Comparison study of heavily irradiated dielectrics for AC-coupled pixel detectors

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Introduction

- The Phase-II upgrade of LHC to HL-LHC by 2026 allows an increase in the operational luminosity value by a factor of 5-7. As a consequence of this, silicon detector layers within the inner tracker of the CMS experiment will be exposed to increased radiation doses up to 2.3×10^{16} n_{eq}/cm^2.
- Use of p-type Si with segmented n^+-implants allows electrons with higher mobility to be collected.

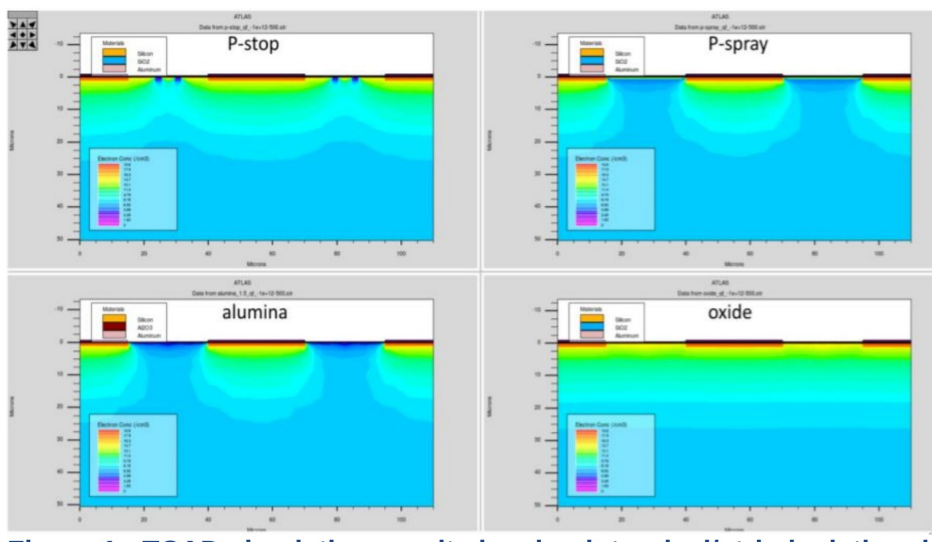

Figure 1 : TCAD simulation result showing interpixel/strip isolation due to p-stop/p-spray [top] and in case of a use of a negative oxide as insulating layer (such as alumina) [bottom-left].

- **Challenge:** electron accumulation near the interface of SiO_2 (positive oxide charge) insulating layer and p-bulk, leading to short circuit channel between n^+ implants.
- **Mitigation:** traditional ways include p-stop and p-spray that requires additional implantation and high temperature process steps.
- **Alternatively**, use of negative oxide like Al_2O_3 or HfO_2 - As high-k value permits higher oxide capacitance and high negative charge ($\sim 10^{-11}$-10^{-13} cm^{-2}).

Thin films of Al_2O_3 or HfO_2 are deposited using **Atomic Layer Deposition (ALD) technique** : require low temperatures, provides high uniformity of layers, very thin layers (tens of nm) with good accuracy [3, 2].

Samples Measured

- Starting material: p-type MCz 6" Si, resistivity : 6-8 kΩcm, thickness: 320 µm. Fabricated at Micronova Nanofabrication Centre, in Finland.
- Main devices characterised for this study are:
  1) MOS capacitors and MOSFET
  2) Pad structure: PIN diodes
  3) AC coupled devices —–> design of PSI46dig sensor (52×80 pixel matrix), 150×100 µm pitch
- Comparison based on the characterisation of devices with : 1) Al_2O_3, 2) Al_2O_3 + HfO_2. HfO_2 2.7 times higher-k value than Al_2O_3 : provides higher capacitive coupling, insulation and improved radiation hardness [Al_2O_3 thickness = 84 nm, HfO_2 thickness = 62 nm].
- The samples were irradiated with 10 MeV protons at the Accelerator Laboratory in University of Helsinki, Finland.

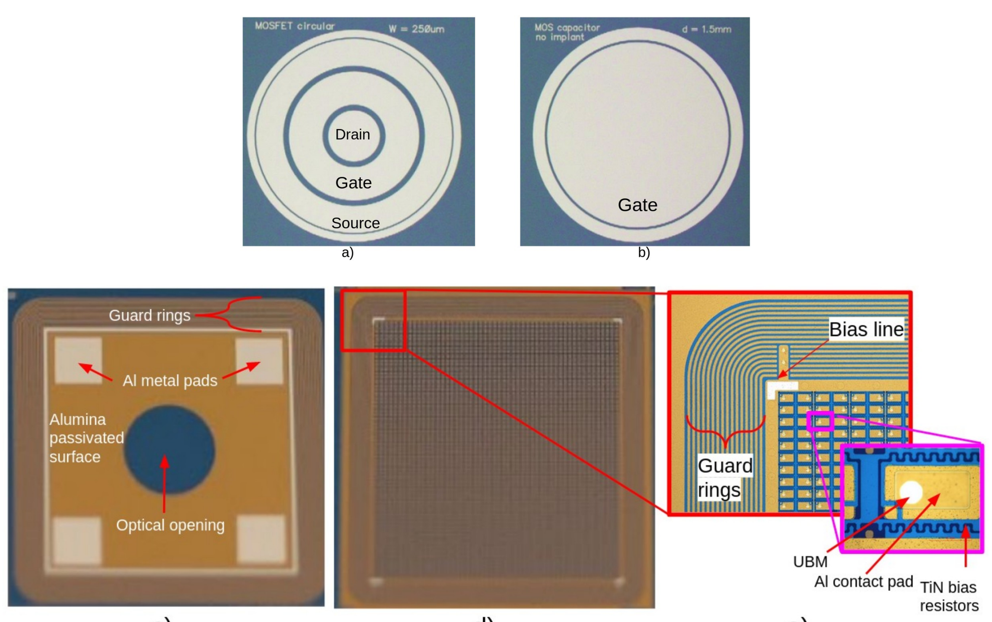

Figure 2 : Measured samples: a) MOSFET, b) MOS capacitor, c) Pad diode, d) AC-coupled pixel sensor with metal bias implants and e) showing zoomed and detailed structures within the pixel detector.

Electrical Characterisation

MOS capacitor

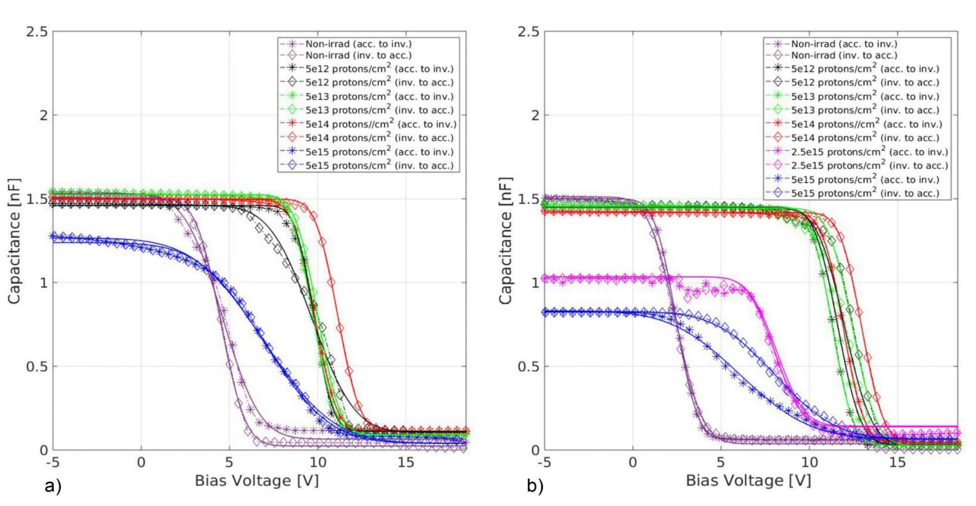

Figure 3 : CV characterisation of pre- and post-irradiated MOS capacitors.

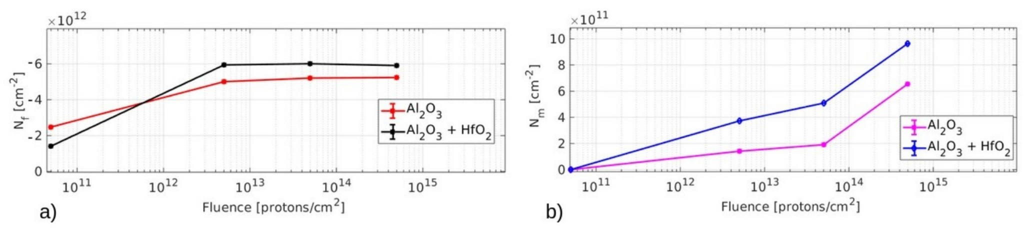

Figure 4 : Evolution of effective a) fixed charges and b) mobile charges in proton irradiated MOS capacitors with different insulating layers.

- MOS capacitors with Al_2O_3 + HfO_2 posses a lower shift in flat-band voltage (V_{fb}) by a magnitude of $\sim (2.18 \pm 0.35)$ V, than those with Al_2O_3 as the dielectric material alone. This corresponds to a decrease in the fixed oxide charges (N_f) by a factor of ~ 1.5 for samples with HfO_2, as shown in Figure 4a.
- Hysteresis of CV curves in Figure 3, aids in analysing the mobile charges in the insulating layer. Concentration of mobile charges (N_m) increases on irradiation of MOS capacitors to a fluence of 5×10^{14} protons/cm^2. N_m is a factor of ~ 1.6 times higher in samples with Al_2O_3 + HfO_2 as dielectric layer.

Comparison of MOSFET Sensitivity

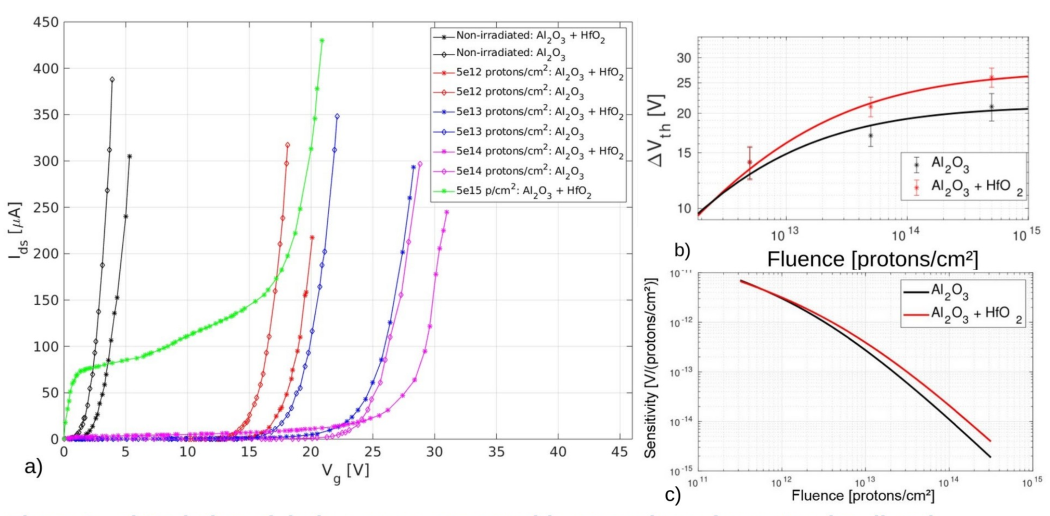

Figure 5 : a) Variation of drain-source current with gate voltage for proton irradiated MOSFETs, measured with a constant drain-to-source voltage of 1 V. b) Change in the shift and c) variation in the sensitivity with fluence for proton irradiated MOSFETs with different oxides.

- Total shift in threshold voltage (ΔV_{th} is sum of the threshold-voltage shifts due to oxide-traps and interface-trap charges. ΔV_{th} is positive for n-channel MOS transistors due to negative charge accumulation at the interface, forming the interface-traps.
- Beyond 5×10^{14} protons/cm^2, the amount of oxide-traps supersede causing an increase in the leakage current, that can potentially cause a breakdown of the IC, shown in Figure 5a.
- ΔV_{th} dependence on fluence is provided by the fitting equation (as shown in Figure 5b):

$$\Delta V_{th} = a + \frac{a}{1 + bD^c} \tag{1}$$

where, D is the proton fluence and (a, b, c) are three curve-fit parameters.

- Sensitivity, defined as the ratio of ΔV_{th} and fluence, can be measured by using the parameters from the above equation for samples with different dielectrics. Figure 5c shows samples with HfO_2 have higher sensitivity to irradiation, specifically at fluences above 10^{12} protons/cm^2.

AC-coupled pixel sensors

IV/CV measurements

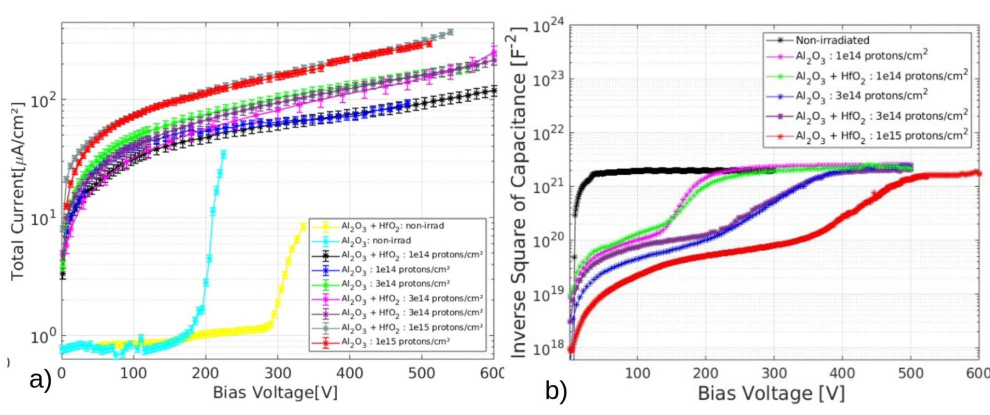

Figure 6 : a) Total leakage current of pre- and post-irradiated pixel sensors versus bias voltage for AC-coupled pixel sensors with different dielectric layers measured at -15ºC. b) Inverse square capacitance versus bias voltage curves for AC-coupled pixel sensors with combination of HfO_2 and Al_2O_3 used as the dielectric layer irradiated up to a fluence of 10^{15} protons/cm^2.

- AC-pixel senors with HfO_2 can sustain higher bias voltages as it provides better insulation than sensors with Al_2O_3 alone as dielectric layer. With irradiation up to fluence of 10^{15} protons/cm^2, sensors with HfO_2 + Al_2O_3 as insulating layer are able to sustain higher electric field and there is no breakdown visible up to maximum test operational voltage of approximately 550 V.
- As shown in Figure 6b, full depletion voltage (V_{fd}) of the active bulk of non-irradiated sensors is approximately 76 V which corresponds to a doping concentration of 1.08×10^{12} cm^{-3} and a resistivity of 12 kΩ-cm. V_{fd} of samples irradiated up to fluence of 10^{15} protons/cm^2 increases up to (570 ± 15) V, which corresponds to a resistivity of 2 kΩ-cm and an increase in the doping concentration by a factor of ~ 7.

TCT measurements

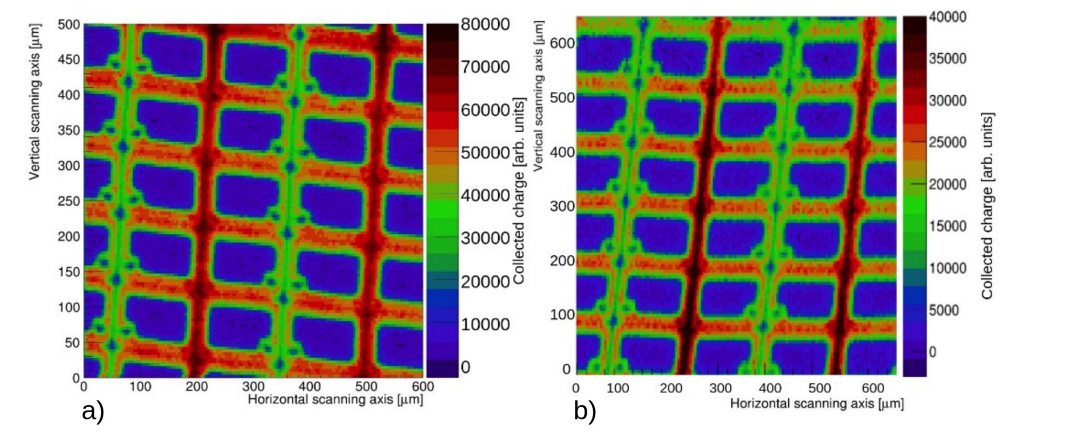

Figure 7 : Spatial homogeneity scans performed at a bias of 300 V with front illumination of IR-laser showing a scanned area of a) 500 × 600 µm² for 10^{14} protons/cm² and b) 620 × 650 µm² for 10^{15} protons/cm² irradiated AC-coupled pixel sensors with combination of HfO2 and Al2O3 used as the dielectric layer.

- Front illumination of IR- laser in TCT characterisation of AC-coupled pixel sensors, shown in Figure 7, portray the spatial homogeneity in charge collection efficiency on irradiation. IR laser intensity was set to magnitude of 60 % at a repetition rate of 1 kHz; corresponding to charge deposited by approximately ~ 10 MIPs.
- The resolution of the pixels based on the collected charge homogeneity scans does not change significantly on irradiation. However, the maximum collected charge within the active region of the sensor is reduced by a factor of 2.25 (approx. 55%) and 1.13 (approx. 11%) for samples irradiated at fluences of 10^{15} protons/cm^2 and 10^{14} protons/cm^2, respectively.

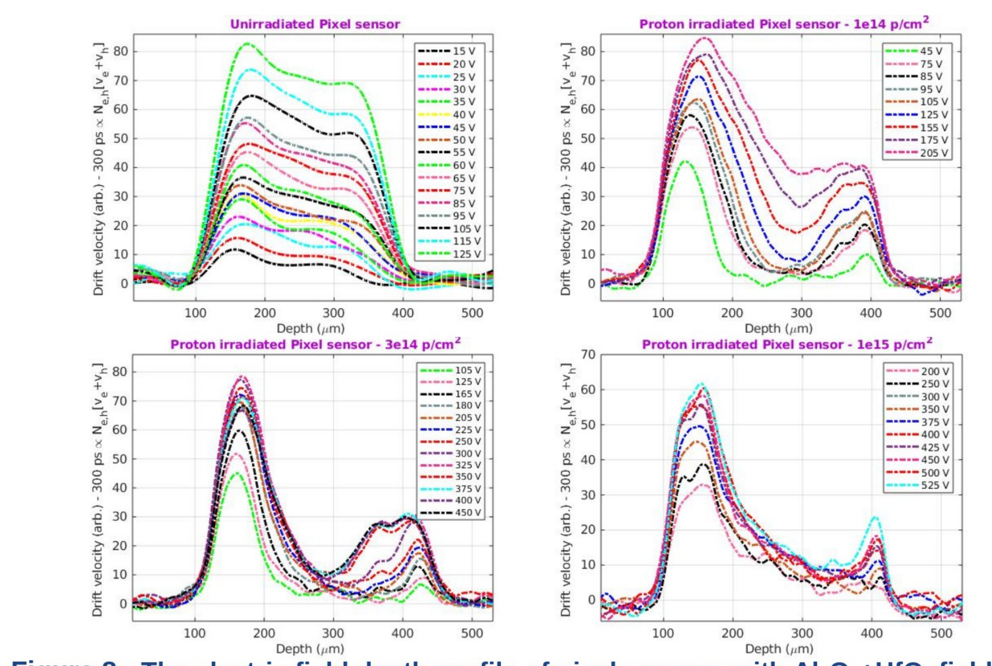

Figure 8 : The electric field depth-profile of pixel sensors with Al_2O_3+HfO_2 field insulation for various bias voltages: (top left to bottom right) non-irradiated; after fluence of 10^{14} p/cm²; after fluence of 3×10^{14} p/cm²; after fluence of 10^{15} p/cm².

- The electric field can be numerically determined from the drift velocity profiles using the prompt method in edge-TCT (e-TCT) measurements. Figure 8a, shows the a uniform gradient in the electric field profiles observed with a maximum at a depth beyond 30 µm from the segmented sides and a gradual minimum towards the back-plane of the sensor.
- Characteristic double-peak distortion in the electric field gets more prominent for sensors irradiated to fluences above 10^{14} protons/cm^2. As can be noticed at 10^{14} protons/cm^2, the double-peak effect gets less pronounced for higher bias voltages as the MCz-silicon wafers possess a high concentration of oxygen of a magnitude of $\sim 10^{17}$ cm^{-3} responsible for the suppression of deep-level trap formation by decreasing the mid-gap defect concentrations [1].

Conclusion

- Characterisation of MOS and MOSFET devices indicates negative charge accumulation induced by proton irradiation based on the study of the flat-band voltage and shift in the threshold voltage, respectively. Negative oxide charge during irradiation is an essential prerequisite of radiation hardness resiliency of $n^+/p-/p+$ (n on p) particle detectors widely intended to be used in future high-luminosity experiments.
- MOS devices with HfO_2 + Al_2O_3 posses higher sensitivity to irradiation, especially when irradiated to high fluences, in comparison with Al_2O_3 alone as the oxide layer.
- Studies based on e-TCT measurements suggest that the impact of different dielectric-silicon interfaces show hardly any difference on the functionality of the AC-pixel sensors. However, double-junction effect as a consequence of deep-level traps in the band-gap of silicon was identified in proton irradiated samples.

References

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