01}
Annealing Problems

- Since we aren’t the only users of the source we had to stop the irradiation for a few hours.

- The time between two consecutive irradiations was ~11h - ~15 hours and the samples were stored at -28 °C.

- After measuring again the IV annealing was observed.

- Annealing process was also observed after storage in liquid N₂.
- Irradiation using $^{60}$Co source of 11TBq
- Total dose ~86kGy
- Irradiation of the MOS structure shows significant change in the Flatband Voltage, Threshold Voltage and depletion region slope (related to the charge concentration)
- Diode CV measurements showed stable depletion voltage with dose as expected by oxygenated structures
- Diode IV measurements showed no breakdown behavior.
- Annealing problems observed when using freezer at -28 deg to store sample between irradiations
- Annealing seems not to stop even at -196 deg
Backup
- **thFZ240**
  - Start with *Float zone oxygenated* p-type Si material
  - Thinning at HPK after most of front side processing
  - Backside implant can only be 1 µm thick
  - 15% higher cost with respect to FZ290 sensor
FZ290 sensor

- FZ290: “HPK standard” sensor
  - Same production technology as currently used sensors (but now in n-on-p)
  - Fixed physical (active) thickness at 320 (290) µm
  - Robust against mechanical damage due to 30 µm deep backside implant
  - Backside implant acts as excellent field stop improving IV characteristics
Radiation Damage

- Bulk damage
  - Primary lattice defects (I and V) form higher order defects (V₂, VO₁,...) or even defect clusters, with energy levels in the band gap of Si
  - Depending on energy level and cross section they contribute to
    - leakage current, effective doping concentration, trapping

- Surface damage
  - Ionizing radiation generates e/h pairs also in SiO₂
  - e much higher mobility than h → positive charge up of oxide
  - Additional, interface traps with dynamic characteristics
  - Theses lead to
    - increased surface currents, altered electric field in surface region, accumulation of electrons at surface