Detector processing on p-type MCz silicon using atomic layer deposition (ALD) grown aluminium oxide

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Outline

- **Recap on Al_2O_3 and ALD**
- **Processing**
  - Devices, layout
  - Process flow
- **Characterization**
  - IV
  - CV, TCT
- **Summary**
- **Outlook**

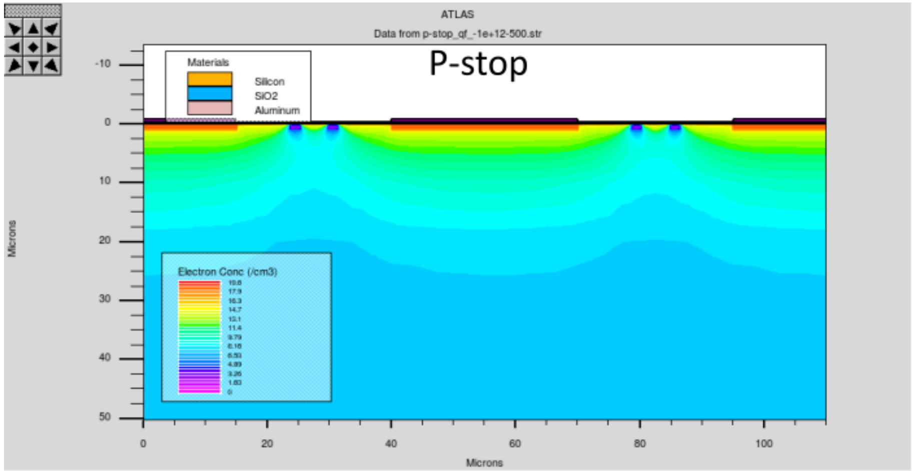
Why aluminium oxide?

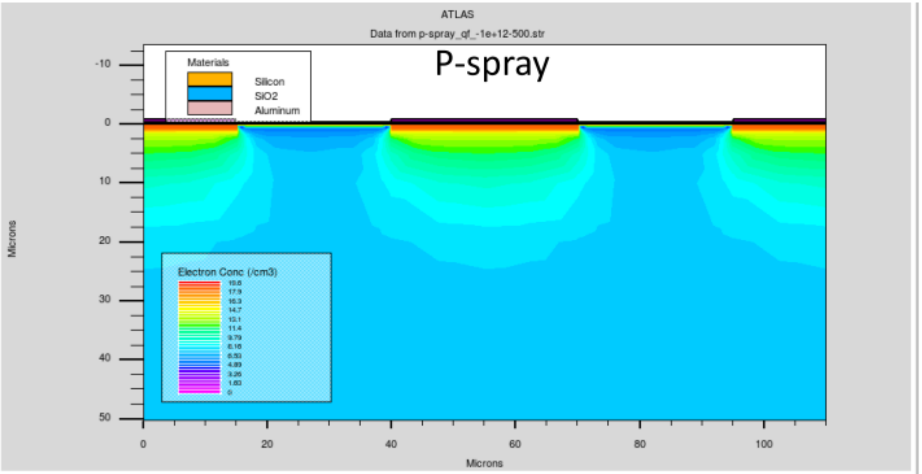
- Increased use of p-type Si in detectors for high-luminosity environments
- Higher mobility of electrons in Si → segmentation of n+ implants
- SiO_2 with its positive oxide charge does not insulate the segments without additional p-spray/p-stop implant

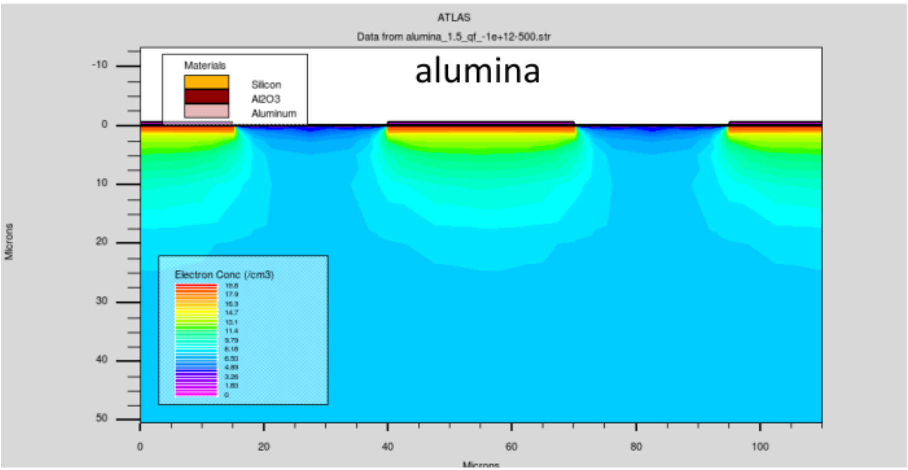
Aluminium oxide (Al_2O_3)

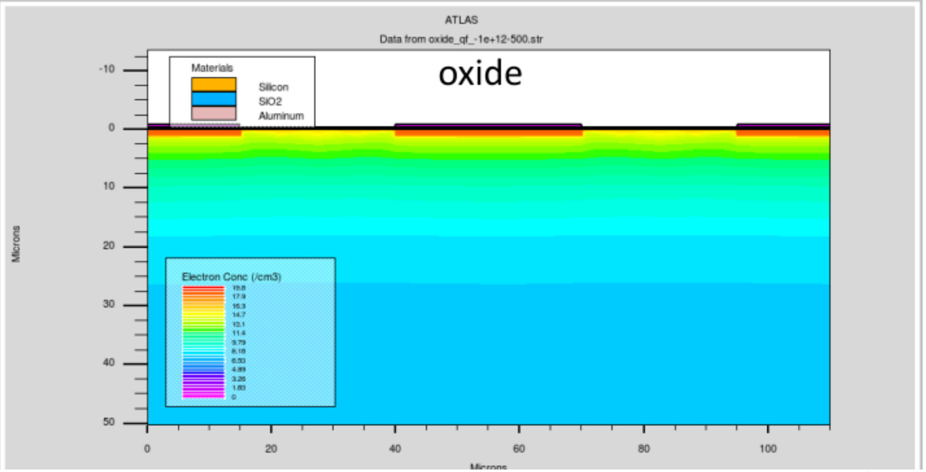
- High negative charge (~1e12 cm^{-2})
- Can be deposited at low temperature
- Good dielectric properties - allows for higher oxide capacitances

Why aluminium oxide?







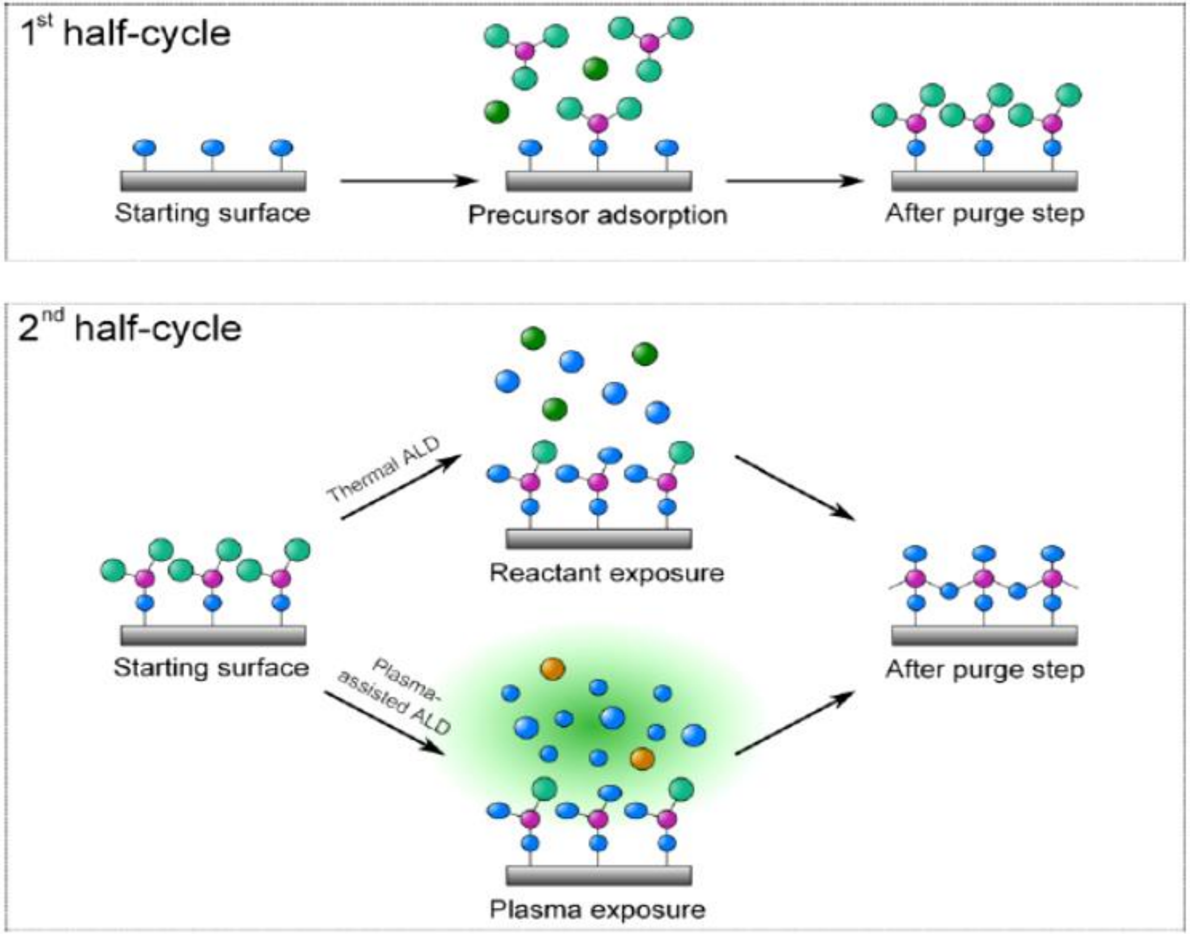


Atomic layer deposition

- A film is deposited by alternate pulsing of gaseous precursors over a substrate
- No gas-phase reactions, purges between the precursor pulses → self-limiting surface reactions

- High film uniformity over relatively large areas
- Film growth slow and occuring in cycles → very thin layers can be grown with good accuracy and repeatability

Atomic layer deposition



H. B. Profijt et al. J.Vac. Sci. Technol. A (2011)

Timeline / ”research flow”

2016

- Characterization methods
- Effect of Al_2O_3 deposition temperature

Talk at RD50 in Krakow

2017

- Effect of oxygen precursor in ALD on Al_2O_3 properties
- Co-60 gamma irradiation

2018

- Pixel processing
- Co-60 gamma irradiation
- Include surface passivation and/or HfO_2 as capping layer

Considerations on Al_2O_3 in processing

Many useful insights and characterization methods
from photovoltaic industry and research

... however, transfer to detector processing requires adaption

- **Film thickness**
- **Thermal treatments (metal sintering, firing)**
- **Oxygen precursor in ALD**
  - The best-known process for Al_2O_3 consists of trimethylaluminium (TMA) and H_2O
  - Best passivation quality (in terms of lifetimes), best diode breakdown properties

  ... but large blister-like delamination areas – unusable in pixelated devices*
  - Addition of ozone improves performance

*** cf. backup slides**

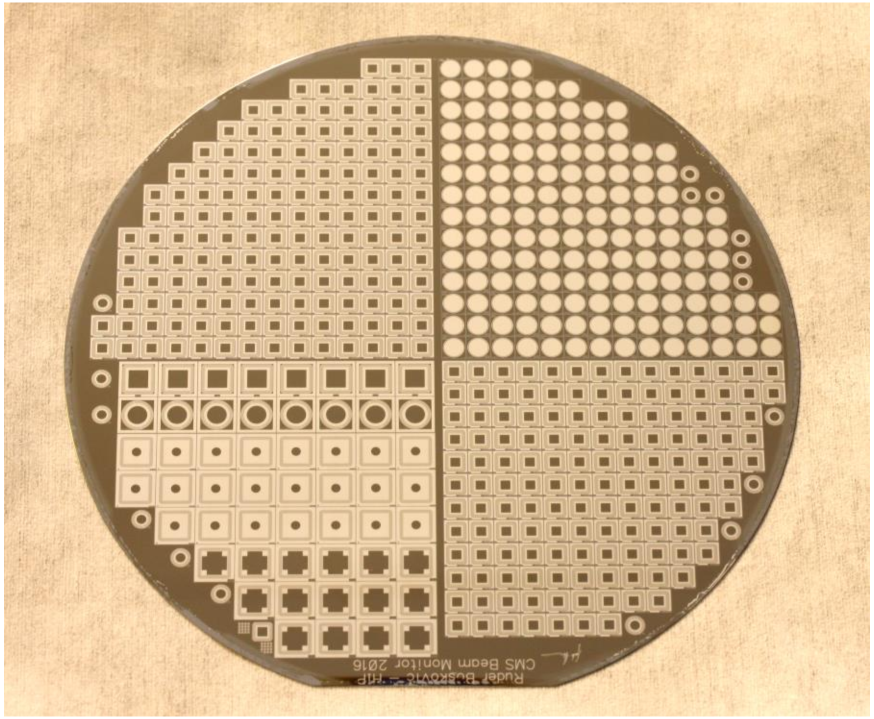
Process flow

- p-type MCz 6” Si, > 4 kΩcm
- Thermal oxidation
- Alignment marks (RIE)
- Implantation: front side P
  Entire back side B
- Implant activation
- BHF etch oxide removal
- ~80 nm Al_2O_3 (ALD)
- Sintering 370 C
- TiN bias resistors (RF sputtering)
- Al metallization
- 30 nm Al_2O_3 surface passivation (ALD)
- Sintering 370 C

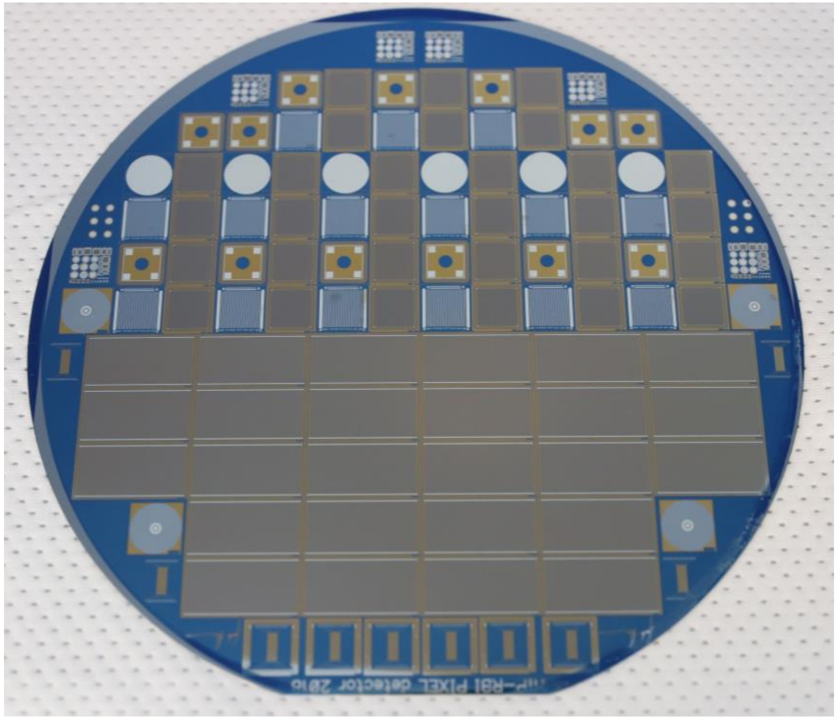
UBM

Structures

2017



2018

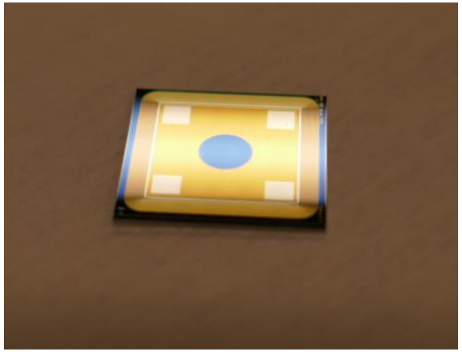


Structures

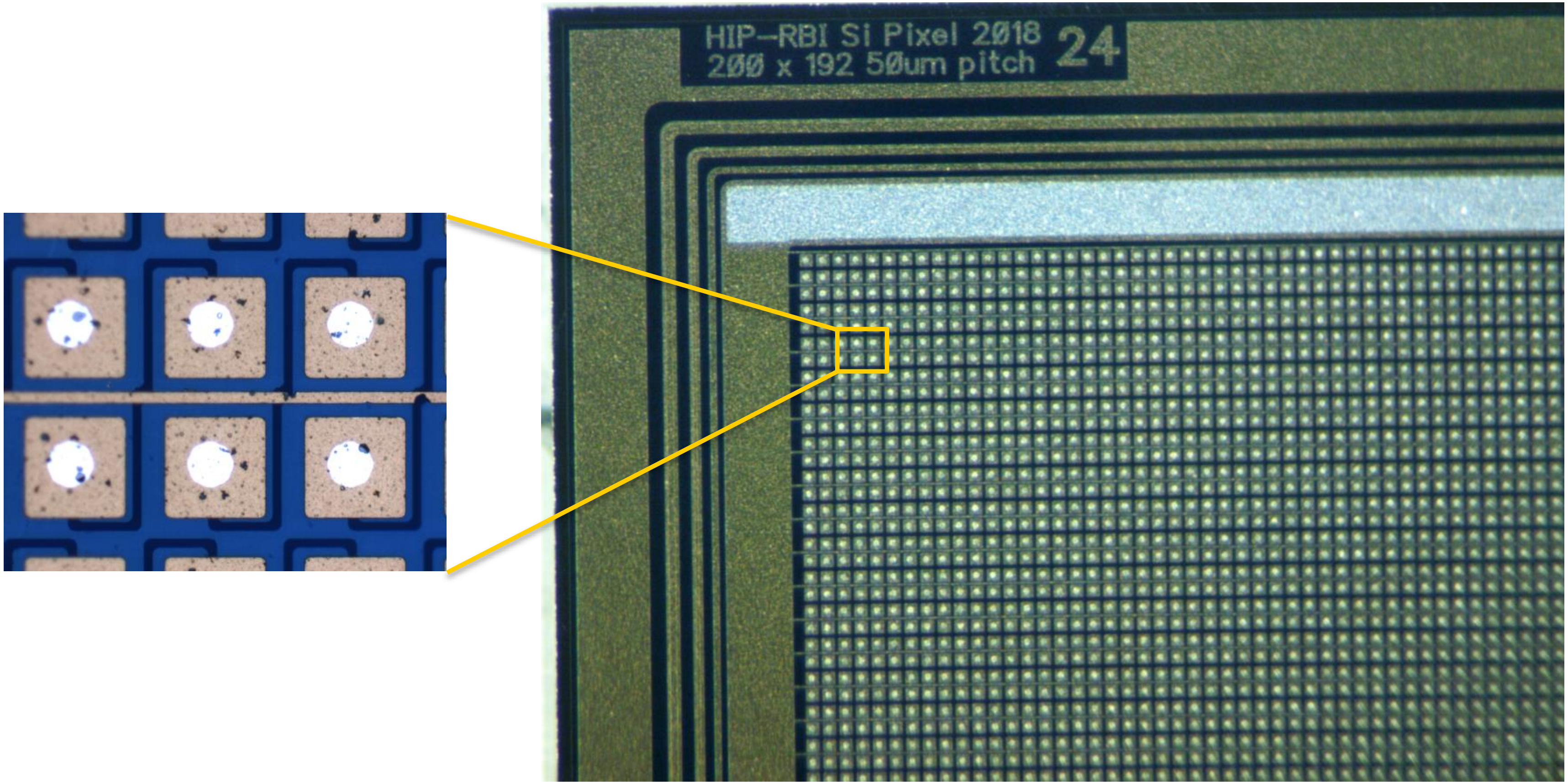
- **Pixel detectors:**
  - AC-coupled pixel sensor, 100 × 150 µm pitch to match PSI46dig
  - DC-coupled pixel sensor, 50 × 50 µm pitch to match RD53A

- **Pad diodes**
- **MOS capacitors**
- **Resistor reference structures**

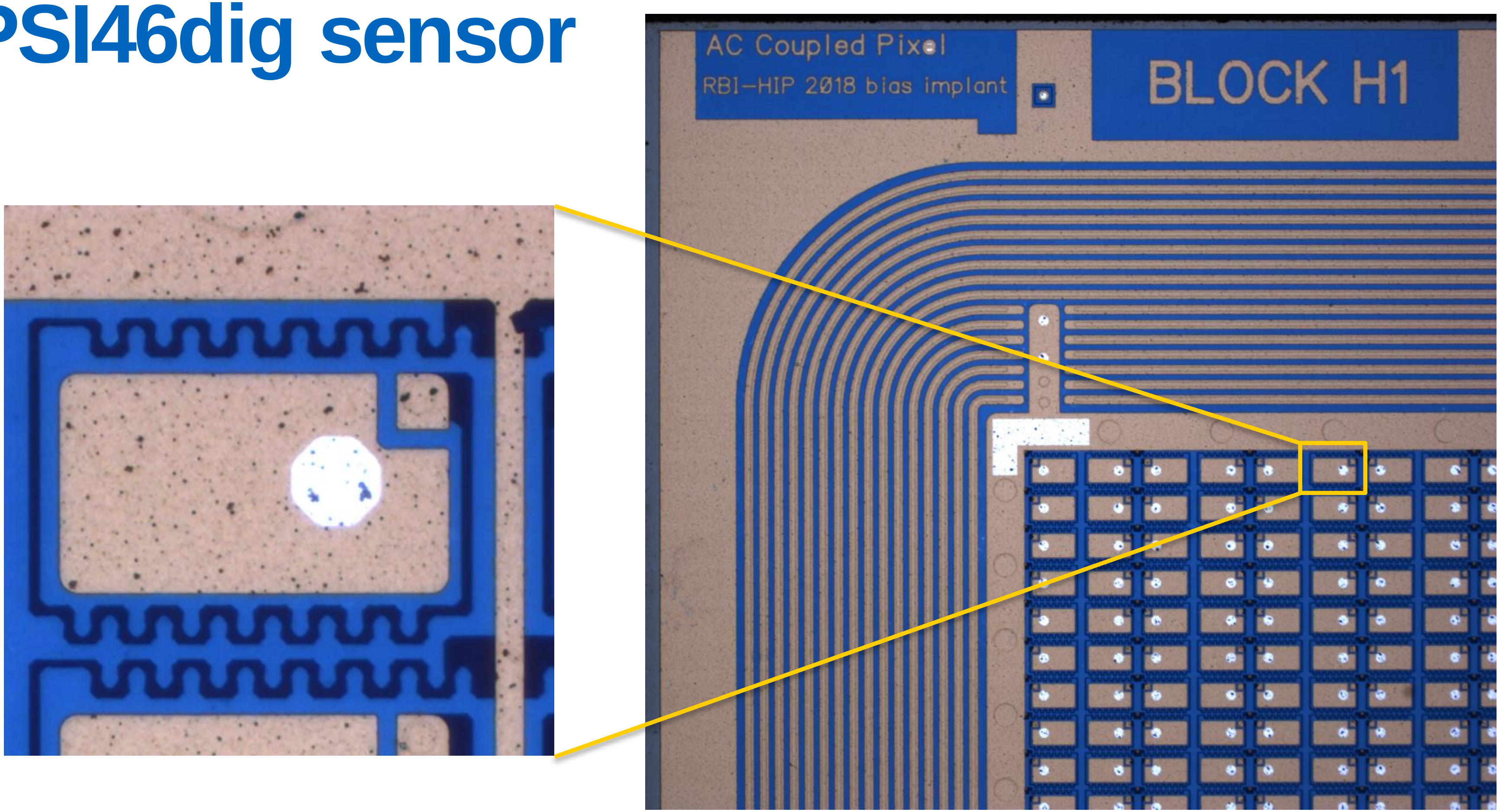
→ easier testing of certain properties



RD53 sensor



PSI46dig sensor



Characterization

- **Pad sensors**
  - IV
  - CV
  - TCT with red and IR laser

- **MOS capacitors**
  - CV

As-processed, and irradiated up to ~1 MGy with Co-60 γ rays at RBI*

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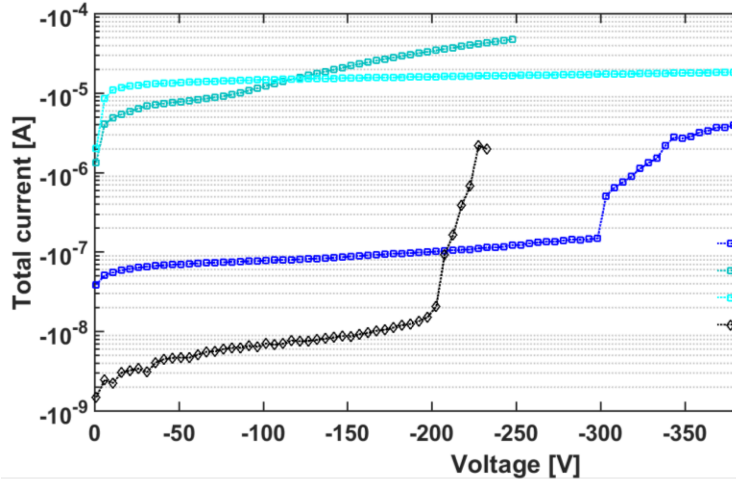
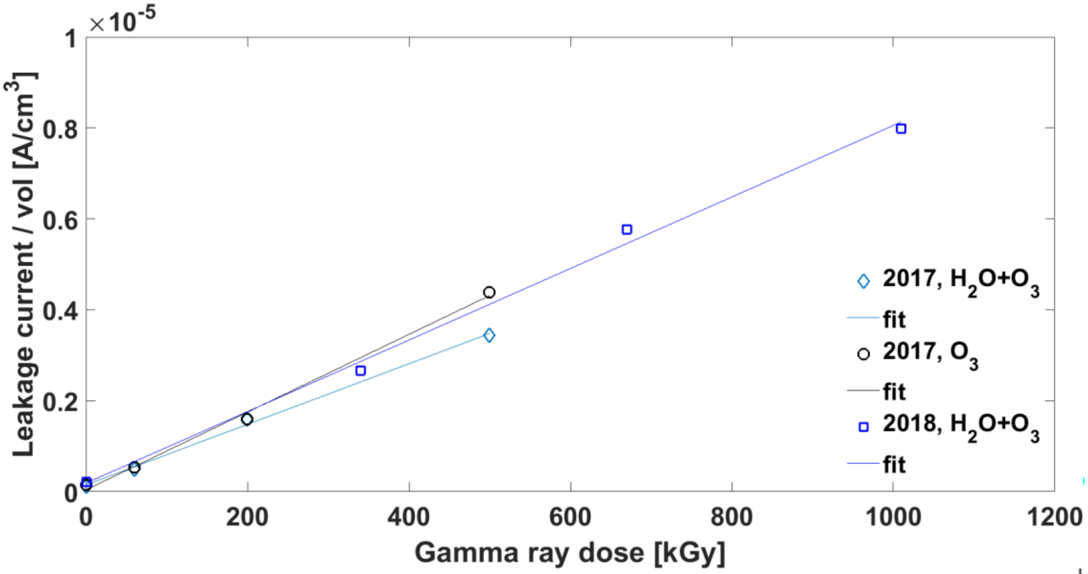
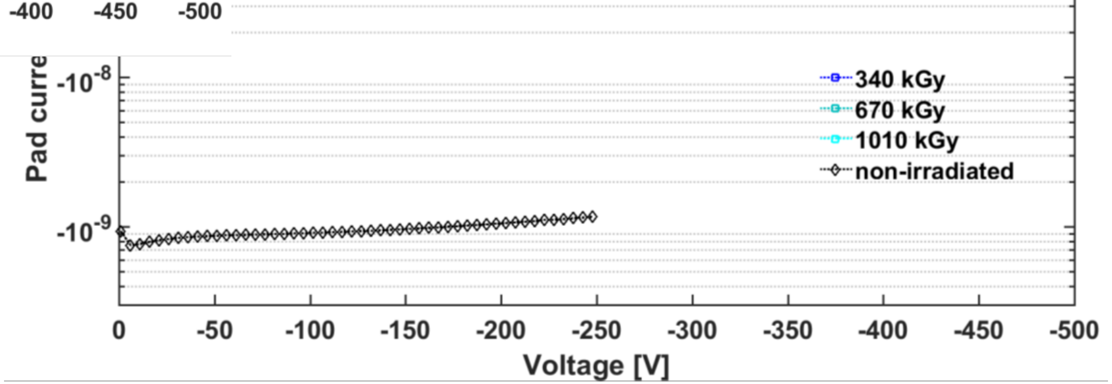
* https://www.irb.hr/eng/Research/Divisions/Division-of-Materials-Chemistry/Radiation-Chemistry-and-Dosimetry-Laboratory

Pad IV

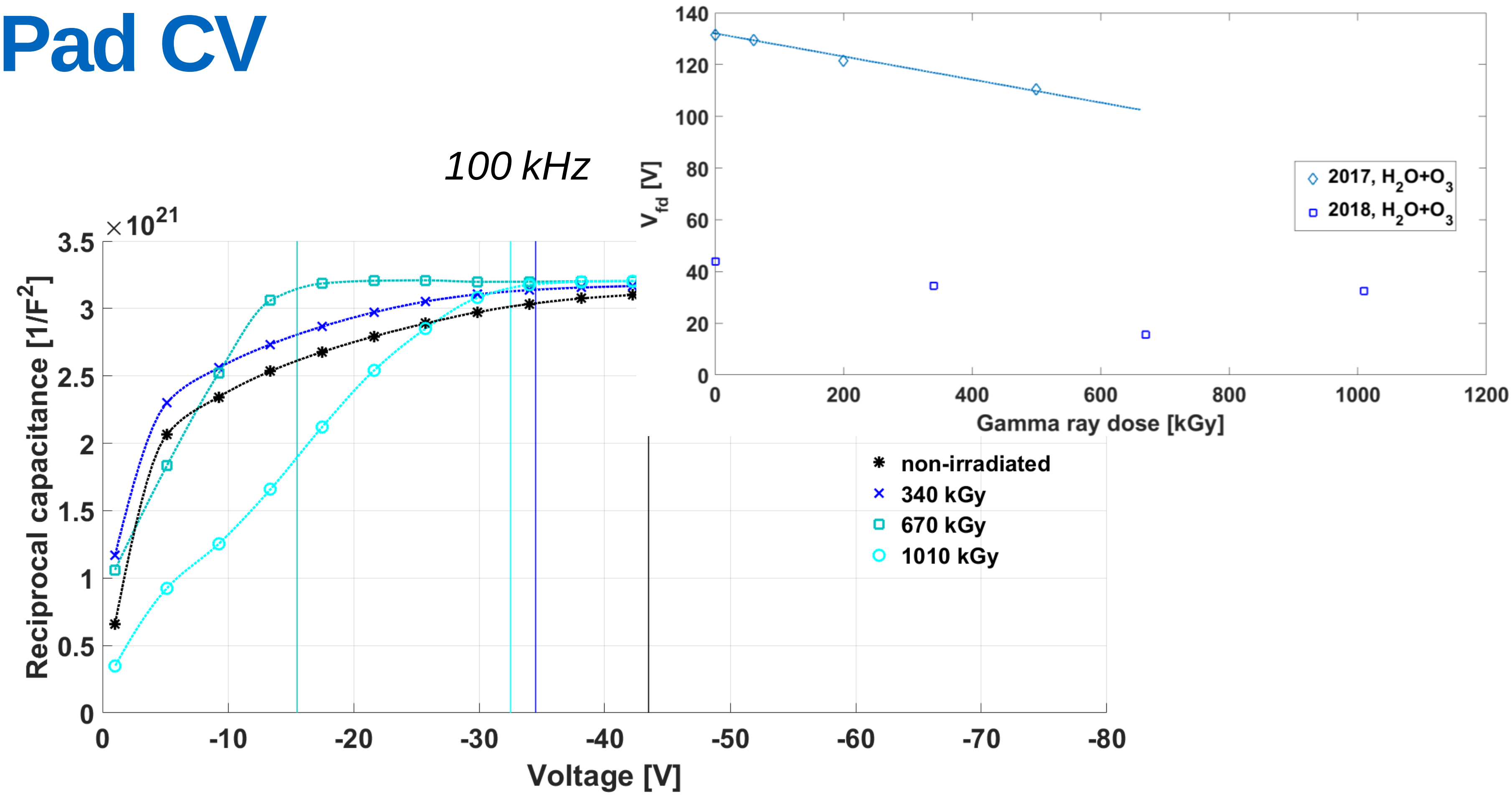




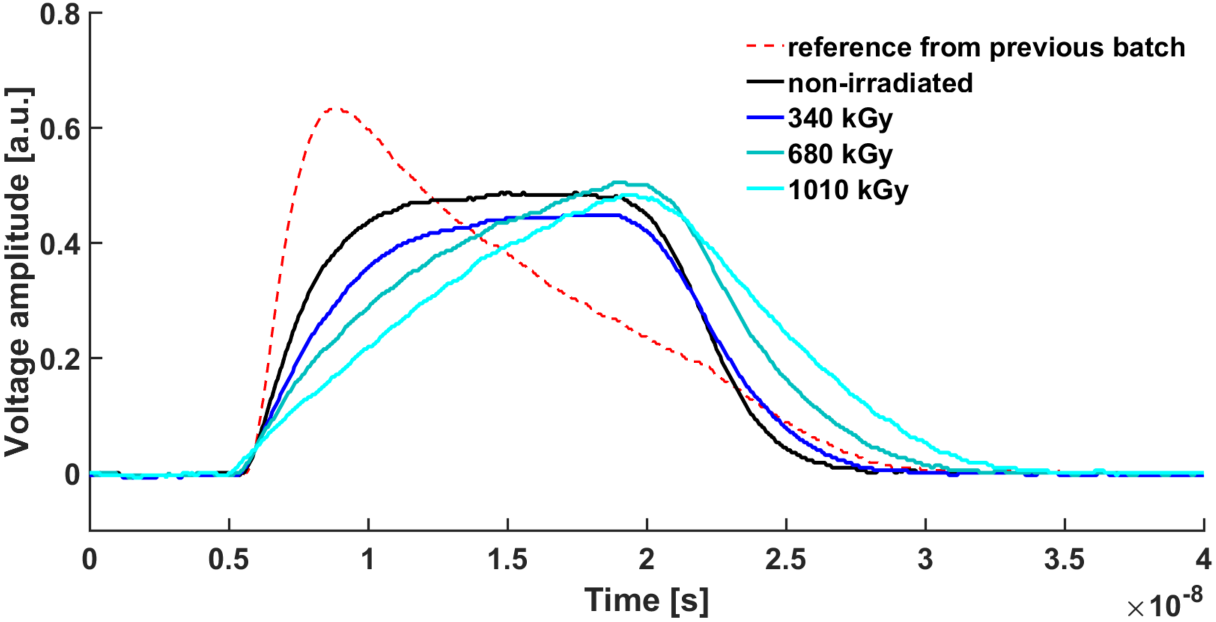


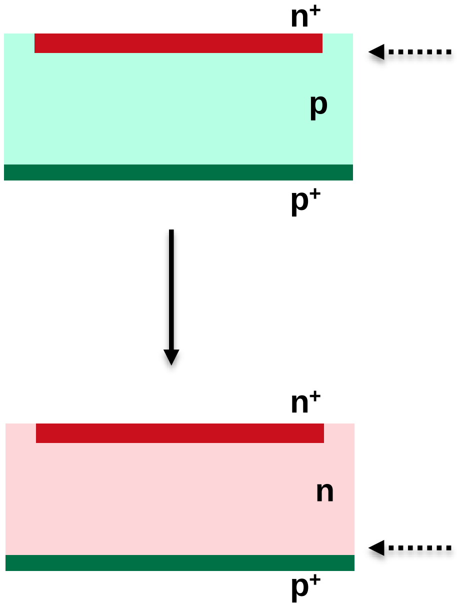
Non-irradiated samples: leakage currents of 5-10 nA/cm^2

Pad CV


100 kHz
×10^21
3.5
3
2.5
2
1.5
1
0.5
0
Reciprocal capacitance [1/F^2]
0
-10
-20
-30
-40
-50
-60
-70
-80
Voltage [V]
non-irradiated
340 kGy
670 kGy
1010 kGy
140
120
100
80
60
40
20
0
V_fd [V]
0
200
400
600
800
1000
1200
Gamma ray dose [kGy]
2017, H2O+O3
2018, H2O+O3

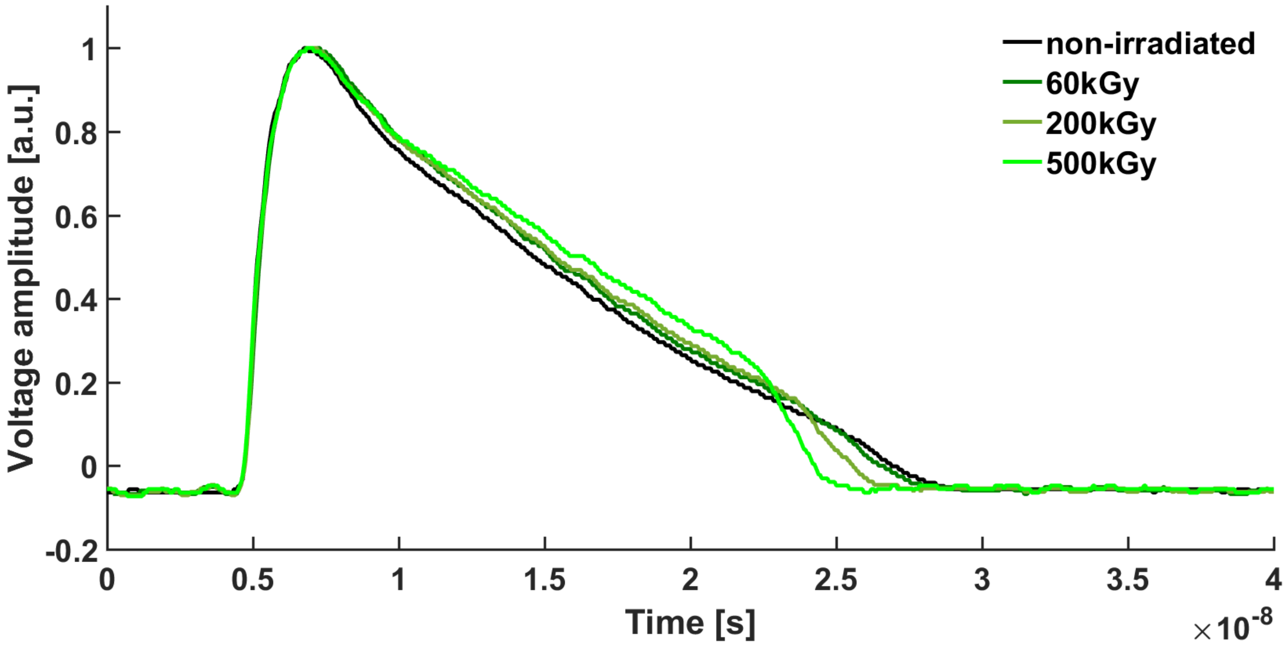
Red laser TCT



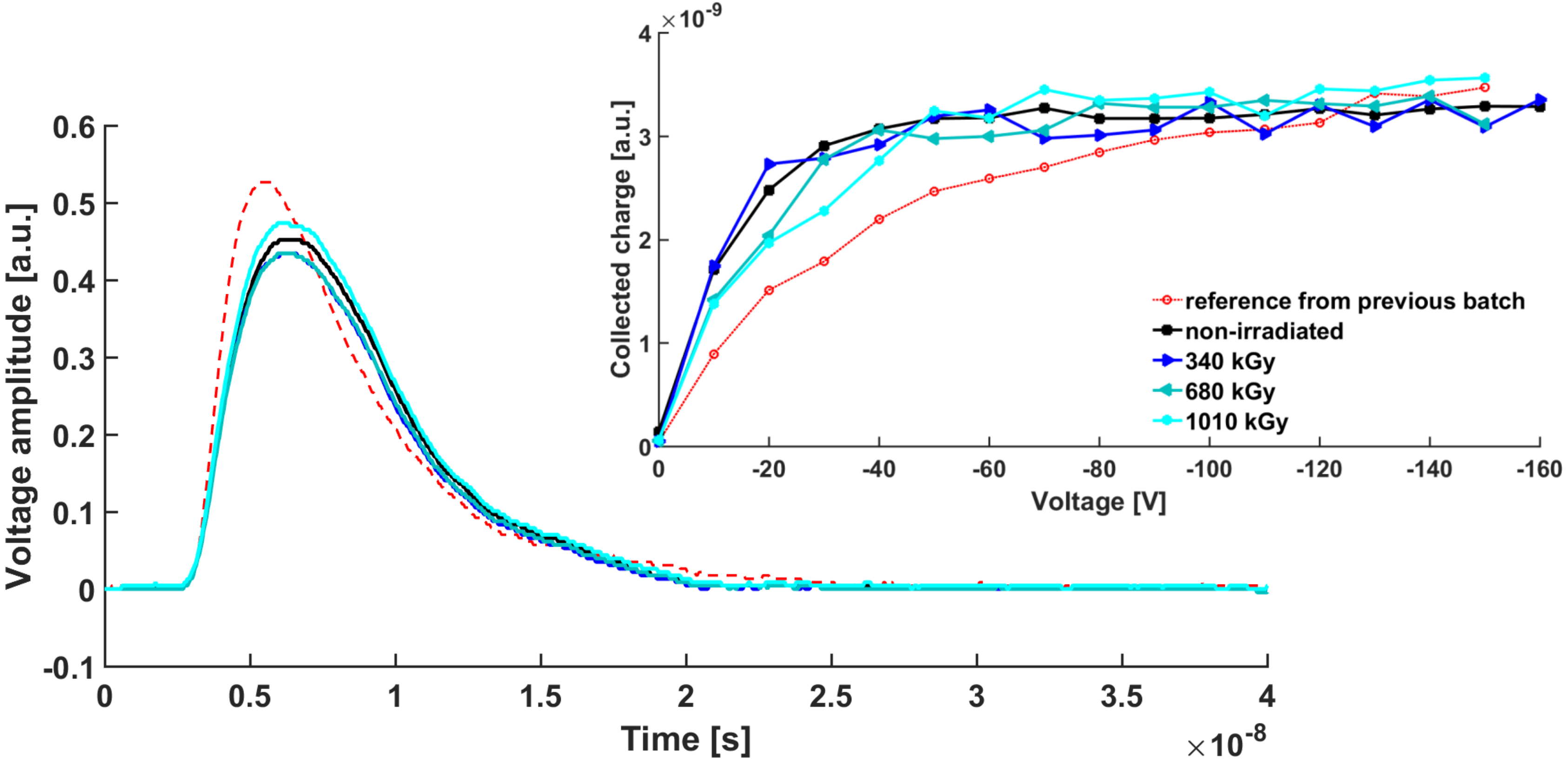


Red laser TCT

2017 batch



IR-TCT



Voltage amplitude [a.u.]
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
0.5
1
1.5
2
2.5
3
3.5
4
Time [s]
$\times 10^{-8}$
Collected charge [a.u.]
$\times 10^{-9}$
4
3
2
1
0
0
-20
-40
-60
-80
-100
-120
-140
-160
Voltage [V]
reference from previous batch
non-irradiated
340 kGy
680 kGy
1010 kGy

Observations

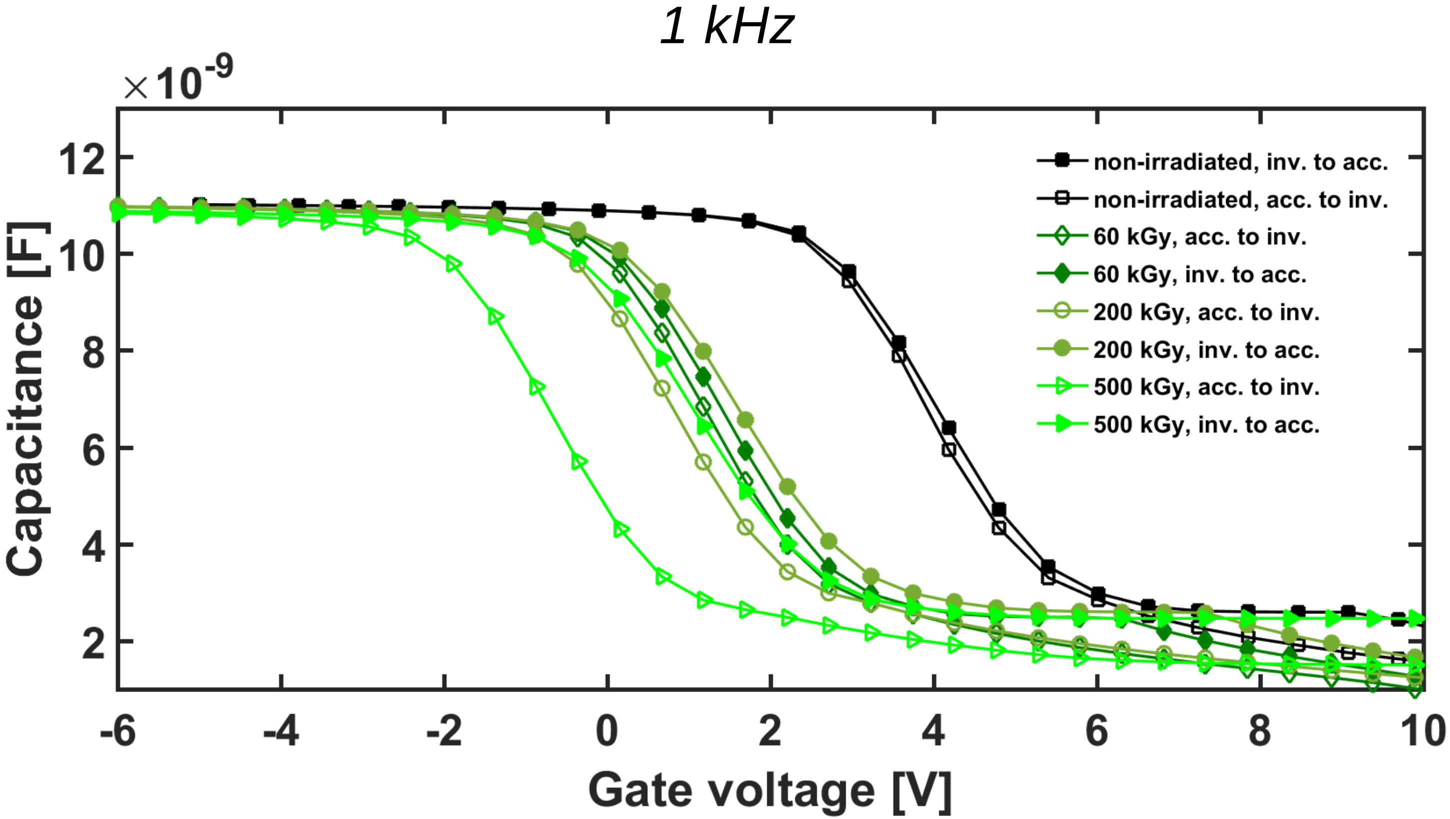
- **Reduction of N_{eff} and subsequent type inversion with increasing gamma ray dose**
  - ”clean”, no double junction effect
- **The same phenomenon is visible also for 2017 batch, but there not up to SCSI due to lower starting resistivity = higher doping**
- **Leakage current scales well with gamma ray dose**
- **Does not appear to affect charge collection significantly**

Acceptor removal? Donor creation?

Hole trapping due to Al_2O_3?

MOS capacitor CV

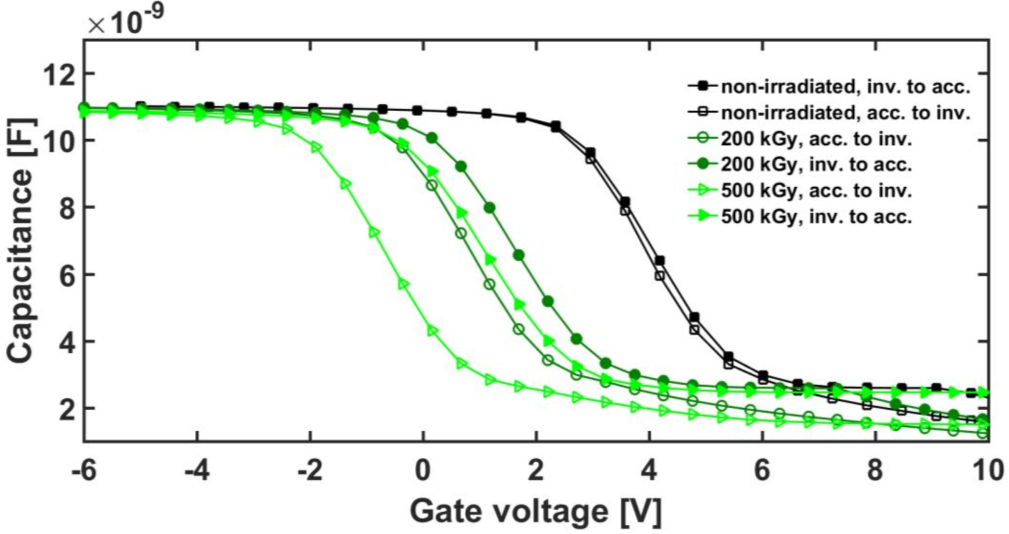
2017 batch



MOS capacitor CV

2017 batch

V_{fb} shifts towards negative:
positive charge formation
as expected,
but Q_{eff} remains negative



- Strong frequency dependence
- V_{fb} measured starting in inversion does not show large change after first irradiation dose, but hysteresis increases

  → indicates formation of positive mobile charge, while Q_f is less affected
- Changes in bulk doping need to be taken into account for accurate charge extraction

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For charge extraction from voltage termination structure simulations, cf. <u>Elena's talk</u>

Summary

- **Al_2O_3 films were successfully integrated into a 6” Si detector process as replacement for the SiO_2 + p-spray/p-stop entity**
- **Devices are well characterizable by standard methods: CV, IV, TCT**

- **These results tell more about the MCz Si bulk properties than the insulator oxide**
  - Positive space charge building up due to irradiation, may lead to type inversion depending on initial doping concentration
  - Interpretation of MOS capacitor CV curves for extraction of oxide charge requires some considerations/assumptions and comparison with pad CV data

What next

- **Further characterization of pixel sensors**
  - Flip-chip bonding
  - ***Evaluation of the assembly in the lab and at test beam***

- **Annealing..?**
  - So far, no anneal after gamma irradiation, all measurements at RT

- **Irradiation with p, n**

- **Defect spectroscopy (DLTS) to study mechanism behind acceptor compensation**

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LUT
University

HELSINKI
INSTITUTE OF
PHYSICS

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Micronova Nanofabrication Centre

Helsinki Detector Laboratory

SUOMALAINEN TIEDEAKATEMIA

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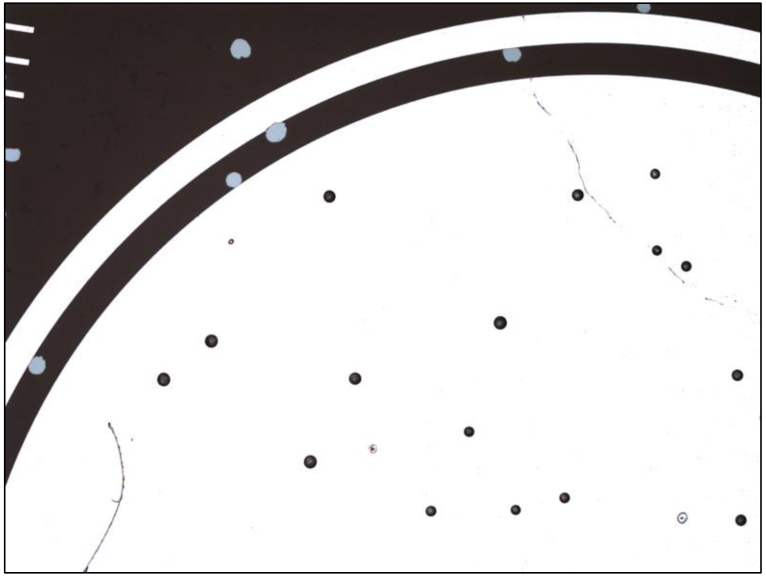
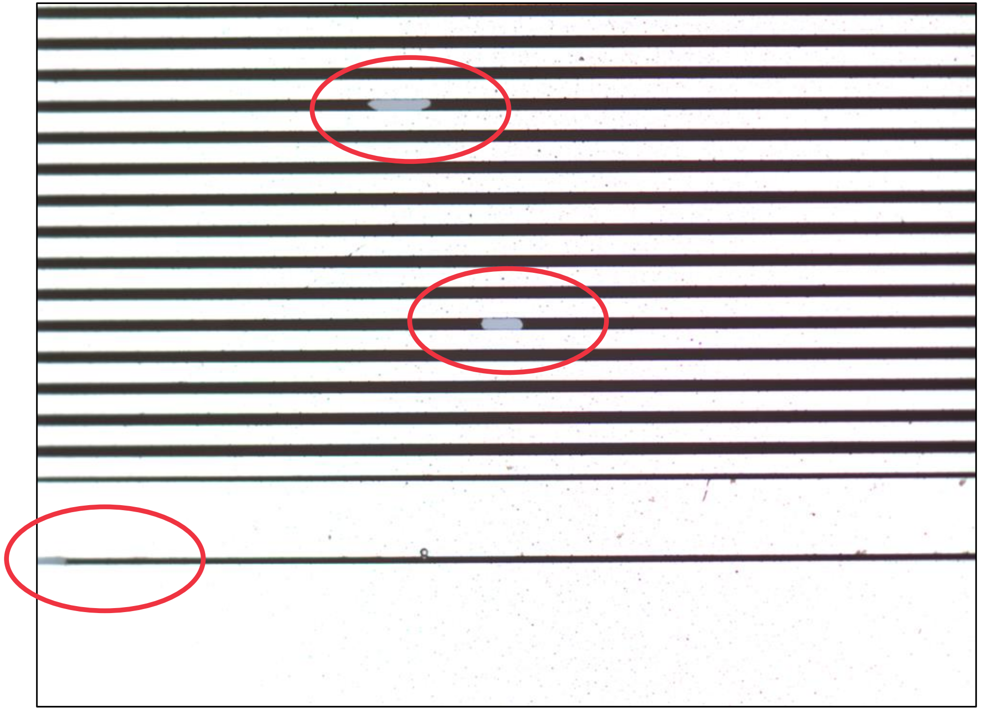
Backup

Considerations on Al_2O_3 in processing

H_2O as precursor:



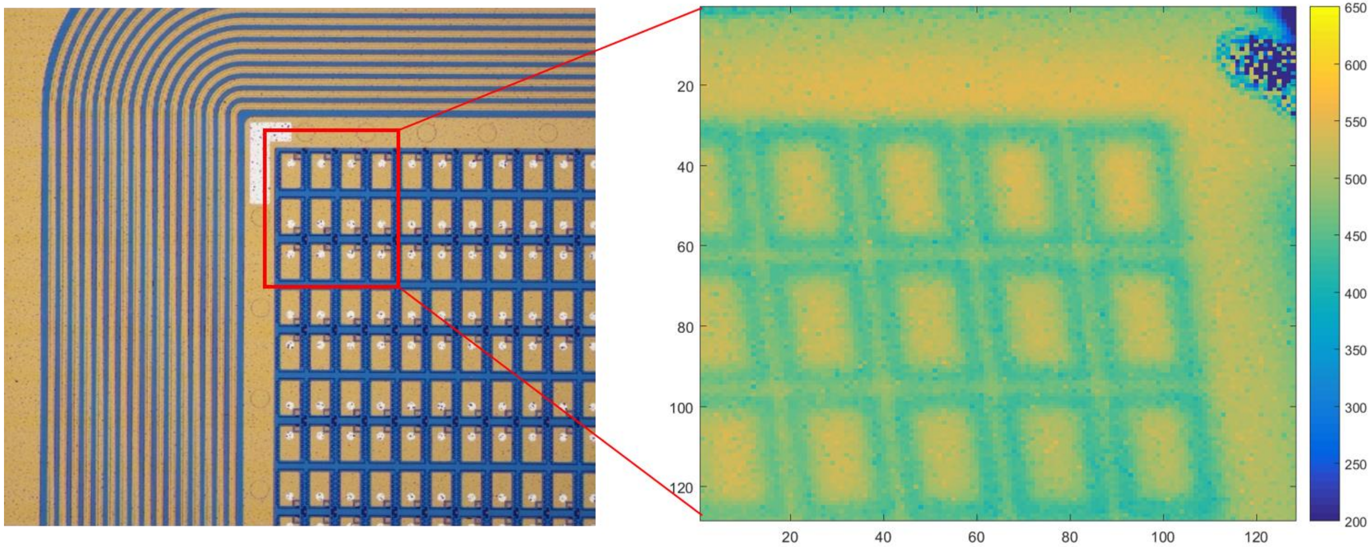


→ **”blistering” of Al_2O_3 film as consequence of H segregation to interface**

→ **blisters can be of the same size as pixels!**

Proton microprobe

At RBI IBIC facilities, cf. <u>Aneliya’s talk</u>



PSI46dig-geometry AC-coupled pixel sensor with Al2O3 insulator

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https://www.irb.hr/eng/Research/Divisions/Division-of-Experimental-Physics/Laboratory-for-ion-beam-interactions