Cobalt-60 gamma irradiation of silicon test structures for high-luminosity collider experiments

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During the era of the High Luminosity LHC (HL-LHC) the devices in the experiments will be subjected to increased radiation levels with fluxes of neutrons and charged hadrons in the inner detectors reaching up to approximately 2.3×10^{16} n_{eq}/cm^2 and total ionization doses up to around 1.2 Grad. A systematic program of radiation tests with neutrons and charged hadrons is being carried out by the CMS and ATLAS Collaborations in order to cope with the higher luminosity of 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-γ photons are presented. The doses are equivalent to those that the outer layers of the silicon tracker systems of the two experiments will be subjected to. The devices in this study are p-type diodes and MOS capacitors.

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1. Introduction

In the coming years, the Large Hadron Collider (LHC) is getting upgraded to the High Luminosity LHC (HL-LHC) with the scope of boosting the accelerator's potential for new discoveries in physics and studying rare processes. The aim is to increase the luminosity of the collider by a factor of 10, up to 10^{35} cm^{-2}s^{-1}, with the integrated luminosity expected to reach 3000 fb^{-1} [1]. For this reason, new silicon tracking detectors with improved radiation hardness are required for the HL-LHC experiments. In the HL-LHC era the total absorbed doses in the outer layers of the tracking systems are estimated to be in the order of 10-100 kGy, depending on the distance from the beam line [2], [3]. A systematic campaign of irradiation tests with neutrons and charged hadrons initiated by the LHC collaborations is ongoing in order to estimate how will the candidate devices for the tracking systems cope with a) the higher luminosity of the HL-LHC and b) the associated increase in pile-up events and radiation fluxes. Complementary radiation studies with ^{60}Co-γ photons are performed with the doses equivalent to those that the outer layers of the silicon tracker systems of the two large LHC experiments will be subjected to. One of the studies is presented here.

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 thick wafers produced by Hamamatsu Photonics K.K. [4]. Each test structure contains one square MOS (area = 4 mm × 4 mm) and two square diodes (area = 2.5 mm × 2.5 mm and area = 1.25 mm × 1.25 mm, respectively).

The ^{60}Co source is a Picker teletherapy unit [5] with a radioactivity of 30 TBq as of March 2012, estimated at approximately 11 TBq today, with a horizontal orientation (Fig. 1, left). It was calculated using FC65-P Ionization Chambers from IBA Dosimetry [6] that the dose rate at irradiation point (40 cm from the source) is ∼1 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 [7]. The cooling system consisted of a thermoelectric cooler (Peltier element, type TEC1 12704) operating at 20 °C, an aluminum plate and a fan for heat dissipation (Fig. 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 (Fig. 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 [8] where the samples were kept during irradiation (Fig. 2, right).

Electrical measurements were performed using an automatic probe station (Carl Suss PA 150) and supplementary equipment (HP4092A, Keithley 6517A) for electrical characterization of microelectronic devices and the samples were annealed in a Weiss WKS 3-180/40/5 climate test chamber.

3. Experimental procedure and protocol

The irradiation was split in slots of 5 hours of irradiation. After each slot, annealing of the
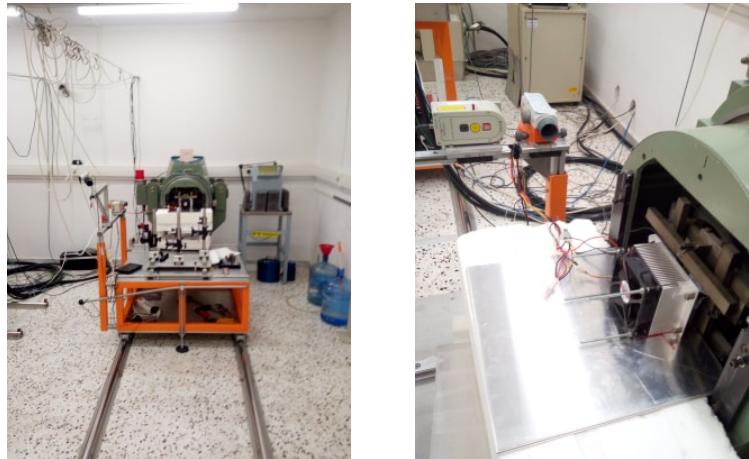
Figure 1: Left: The Cobalt-60 source: Picker therapy unit. Right: The container with the samples in front of the source. The fan and the thermoelectric cooler are visible.
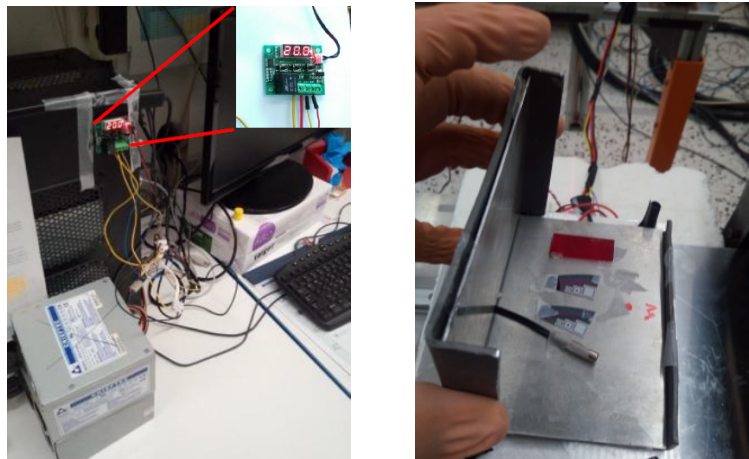

Figure 2: Left: The microcontroller and power supplies of the experimental setup. Right: The lead-aluminum container for charged particle equilibrium. Two samples can also be seen here (gray-colored test structures). Each of the two structures contains (from left to right): square diode with area = 1.25 mm $\times$ 1.25 mm, square diode with area = 2.5 mm $\times$ 2.5 mm, square MOS capacitor with area = 4 mm $\times$ 4 mm.

samples was performed in the climate test chamber at 60 °C for 10 min (corresponding to four days of annealing at room temperature). The electrical tests at the probe station after the annealing were performed at 22-24 °C using LabVIEW as operation and control software. 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; 10 kHz, 100 kHz, 1 MHz for diodes). Between each set of electrical measurements and the following irradiation slot, the samples were stored in a freezer at -28 °C.

4. Results from MOS (CV analysis)

After the exposure to gamma photons there is a clear evidence of positive charge induced in

Absorbed dose [kGy]	C_{acc} [pF]	C_{inv} [pF]	t_{ox} [μm]	V_{FB} [V]	N_a [cm^{-3}]
0	851.65	203.42	0.65	-1.32	8.30×10^{12}
5	839.06	202.75	0.66	-22.80	8.37×10^{13}
10	835.72	202.75	0.66	-29.80	8.16×10^{13}
15	835.73	187.41	0.66	-36.43	9.12×10^{13}
25	811.08	178.22	0.68	-43.66	1.01×10^{14}
30	803.90	182.97	0.69	-45.71	1.03×10^{14}

Table 1: Various features of a MOS capacitor before and after irradiation; measurement frequency = 10 kHz. (Derived from Chapter 6 of [9].)

the oxide of the p-type MOS capacitors as seen in Fig. 3, where a shift of the flat band voltage (V_{FB}) to higher absolute values is observed at higher doses. This also implies an increase of the doping concentration (N_a). Some other features of MOS capacitors (capacitance in the accumulation region C_{acc}, capacitance in the inversion region C_{inv}, oxide thickness t_{ox}) before and after irradiation are summarized in Table 1. The derivation for these have been done by known rules [9]. In the analysis it is noticed that the oxide thickness remains stable as expected, since it is a geometric characteristic of the device. In addition, with higher doses the transition from the depletion region to the inversion region becomes inertial due to the delay of the generation of carriers while increasing the voltage.
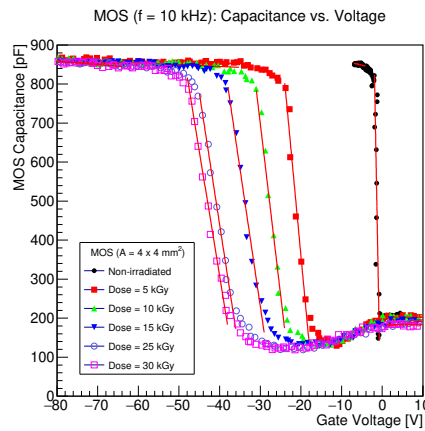

Figure 3: Capacitance-voltage curve for a MOS capacitor for various doses; measurement frequency = 10 kHz.

5. Results from a 2.5 mm sized diode (CV and IV analysis)

The CV curves of a 2.5 mm sized diode before and after irradiation are almost identical (Fig. 4, left). Using $1/C^2$ calculated after the CV measurement (Fig. 4, right), useful information about the depletion voltage (V_d), capacitance in the depletion region (C_d) and acceptor concentration (N_a) can be obtained using known relations [9]. The results are summarized in Table 2. It is also observed that the depletion voltage remains almost unchanged after irradiation. This occurs as

Absorbed dose [kGy]	V_d [V]	C_d [pF]	N_a [cm^{-3}]
0	-195.50	3.53	7.129×10^{12}
5	-223.79	3.38	7.104×10^{12}
10	-200.05	3.43	6.723×10^{12}
15	-191.37	3.54	6.935×10^{12}
25	-193.50	3.43	6.886×10^{12}
30	-198.12	3.43	7.003×10^{12}

Table 2: Various features of a square diode with area = 2.5 mm × 2.5 mm before and after irradiation; measurement frequency = 100 kHz. (Derived from Chapter 4 of [9].)

a result of the oxygen enrichment of silicon which is known to improve the radiation hardness properties of silicon detectors [10].

The IV results were scaled to 20 °C [11] and the increase of the diode leakage current (absolute value) with the irradiation dose is presented in Fig. 5, left. The increase in ΔI with the increase of the absorbed dose can be seen in Fig. 5, right.
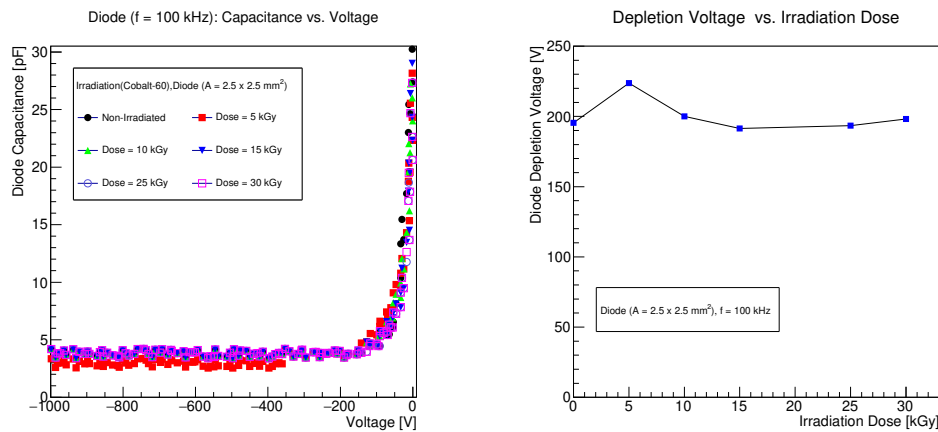

Figure 4: Left: CV curve for a 2.5 mm sized diode for various doses; measurement frequency = 100 kHz. Right: Depletion voltage as function of the absorbed dose for a 2.5 mm sized diode; measurement frequency = 100 kHz.

6. Conclusions

In this work silicon MOS capacitors and n-in-p diodes were irradiated with ^{60}Co-γ photons from a ~11 TBq source. The total absorbed dose obtained in several steps was ~30 kGy. The level of the radiation-induced charge in the test structures was determined from the shift of the flat band voltage in the MOS after irradiation. In the diodes it was observed that even for high doses the leakage current is in the order of 10-100 nA, while the depletion voltage remains almost unchanged with the increasing dose. This is an indication that the material and the devices are suitable for high-luminosity applications. To understand better the behavior of the material and the
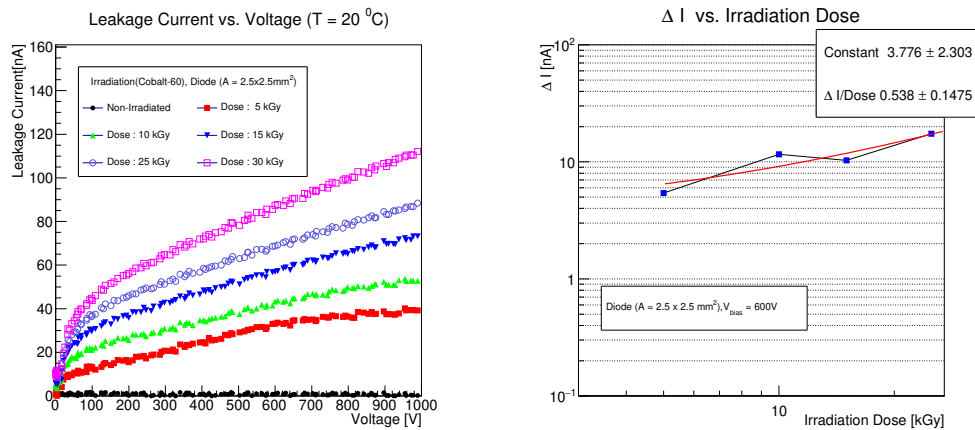
Figure 5: Left: IV curves for a 2.5 mm sized diode for various doses. Right: ΔI-dose curve at V = -600 V for a 2.5 mm sized diode.

devices, the irradiation campaign is still ongoing with the intention of reaching a three times higher absorbed dose compared to this study.

Acknowledgments

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