Cobalt-60 gamma irradiation of p-type silicon test structures for the HL-LHC

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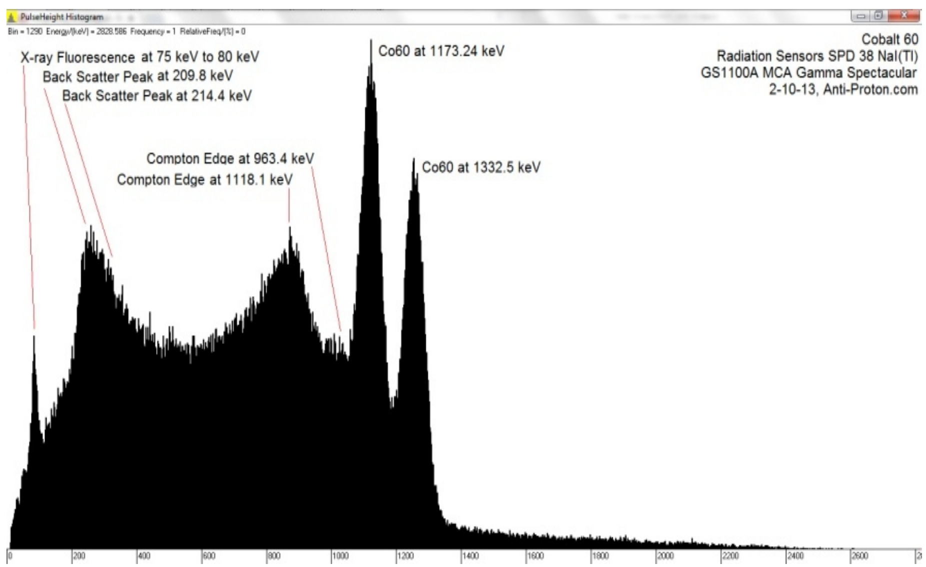
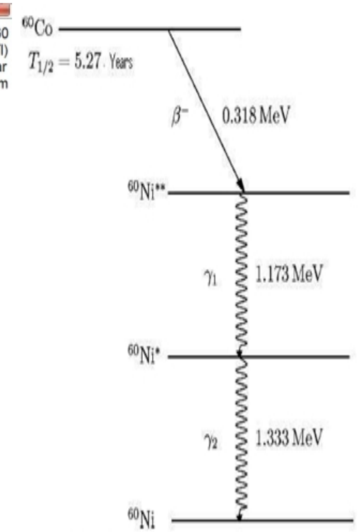
Irradiation Facility (I)

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/).

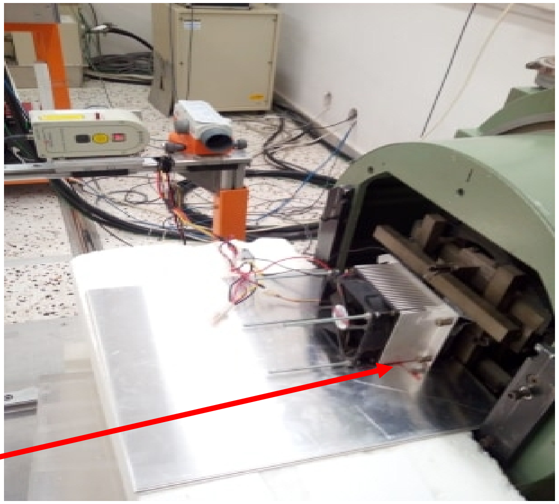
^{60}Co source: Picker therapy unit 30 TBq (March 2012) horizontal orientation (~11 TBq October 2019)

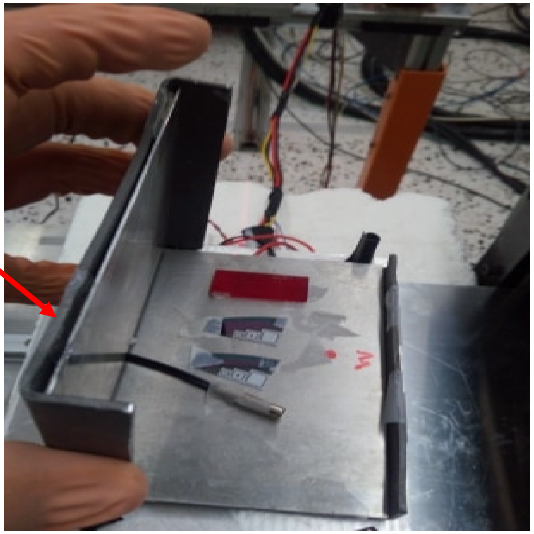




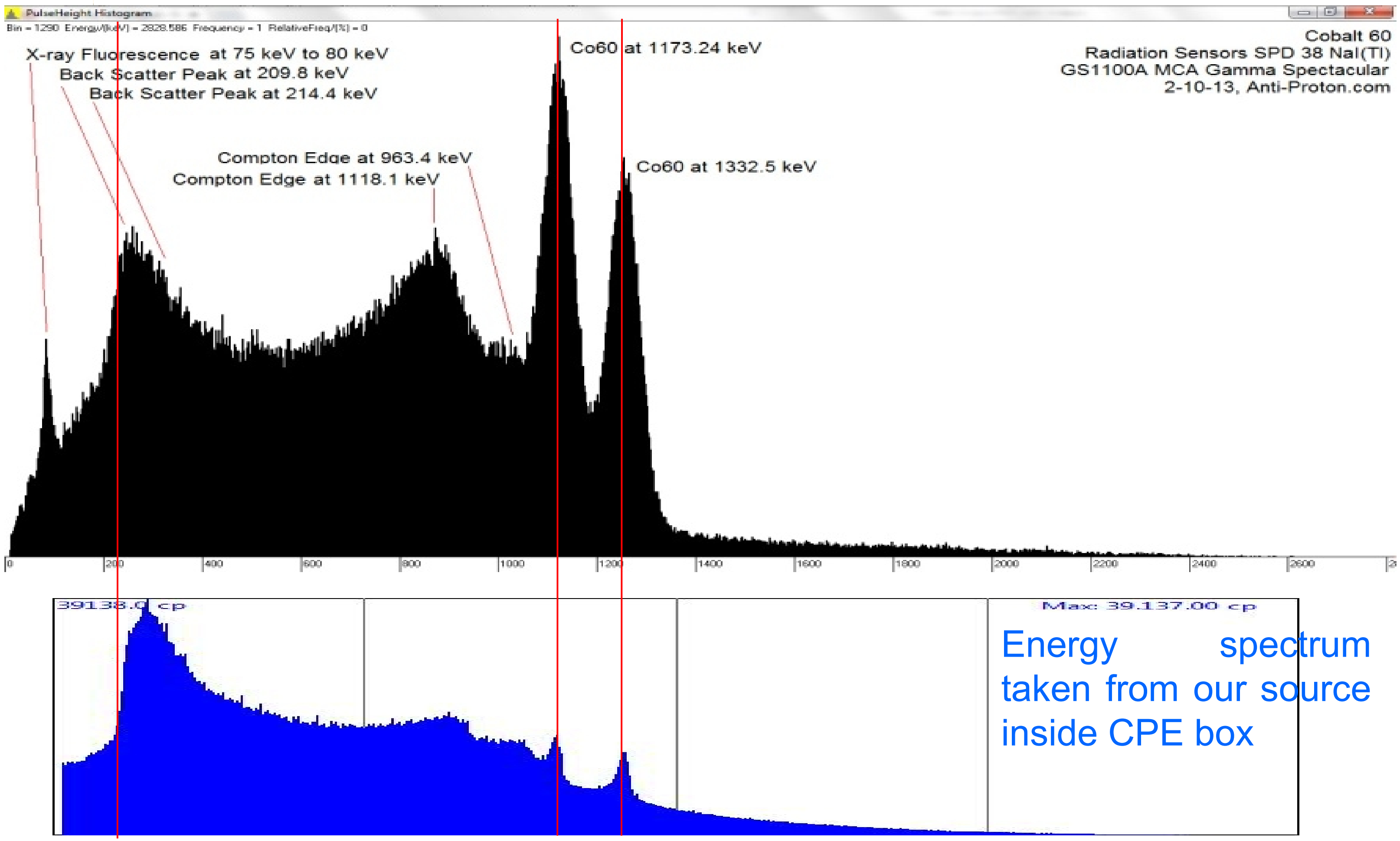
Irradiation Facility (II)

- Calculated dose rate (in air) at irradiation point (40 cm from the source): 0.96 kGy/h using FC65-P Ionization Chambers from IBA Dosymetry.
- 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)

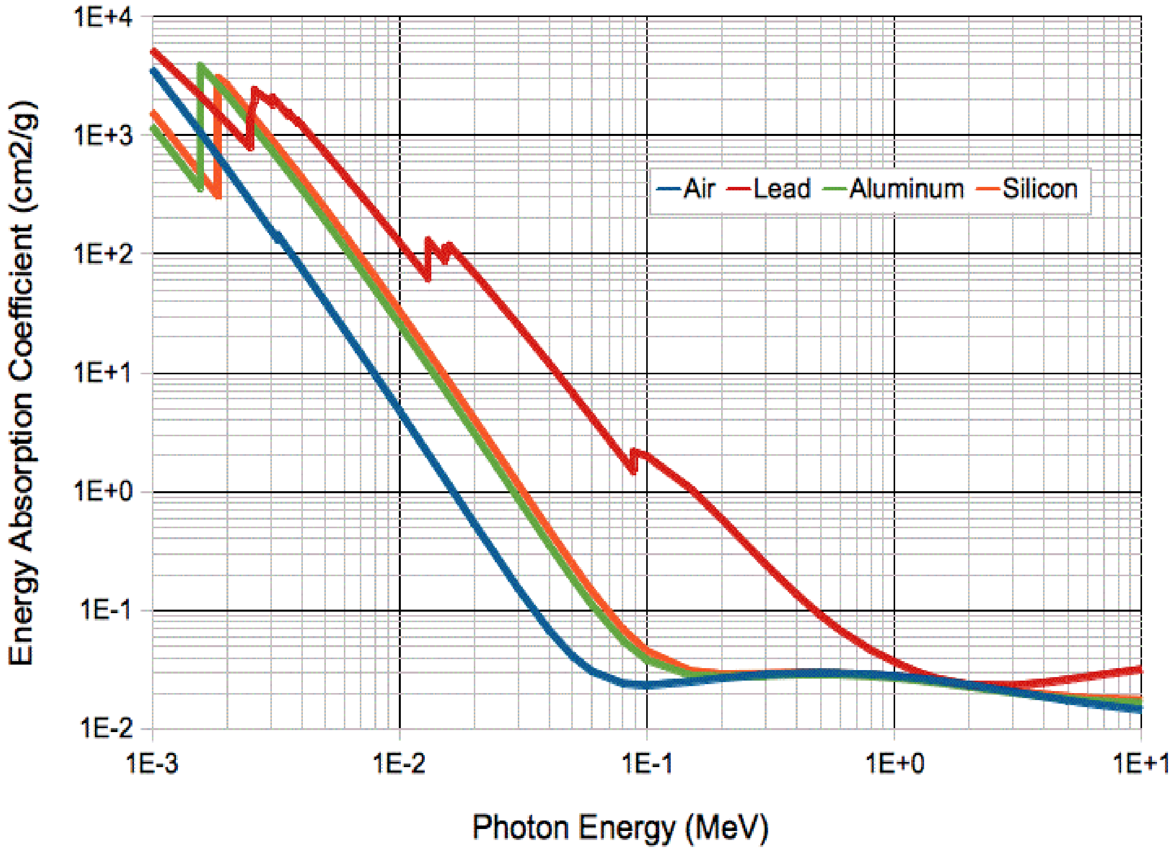




^{60}Co Energy Spectrum



μ/ρ [cm²/g] vs. Energy



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

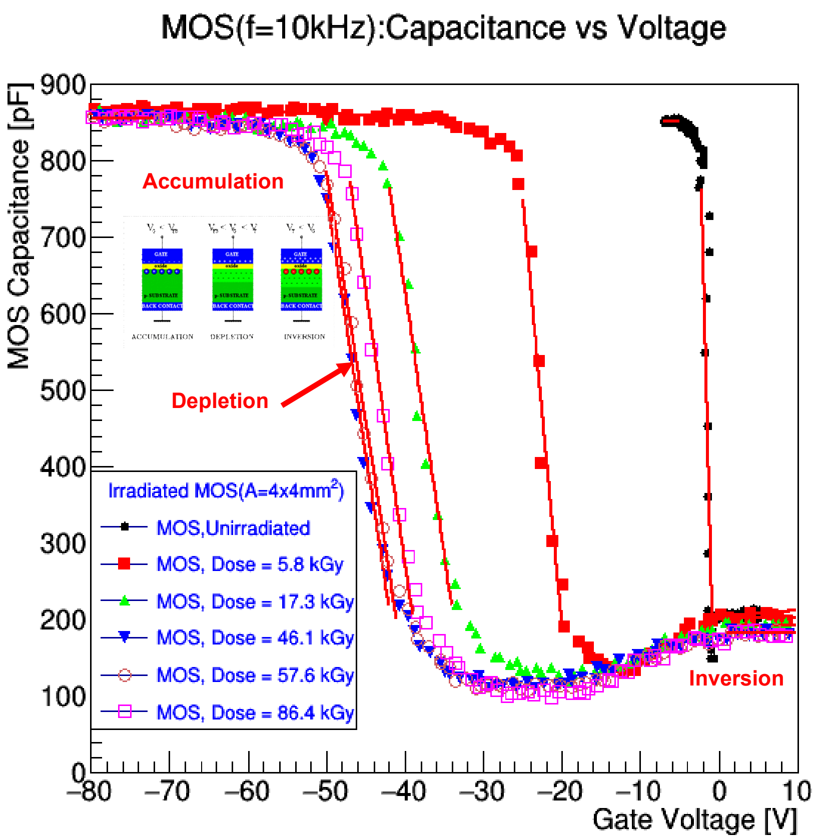
- During irradiation temperature kept at (20.0 ± 0.2) °C

- 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

MOS Structures: CV Measurement

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

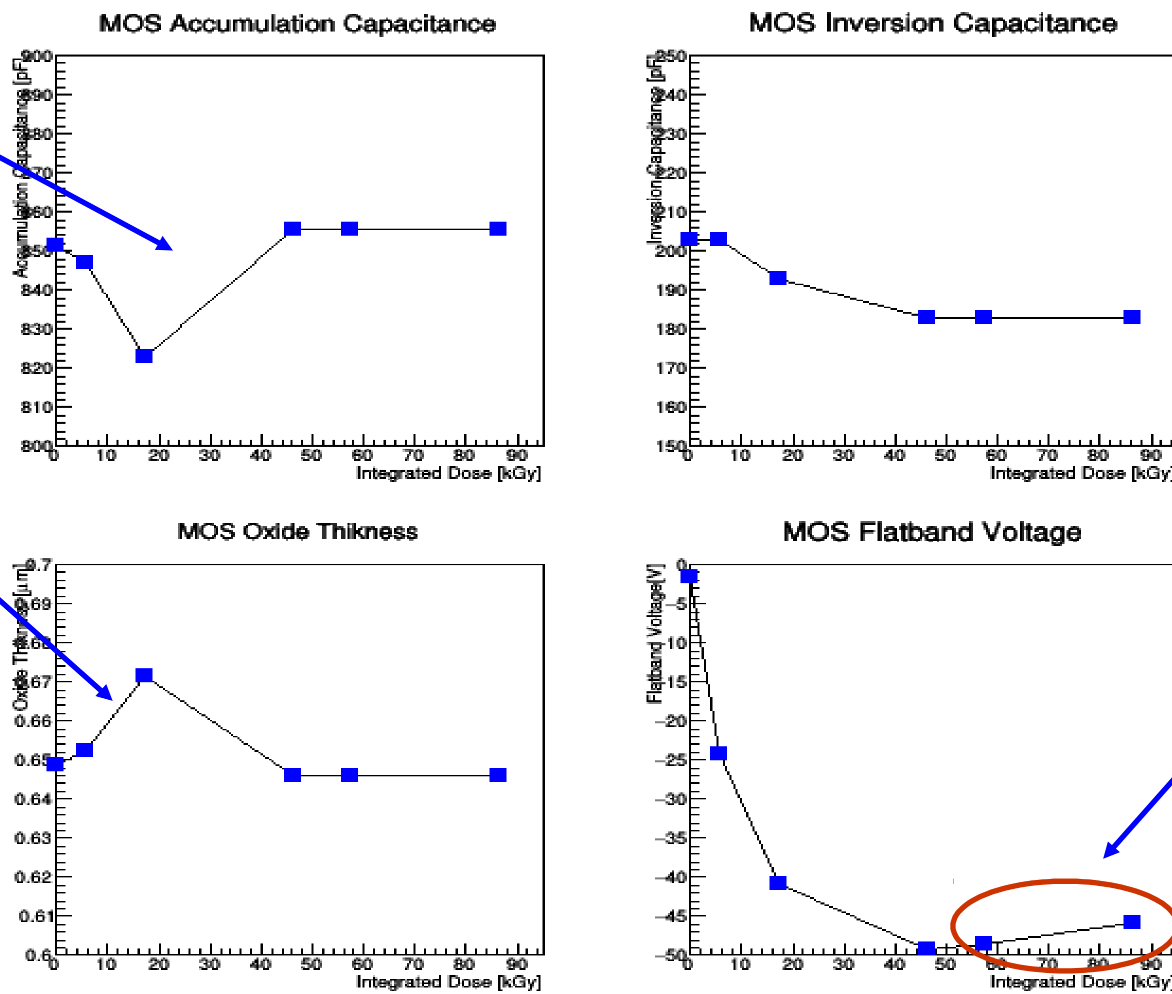


- Clear evidence of positive charge induced in the oxide of the MOS structures after exposure to γ photons
- Initial shift of the flat band voltage (V_{fb}), i.e. the voltage where the MOS behavior changes from accumulation to depletion, to higher absolute values
- The above trend is reversed after an 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 to attract negative charges from the surrounding material

MOS Features from CV (I)

MOS accumulation capacitance within 4%

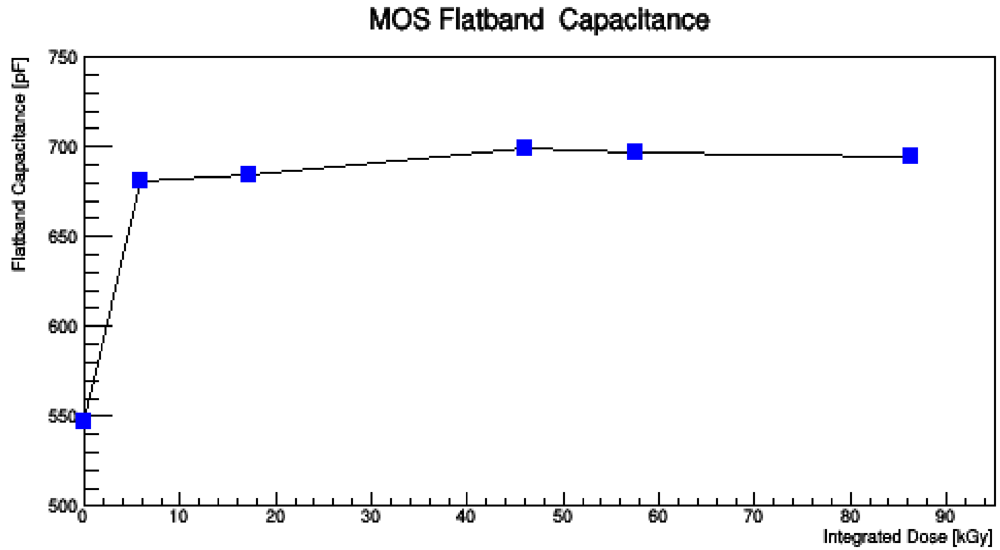
MOS inversion capacitance within 10%



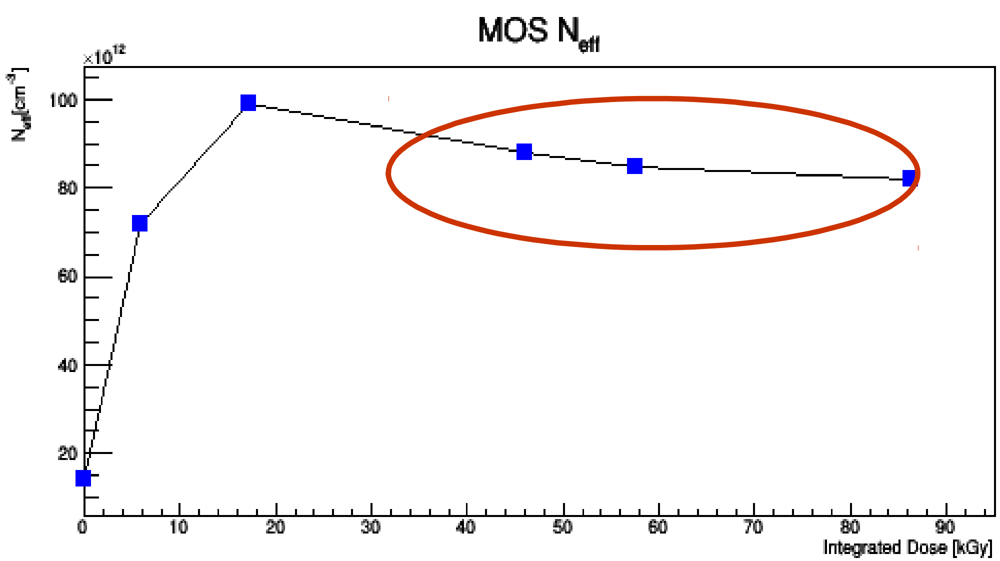
Oxide thickness not affected because it is a geometric characteristic of the device

Reverse of flat band voltage increase

MOS Features from CV (II)



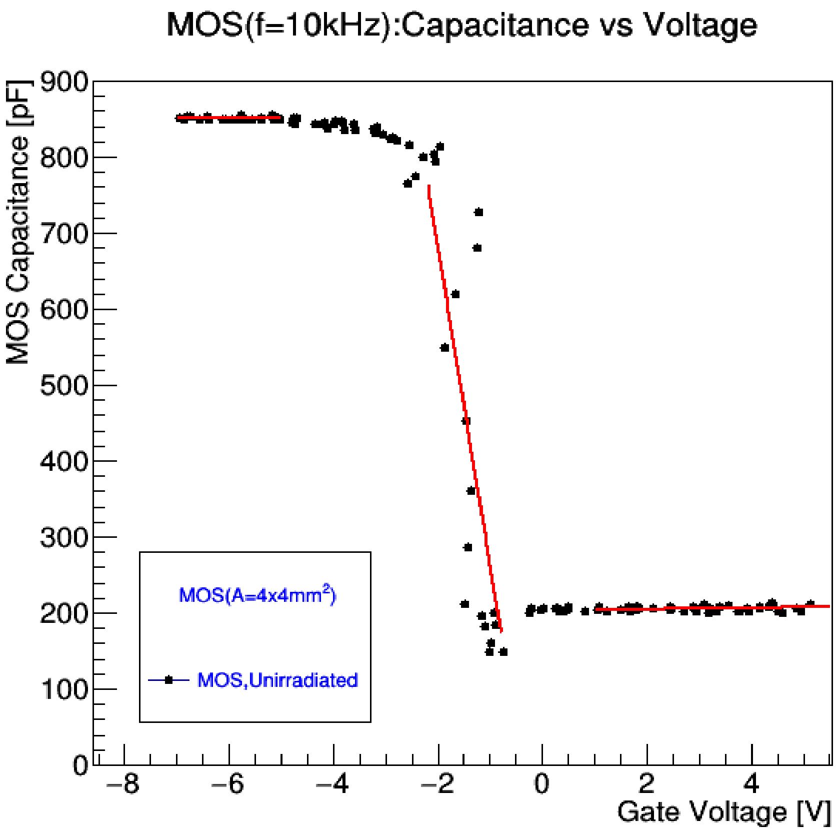
Flat band capacitance increases after irradiation but remains almost stable afterwards

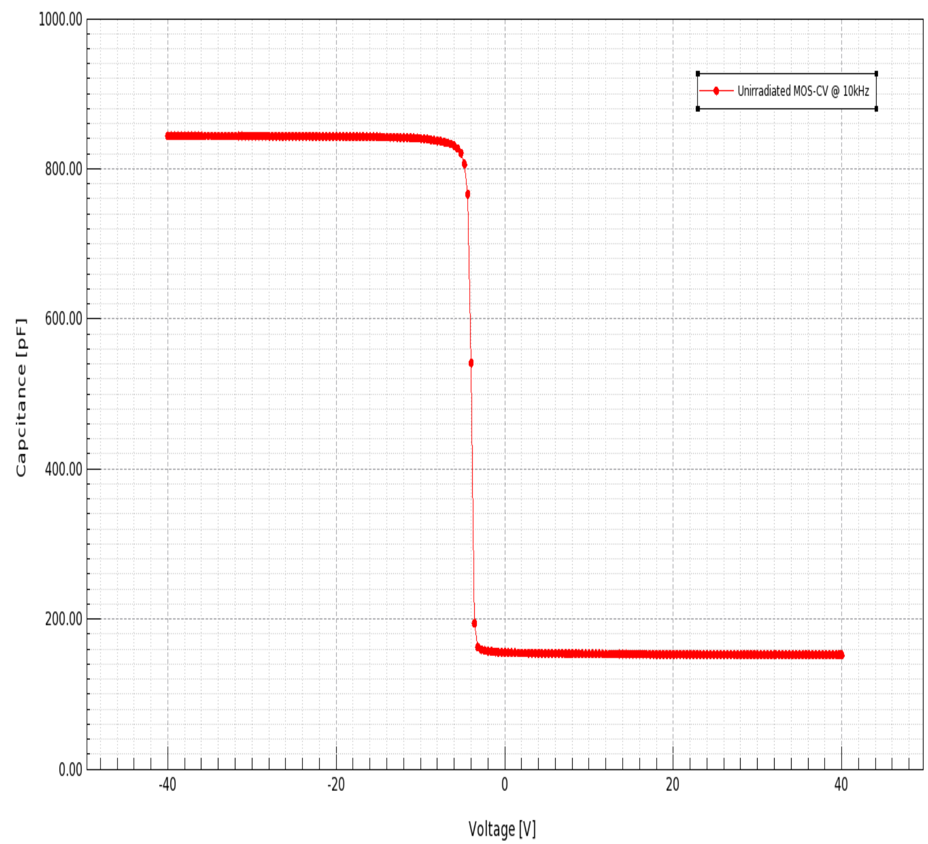


Reverse of N_{eff} initial increase after ~50kGy

TCAD MOS Simulation

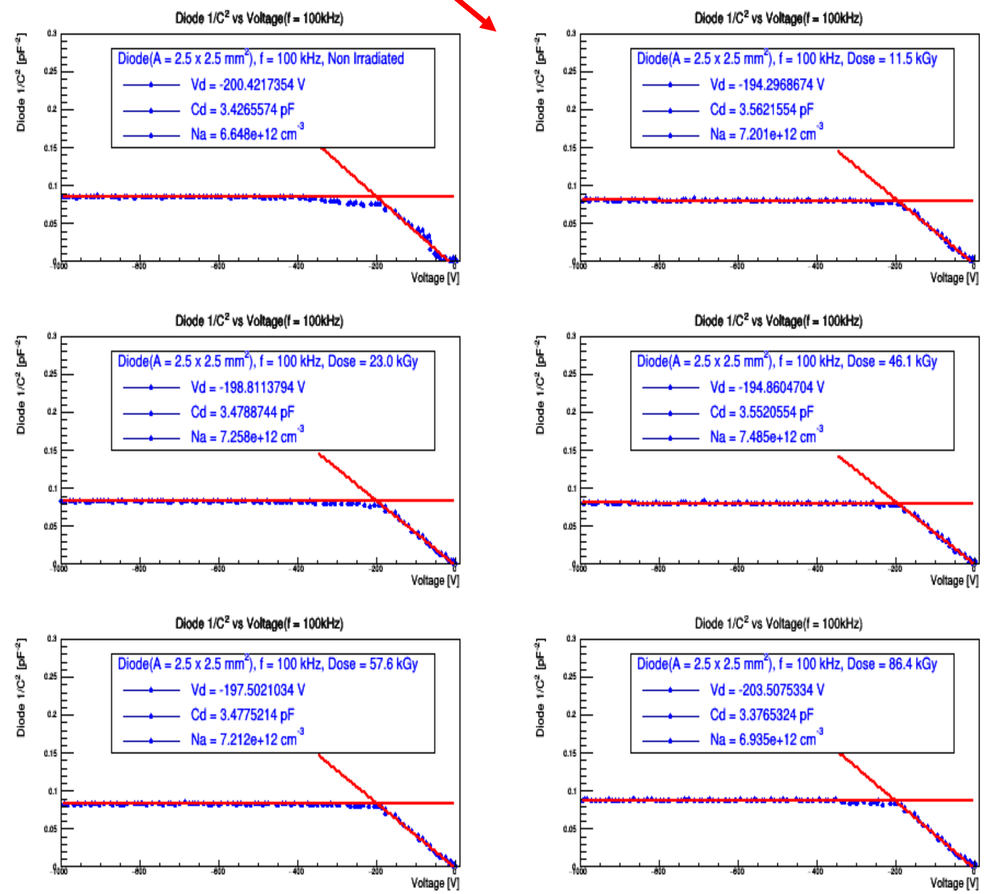
CV taken from measurements (left) and TCAD simulation (right) for non-irradiated MOS structures

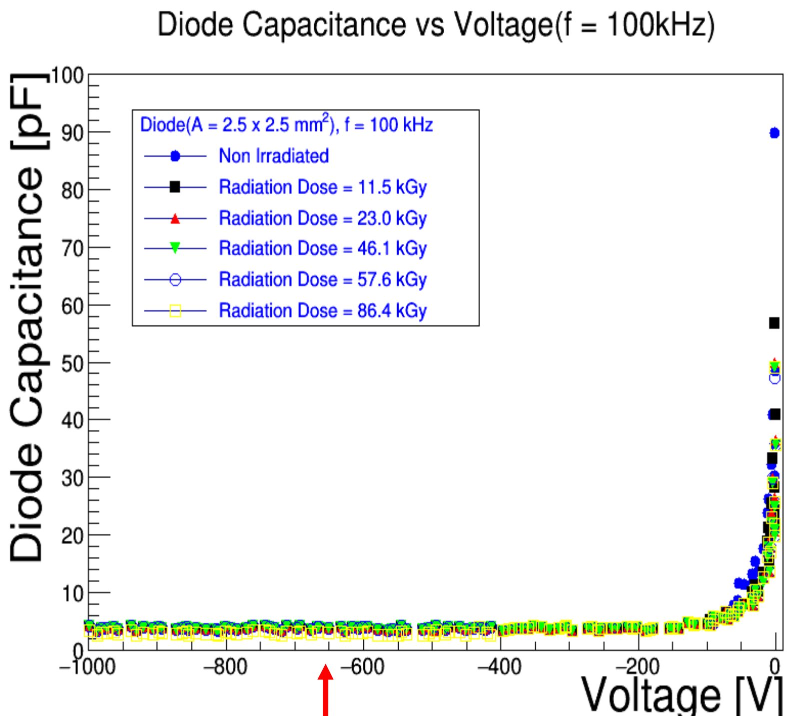




Diode CV Curves (I)

Diode 1/C² vs. bias voltage before and after irradiation

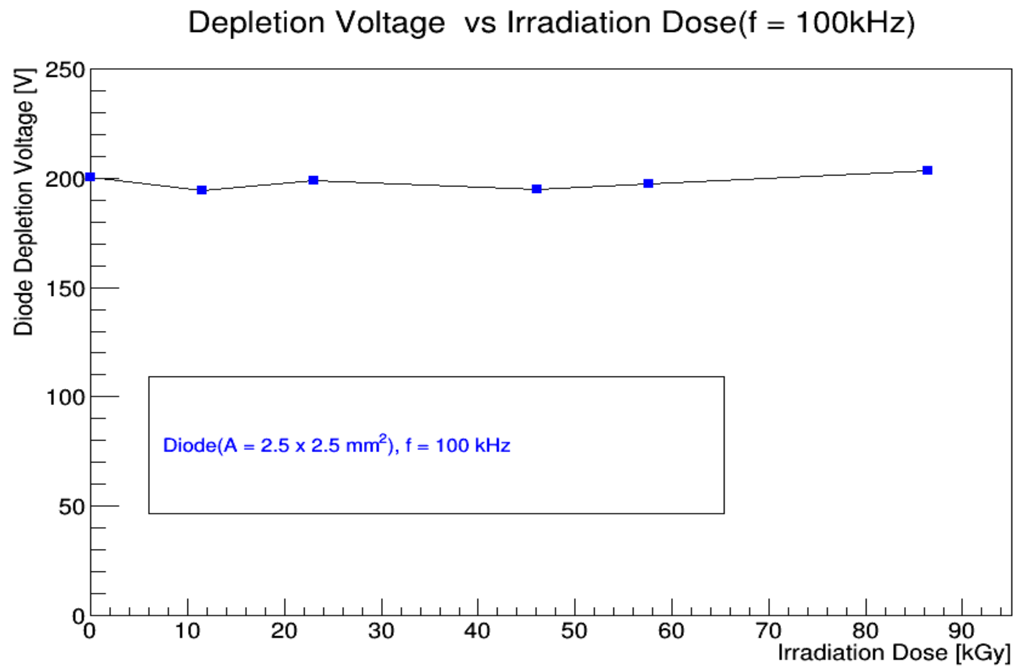




Diode capacitance (C) vs. bias voltage before and after irradiation

Diode CV Curves (II)

Depletion voltage remains almost unchanged after irradiation as a result of the oxygenated structures



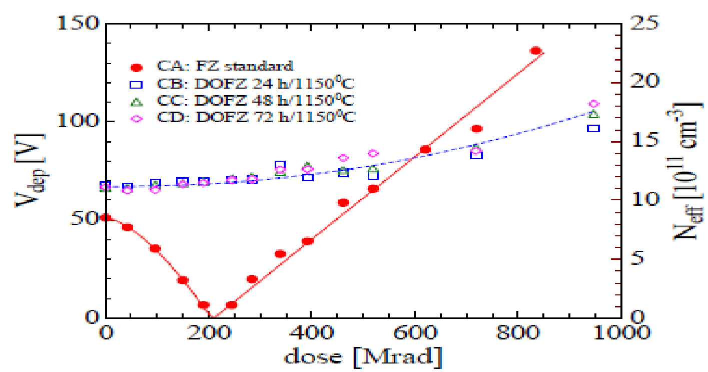


Fig. 20. Effective doping concentration as function of gamma dose for standard (closed) and DOFZ silicon (open symbols) [43].

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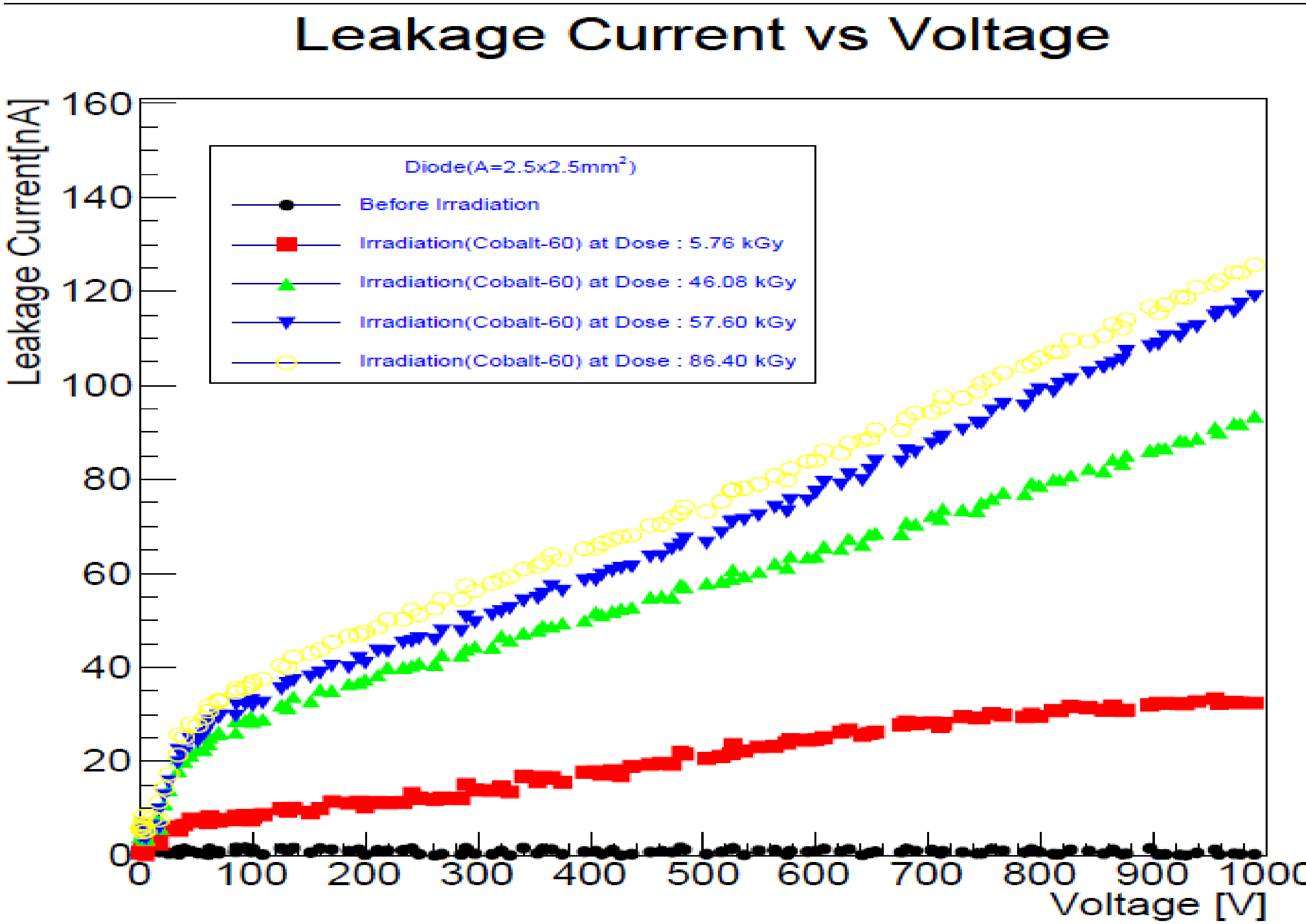
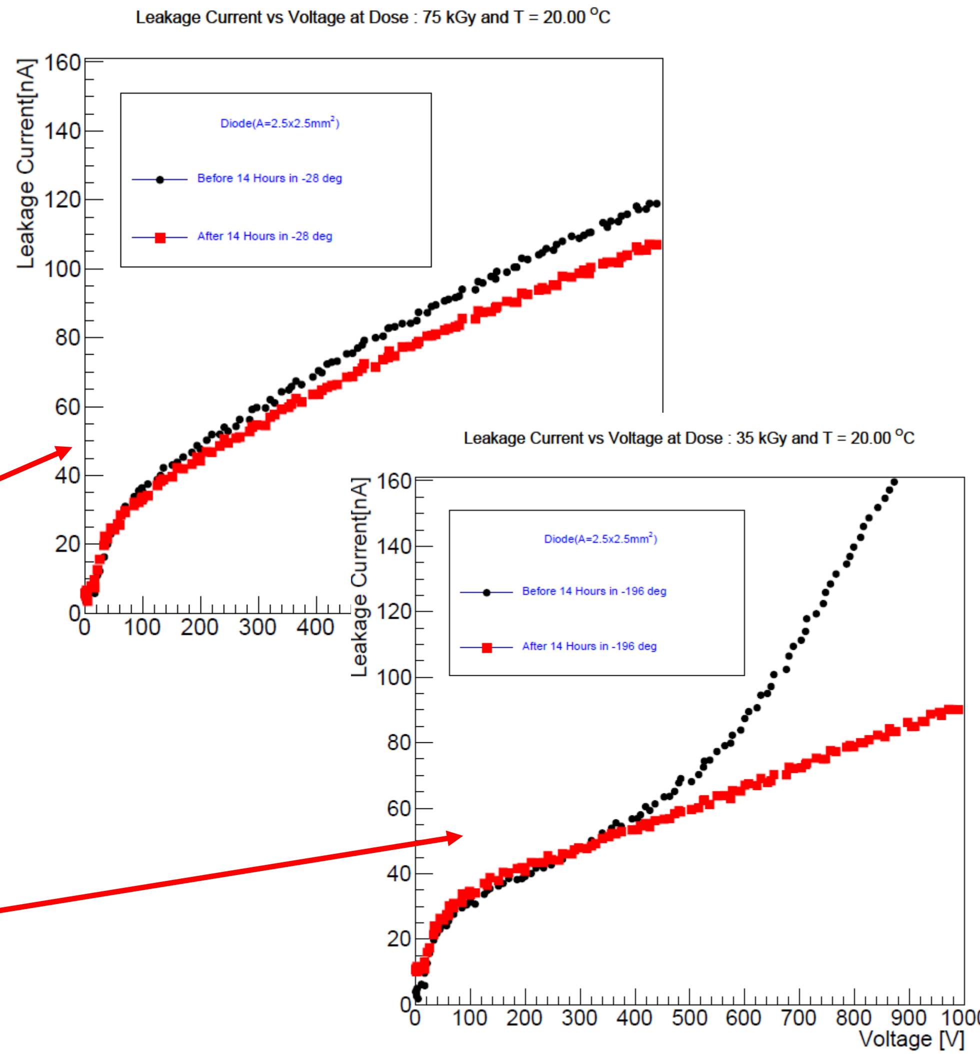
Diode IV Curves



$I(20\ ^{o}C) = I(T)\times(293\ K/T)^{2}\times\exp[-(E_g/(2k_B))(1/(293\ K) - 1/T)]$, $E_g = 1.21$ eV, RD50 TN 2011-01

Annealing Problems

- Since we aren't the only users of the source we were being forced to stop the irradiation for a few hours every day
- The time lapses between two consecutive irradiation slots were ~11 h - 15 h → the samples were stored at -28 °C during these lapses
- When measuring the IV after each period of storage in the freezer → annealing was being observed
- Annealing process was also observed after storage of the samples in a bottle of liquid N_2



Summary

- Irradiation using ^{60}Co source of 11 TBq
- Total dose ~86 kGy
- Irradiation of the MOS structure shows significant change in the flat band 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 °C to store sample between irradiation slots.
- Annealing seems not to stop even at -196 °C. **How to stop it? Any suggestions are welcome!**

Backup