Study of p-type silicon MOS, GCD and FET structures irradiated with a ^{60}Co gamma source at HL-LHC radiation levels and TCAD simulations.

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1 Introduction

During the era of HL-LHC the expected luminosity will be up to 3000-4000 fb^{-1} [1]. In the upgraded Outer Tracker of the CMS experiment (radius from the beam axis 200 to 1200 mm) the expected radiation dose will be from 10 to 750 kGy, depending on the distance from the beam (e.g. nominal integrated dose for the CMS Outer Tracker: 77.5 kGy). The upgraded Tracker will be comprised of modules, of two closely spaced radiation-hard sensors that are read out by a common ASIC, capable of discriminating high p_T from low p_T tracks ($p_T >$ 2 GeV), locally in module level. CMS Tracker collaboration follows a dedicated quality assurance plan in order to ensure that the characteristics of each sensor meet the requirements. In this work, we present irradiation studies on test structures with gamma photons from a ^{60}Co source, complementary to already performed x-ray and particle irradiation studies. These test structures containing among others gate-controlled diodes (GCD), field effect transistors (FET) and MOS capacitors, that are fabricated in the same wafer as the main sensor.

2 Laboratory equipment and measurement procedure

2.1 Test structures

- The test structures are fabricated on oxygenated float-zone 6″ silicon wafer: thinned at 290 µm and produced by Hamamatcu Photonics K.K [2].
- Each test structure set contains among others, one square MOS (area = 1.29 mm^2), one gated controlled diode (GCD) (diode area = 0.631 mm^2, MOS area = 0.723 mm^2) and a FET structure (channel width 75 µm)

2.2 Irradiation procedure and protocol

- Irradiation performed with a picker therapy ^{60}Co unit [3] used as a source (figure 1):
  - Radioactivity: 9.86 TBq
  - Dose rate: 0.84 kGy/h at 40 cm from the source
- A charged equilibrium box was used for absorbing low energy electrons and photons, made of 2 mm thick Pb with a 0.8 mm layer of Al in the interior.
- During irradiation, the samples were cooled down to (at 8±0.5 °C) by using a Peltier element (figure 2) with microcontroller for the stabilization of the temperature and power (figure 3).
- Irradiation procedure was split in slots of 10-12 hours of irradiation.
- After every slot of irradiation: Annealing in the climatic test chamber at 80 °C for 10 min
- Between irradiation slots: samples stored in freezer at -28 °C

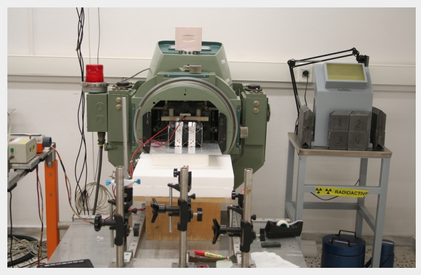

Figure 1: The Picker therapy ^{60}Co source unit thta was used for irradiation

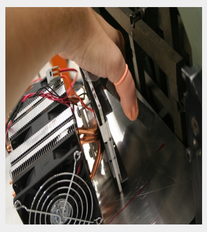

Figure 2: The fan and the thermoelectric/Peltier element

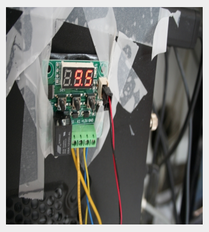

Figure 3: The microcontroller and power supplies of the experimental setup

2.3 Measurement procedure

- Automatic probe station (Carl Suss PA 150) for electrical characterization of microelectronic devices (figure 4).
- The measurements were performed by using dedicated flute pads that allow automated measurements to be performed by using a probe card and a switching matrix.
- Enviromental conditions are constantly monitored:
  - Relative humidity < 30%
  - Temperature fixed at 20 °C
- Measurement configuration:
  - MOS capacitor: oscillation level = 250 mV, frequency = 10 kHz, waiting time = 0.5s
  - GCD: diode bias varying from -5 to -11 V, waiting time = 0.5s
  - FET: V_{DS} 100 mV, waiting time = 0.5s

Figure 4: The probe station and supplementary equipment for electrical measurements.

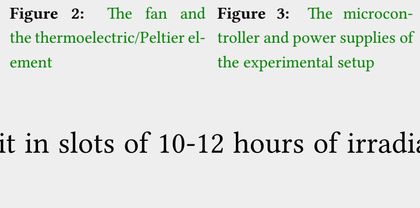

Figure 5: The probe card that is used for the automated measurments (left), the "flute" pads that are connected to various test structures

3 Results

3.1 MOS capacitors

- The flatband voltage ($V_{fb} \propto N_{ox}$) shifts to higher absolute values with due to the increase of the effective oxide concentration (figure 6).
- Clear evidence of positive charge induced in the oxide of the MOS capacitor after exposure to gamma photons
- Various features of the MOS structure before and after irradiation summarized in figures 7 and 8.

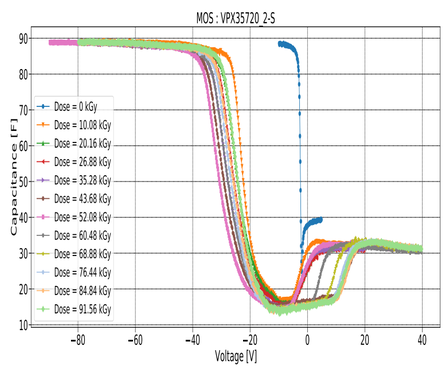

Figure 6: MOS capacitance vs gate voltage before irradiation for various total irradiation doses.

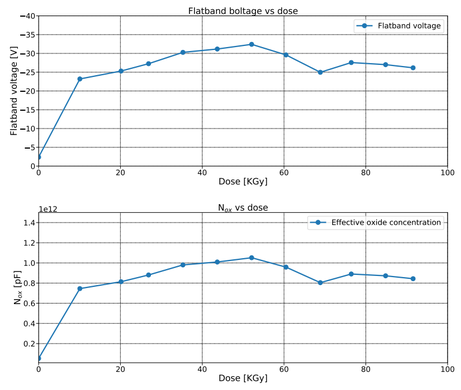

Figure 7: Flatband voltage (top) and N_{ox} (bottom) versus total irradiation dose

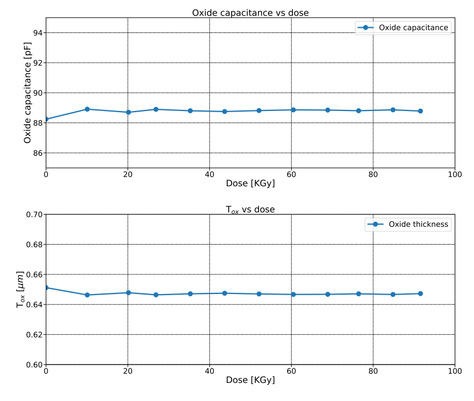

Figure 8: Oxide capaitance (top) and oxide thickness (bottom) versus total irradiation dose

3.2 Gated controlled diodes

- Increase of diode total current with irradiation dose (figure 9) due to surface damage
- Surface generation velocity (S_0) and surface current ($I_s = I_{depl} - I_{inv}$) increase with total irradiation dose (figure 10), $I_{surf} \propto S_0$
- Evidence of increase of the interface trap density $D_{it} \propto S_0$

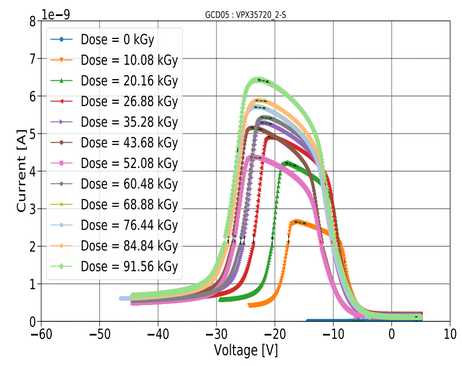

Figure 9: GCD diode current vs. gatevoltage before irradiation for variousto-tal irradiation doses.

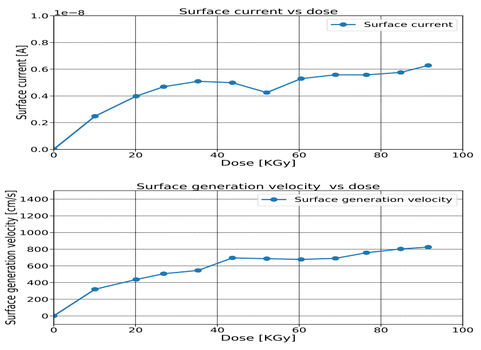

Figure 10: Surface current (top) and surface generation velocity (bottom) vs total irradiation dose.

3.3 Metal–Oxide–Semiconductor Field-Effect Transistor

- Shift of the slope of the MOSFET IV curve (figure 11) and also decrease of the total transconductance of the MOSFET (figure 12).
- Threshold voltage remains almost stable while the total dose increase (FET Vth give qualitative determination of the strip isolation properties [4, 5]). Evidence of the good quality of the p-stop and good isolation of the channels even after several doses of radiation (top figure 13).
- Mobility degradation in the device channel caused by charges trapped at, or very close to, the Si/oxide interface(bottom figure 13). Consistent with reference [6].
- Maximum transconductance (g_m) of the MOSFET transistor decreased by radiation-induced reduction in carrier mobility (µ) (middle figure 13).

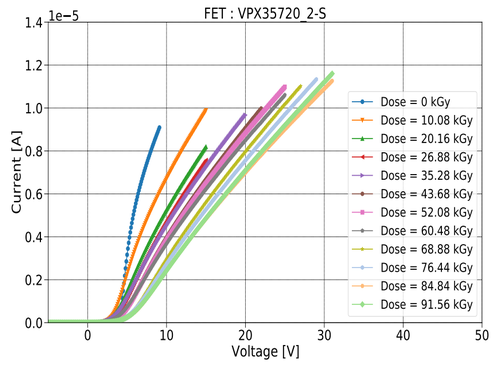

Figure 11: FET drain current vs. gate voltage before irradiation for varioustotal irradiation doses.

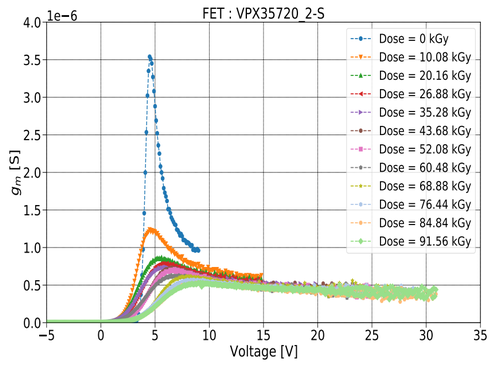

Figure 12: Transconductance vs gate voltage before irradiation for varioustotal irradiation doses.

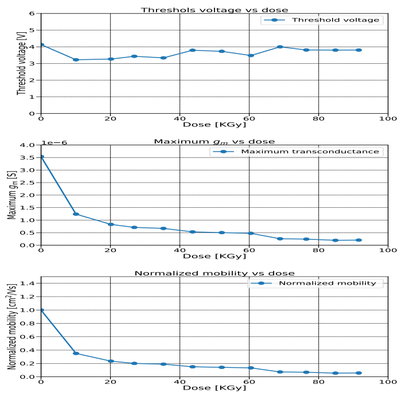

Figure 13: Threshold voltage (top), maximum g_m middle and normalized mobility (bottom) vs total irradiation dose.

3.4 TCAD simulations

- The TCAD suite that was used in this project is TCAD sentuarus [7].
- A 3D design is used for the FET (figure 14) and a 2D for the GCD (figure 16) with 11 gates intertwined with 12 diodes.
- Simulation of TCAD FET drain current (figure 17) and GCD diode total current (figure 15) and comparison with the experimental data are very promising"

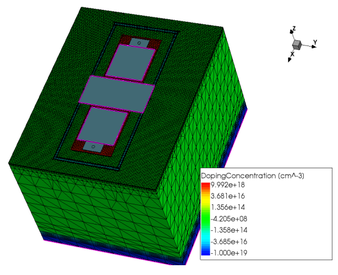

Figure 14: 3D TCAD simulation of FET structures

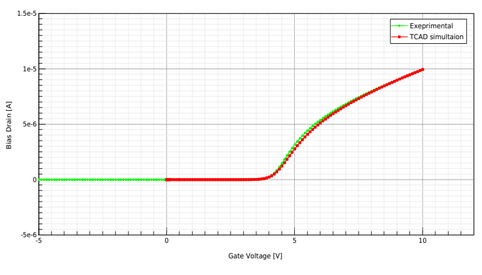

Figure 15: Comparison of TCAD and experimental results for the unirradiated case

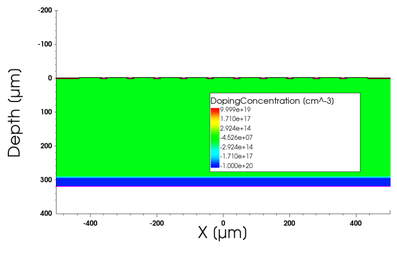

Figure 16: 2D TCAD simulation of GCD structures

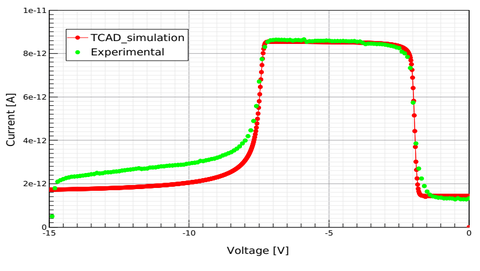

Figure 17: Comparison of TCAD and experimental results for the unirradiated case

4 Conclusion

- Silicon MOS capacitor, GCD and FET structures irradiated by Co-60 gamma photons; doses up to 91.56 kGy
- MOS capacitor: initial shift of V_{fb} to higher absolute values due to increase of N_{ox}
- GCD: Increase of surface generation current due to radiation-induced defects in the interface
- FET: Threshold voltage stable showing a good isolation between the channels. Degradation of mobility and transconductance due to radiation-induced defects.

References

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