MOS irradiation studies for Phase II CMS Tracker Upgrade and TCAD model

Outline:

- Phase II, Tracker, Samples
- Irradiation Facility
- Irradiation Protocol
- MOS CV measurements
- TCAD MOS simulation
- TCAD $^{60}$Co Irradiation Model
- Conclusions

Working Team

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Phase II – CMS Tracker Layout

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>

1Gy = 100rad

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

2 types of Inner Tracker modules
- 2×2 Pixel Chip modules
- 2×1 Pixel Chip modules

42M strips on 192m²
170M macro-pixels on 25m²
Outer Tracker 6’’ wafer

Used for Irradiation Studies

n→p structure
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/).

60Co 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. (https://www.iba-dosimetry.com/product/fc65-g-fc65-p-ionization-chambers/)
- 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)
For $\gamma$-rays of energy 200 keV to 2 MeV, dose rate in Air is equivalent to dose rate in Si and also SiO$_2$.
Irradiation Protocol

- Irradiation procedure was split into slots of 6 hours of irradiation.
- During irradiation, the temperature was kept at $(20.0 \pm 0.2)$ °C.
- After every 6 hours of irradiation:
  - Annealing in the climate test chamber at 60 °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.
Clear evidence of positive charge induced in the SiO$_2$ of the MOS structures after exposure to gamma photons: e/h produced by irradiation but since electrons have higher mobility they shift towards surface.

Shift of the flatband voltage ($V_{fb}$) i.e. the voltage where the MOS behavior changes from accumulation to depletion, to higher negative values since $V_{fb} = \varphi_A - \varphi_{Si}$ and more and more electrons accumulated in Al.
MOS features from CV (I)

MOS accumulation capacitance within 4%
Geometrical Layout of the MOS device in TCAD

Main contribution from Panagiotis Assiouras
MOS CV is described well by the “New Perugia model[1]”

The model describes both “Surface Damage” i.e. bulk SiO$_2$ traps and interface traps produced mainly from X-rays and γ-rays and “Bulk Damage” i.e. traps in the silicon bulk produced mainly by charged and neutral particles.

Works well for X-rays up to 10Mrads and neutron equivalent fluxes up to $10^{15}$ n$_{eq}$/cm$^2$

Modified TCAD Model

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy (eV)</th>
<th>Band width (eV)</th>
<th>$\sigma_e$ (cm$^2$)</th>
<th>$\sigma_h$ (cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Donor</td>
<td>$E_V &lt; E_T &lt; E_V + 0.54$</td>
<td>0.54</td>
<td>$1.0 \times 10^{-15}$</td>
<td>$1.0 \times 10^{-16}$</td>
</tr>
<tr>
<td>Acceptor</td>
<td>$E_C - 0.58 &lt; E_T &lt; E_c$</td>
<td>0.58</td>
<td>$1.0 \times 10^{-16}$</td>
<td>$1.0 \times 10^{-15}$</td>
</tr>
</tbody>
</table>

$$\Delta Q_{ox}(x) = 1.08 \cdot 10^{12} + 3.41 \cdot 10^{11} \ln(x) \text{ [cm}^{-2}\text{]}$$
$$\Delta N_{IT_{acc}}(x) = 2.30 \cdot 10^{12} + 2.65 \cdot 10^{11} \ln(x) \text{ [cm}^{-2}\text{]}$$
$$\Delta N_{IT_{don}}(x) = 4.26 \cdot 10^{11} + 1.98 \cdot 10^{11} \ln(x) \text{ [cm}^{-2}\text{]}$$

$x$ is the dose in Mrad
The proposed modifications work reasonably well for $^{60}$Co γ-ray doses up to $74\text{kGy} = 7.4\text{Mrad}$.
On the process for publication in JINST_022P_0321

Study of p-type silicon MOS capacitors at HL-LHC radiation levels through cobalt-60 gamma source and TCAD simulation


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Abstract

During the era of the High Luminosity LHC (HL-LHC) the devices in its experiments will be subjected to increased radiation levels with high fluxes of neutrons and charged hadrons, especially in the inner detectors. A systematic program of radiation tests with neutrons and charged hadrons is being carried out by the CMS and ATLAS Collaborations in view of the upgrade of the experiments, in order to cope with the higher luminosity at HL-LHC and the associated increase in the pile-up events and radiation fluxes. In this work, results from a complementary radiation study with $^{60}$Co-$\gamma$ photons are presented. The doses are equivalent to those that the outer layers of the silicon tracker systems of the two big LHC experiments will be subjected to. The devices in this study are float-zone oxygenated p-type MOS capacitors. The results of CV measurements on these devices are presented as a function of the total absorbed radiation dose following a specific annealing protocol. The measurements are compared with the results of a TCAD simulation.
Conclusions

- In this work silicon MOS capacitors were irradiated with $^{60}$Co- photons from a 11 TBq source. The total absorbed dose was 74 kGy = 7.4Mrad.
- The level of the radiation-induced charge in the test structures was determined from the shift of the flat band voltage in the MOS capacitors after irradiation and a saturation effect was observed.
- Apart from the flat band voltage, the irradiation of the MOS capacitors showed significant change in the threshold voltage and depletion region slope, which is related to the interface charge concentration.
- The measurements were compared with the results of a TCAD simulation based on a modified version of the "New Perugia model", which takes into account several radiation damage effects.
- The modified model describes reasonably well our experimental measurements from the $^{60}$Co γ-rays and could be seen as a complementary model to the “New Perugia model” that describes well the X-ray irradiation and the irradiation with charge and neutral particles.
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: “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, VO, ...) 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 has 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

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M. Moll, VERTEX13

HEP 2021, Thessaloniki, 18 June 2021

Aristotelis Kyriakis, NCSR "Demokritos"

J. Zhang, PhD. DESY, 2013