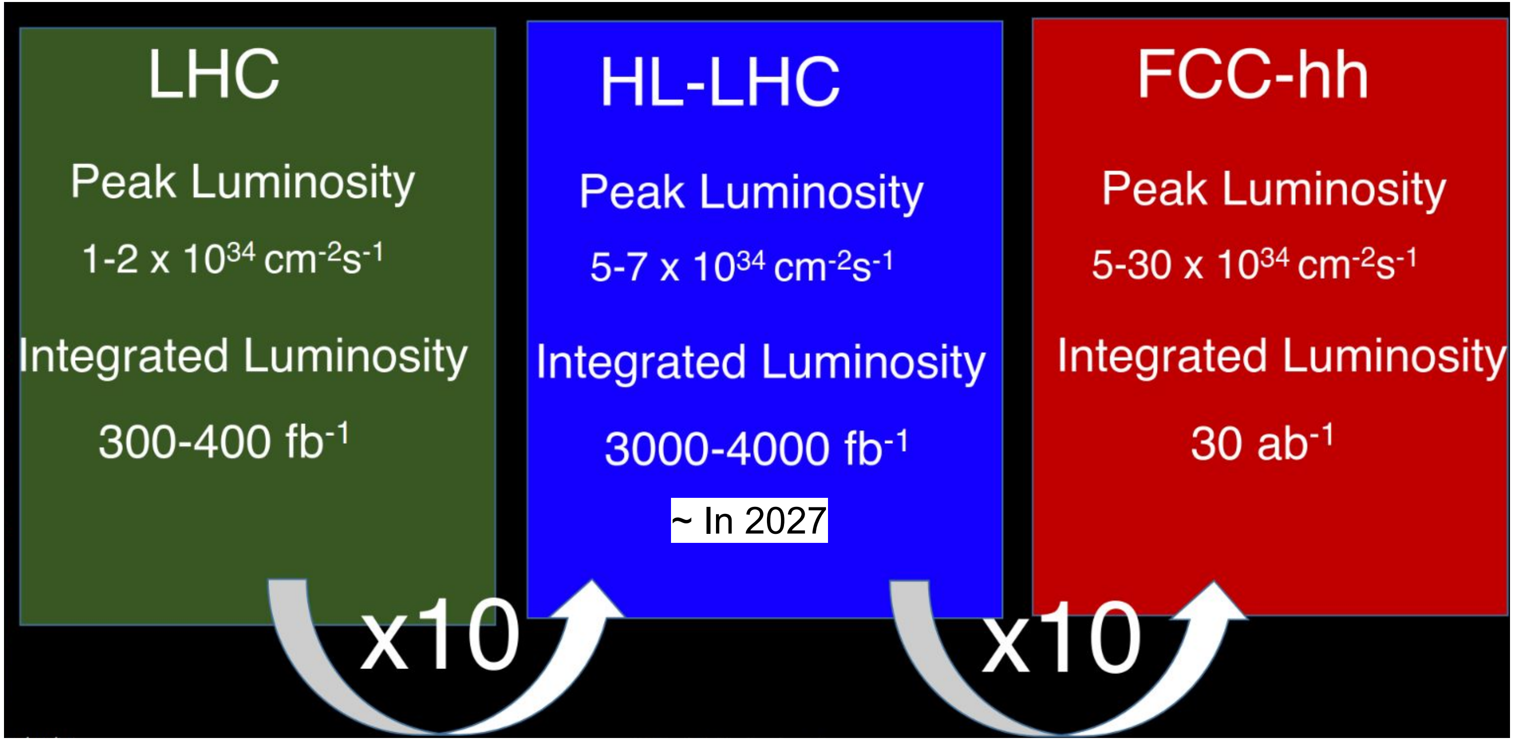
Characterisation studies of silicon detectors with ALD-grown alumina as field insulator

- Shudhashil Bharthuar

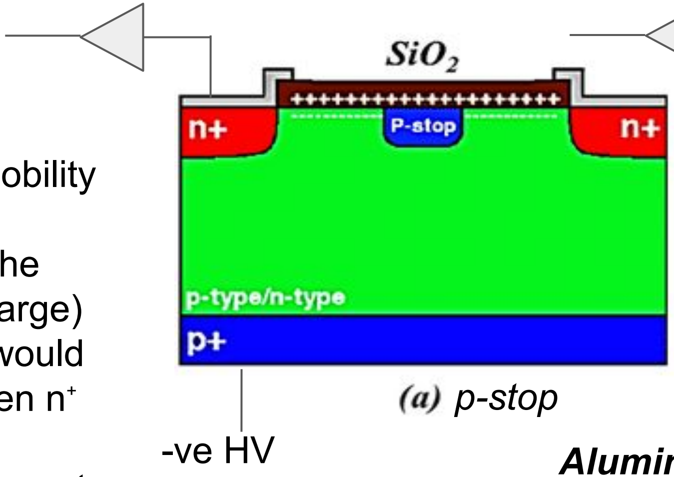
Need for R&D of detector prototypes



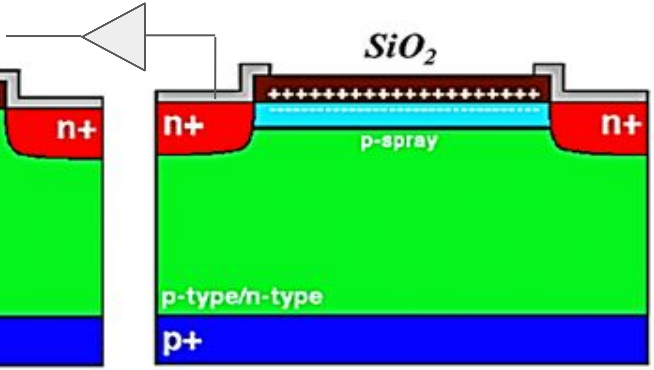
Exposure of inner tracker pixel layers to radiation levels up to:
− fluence of 2×10^{16} 1 MeV neq/cm²
− Total Ionizing Dose (TID) ~ 12 MGy

Motivation

- Use of P-type Si with segmented n^+-implants ⟶ e^- with higher mobility are collected
- **Challenge:** e^- accumulation near the interface of SiO_2 (positive oxide charge) insulating layer and p-bulk ⟶ would lead to short circuit channel between n^+ implants
- **Mitigation:** traditional ways include p-stop and p-spray -----> requires additional implantation and high temperature process steps.

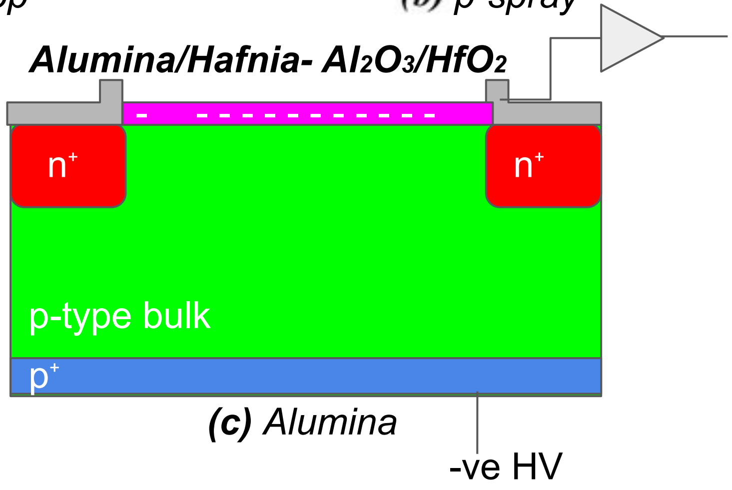


(a) p-stop



(b) p-spray

Alumina/Hafnia- Al_2O_3/HfO_2



***(c)** Alumina*

Alternatively, use of negative charged oxide like Al_2O_3 or HfO_2 -

a) good dielectric constant ----> higher oxide capacitance

b) high negative charge (~ 10^{11} - 10^{13} cm^{-2})

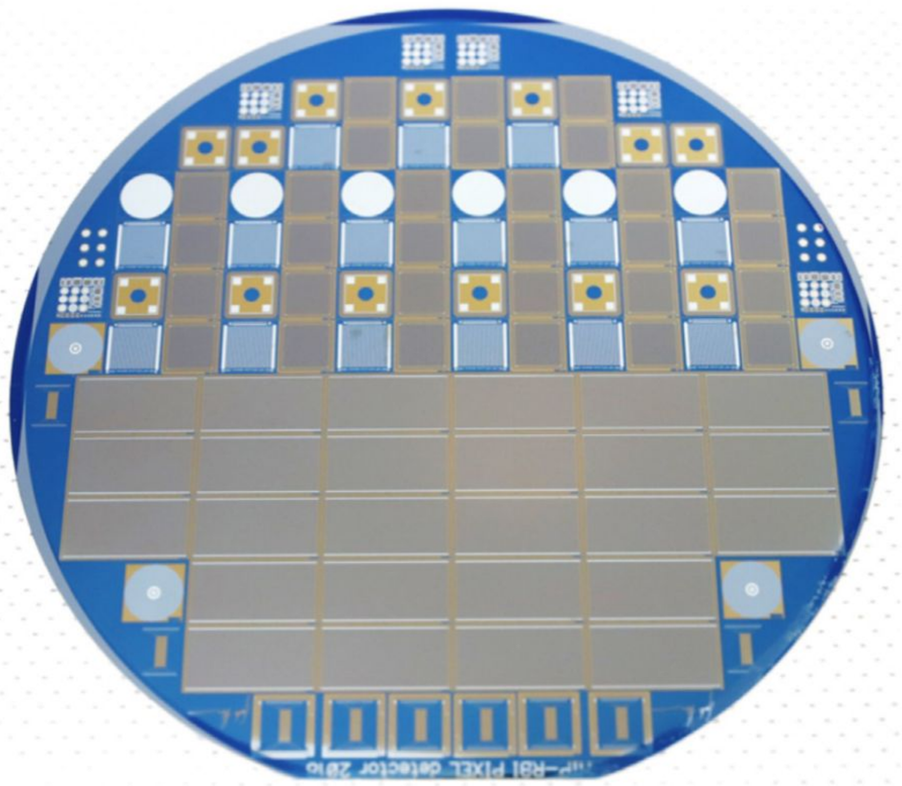
Deposited using Atomic Layer Deposition (ALD) technique

- low temperatures, high uniformity of layers, very thin layers (tens of nm) with good accuracy

Measured samples

- Fabricated at Micronova
- Starting material ⟶

p-type MCz 6” Si, resistivity : 5-8 kΩcm, thickness: 320 μm



Processing of the devices ref:

[1] J. Ott et al, Processing of AC-coupled n-in-p pixel detectors on MCz silicon using atomic layer deposited aluminium oxide, NIM A 958 (2020) 162547

[2] A. Gädda et al, AC-coupled n-in-p pixel detectors on MCz silicon with atomic layer deposition (ALD) grown thin film, NIM A 986 (2021) 164714

[3] J. Ott et al, Characterization of magnetic Czochralski silicon devices with aluminium oxide field insulator: effect of oxygen precursor on electrical properties and radiation hardness, (2021) JINST 16 P05011

Measured samples

- Fabricated at Micronova
- Starting material ⟶

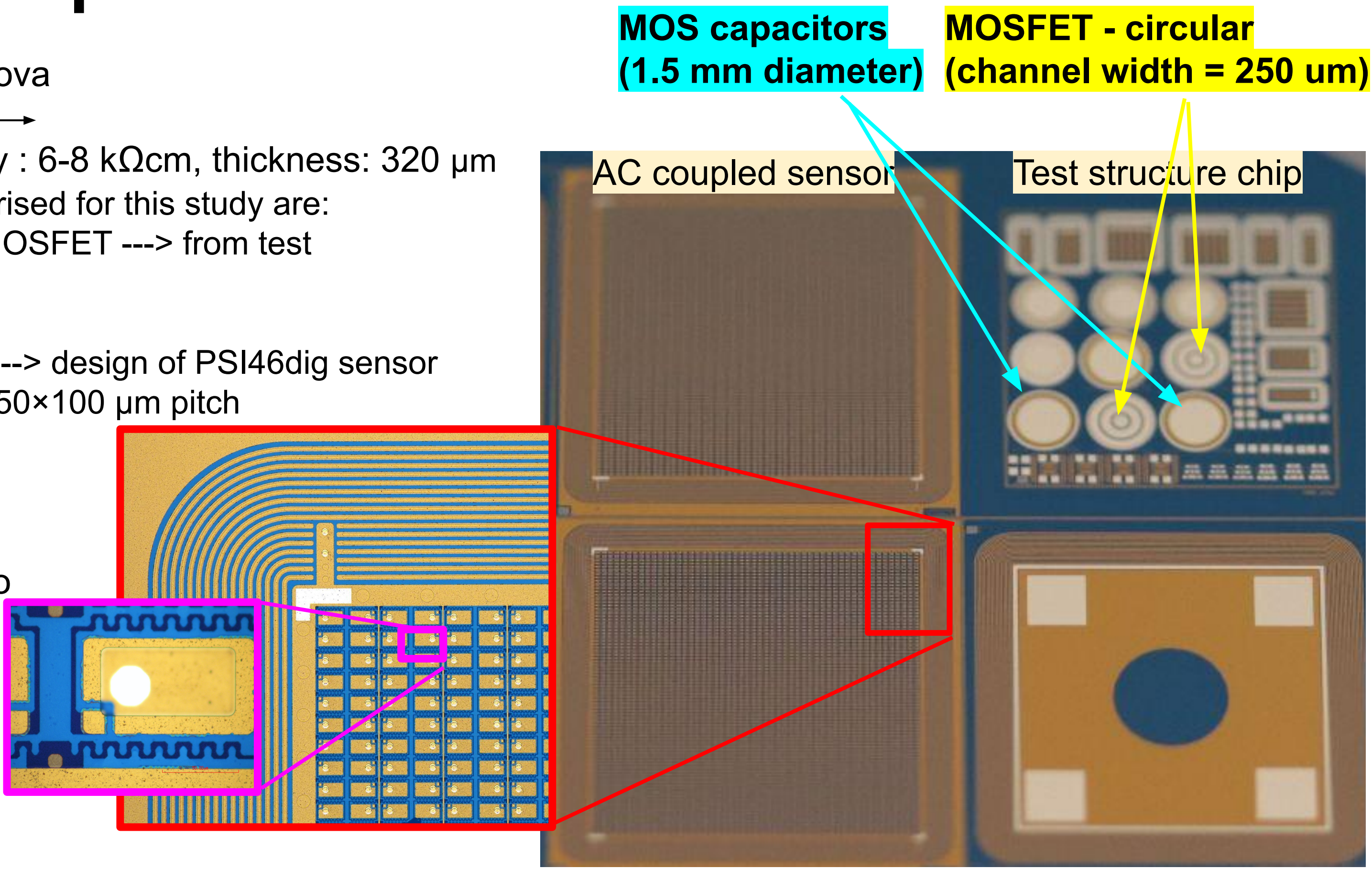
p-type MCz 6” Si, resistivity : 6-8 kΩcm, thickness: 320 μm

- Main devices characterised for this study are:

1) MOS capacitors and MOSFET ---> from test structure
2) Pad Diodes
3) AC coupled devices -----> design of PSI46dig sensor (52×80 pixel matrix), 150×100 μm pitch

AC coupled sensors:

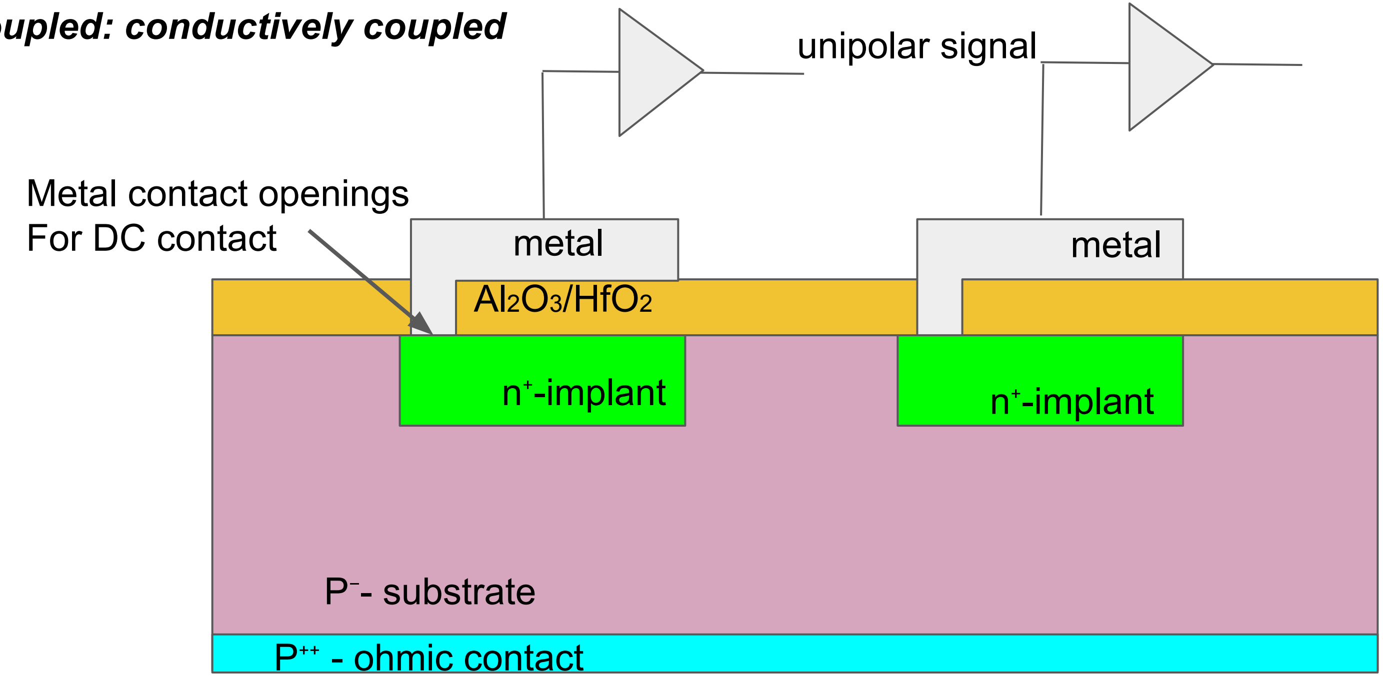
Alumina/Alumina + hafnia to permit better capacitive coupling of pixels
+
Thin film TiN bias resistor



For Future collider experiments

mitigate challenges associated to increment in leakage current

DC-coupled: conductively coupled

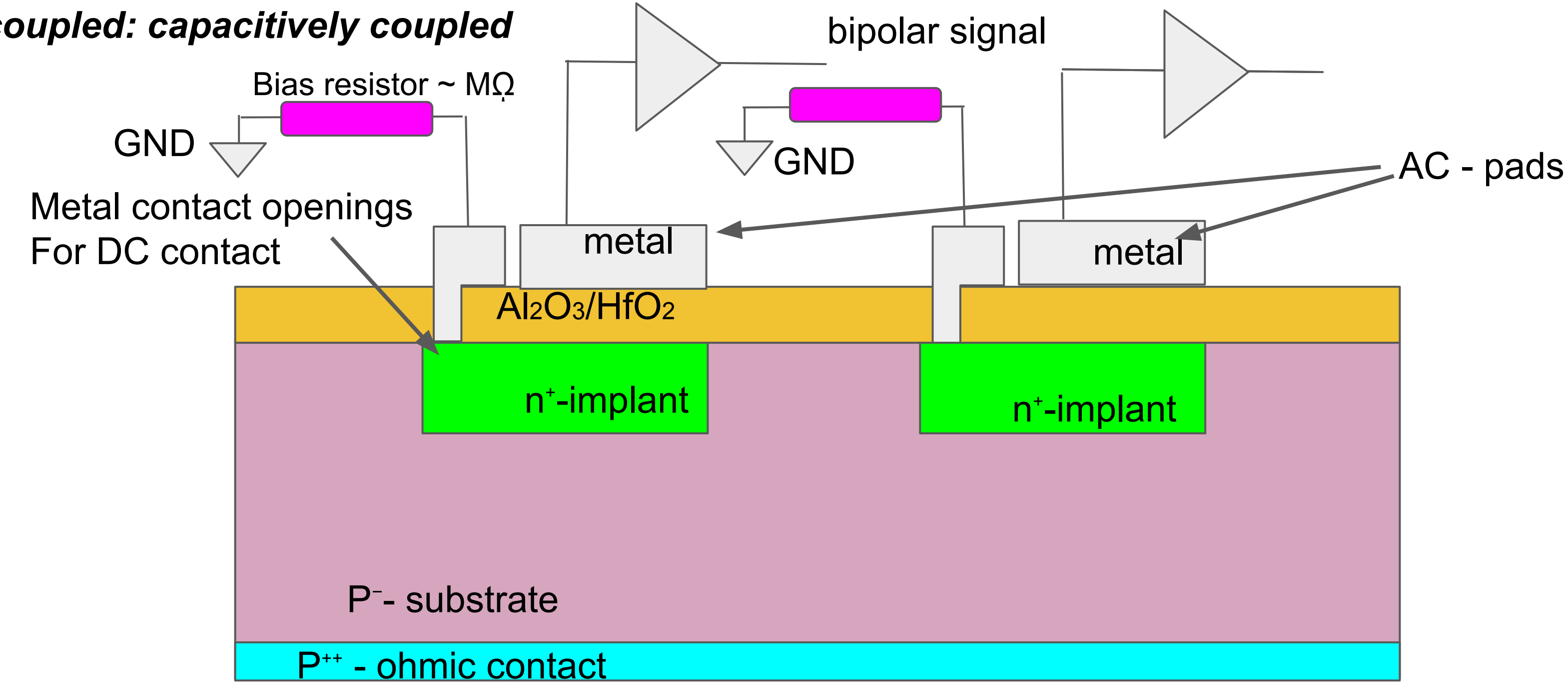


2 adjacent DC-pixels [not to scale]

For Future collider experiments

mitigate challenges associated to increment in leakage current

AC-coupled: capacitively coupled



2 adjacent DC-pixels [not to scale]

Main aspects of the studies based on measured samples

Initial study : **Characterization of Heavily Irradiated Dielectrics for Pixel Sensors Coupling Insulator Applications [https://doi.org/10.3389/fmats.2021.769947]** —---------------> 10 MeV proton irradiation: Accelerator laboratory in University of Helsinki, Finland

- Study the dielectric and interface (oxide charges) : MOS capacitors, MOSFET
- IV-CV & e-TCT (proton irradiation) : Dielectric implemented in the AC-coupled pixel sensors fabricated on MCz-Si

----> coherence studies with simulation as well

Further results on gamma irrad: —-> **Characterisation of Gamma-irradiated MCz-Silicon Detectors with a High-*K* Negative Oxide as Field Insulator, Jinst 2022 - - - - - > further investigation on defect characterisation**
2018,2020 samples irradiated with Co-60 @ RBI (Zagreb, Croatia)

- CV measurements of MOS capacitors: to study the concentration of oxide and mobile charges due to gamma irradiation —-> interesting to study the surface damage
- Transfer characteristics of MOSFETs: to determine the oxide and interface traps with increase in dose.
- Edge-TCT: Electric field studies of diode and AC-coupled pixel detectors (gamma irradiated)
- IV and CV measurements of diodes and AC-pixel detectors : includes interpixel resistance studies.

Proton irradiated MOS capacitors

- Shift in the flat-band voltage from ideal condition : estimation of effective oxide charges

$$N_f = -\frac{\Delta V_{fb} \times C_{ox}}{charge}$$ [Measured from CV at 1 kHz]

- Hysteresis in sweep from inversion to accumulation and vice-versa : estimation of mobile interface traps

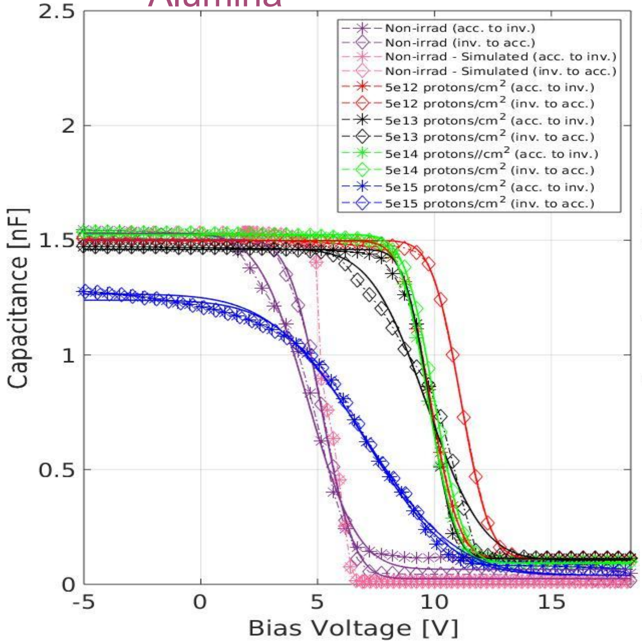
Higher susceptibility observed in Hafnia + alumina samples to irradiation

- Qeff oxide charges : Hafnia + alumina << Alumina (conformity to simulated results) - non irradiated

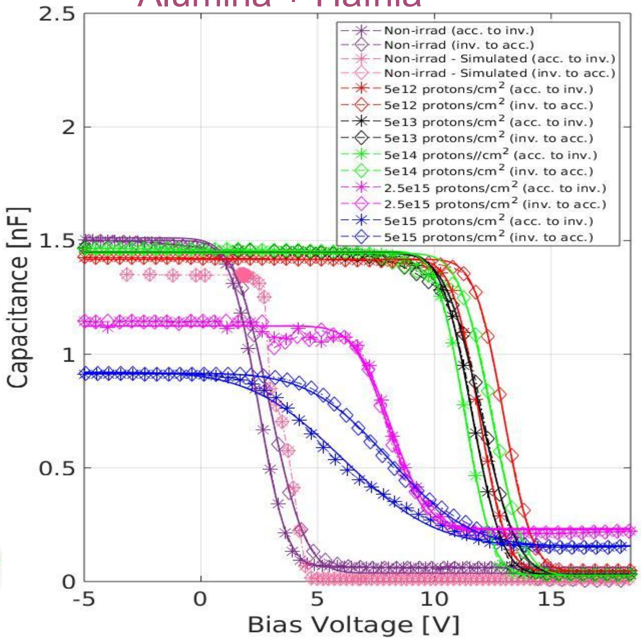
- Higher ΔV_{fb} with increasing fluence ------> Negative charge accumulation (as expected) ------> More positive voltage to compensate negative interface charge to attain flat band condition.

- Effective oxide charges increases by factor of ~ 2-4 with fluence upto 5e14 protons/cm²

Alumina



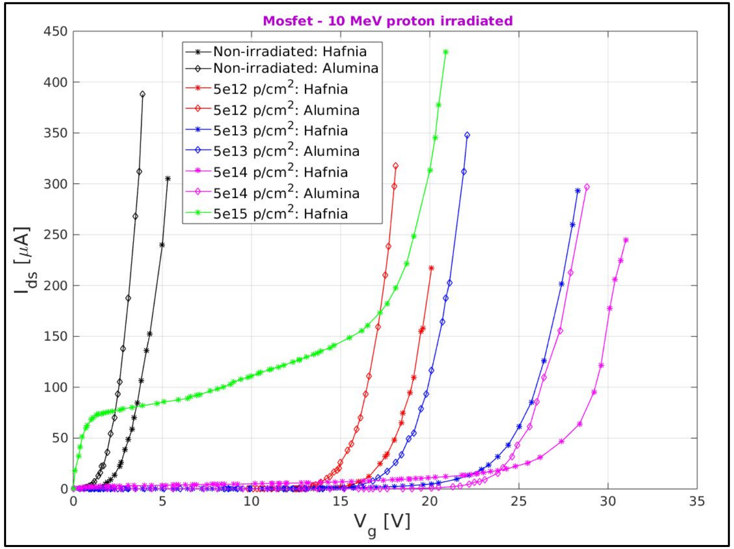
Alumina + Hafnia

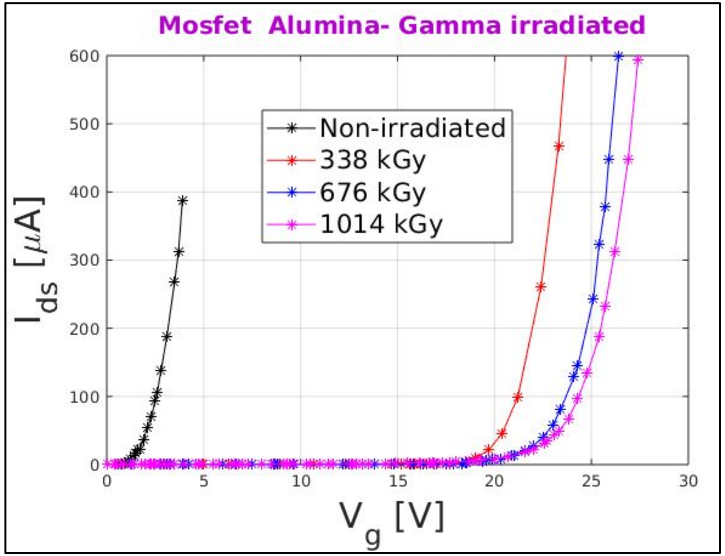


Proton irradiated MOSFET

- Threshold voltage determined from the point of inflection in drain-source current versus gate voltage curve (at constant drain-source voltage)
- Shift in threshold voltage - parameter to observe negative charge accumulation in MOSFETs.
- I (drain-source) increases by ~2 orders of magnitude when irradiated upto 5e15 protons/cm² ---> expected due to negative shift in the threshold voltage
- Similar trend in shift of threshold voltage is observed in gamma irradiated samples

Drain-source voltage fixed @ 0.1 V ---> (250 micron channel length) ---> Low field regime (<< 5 V/micron)
Expected to observe high shift in threshold for high fluence irradiation





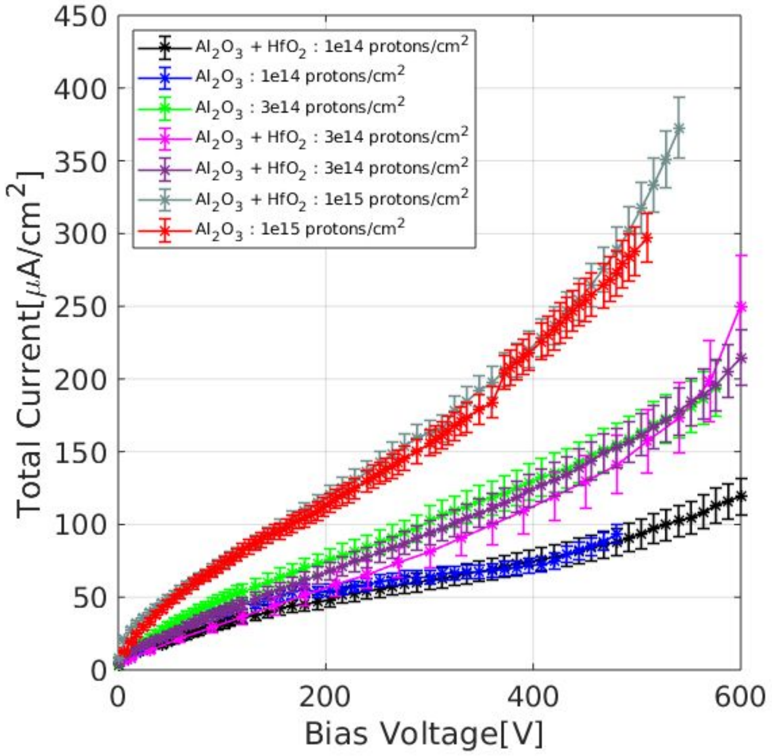
* Gamma irrad. Using Co-60 source at the Radiation Chemistry and Dosimetry Laboratory at the Ruder Boškovic Institute in Zagreb, Croatia

Note: conversion factor not scaled for SI

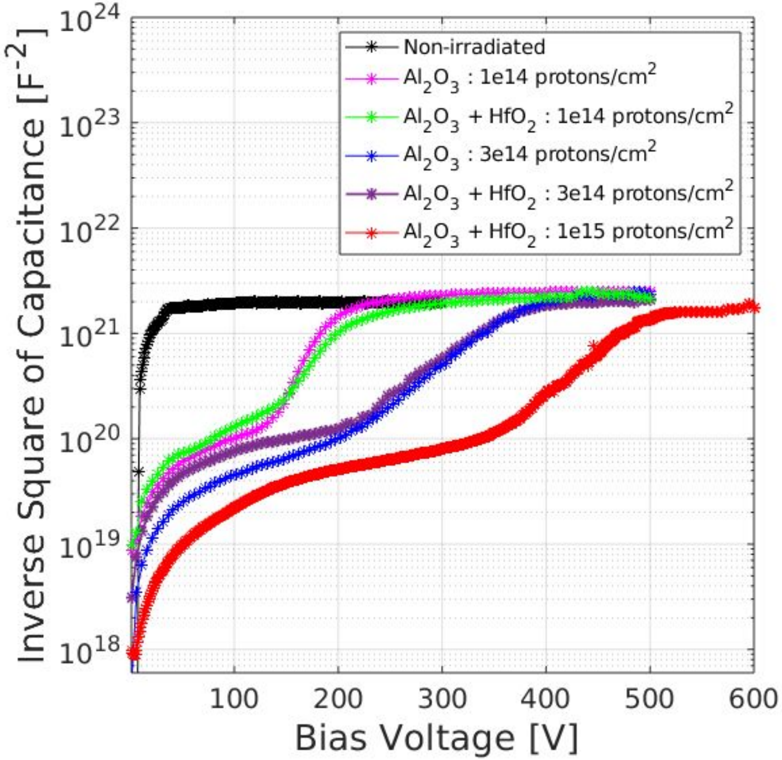
Proton irradiated AC coupled pixel devices - IV & CV characterization

- Full depletion voltage attainable for hafnia irradiated samples able to sustain high bias before undergoing breakdown.
- IV : total dark current increases by factor ~ 2.5.

[Measured @ -15ºC]



[Based on CV measurements @ 1 kHz]

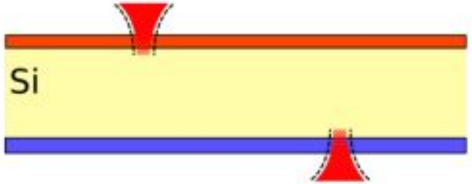


Transient Current Technique (TCT)

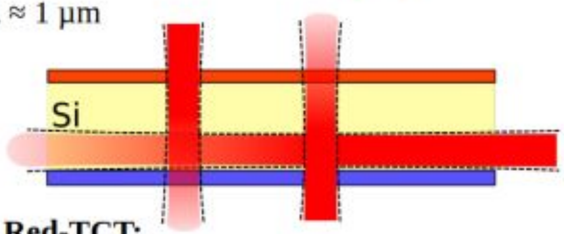
TPA-TCT measurements performed at SSD lab (CERN) & ELI (Prague)

Single Photon Absorption-TCT

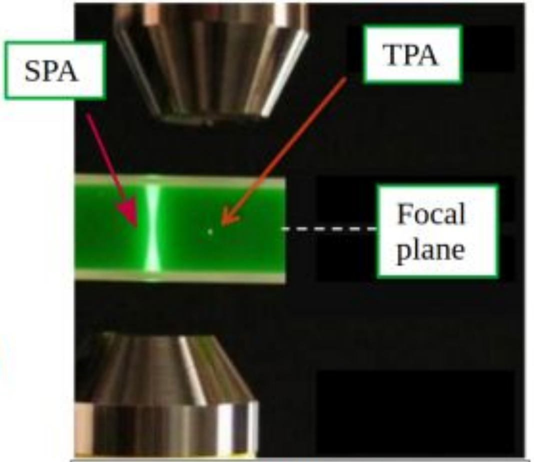
λ ≈ 700 nm



λ ≈ 1 μm



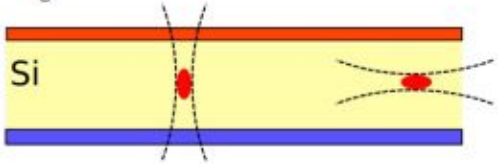
- **Red-TCT:**
  - Full light absorption in ~3-10 μm depth
  - optimal for e/h separation
  - Laser can be micro focused to < 5 μm: **2D resolution**
- **IR-TCT:**
  - To mimic MIPs (continuous laser absorption)
  - Normally 6-10 μm **2D resolution**
  - Edge injection in thick devices allows a depth study



Photography: **Ciceron Yanez**, University of Central Florida

Two Photon Absorption-TCT

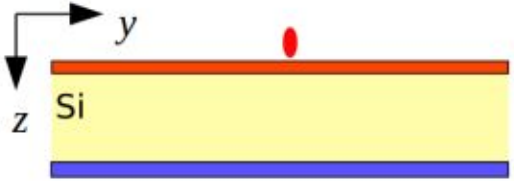
$\lambda > E_g$



- **TPA** excites charge carriers into the CB
- Non-linear effect, depends quadratic on the intensity

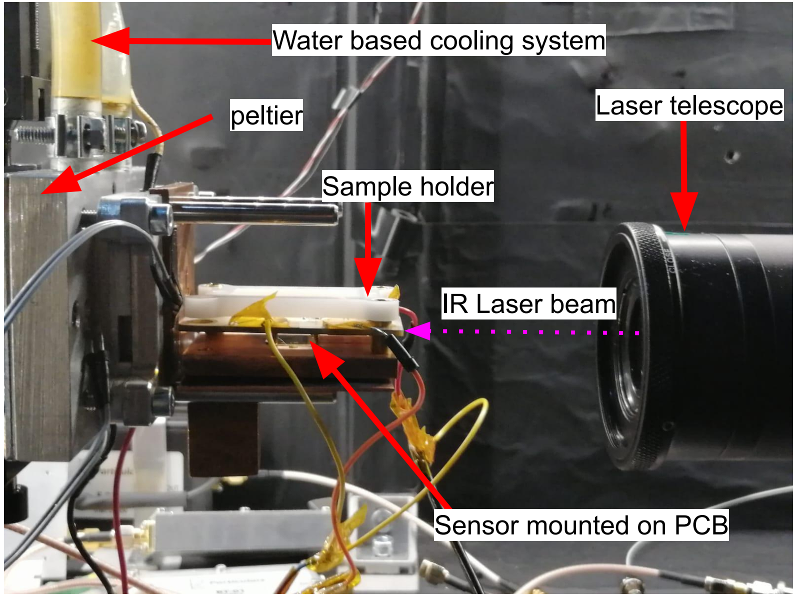
→ main excitation around focal point

- **3D resolution** tool to scan silicon devices:



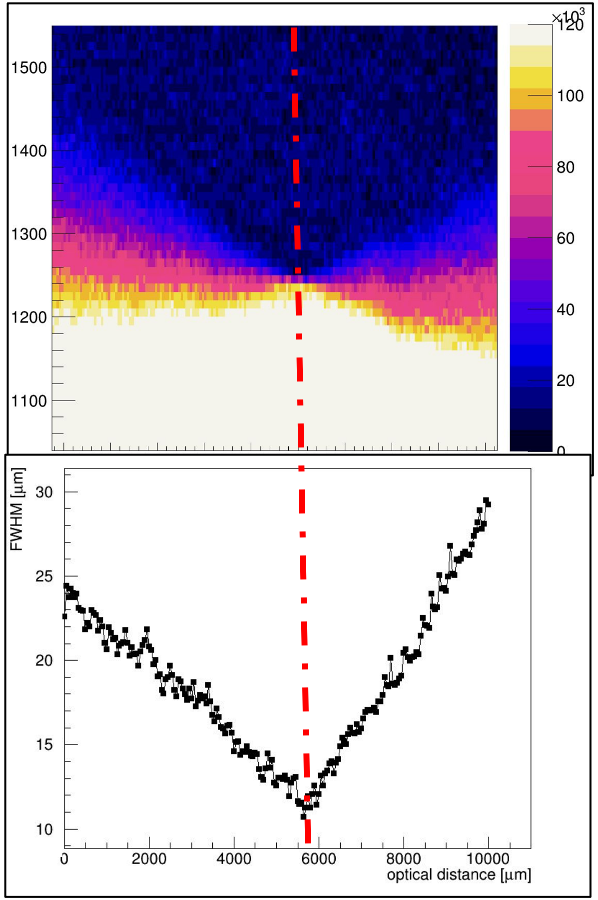
IR laser characterization (Edge-TCT)

Set-up Particulars based



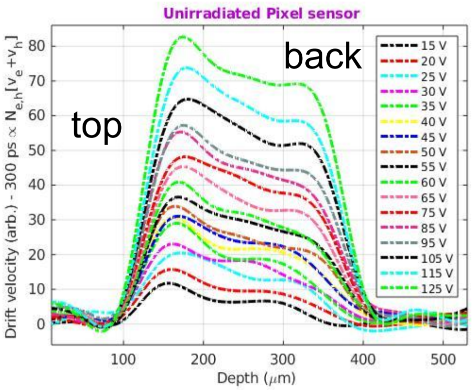
- All measurements performed at -15⁰C
- Focus scan performed for every sample.
- IR Laser intensity kept constant : 60 %, repetition rate of 1 kHz : equivalent to 5-10 MIPs
- Bias provided from backplane. Total current read out from SMU.
- Signal read-out from front bias line, Guard ring grounded.

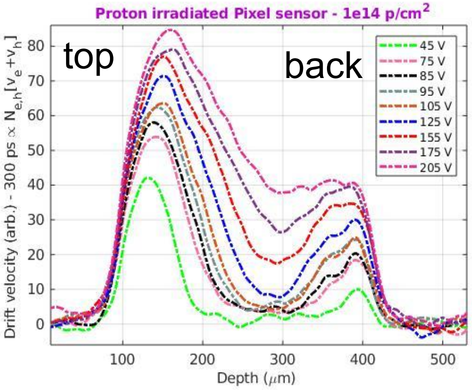
Focus scan - ACpixel -Hafnia

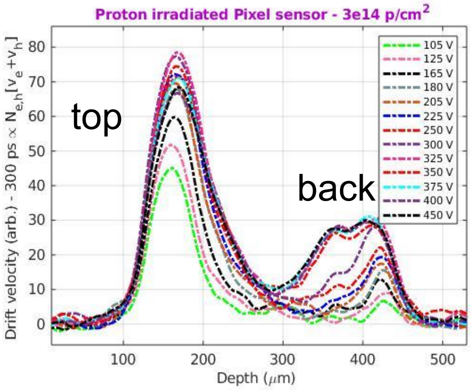


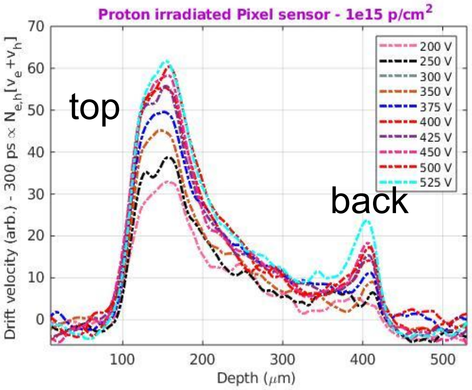
Laser beam size: ~ 12 µm from focus scan

Proton irradiated AC coupled pixel devices
- Drift velocity vs depth profiles









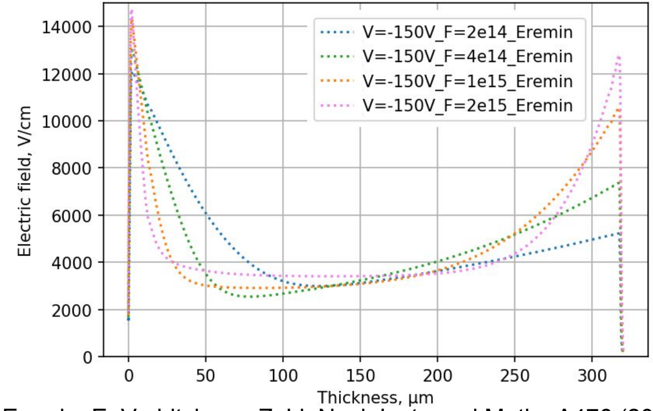
Electric field profile produced using prompt current method: Drift velocity proportional to integrated current over rise time of the signal ~300 ps ---> charge generated within certain depth of the the scan.

- Double- junction effect (double peak) distinct at very high fluences of 3e14 and 1e15 p/cm².
- Double peak less prominent for high bias sweeps for 1e14 p/cm² sample.

-> reason for double peak : deep level traps of charge carriers due to irradiation.

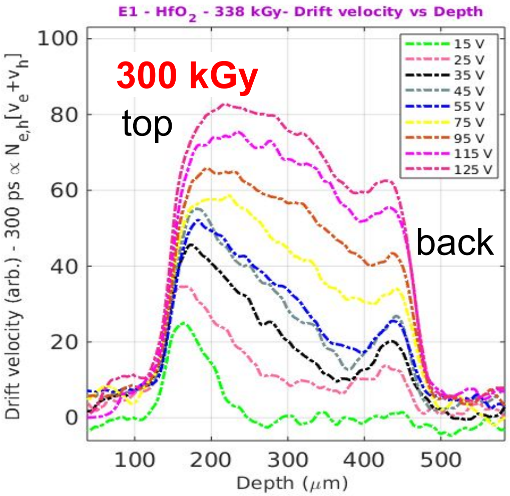
Coherence study with TCAD simulation:

- Consistency in double peak due to trapping of charges observed in Eremin model.



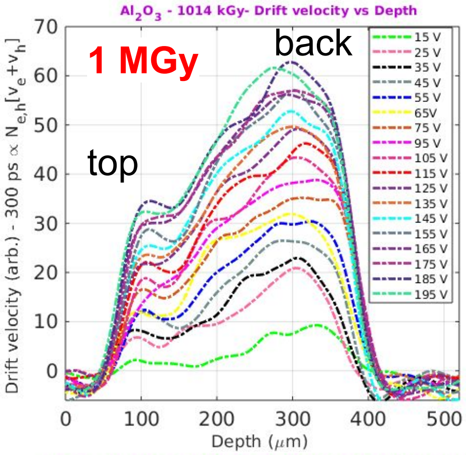
[ref: V. Eremin, E. Verbitskaya, Z. Li, Nucl. Instr. and Meth., A476 (2002) 556]

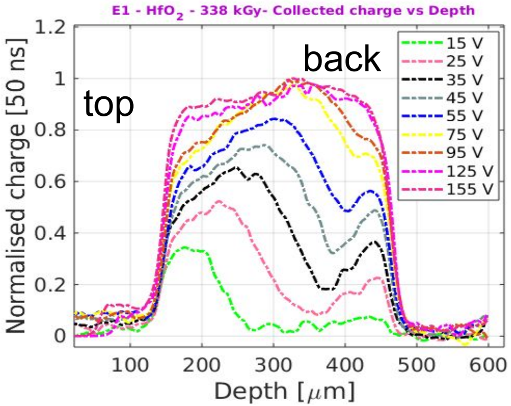
Gamma irradiated - 2021 Co-60 irrad [RBI Zagreb]

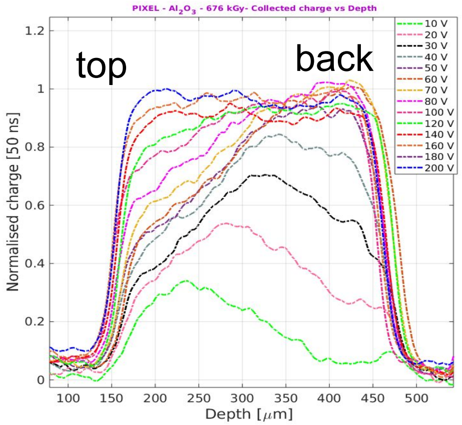


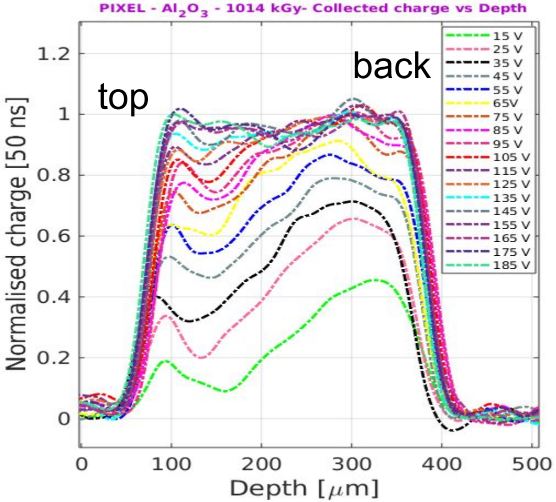
Why electric field profiles look like Space charge sign inversion of the detector bulk at 1 MGy?

- Possible explanation could be influence of positive oxide charge in alumina ?
- Defect concentration higher than hole concentration..possibly lead to SCSI ?



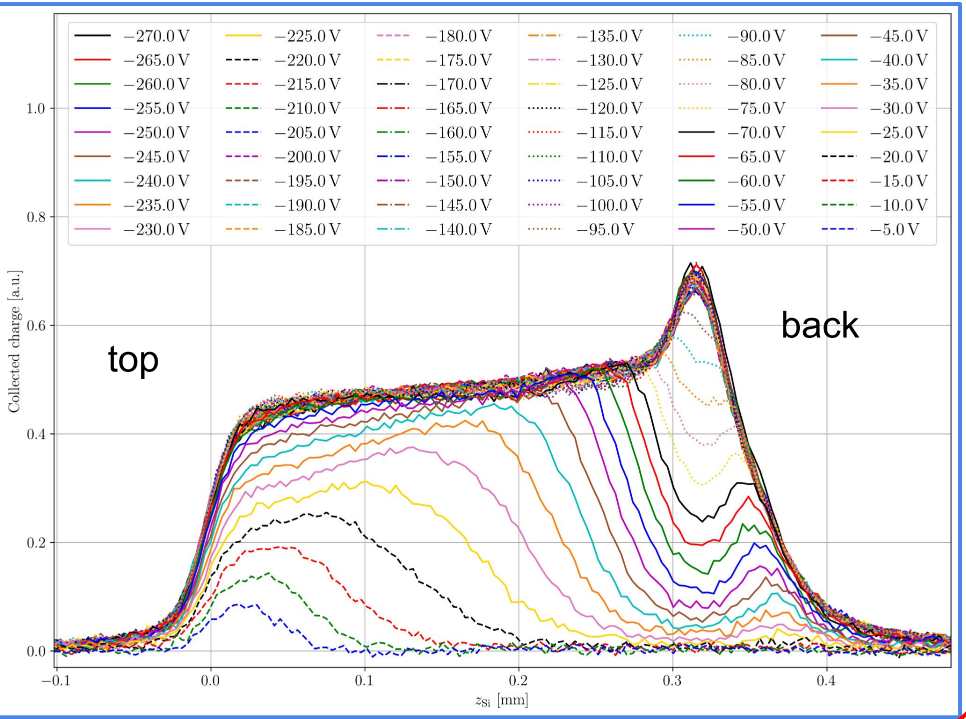


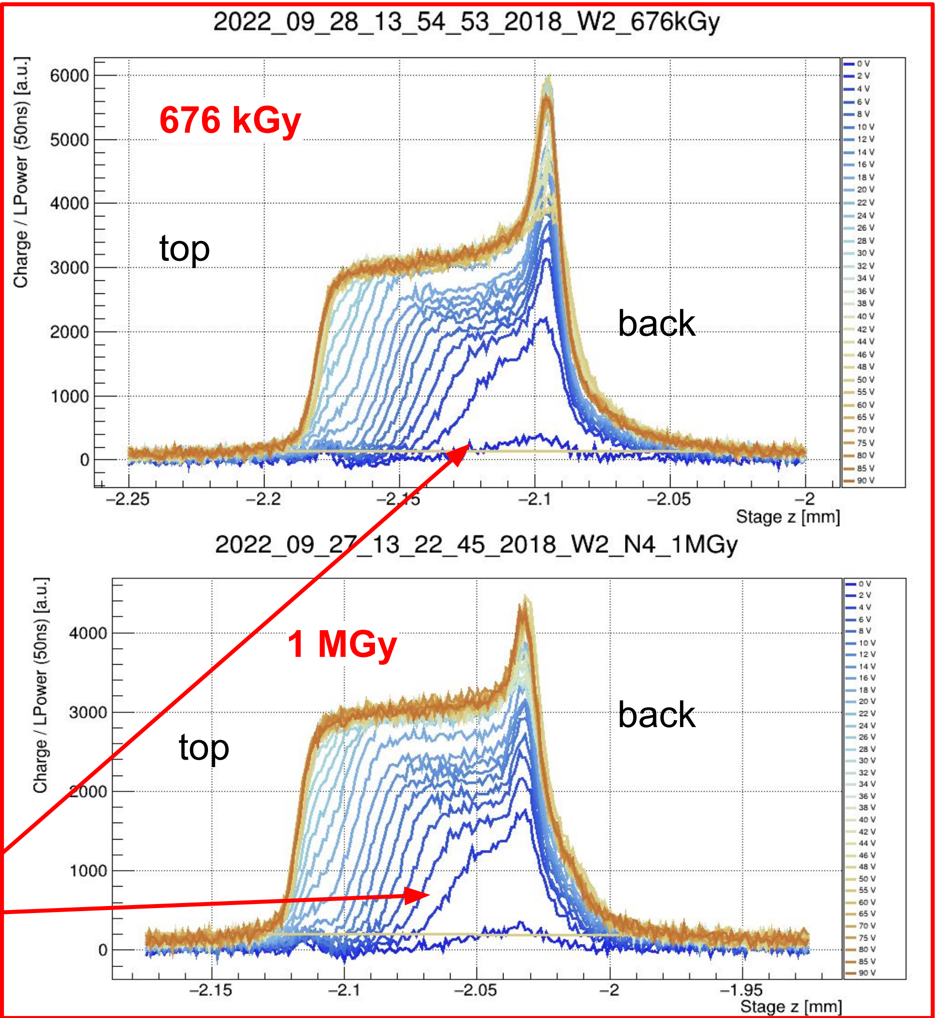




Coherent studies to Two-photon absorption - TCT studies at SSD lab in CERN

Non-irradiated sample: depletion from implant





Gamma irradiated sample: depletion from backplane ohmic contact - - - - - > SCSI of the bulk (due to shallow defects)

Summary and Outlook

- Use a-Al_2O_3 (negative charged oxide) as field insulator, instead of traditionally used p-stop/p-spray, to electrically isolate segmented implants
- Study the radiation hardness tolerance of dielectrics show samples with Hafnia possess-
  - improved sensitivity to fluence in MOS devices
  - less prone to an early breakdown in pixel detectors.
- Possibility to study electric field properties of irradiated devices: both hadron and gamma irradiation with SPA and TPA -TCT measurements.

Possible studies:

- Defect characterisation of MOS devices to study the impact of surface damage
  - Deep-level transient spectroscopy
  - Thermally stimulated current

- Study the origin of native defects generated during the thin film deposition process - origin of negative charges remains unclear in a-Al_2O_3

- Optimisation of hydrogen impurity concentration - most common in metal oxides : possibly dependent on precursor (hydrogen + ozone) used for ALD process ?

Back- up

Main aspects of the studies based on measured samples

Comparison based on the characterisation of devices with :

- Alumina
- Alumina + Hafnia

Hafnia ~ 2.7 times higher dielectric constant than alumina : provides higher capacitive coupling, insulation and improved radiation hardness

Alumina thickness = 84 nm
Hafnia thickness = 62 nm

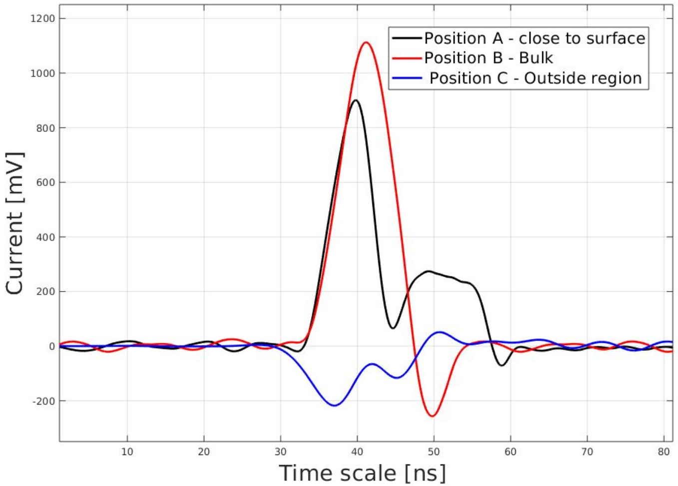
EOT (calculated wrt SiO_2) reduced by ~54 nm with hafnia (high dielectric constant) compared to alumina with same dielectric thickness ------> enables to achieve similar capacitance and yet increase the insulation resistance

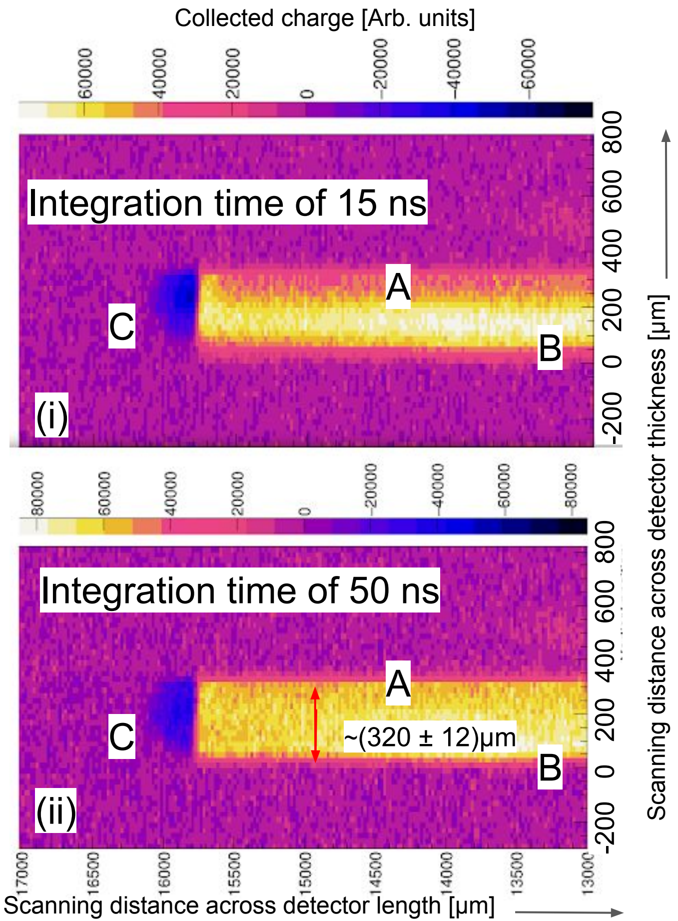
- Study the dielectric and interface (oxide charges) : MOS capacitor + MOSFET devices → proton irradiation performed at Accelerator Laboratory in University of Helsinki -----> 10 MeV protons, Hardness factor (NIEL) : 3.87 - theoretical value for silicon

- IV-CV & e-TCT (proton irradiation) : Dielectric implemented in the AC-coupled pixel sensors fabricated on MCz-Si

  ----> coherence studies with simulation as well

AC coupled pixel devices non-irradiated - IR laser characterization (Edge-TCT)

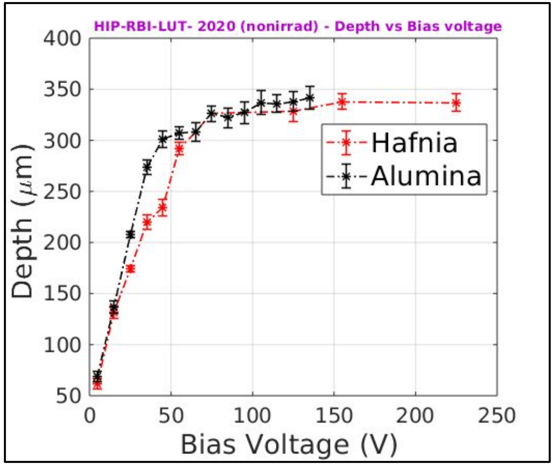


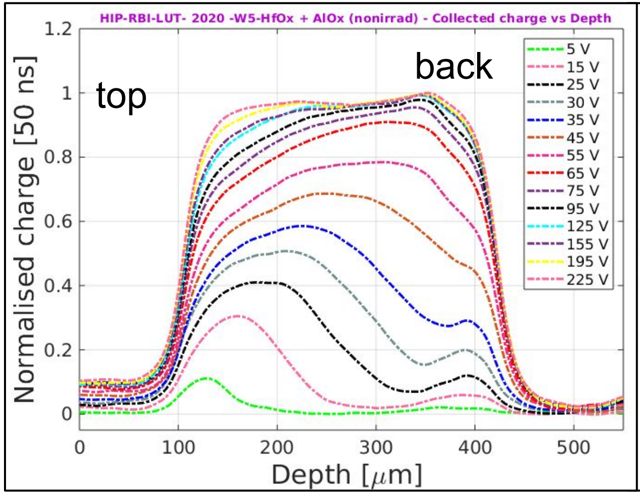


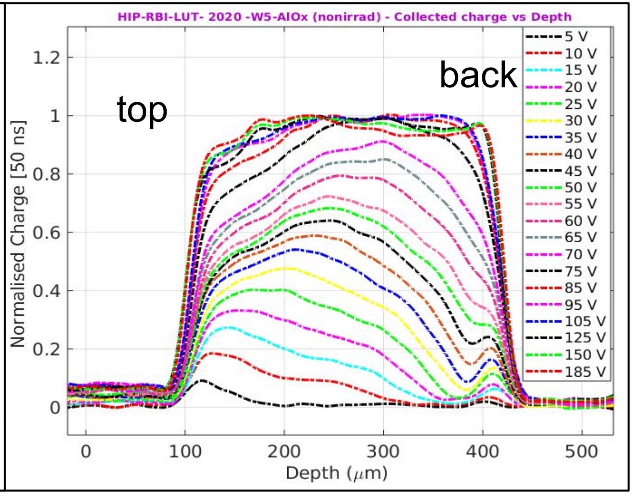
- **Position A** : Closer to the pixel side (in the high electric field) the signal is a superposition of currents induced by the drift of electrons and holes
- **Position B** : Laser projection into the bulk (grows), the contribution of electrons becomes wider and at the same time the long tail due to hole drift becomes shorter.
- **Position C** : Negative signal observed within the guard ring region ---> grounded. Due to 'cross-talk' with the active region as they share a common ohmic contact (back-plane)

AC coupled pixel devices non-irradiated - charge collected vs Depth

- Full depletion of the active thickness (320 micron) of bulk attained at ~75 V, irrespective of the nature of the dielectric.
- Saturation of collected charge (normalised to maximum value) observed at bias beyond full depletion in depth profiles
- Systematic uncertainty of ± 10 μm arising from laser width.



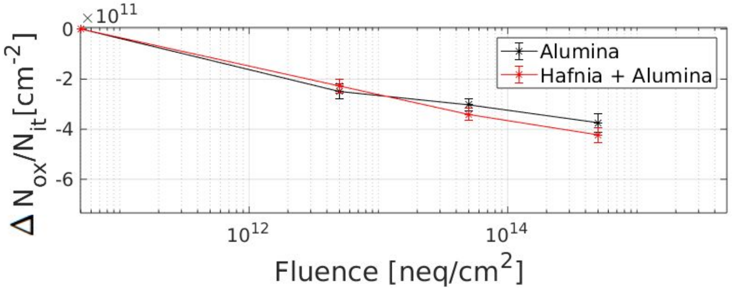




Inference based on characterisation of irradiated dielectrics :

ΔVth = ΔV(oxide charge) + ΔV (interface trapped charges)

ΔNo/Ni = ΔVth x Oxide capacitance / charge

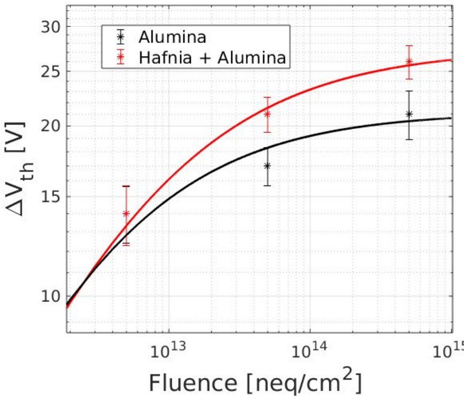


- ΔV (interface trapped charges) dominates at fluences upto 5e14 protons/cm² ---> large concentration of interface traps decrease mobility of charge carriers ----> increase in threshold voltage
- ΔV(oxide charge) dominates at fluences above 5e14 protons/cm² ----> leads to increase in leakage current

Fit for ΔVth vs Fluence:

For devices operational in Low field regime

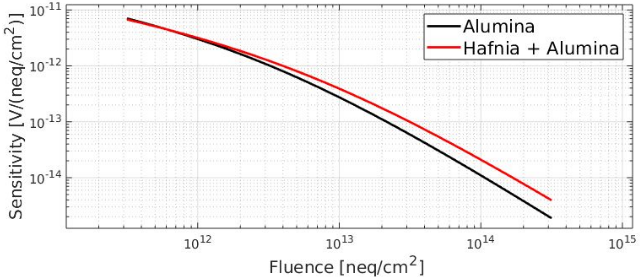
$$\Delta V_{th} = a - \frac{a}{1 + bD^c}$$



Sensitivity can be calculated by using the fit parameters

Sensitivity is the change in threshold voltage with respect to the fluence

Higher sensitivity to higher doses observed in case of hafnia samples



In congruous with MOS Capacitors + simulation results (upto 5e14 p/cm²)