Study of p-type silicon MOS capacitors at HL-LHC radiation levels through irradiation with a cobalt-60 gamma source and a 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 MOS capacitors fabricated on the float-zone oxygenated p-type silicon wafer. 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.

KEYWORDS: Detector modelling and simulations II (electric fields, charge transport, multiplication and induction, pulse formation, electron emission, etc); Particle tracking detectors (Solid-state detectors); Radiation-hard detectors; Solid state detectors

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1 Introduction

The High Luminosity Large Hadron Collider (HL-LHC) at CERN is expected to collide protons at a centre-of-mass energy of 14 TeV. It will reach the unprecedented peak instantaneous luminosity of $5\times10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with an average number of pileup events of 140–200. This will allow the LHC experiments to collect integrated luminosities up to 3000–4000 fb$^{-1}$ during the project lifetime [1] in order to search for new physics and study rare interactions. The increased statistics and extended physics reach however, come along with higher particle fluxes and total radiation doses which require more radiation-tolerant detectors and front-end electronics technologies. For this reason, new silicon tracking detectors with improved radiation hardness are needed for the HL-LHC experiments.

In the High Luminosity era the total absorbed doses in the outer layers of the tracking systems of the major LHC experiments are estimated to be in the order of 10–100 kGy, depending on the distance from the beam line. A systematic campaign of irradiation tests with neutrons and charged hadrons (which cause long-term displacement effects in silicon) initiated by the LHC collaborations is ongoing in order to estimate how will the tracking systems cope with the demands for higher luminosity and radiation fluxes. Complementary radiation studies with X-ray photons of various energies and $^{60}\text{Co-}\gamma$ photons (which are responsible for the transient surface damage localized at Si/SiO$_2$ interfaces) are performed with doses equivalent to those that the outer layers of the silicon tracker systems of the two large LHC experiments will be subjected to, along with the related TCAD simulations. One such study with $^{60}\text{Co-}\gamma$ photons is presented here.

\footnote{The units of Gy and rad are used in the paper. They are interchangeable as 1 Gy = 100 rad.}
2 Samples and laboratory equipment

The samples used for irradiation in this study are float-zone oxygenated silicon n-in-p test structures from thinned 240 μm (initially 300 μm thick) wafers produced by Hamamatsu Photonics K.K. (HPK) [2]. Each test structure contains one square MOS (area = 4 mm × 4 mm).

Cobalt-60 has two characteristic gamma-ray decay modes with energies 1.1732 MeV and 1.3325 MeV, respectively. These energies are much harder than those used in common X-ray irradiation tests. The 60Co source used in the current study is a Picker teletherapy unit ([3], discussion 501-2) with a radioactivity of 30 TBq as of March 2012, estimated at approximately 11 TBq by the time the measurements were performed, with a horizontal orientation (figure 1, left). It was calculated by using FC65-P Ionization Chambers from IBA Dosimetry [4] that the dose rate at irradiation point (40 cm from the source) is 0.96 kGy/h. The irradiation was performed in the secondary standard ionizing radiation laboratory of the Greek Atomic Energy Commission (GAEC), accredited according to ISO 17025 in the field of radiotherapy, and the relevant CMCs (calibration and measurement capabilities) are published in the BIPM database [5].

![Figure 1](image-url). Left: the Cobalt-60 source: Picker therapy unit. Right: the container with the samples in front of the source. The fan and the thermoelectric cooler are visible.

The cooling system consisted of a thermoelectric cooler (Peltier element, type TEC1 12704) operating at temperature lower than room temperature (8°C ± 1°C), an aluminum plate and a fan for heat dissipation (figure 1, right). The selected Peltier is sealed with 704 silicon rubbers and proved to be robust against γ-irradiation from the Cobalt-60 source. A microcontroller for the stabilization of temperature and the respective power supplies were used in addition (figure 2, left). Charged particle equilibrium (CPE) was achieved due to a box of 2 mm thick Pb and 0.8 mm of inner lining Al sheet, i.e. a lead-aluminum container for the absorption of low energy photons and secondary electrons [6] where the samples were kept during irradiation (figure 2, right). The energy spectrum inside the CPE container, 4 m away from the source, was measured (figure 3) with a Micro-sized CZT Gamma Spectrometer with a volume of 0.5 cm³, a spectral response in the range 30 keV–3 MeV and an energy resolution < 2.5% at 662 keV (137Cs) [7]. As for the calculation of absorbed doses in silicon and SiO₂, it should be noted that this is quite straightforward since for γ-rays of energies ranging from 200 keV to 2 MeV (where the bulk spectrum of the used 60Co source lies within) conversion from gray [Gy] in Air to gray [Gy] in Silicon is simply done using a unity multiplication factor [8, 9].
Figure 2. Left: the microcontroller and power supplies of the irradiation setup. Right: the lead-aluminum container for charged particle equilibrium (CPE).

Figure 3. Energy spectrum taken 4 m away from the cobalt-60 source and after 5.2 cm of Pb (a 5 cm thick Pb block was placed between the source and the CPE box and the Pb thickness of the CPE box was 0.2 cm), as measured inside the charged particle equilibrium (CPE) box. The left peak is a backscatter peak at approximately 200 keV which emerges when γ-rays enter the material around the detector and are scattered back into the detector. The right peaks are the peaks corresponding to the 1.1732 MeV and 1.3325 MeV characteristic gamma-ray decay modes of cobalt-60.

Electrical measurements were performed in the range 15°C–20°C (and below) using an automatic probe station (Carl Suss PA 150) and supplementary equipment (HP4192A, Keithley 6517A) for electrical characterization of microelectronic devices and the samples were annealed in a Weiss WKS 3-180/40/5 climate test chamber. Data analysis was subsequently performed using the ROOT analysis software [10].

3 Experimental procedure and protocol

The CPE container with the samples was held 40 cm away from the source while being irradiated. The irradiation was split in slots of approximately 14–16 hours of irradiation. After each slot, thermal annealing of the samples was performed in the climate test chamber at 60°C for 10 min
(corresponding to four days of annealing at room temperature, as extracted from eq. 5.4 and table 5.2 in [11] where the overall annealing of the current related damage rate $a(t)$ is described as a function of the annealing time for different annealing temperatures) in order to reduce the trapping centers. The electrical tests at the probe station after the annealing were performed at 15–23°C using LabVIEW as data taking and control software. Humidity in the lab was controlled with a desiccator and during all measurements RH was below 30%. The oscillation amplitude for the CV measurements was set at 250 mV. CV measurements were carried out for various frequencies (100 Hz, 1 kHz, 10 kHz, 100 kHz, 1 MHz for MOS capacitors).

Since in a MOS capacitor the charge in the inversion region is due to the minority carriers which have a definite generation and recombination rate, if the measurement frequency is higher than that rate, then the inversion charge cannot follow the change. On the other hand, the low-frequency measurements proved to be extremely noisy with the instruments available in our lab. Thus, the 10 kHz frequency was selected as the optimal one, and this decision was later corroborated by the comparison with simulation results.

4 Experimental results of MOS capacitors (CV analysis)

Figure 4 shows a typical capacitance-voltage curve of a MOS capacitor for various doses. After the exposure to gamma photons there is a clear evidence of positive charge induced in the oxide of the p-type MOS capacitors. Various interesting parameters can be extracted from this figure, such as the oxide capacitance ($C_{oxide}$) and the oxide thickness ($t_{oxide}$), but also the effective oxide charge density ($N_{oxide}$) and the flatband voltage ($V_{FB}$) which are shown in figure 5. The flatband voltage is calculated by using the maximum of the first derivative of the MOS CV curve, which yields the flatband voltage as the inflection point of the curve. To improve the performance of this method, a cubic spline interpolation is performed on the data before calculating the first derivative. The oxide capacitance is considered to be the capacitance measured in accumulation, which is the intersection point of a linear fit with slope fixed to zero to the data points in the accumulation region with the capacitance axis. The oxide thickness is calculated from the oxide capacitance ($C_{oxide}$) using the following relation:

$$t_{oxide} = \frac{\varepsilon_{oxide} A_{gate}}{C_{oxide}}$$  \hspace{1cm} (4.1)

where $\varepsilon_{oxide} = 0.3453 \text{ pF/cm}$ is the permittivity of the oxide material and $A_{gate} = 0.16 \text{ cm}^2$ is the gate area of the MOS device. The oxide thickness is calculated to be 0.67 μm in our device. Finally, the effective oxide charge density is calculated as follows:

$$N_{oxide} = \frac{C_{oxide}}{q A_{gate}} (\phi_{ms} - V_{FB})$$  \hspace{1cm} (4.2)

where $\phi_{ms}$ is the work function difference between the aluminum gate layer and p-type silicon. From figure 5 it is observed that there is a saturation of the value of the flatband voltage at around −52 V. This leads to stabilization of $N_{oxide}$ after the initial increase even at high doses.
Figure 4. Capacitance-voltage curves for a MOS capacitor for various doses; measurement frequency at 10 kHz.

Figure 5. Parameters of a MOS capacitor before and after irradiation; measurement frequency at 10 kHz. Left: effective oxide charge density. Right: flatband voltage.

5 TCAD simulation of MOS capacitors

Technology computer aided design (TCAD) [12] is used in order to provide a better insight of the complex phenomena related to semiconductor devices. It follows a numerical modeling approach and it can be used in order to simulate the fabrication process of new devices, operation and reliability under real conditions or even endurance of the devices in harsh environments. As the next generation of silicon sensors for the HL-LHC era will have to withstand unprecedentedly high fluences, TCAD simulations and experimental studies have been performed in order to provide a better understanding of the mechanisms of radiation damage in silicon devices [11, 13–16].

5.1 Description of the radiation model

Particles passing through the silicon bulk produce radiation effects in the medium, some of which are reversible and other irreversible. In principle, the radiation damage in silicon sensors is caused by two different factors: the ionizing energy loss and the non-ionizing energy loss. Although the ionizing energy loss is important for the signal formation and is usually reversible, it can cause irreversible effects on the oxide by introducing positive oxide charge in the SiO$_2$, by increasing the
number of bulk oxide traps and by increasing the number of interface traps. These effects are usually referred to *surface damage*, and they influence the operation of segmented silicon sensors with respect to the inter-electrode isolation, the breakdown voltage and the charge collection efficiency. The non-ionizing energy loss is responsible for the introduction of defects into the silicon lattice through the displacement of crystal atoms, usually produced due to the impact of high-momentum particles. These impacts lead to point and cluster defect generation and hence to the introduction of deep-level trap states which act like generation-recombination centers [11]. Non-ionizing effects are referred to as *bulk damage* and on a macroscopic scale they are responsible for the increase of the leakage current in silicon sensors, the changes in the effective space charge concentration and the charge collection efficiency.

In [14] and [15] a three level model is presented for simulating the bulk damage effects for n-type and p-type substrates, which is usually referred to as the *Perugia model*. In order to incorporate also the surface damage effects an extension of the model has been made referred to as the *Perugia surface model 2019* presented in [17, 18]. The surface damage effects can be mainly described by three parameters: the oxide charge ($Q_{ox}$) and the two interface trap states ($N_{IT}$) for donors and acceptors. The values of the above quantities can be extracted from high-frequency and quasi-static CV measurements by following the procedure described in ([20], pp. 319–356). The model is able to reproduce the radiation damage macroscopic effects up to the order of $10^{15}$ $n_{eq}$/cm$^2$ 1 MeV neutron equivalent fluences and X-ray photon doses of up to 10 Mrad.

The three variables, oxide charge density $Q_{ox}$ [cm$^{-2}$], acceptor integrated interface trap state density $N_{IT_{acc}}$ [cm$^{-2}$] and donor integrated interface trap state density $N_{IT_{don}}$ [cm$^{-2}$] are used as input parameters for the simulation where the macroscopic factors, such as the capacitance or the leakage current, are calculated. They are related to the surface damage effects, vary with the dose/fluence and can be represented by the following equations, according to [19]:

$$Q_{ox}(x) = Q_{ox}(0) + \Delta Q_{ox}(x) \quad (5.1)$$

$$N_{IT_{acc}}(x) = N_{IT_{acc}}(0) + \Delta N_{IT_{acc}}(x) \quad (5.2)$$

$$N_{IT_{don}}(x) = N_{IT_{don}}(0) + \Delta N_{IT_{don}}(x) \quad (5.3)$$

where $Q_{ox}(0)$, $N_{IT_{acc}}(0)$ and $N_{IT_{don}}(0)$ are the values before irradiation and $\Delta Q_{ox}(x)$, $\Delta N_{IT_{acc}}(x)$ and $\Delta N_{IT_{don}}(x)$ are the values after irradiation, where $x$ is the dose in Mrad. $Q_{ox}$ is extracted directly from the CV measurements. $N_{IT_{acc}}$ and $N_{IT_{don}}$ have to be fine-tuned in order to obtain the simulated CV curves that best match the experimental data. This is due to the fact that limitations of our instrumentation does not permit us to perform quasi-static measurements.

The radiation model that is used in this work is a modified version of the surface damage model presented in [18]. It also relies on two uniform defect energy band distributions: one which accounts for the acceptor-like interface trap states near the conduction band and another one which accounts for the donor-like interface defects near the valence band. Table 1 summarizes the energy band range ($E_T$) for the acceptor and donor states, the band width and the trap capture cross sections of electrons $\sigma_e$ and holes $\sigma_h$ that are used in our modified model, in accordance to [18]. The trap capture cross sections of electrons and holes are the magnitudes which mainly account for the uncertainties in the model. Due to the fact that the MOS capacitance characteristics are strongly
affected by the complex phenomena taking place in the SiO$_2$ region and the Si-SiO$_2$ interface, only the surface damage effects are taken into consideration.

Table 1. The energy band range ($E_T$) for the acceptor and donor states, the band width and the trap capture cross section of electron $\sigma_e$ and holes $\sigma_h$ that are used in our modified Perugia surface model 2019, in accordance to [19]. $E_V$ and $E_C$ refer to the valence and conduction energy levels respectively.

| Type   | Energy (eV) | Band width (eV) | $\sigma_e$ (cm$^2$) | $\sigma_h$ (cm$^2$) |
|--------|-------------|-----------------|---------------------|---------------------|
| Donor  | $E_V < E_T < E_V + 0.54$ | 0.54            | $1.0 \times 10^{-15}$ | $1.0 \times 10^{-16}$ |
| Acceptor | $E_C - 0.58 < E_T < E_C$ | 0.58            | $1.0 \times 10^{-16}$ | $1.0 \times 10^{-15}$ |

5.2 Description of the TCAD simulations

Figures 6, top, and 6, bottom, show a section of the 2D structure that is used in this work for the simulation of the MOS capacitors. The silicon substrate is indicated in light red, the oxide is indicated in dark red, and the aluminum metal is indicated in gray. The geometrical characteristics that were used for the simulation are summarized in the appendix A.

![Image](image1.png)

**Figure 6.** The structure that is used for the 2D simulation of the MOS capacitors: a segment of the structure depicting the depth of the whole structure (top) and a close-up view of the simulated structure near a metal edge (bottom). The color variation depicts the doping concentration. The aluminum contacts are displayed in gray, the SiO$_2$ is displayed in dark red and the p-type implant is displayed in red.
In order to calculate the capacitances, a small signal AC analysis is performed at 10 kHz. This frequency corresponds to the frequency at which the experimental measurements have been performed. Some of the physical models that are used in this work are the Auger recombination, Shockley-Read-Hall recombination, avalanche electron-hole generation, doping dependence mobility and high field saturation [21]. The temperature in the simulations was set at 293 K which corresponds to the experimental temperature during measurements. The physical models used for the simulations are shown in appendix B. Figure 7 shows the simulated CV results for the non-irradiated MOS capacitor in comparison with the experimental data, and the matching is extremely good.

The effective oxide charge density is shown in figure 5 and it has been calculated using equation (4.2). These values have been set as inputs for the $Q_{ox}$ parameter of the TCAD model. The non-irradiated term $Q_{ox}(0)$ is set equal to $2.4 \cdot 10^{10}$ cm$^{-2}$ and the irradiated one $\Delta Q_{ox}(x)$ is set according to equation (5.4) ($x$ is the total dose in Mrad). The parameters $N_{IT_{acc}}(0)$ and $N_{IT_{don}}(0)$ are set equal to $2.0 \cdot 10^9$ cm$^{-2}$ according to [18].

Although experimental measurements haven’t been performed for extracting the values of $N_{IT_{acc}}$ and $N_{IT_{don}}$ in this work, their values have been fine-tuned in our simulation, since their optimization plays a crucial role in the correct determination of the slope of the CV curves. Figure 8, top, shows the TCAD simulated CV plots at an indicative total dose of 4.42 Mrad by keeping $N_{IT_{acc}}$ stable at $2.5 \cdot 10^{12}$ cm$^{-2}$ and by changing the $N_{IT_{don}}$ from $1.0 \cdot 10^9$ cm$^{-2}$ to $7.5 \cdot 10^{12}$ cm$^{-2}$, compared with the experimental results at the same dose level. In a similar manner, figure 8, bottom, shows the TCAD simulated CV plots at the same dose by keeping $N_{IT_{don}}$ stable at $1.0 \cdot 10^{11}$ cm$^{-2}$ and by changing $N_{IT_{acc}}$ from $1.0 \cdot 10^9$ cm$^{-2}$ to $7.5 \cdot 10^{12}$ cm$^{-2}$. Figure 9 shows the experimental values of $\Delta Q_{ox}(x)$ (top), along with the optimized values of $\Delta N_{IT_{acc}}(x)$ (middle) and $\Delta N_{IT_{don}}(x)$ (bottom) that when used as inputs to TCAD for the calculation of the capacitance, return values that better match the capacitance values from our experimental data. The fitted parameters are shown in

![Figure 7. TCAD Simulated CV plot for a non-irradiated MOS capacitor compared to the related one from experimental measurements.](image-url)
equations (5.4), (5.5) and (5.6) for $\Delta Q_{ox}(x)$, $\Delta N_{IT_{acc}}(x)$ and $\Delta N_{IT_{don}}(x)$ ($x$ is the dose in Mrad), respectively, where the fit in each equation was performed independently of the fits in the others:

$$\Delta Q_{ox}(x) = 1.08 \cdot 10^{12} + 3.41 \cdot 10^{11} \ln(x) \quad \text{[cm}^{-2}\text{]} \quad (5.4)$$

$$\Delta N_{IT_{acc}}(x) = 2.30 \cdot 10^{12} + 2.65 \cdot 10^{11} \ln(x) \quad \text{[cm}^{-2}\text{]} \quad (5.5)$$

$$\Delta N_{IT_{don}}(x) = 4.26 \cdot 10^{11} + 1.98 \cdot 10^{11} \ln(x) \quad \text{[cm}^{-2}\text{]} \quad (5.6)$$

Since the traps tend to saturate as the dose increases, the increase in the above magnitudes is a logarithmic one. Thus, a logarithmic function of the form $p_0 + p_1 \ln(x)$ was fitted to the values of all the above magnitudes.

![CV MOS: Dose=4.42 Mrad](image)

**Figure 8.** Simulated CV plots at Dose = 4.42 Mrad by keeping $N_{IT_{acc}}$ stable and changing the $N_{IT_{don}}$ (top) and by keeping $N_{IT_{don}}$ stable and changing $N_{IT_{acc}}$ (bottom), respectively, compared to the experimental results at the same dose level.
**Figure 9.** The experimental $\Delta Q_{ox}(x)$ (top), and TCAD model parameters $\Delta N_{IT\,acc}(x)$ (middle) and $\Delta N_{IT\,don}(x)$ (bottom) values which when used for the calculation of the capacitance return values that better match the capacitance values from our experimental data. All of them are expressed in the form of $p_0 + p_1 \ln(x)$, where $p_0$ and $p_1$ are in cm$^{-2}$ and $x$ is the dose in Mrad. In each case, $p_0$ would correspond to the value of the respective magnitude at a dose of 1 Mrad, while $p_1$ would be a multiplication factor to the logarithm of any dose.

Figure 10 shows the experimental (solid line) and simulated (dashed line) MOS CV characteristics for various doses. The $\Delta N_{IT\,acc}(x)$ and $\Delta N_{IT\,don}(x)$ values for a total dose of 4.42 Mrad were evaluated from our model given by equations (5.4), (5.5) and (5.6). As can be seen, the TCAD simulation based on our modified Perugia surface model 2019 describes well the results of our $^{60}$Co irradiation measurements. The slight discrepancy in the inversion region is due to the difficulty to evaluate precisely the transient interface trap density.
Figure 10. Experimental and TCAD simulated CV curves for a MOS capacitor for various doses; measurement frequency = 10 kHz. The model describes well the experimental data.

6 Conclusions

In this work silicon MOS capacitors produced by HPK were irradiated with $^{60}\text{Co}$-γ photons from a $\sim 11$ TBq source. The total absorbed dose was $\sim 7.4$ Mrad. The level of the radiation-induced charge in the test structures was determined from the shift of the flatband voltage in the MOS capacitors after irradiation and a saturation effect was observed. The measurements were compared with the results of a TCAD simulation based on a modified version of the Perugia surface model 2019, which takes into account ionizing radiation damage effects which result in the increase of both trapped oxide charge and interface traps. The model describes very well our experimental measurements in terms of flatband voltage and capacitance values, especially in the accumulation and depletion regions.
A  Geometrical properties used for the TCAD simulation

The following geometrical properties were used for the simulation of the 2D MOS structure with the TCAD Synopsys:

Table 2. Geometrical properties and doping concentration used for the TCAD simulation of the MOS capacitors.

| Property             | Value                        |
|----------------------|------------------------------|
| Detector thickness   | 250 μm                       |
| Backplane thickness  | 10 μm                        |
| $N_{\text{bulk}}$    | $5.3 \times 10^{12}$ cm$^{-3}$ |
| Oxide thickness      | 0.65 μm                      |

B  Physical models used for the TCAD simulation

The following physical models were used for the simulations in Synopsys TCAD:

```plaintext
Physics{
  AreaFactor = @Width@
  Temperature = @Temp@
  Mobility(DopingDep HighFieldSat Enormal)
  Recombination( SRH (TempDependence DopingDependence)
    Avalanche (UniBo)
    Auger)

  EffectiveIntrinsicDensity ( OldSlotboom )
  #if "@Fluence@" != "0"
    Traps {
      (Donor Conc = @ConcDon1@ Level EnergyMid = 0.23 fromCondBand
        eXsection = 2.3e−14 hXsection = 2.3e−15 Add2TotalDoping)
      (Acceptor Conc = @ConcAcc1@ Level EnergyMid = 0.42 fromCondBand
        eXsection = 1.0e−14 hXsection = 1.0e−14 Add2TotalDoping)
      (Acceptor Conc = @ConcAcc2@ Level EnergyMid = 0.46 fromCondBand
        eXsection = 7.00e−14 hXsection = 7.00e−13 Add2TotalDoping)
    }
  #endif

  Physics(MaterialInterface= "Silicon/Oxide"){
    Recombination(surfaceSRH)
    Traps{
      (FixedCharge Conc=@Qox@)
      (Acceptor Conc=@Dit_acc@ Uniform EnergyMid=0.83 EnergySig=0.58
        fromValBand eXsection=1e−16 hXsection=1e−15 Add2TotalDoping)
      (Donor Conc=@Dit_don@ Uniform EnergyMid=0.27 EnergySig=0.54
        fromValBand eXsection=1e−15 hXsection=1e−16 Add2TotalDoping)
    }
}
```
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Note added. Patrick Asenov and Panagiotis Assiouras would like to declare that they have contributed equally to this work.

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