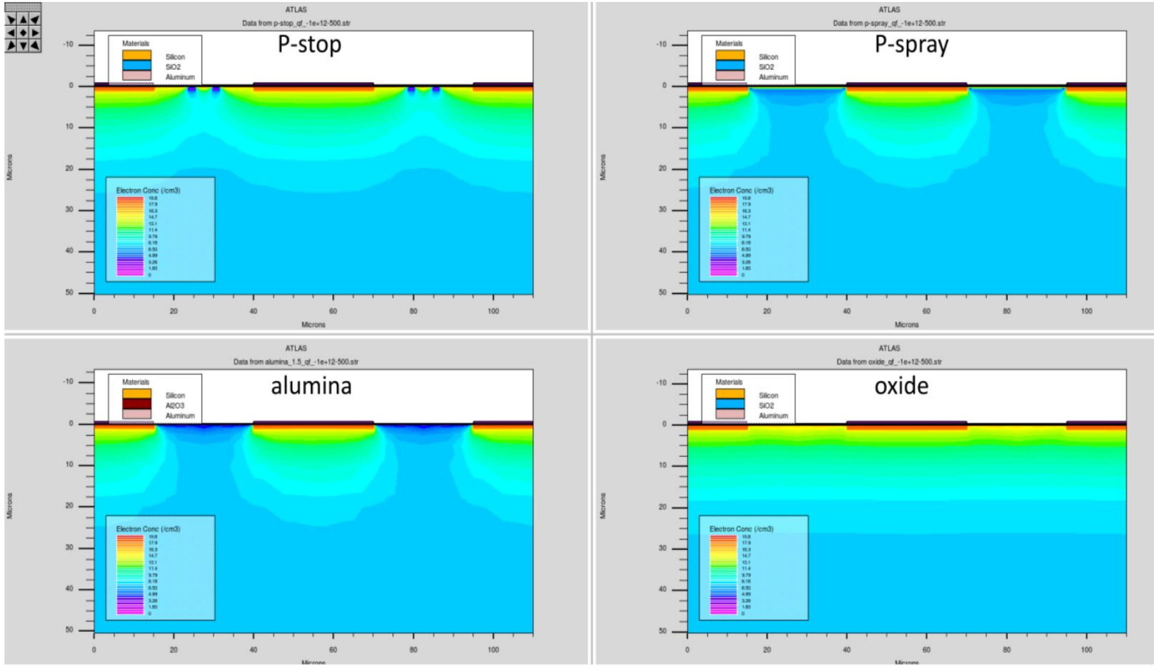
Comparison studies of heavily irradiated dielectrics for AC-coupled pixel detectors on MCz silicon

- **S. Bharthuar**, M. Golovleva, M. Bezak, E. Brücken, A. Gädda, J. Härkönen, A. Karadzhinova-Ferrer, S. Kirschenmann, N. Kramarenko, P. Luukka, J. Ott, E. Tuominen

Motivation

- Use of P-type Si with segmented n^+-implants ⟶ e^- with higher mobility are collected



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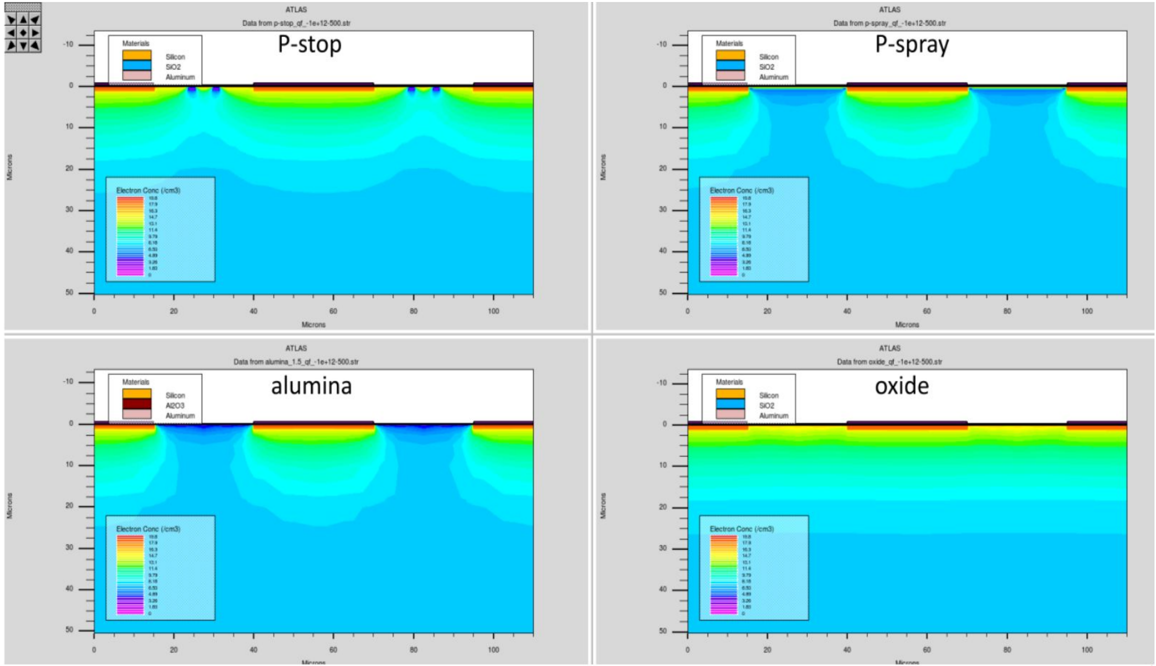

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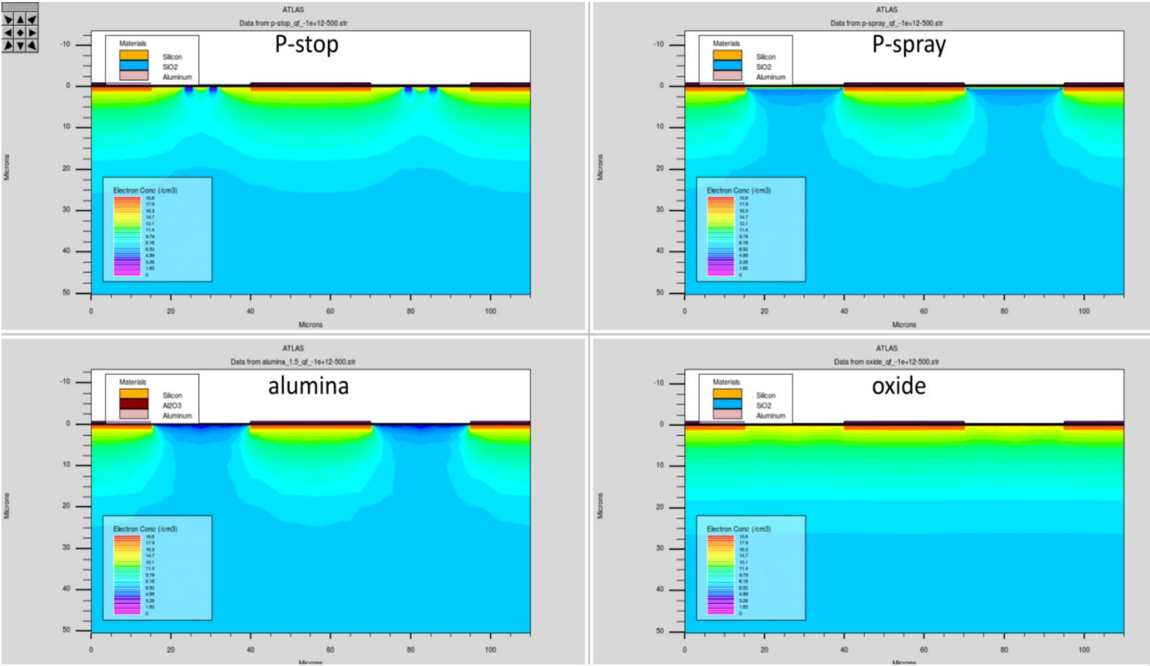

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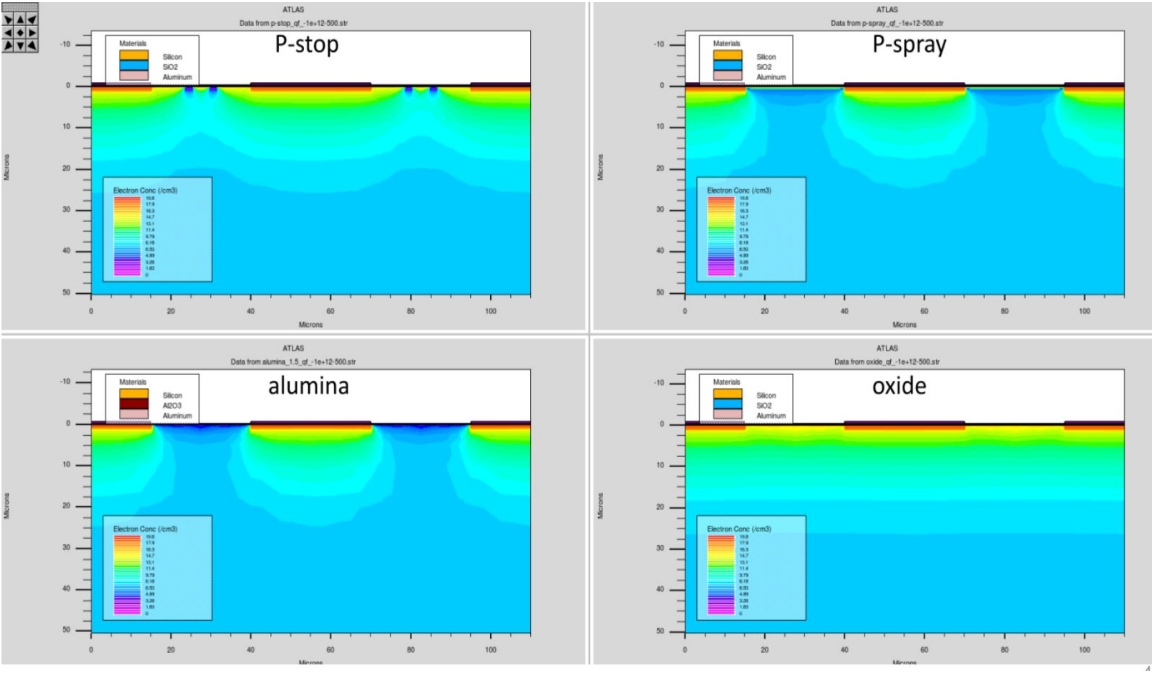


Alternatively, use of negative oxide like Al_2O_3 or HfO_2 -

a) good dielectric constant ----> higher oxide capacitance
b) high negative charge (~ 10^{-11} - 10^{-13} cm^{-2})

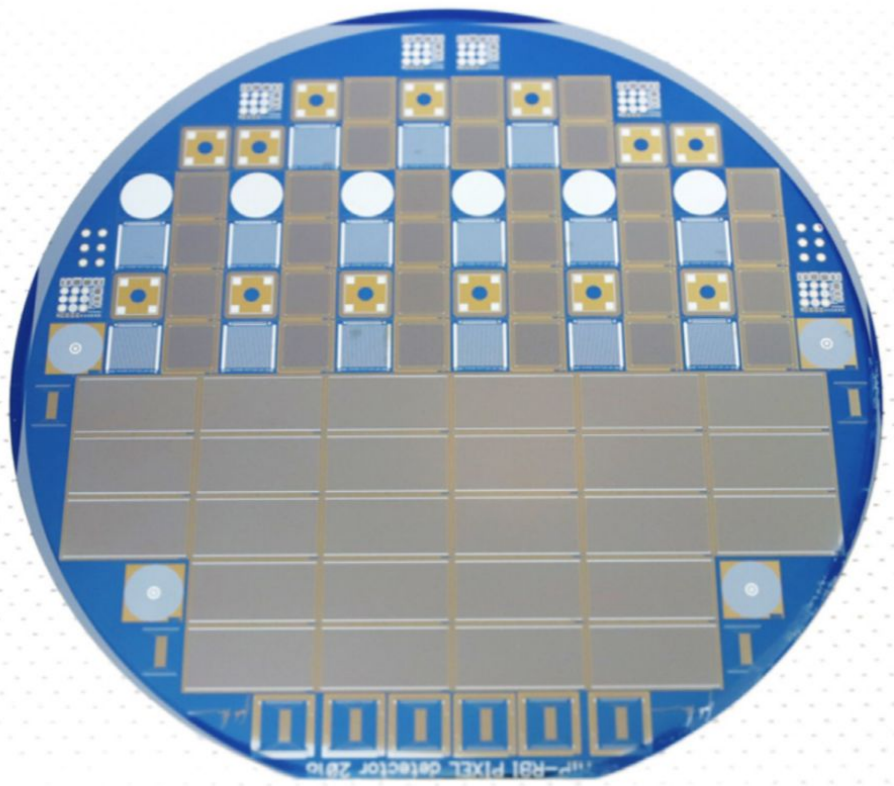
Deposited using Atomic Layer Deposition (ALD) technique

- 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 : 6-8 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

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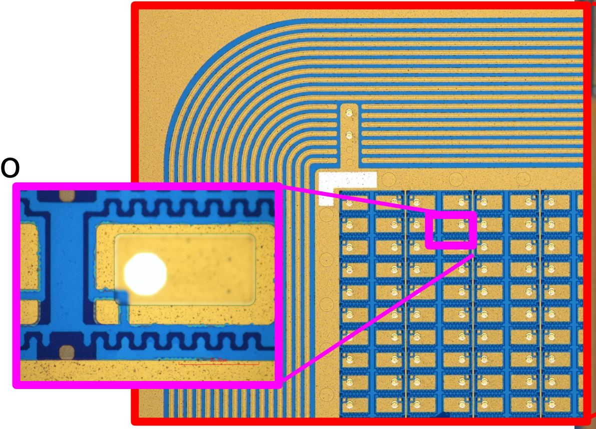
p-type MCz 6” Si, resistivity : 6-8 kΩcm, thickness: 320 μm

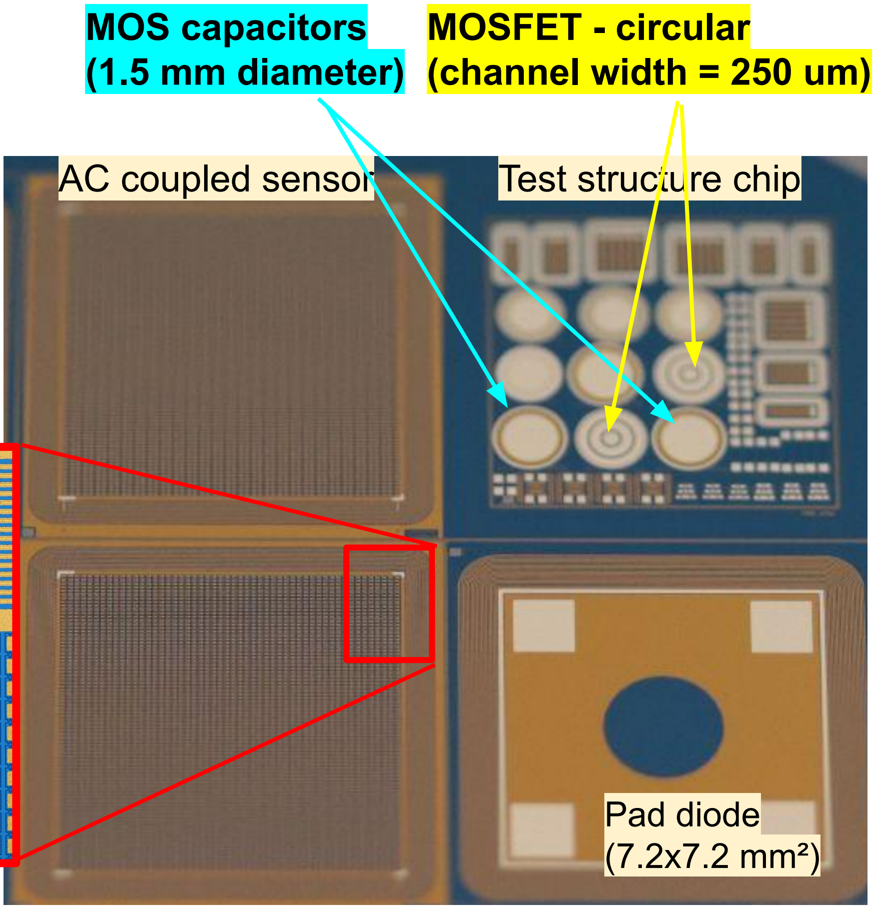
- Main devices characterised for this study are:

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





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

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

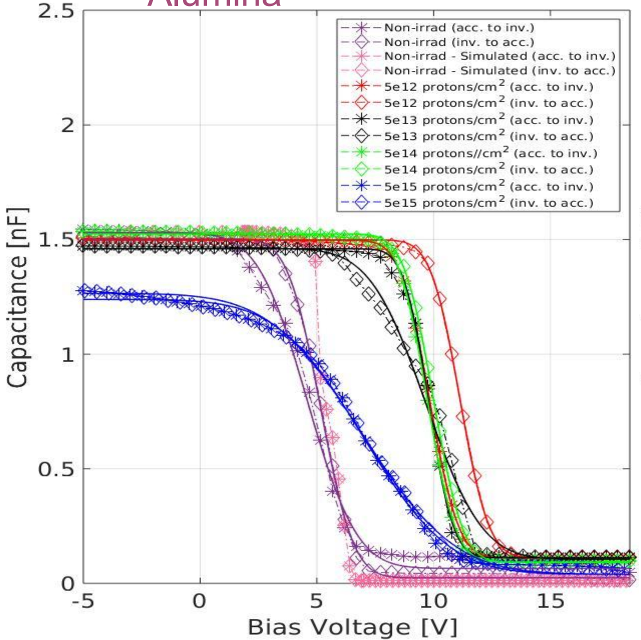
Higher susceptibility observed in Hafnia + alumina samples to irradiation

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

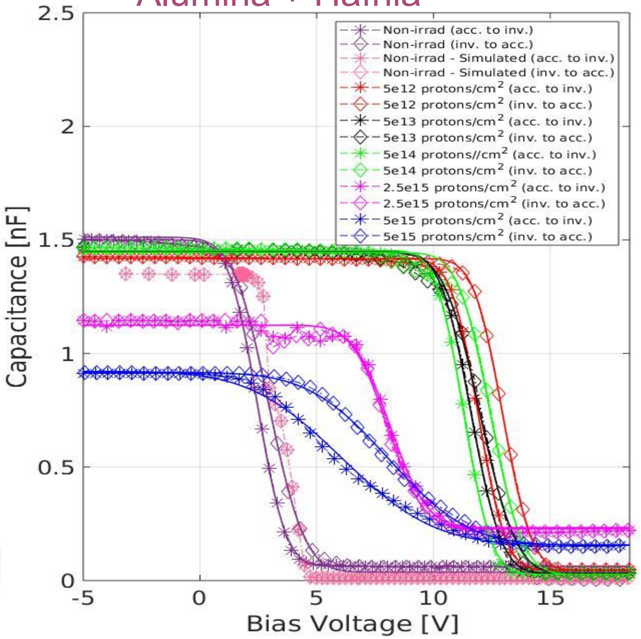
- Higher ΔV_{fb} with increasing fluence ------> Negative charge accumulation (as expected) ------> More positive voltage to compensate negative interface charge to attain flat band condition.

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

Alumina



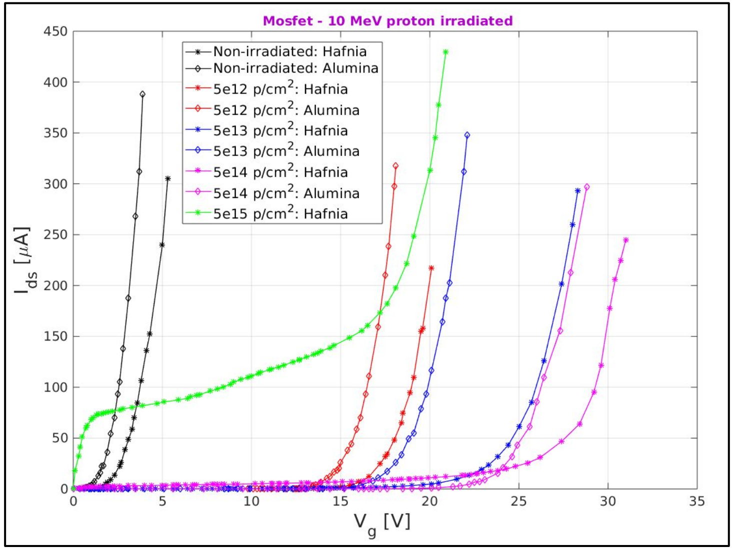
Alumina + Hafnia

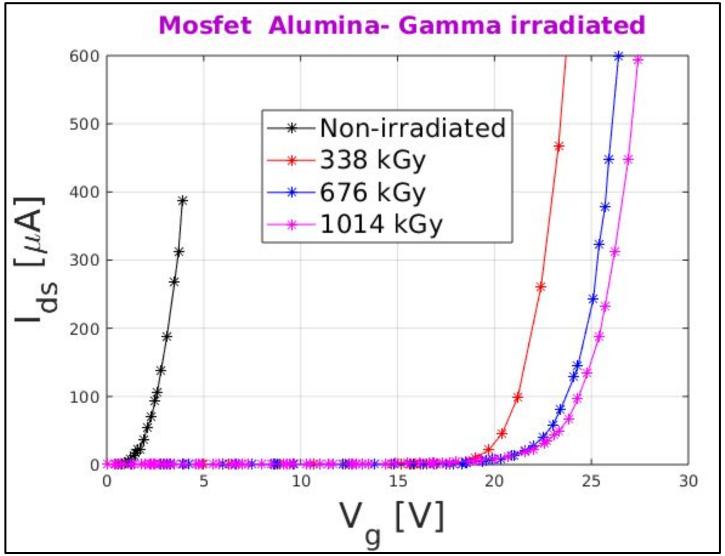


Proton irradiated MOSFET

- 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





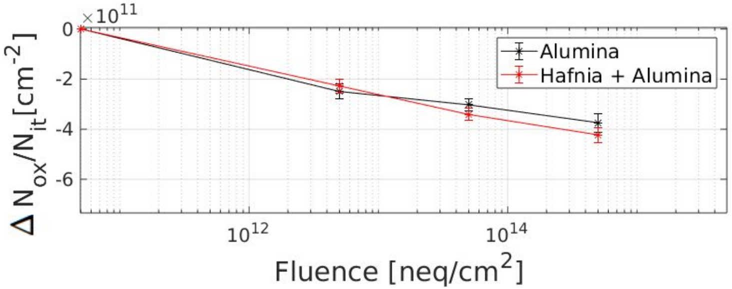
* Gamma irrad. Using Co-60 source at the Radiation Chemistry and Dosimetry Laboratory at the Ruder Boškovic Institute in Zagreb, Croatia

Note: conversion factor not scaled for SI

Inference based on characterisation of irradiated dielectrics :

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

ΔNo/Ni = ΔVth x Oxide capacitance / charge

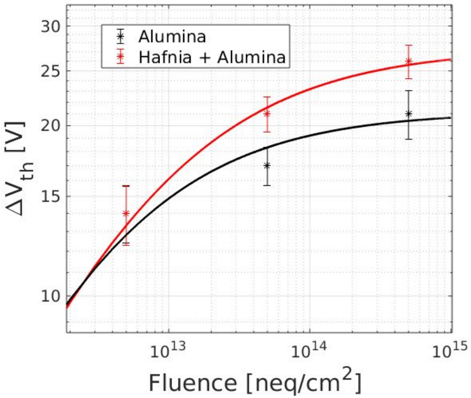


- ΔV (interface trapped charges) dominates at fluences upto 5e14 protons/cm² ---> large concentration of interface traps decrease mobility of charge carriers ----> increase in threshold voltage
- ΔV(oxide charge) dominates at fluences above 5e14 protons/cm² ----> leads to increase in leakage current

Fit for ΔVth vs Fluence:

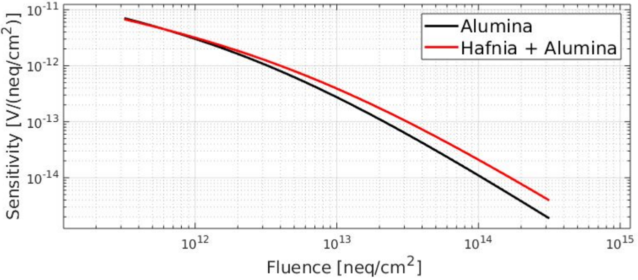
For devices operational in Low field regime

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



Sensitivity can be calculated by using the fit parameters

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

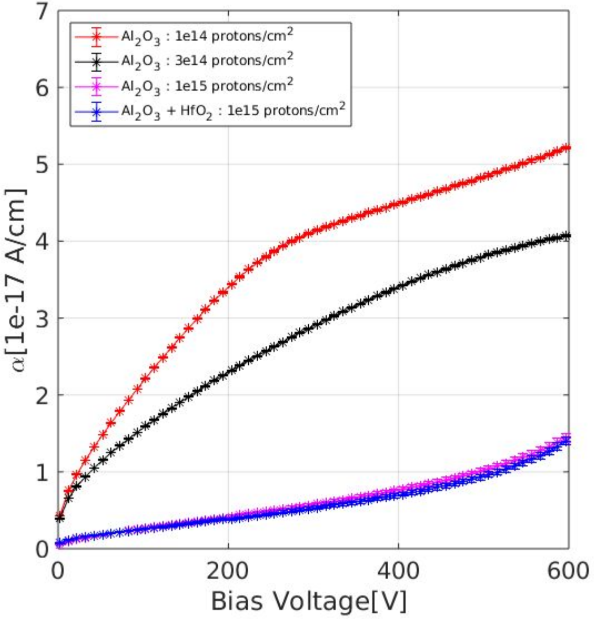


Higher sensitivity to higher doses observed in case of hafnia samples

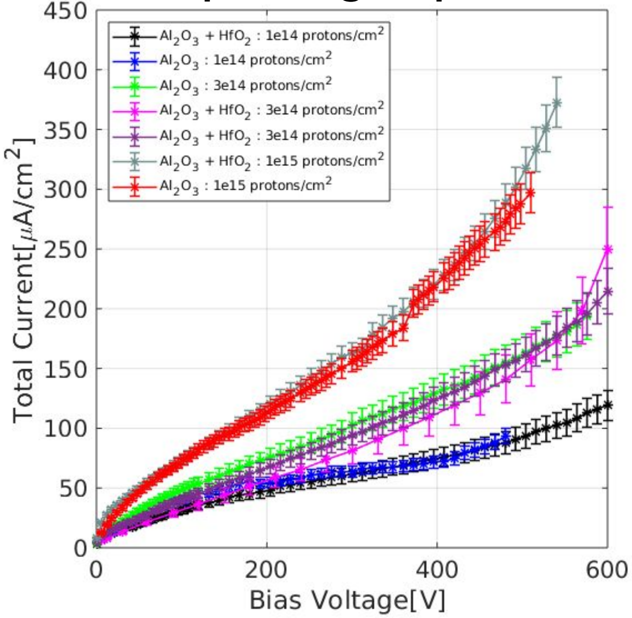
In congruous with MOS Capacitors + simulation results (upto 5e14 p/cm²)

Proton irradiated AC coupled pixel devices - IV & CV characterization

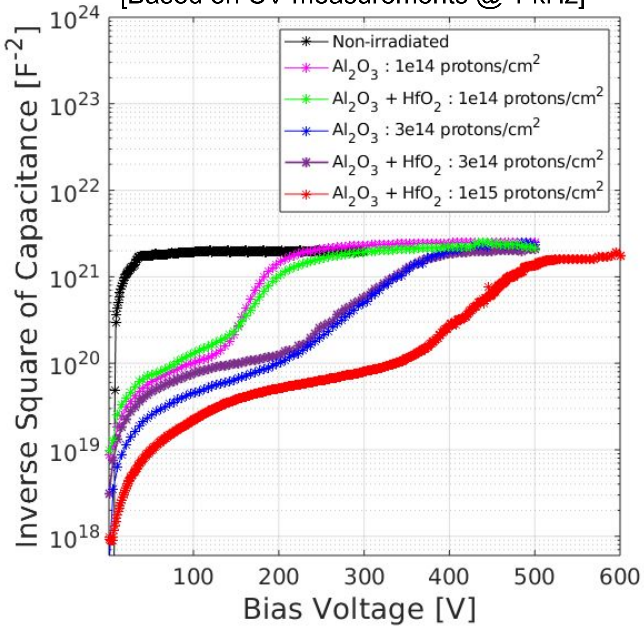
- Full depletion voltage attainable for hafnia irradiated samples able to sustain high bias before undergoing breakdown.
- IV : total dark current increases by factor ~ 2.5.
- League current damage factor (α) : for samples annealed at RT for 1 day. Value within 2-5e-17 A/cm for low fluence (1e14 & 3e14). α decreases upto 1e-17 A/cm before breakdown.



[Measured @ -15ºC]

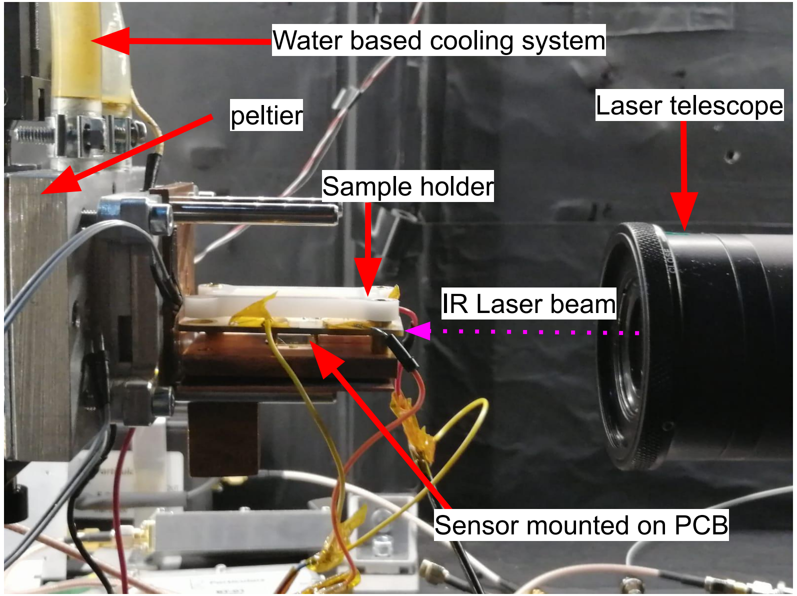


[Based on CV measurements @ 1 kHz]



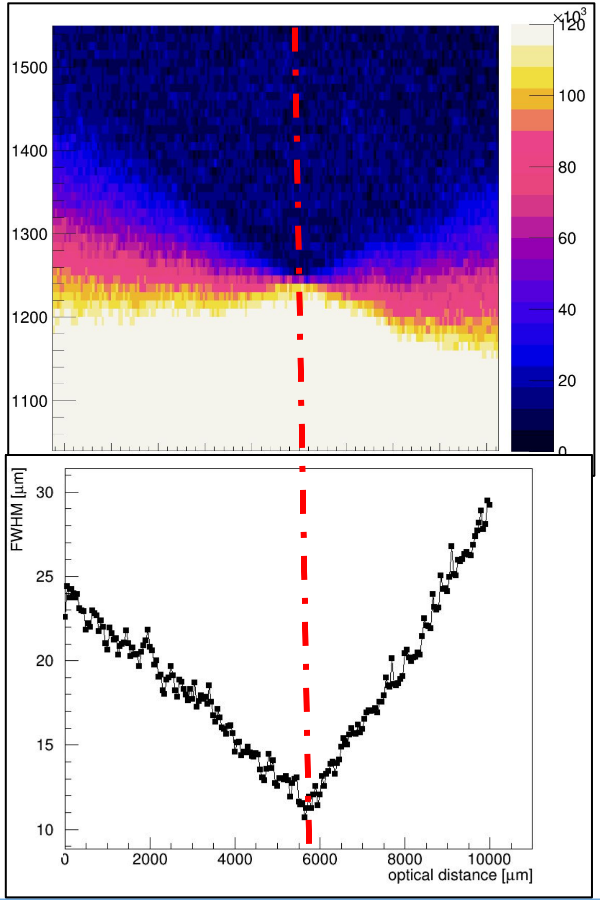
IR laser characterization (Edge-TCT)

Set-up Particulars based



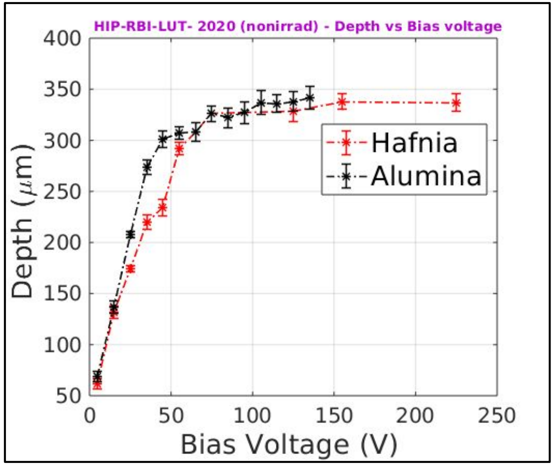
- All measurements performed at -15^{0}C
- Focus scan performed for every sample.
- IR Laser intensity kept constant : 60 %, repetition rate of 1 kHz : equivalent to 5-10 MIPs
- Bias provided from backplane. Total current read out from SMU.
- Signal read-out from front bias line, Guard ring grounded.

Focus scan - ACpixel -Hafnia

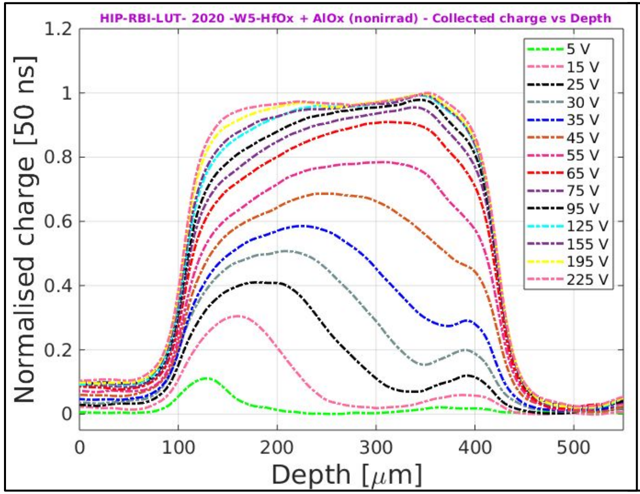


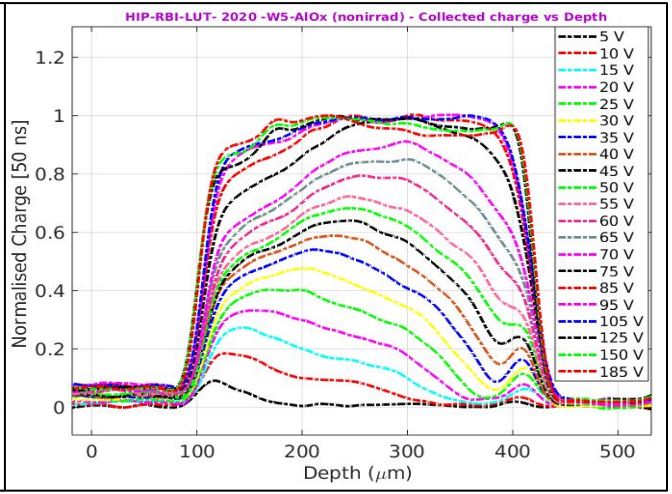
Laser beam size: ~ 12 µm from focus scan

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



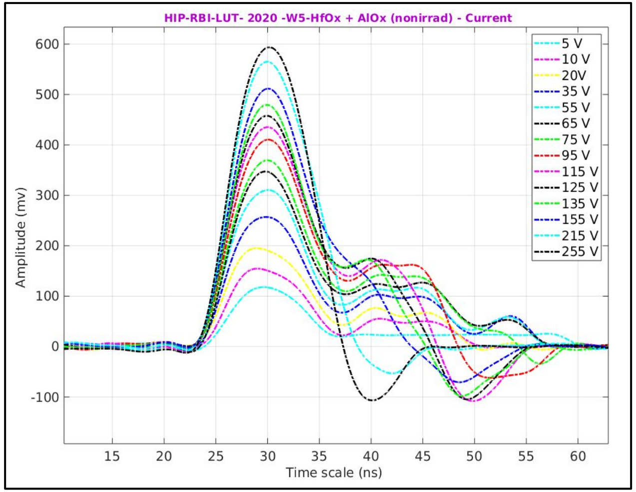
- Full depletion of the active thickness (320 micron) of bulk attained at ~75 V, irrespective of the nature of the dielectric.
- Saturation of collected charge (normalised to maximum value) observed at bias beyond full depletion in depth profiles
- Systematic uncertainty of ± 10 μm arising from laser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



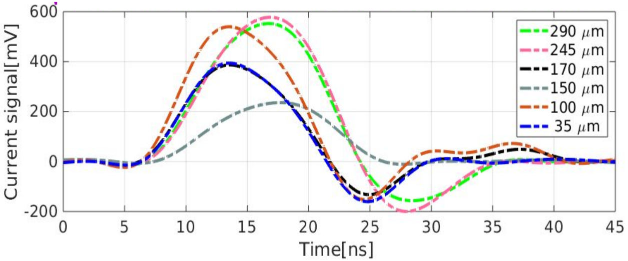


Proton irradiated AC coupled pixel devices
- Waveform vs depth

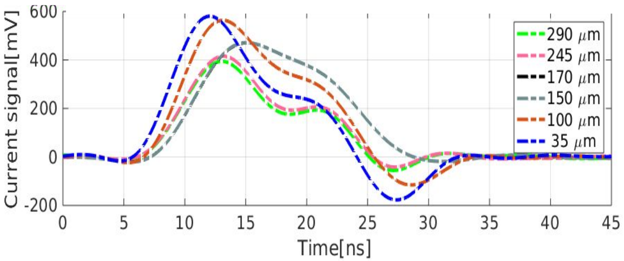
- AC -signal observed at high bias due to imperfect impedance matching between the detector and bias-T
- The signals are much shorter which is a consequence of high drift velocities and trapping effects. The peaking time of the induced current decreases with increasing voltage as the electric field strength at the pixelated side increases.



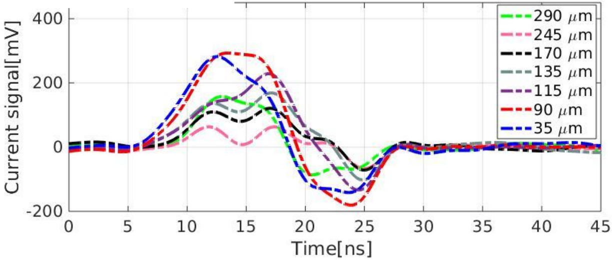
1e14 protons/cm²



3e14 protons/cm²

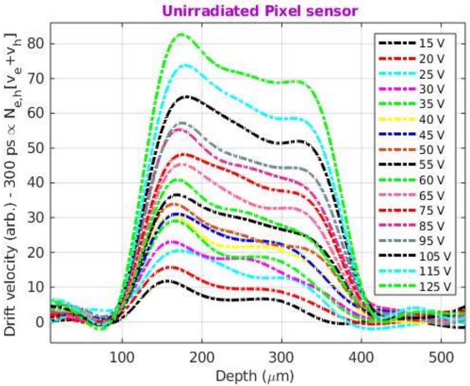


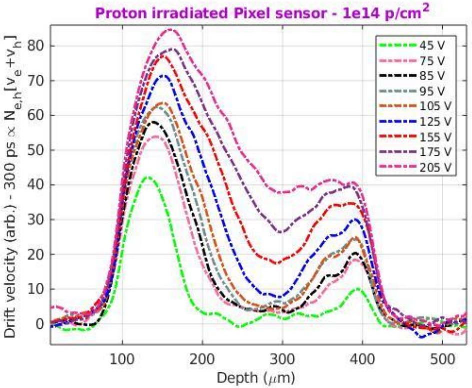
1e15 protons/cm²

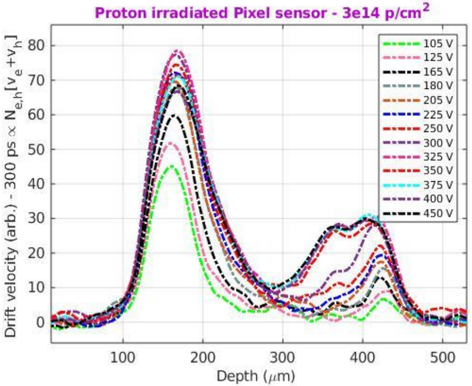


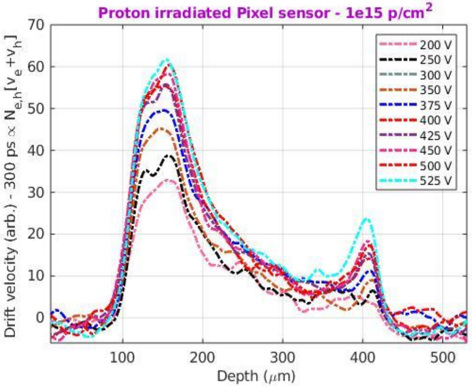
- Waveforms of irradiated samples at 250 V

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









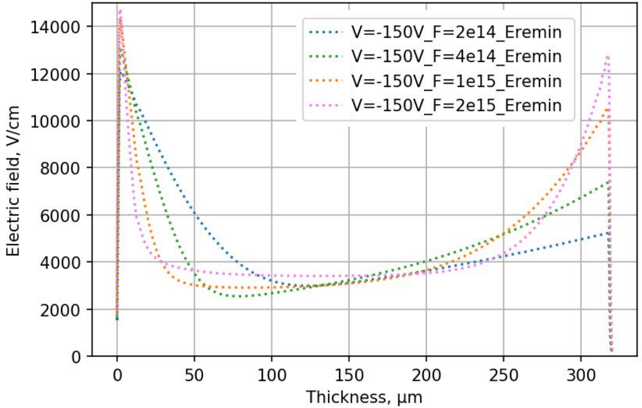
Electric field profile produced using prompt current method: Drift velocity proportional to integrated current over rise time of the signal ~300 ps ---> charge generated within certain depth of the the scan.

- 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.

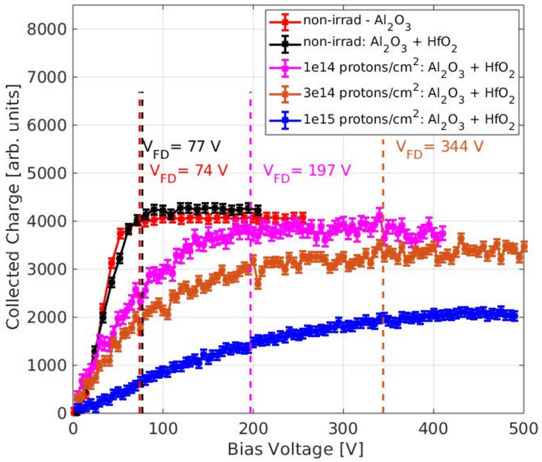
Coherence study with TCAD simulation:

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



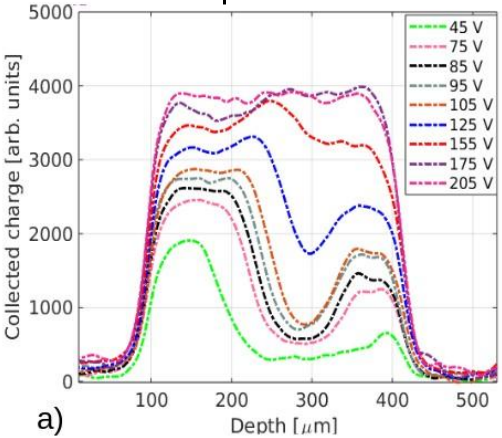
[ref: V. Eremin, E. Verbitskaya, Z. Li, Nucl. Instr. and Meth., A476 (2002) 556]

Proton irradiated AC coupled pixel devices
- collected charge versus depth and voltage variation

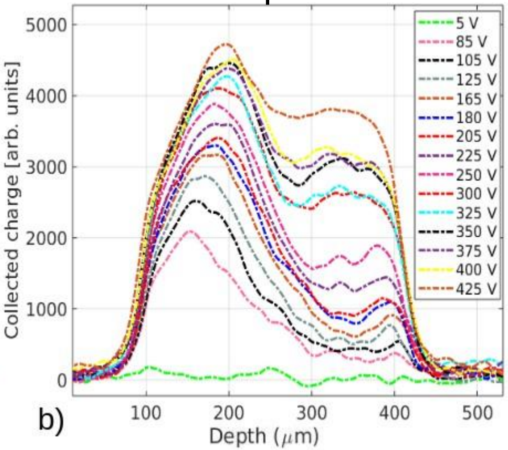


- Reduced collection decreases by factor of ~ 2 due to traps
- Change in full depletion voltage of the bulk observed at the point of inflection for sensors irradiated upto 3e14 p/cm².

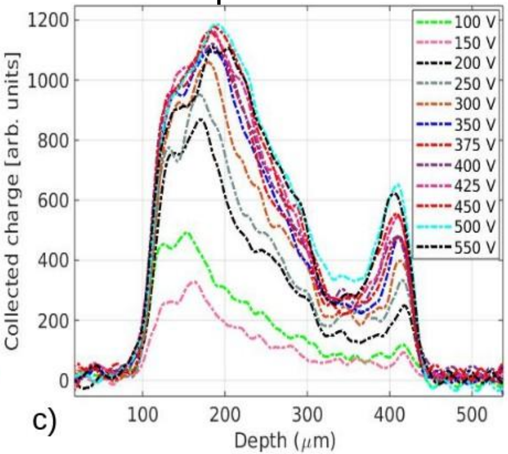
1e14 protons/cm²



3e14 protons/cm²



1e15 protons/cm²



Summary

- Based on dielectric studies: Shift in flat band condition from MOS capacitors and shift in threshold voltage of MOSFET show that Hafnia have higher sensitivity with negative charge accumulation on proton irradiation (compatible results with gamma irradiated MOSFET samples)
- At fluences above 5e14 protons/cm², oxide trapped charges increase -------> leads to negative shift in the threshold voltage with increase in leakage current
- Comparison of dielectrics implemented in AC coupled devices: samples with hafnia reduce susceptibility to undergo early breakdown. Full depletion voltage achievable for hafnia samples when irradiated upto 1e15 protons/cm² before reaching compliance.
- However, with eTCT: no significant difference in electric field and collected charge over voltage scans for non-irradiated devices.
- Double junction effect observed in heavily proton irradiated samples; gets prominent with higher fluences. Congruous with simulation results in accordance with Eremin model.

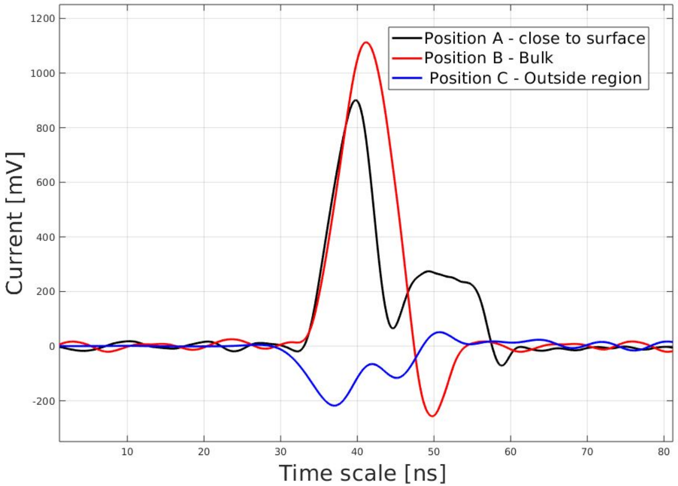
Acknowledgements

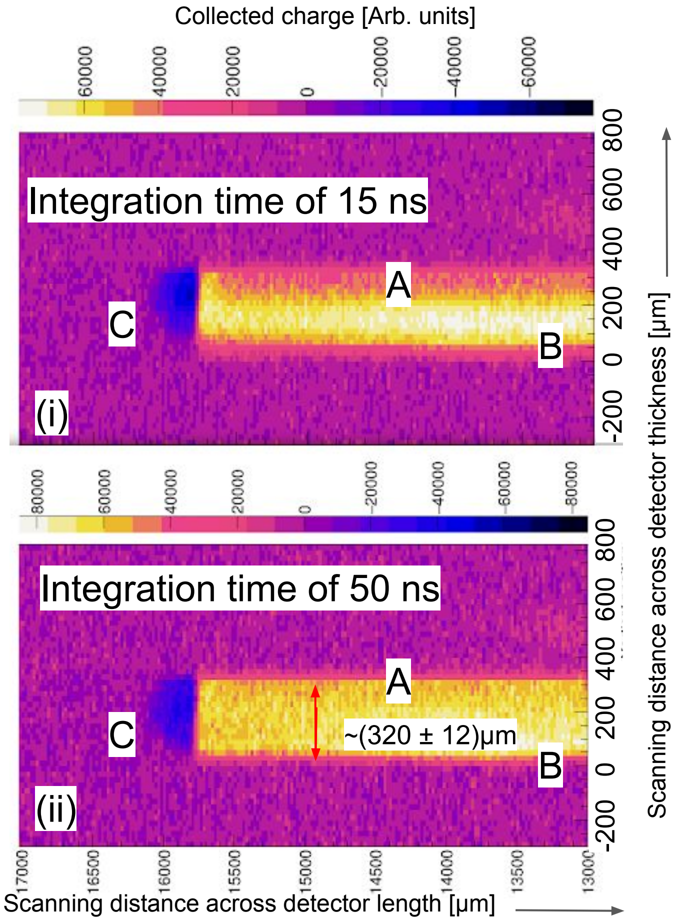
- for semiconductor processing: Finland's national research infrastructure for micro- and nanotechnology Micronova
- for proton irradiation: UH accelerator lab
- for gamma irradiation: Radiation Chemistry and Dosimetry Laboratory at Rudjer Boskovic Institute

  https://www.irb.hr/eng/Divisions/Division-of-Materials-Chemistry/Radiation-Chemistry-and-Dosimetry-Laboratory

Thank You !

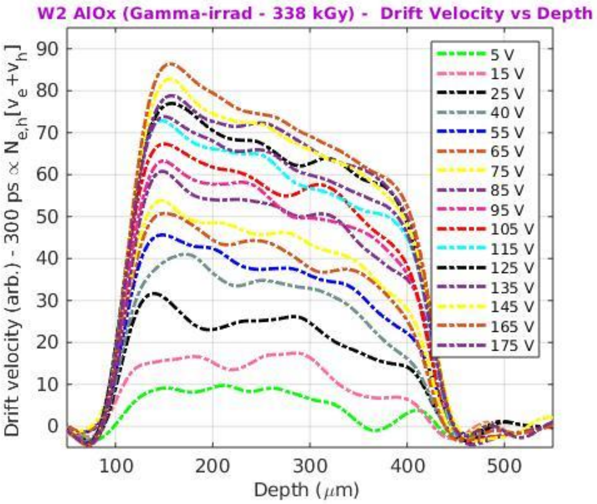
AC coupled pixel devices non-irradiated - IR laser characterization (Edge-TCT)

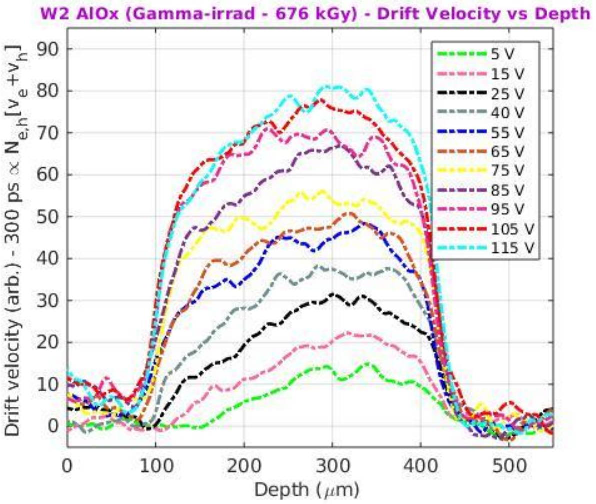


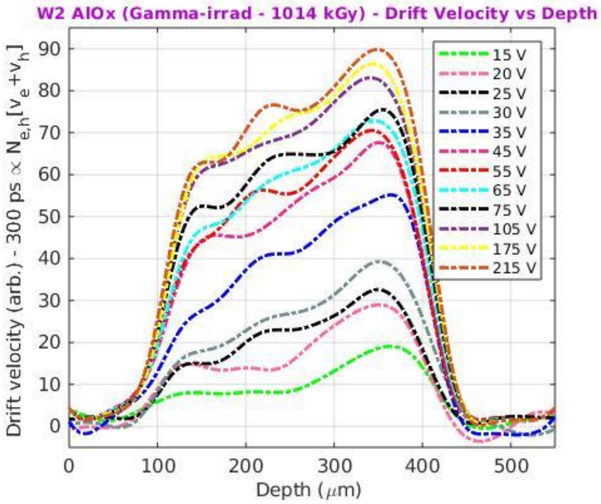


- **Position A** : Closer to the pixel side (in the high electric field) the signal is a superposition of currents induced by the drift of electrons and holes
- **Position B** : Laser projection into the bulk (grows), the contribution of electrons becomes wider and at the same time the long tail due 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)

Gamma irradiated

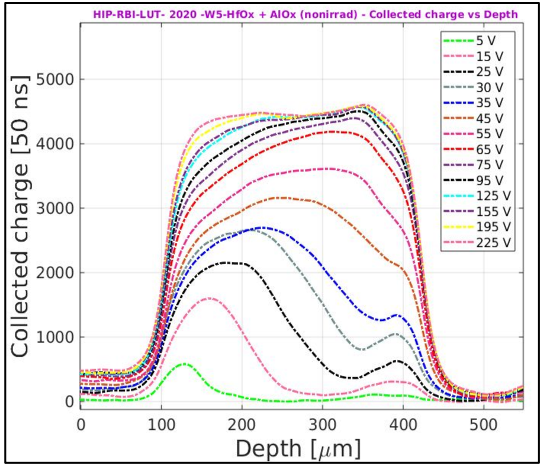


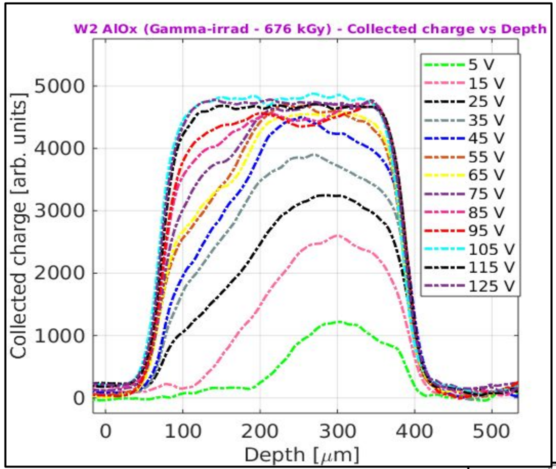


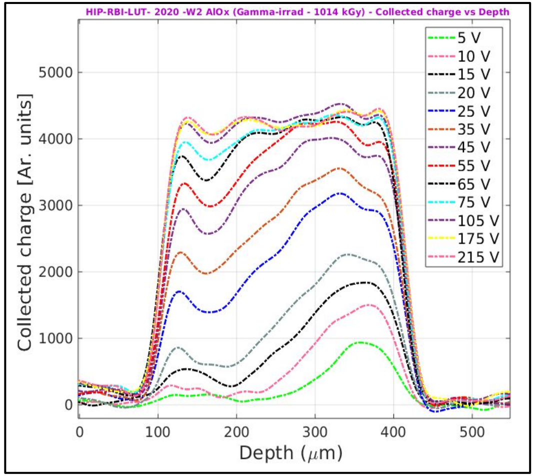


- Space charge sign inversion ?

Gamma irradiated







- NO change in full depletion voltage as (saturated) maximum collected charge attained at point of deflection is same for different doses.