AC-coupled pixel detectors with aluminium oxide field insulator on p-type MCz silicon

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15th Trento workshop, 17.-19.2.2020 (TREDI2020)

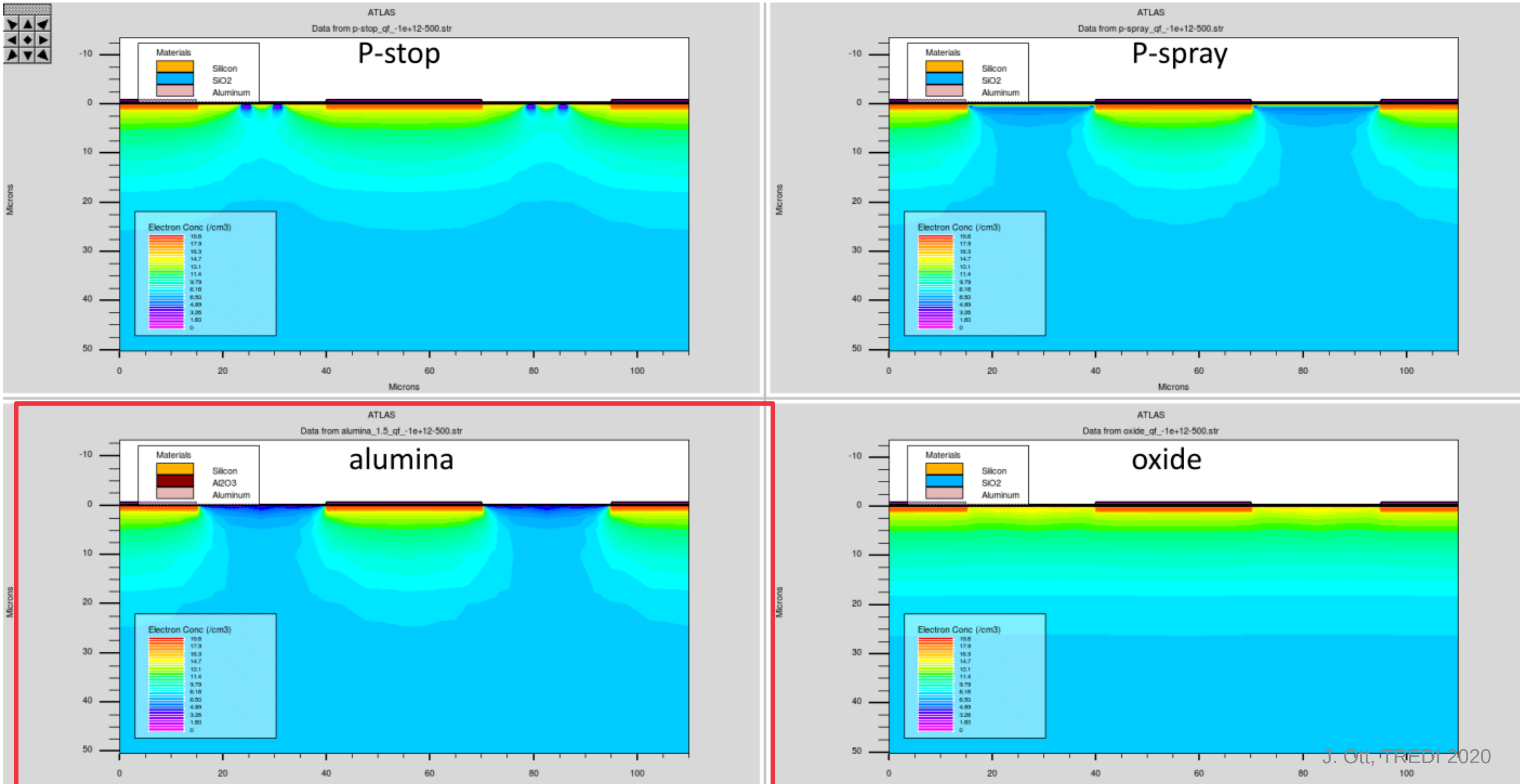
Why aluminium oxide?

- 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 (~ 10^{12} cm^{-2})
- Can be deposited at low temperature
- Good dielectric properties - allows for higher oxide capacitances

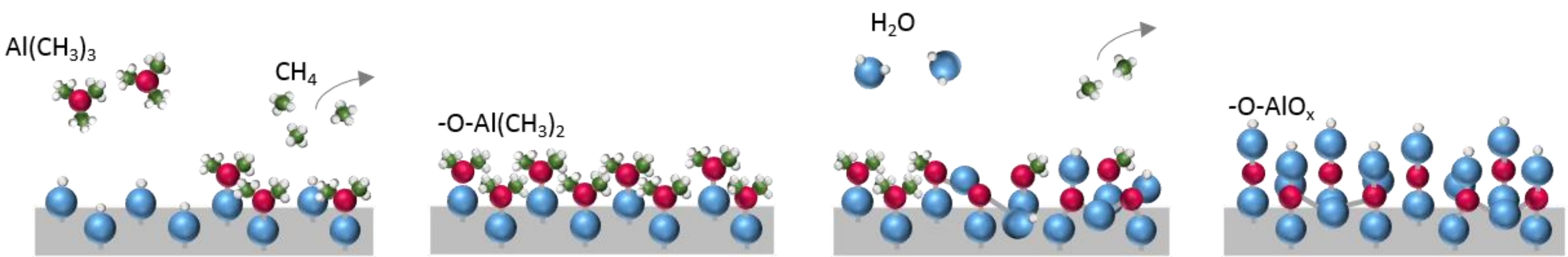
Why aluminium oxide?



J. Ott, TREDI 2020

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



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

- Film growth slow and occuring in cycles → very thin layers can be grown with good precision
- Good film uniformity over relatively large areas, conformal growth

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 uses water as oxidant: indeed, best passivation quality (in terms of carrier lifetimes), best diode breakdown properties

  ... but large blister-like delamination areas – unusable in pixelated devices*
  - Addition of ozone improves performance → **consecutive pulsing of H_2O and O_3**

*** cf. backup slides**

Wet oxidation

Alignment marks

Ion implantation

Dry oxidation (implant drive-in)

Thermal oxide removal

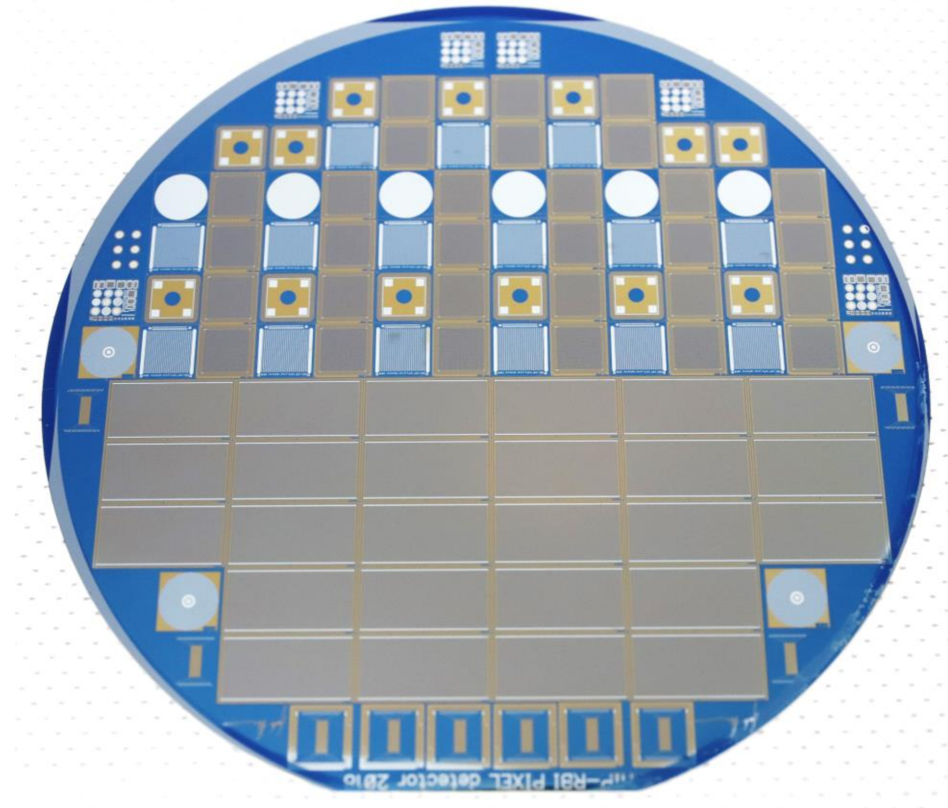
Al_2O_3 field insulator

TiN bias resistors

Al metallization

Al_2O_3 surface passivation

Under-bump metallization

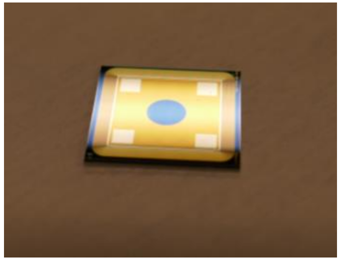


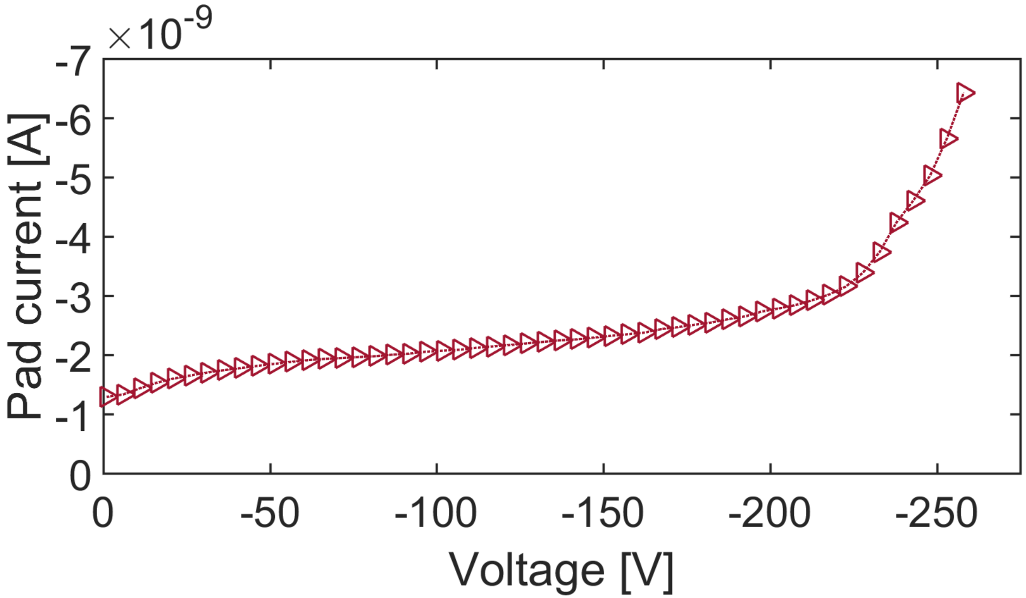
Characterization

Single-pad diodes

- IV
- CV
- TCT with red and IR laser

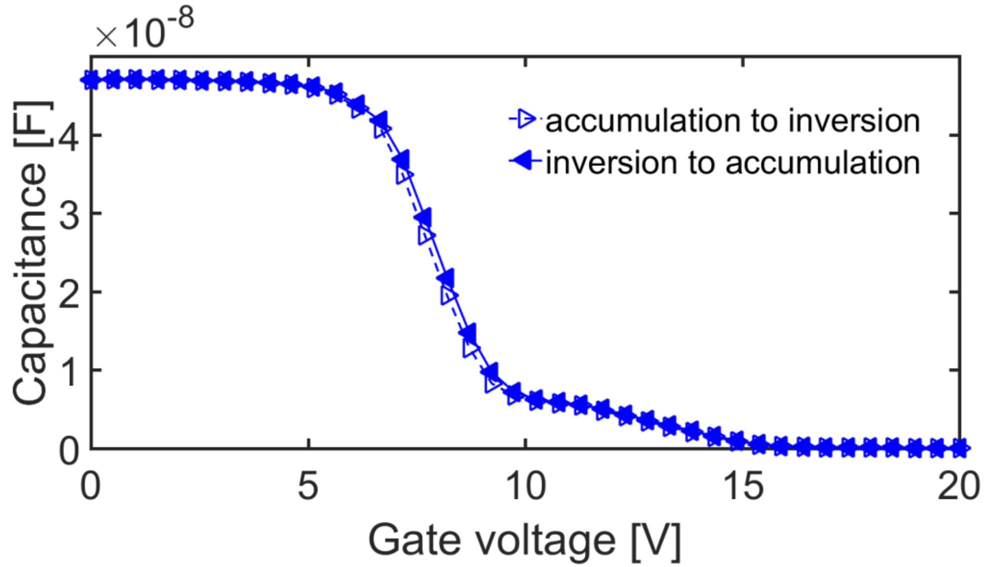
More in M. Bezak's talk



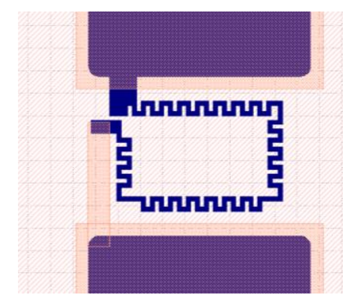


Characterization

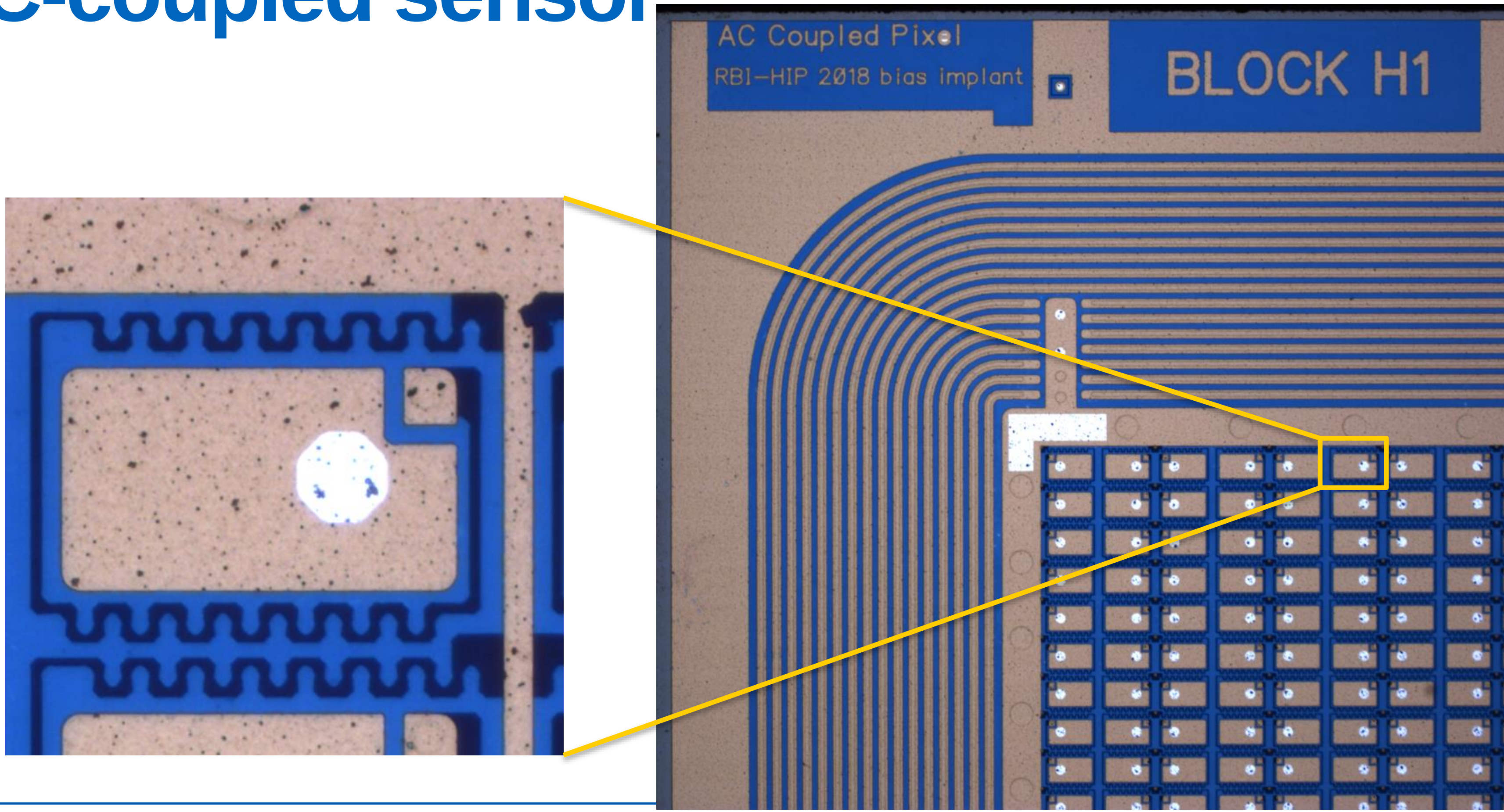
- **MOS capacitors**
  - CV → C_{ox}, V_{fb} → Q_{eff}
  - ≈ $-3\cdot10^{12}$ cm^{-2}



- **Resistor structures**
  - IV → resistance: ≈ 15 kΩ / pixel resistor



AC-coupled sensor

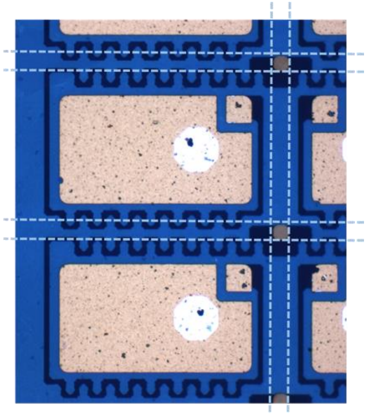


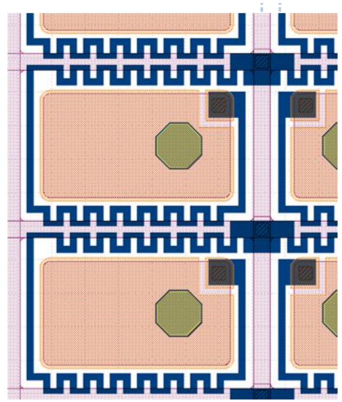
AC-coupled pixel sensor

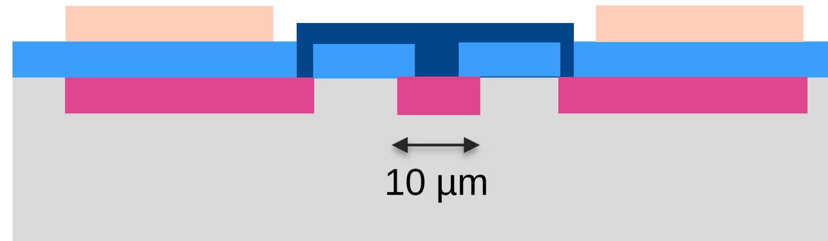
- 52x80 double columns, pixel pitch 100×150 µm
- Capacitive coupling using Al_2O_3 and TiN biasing resistor: separation of DC leakage current from signal
- Two different bias grid schemes: bias line by implant or metal line

- TiW/Au under-bump metallization on sensor realized by lift-off lithography on individual samples, not full wafer

AC-coupled pixel sensor

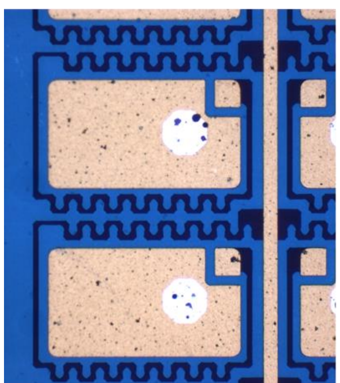


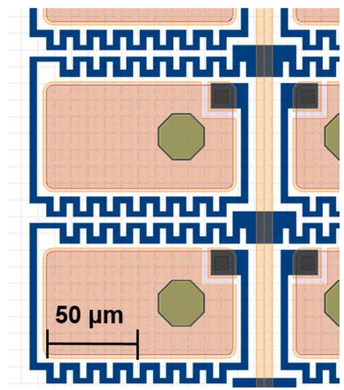


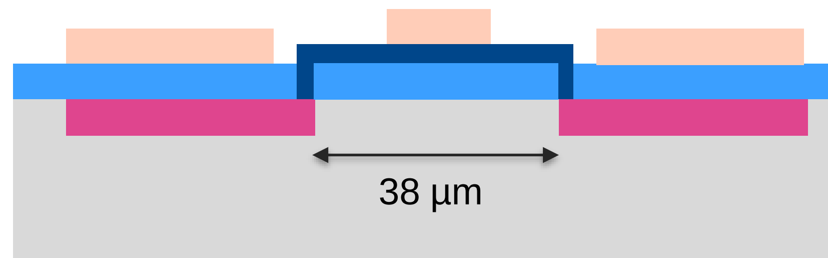


Implanted bias line

Drawing not to scale

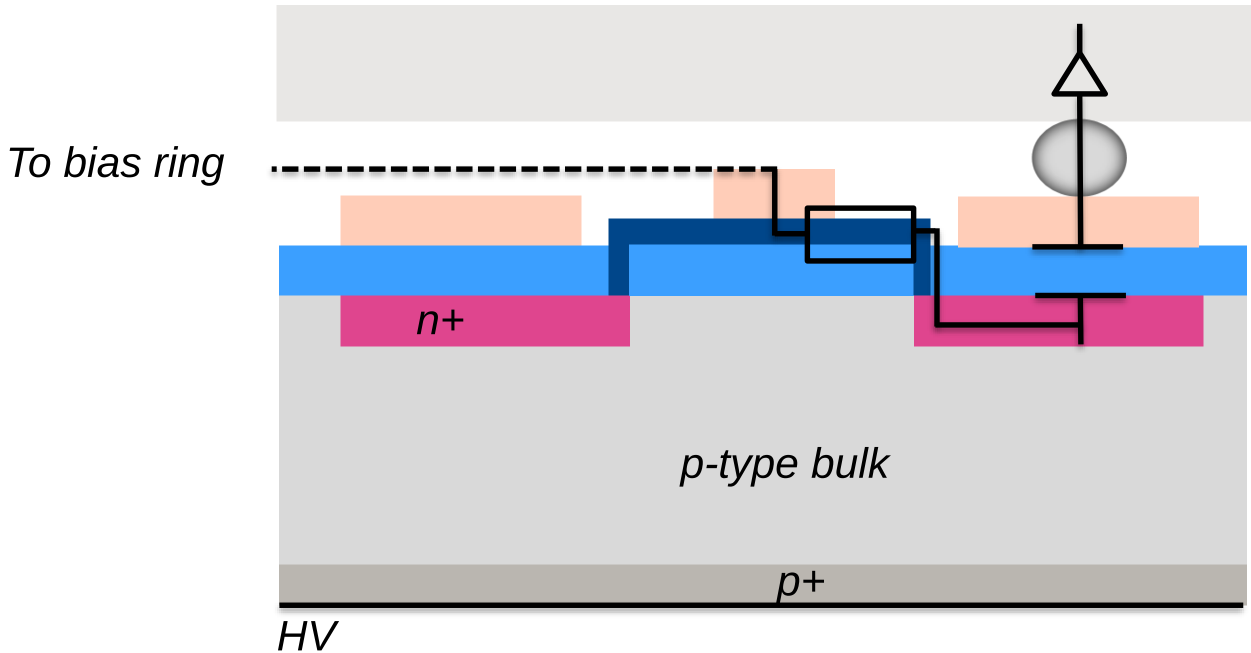






Metal bias line

AC-coupled pixel sensor



For 100 × 150 µm area:

C_{ox}: 12.3 pF

Drawing not to scale

C_{Si}: 6 fF

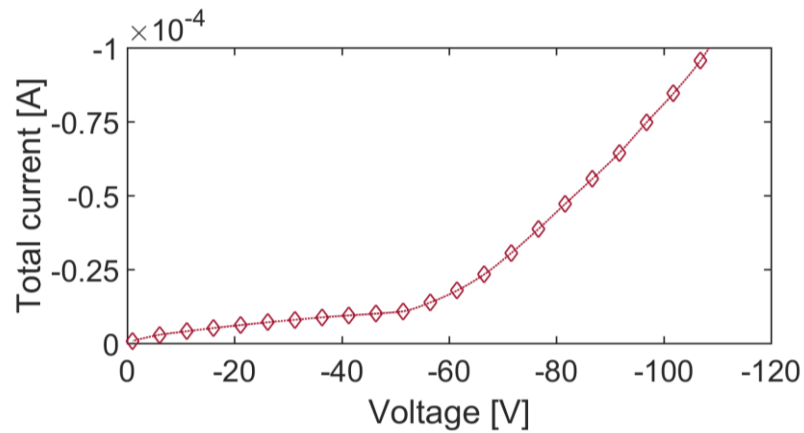
AC-coupled pixel detectors

- Sensors flip-chip bonded to PSI46dig readout chip, from CMS Pixel outer layers Phase-I upgrade

- **Configured and tested with detector test board (DTB) and pXar software**
  - Dead pixels
  - Trimming = fine-tuning of individual pixel thresholds through trimbits
  - Adjusting of pulse height / gain pedestal
  - Finding and masking of hot pixels
  - Testing with laboratory gamma ray sources

AC-coupled pixel detectors

- **Increase in leakage current – especially if bias voltage is ramped too fast – soon after full depletion of the sensor**
  - Current flow over the surface or the edge…
  - Measurements close to depletion voltage, ca. -40 V



- **Trimming to low thresholds not feasible: 100-120 (5-6 ke⁻) as opposed to CMS pixel sensor default 35 (1.75 ke⁻)**

AC-coupled pixel detectors

- **Testing with gamma ray sources:**
  - \+ good for "calibration" and understanding the properties of our detector
  - \- no external triggering possible, very low absorption in Si

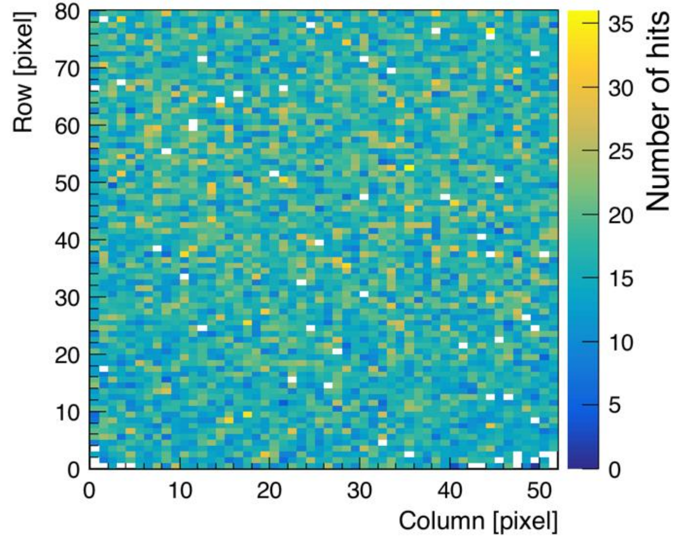
- Limited energy range due to a) lower absorption of Si towards higher energies, b) saturation of PSI46dig amplifier and ADC

- Mainly: Am-241 with 26.3 keV and 59.5 keV, Ba-133 with 31 keV and 81 keV, (Co-57 120 keV)

AC-coupled pixel detectors

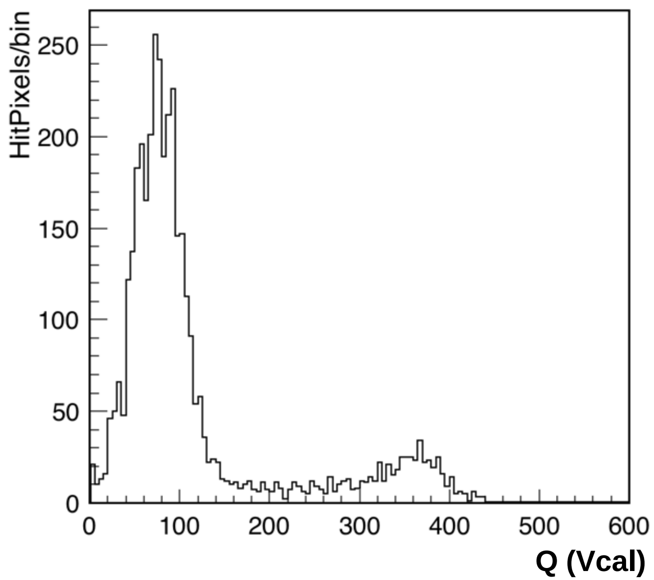
- **Typically 10-20 dead pixels / assembly: < 0.5 %**
- **Similar number of hot or noisy pixels masked**

- Clustering by obtaining pixel-by-pixel hit information: may improve resolution if there is charge sharing between pixels

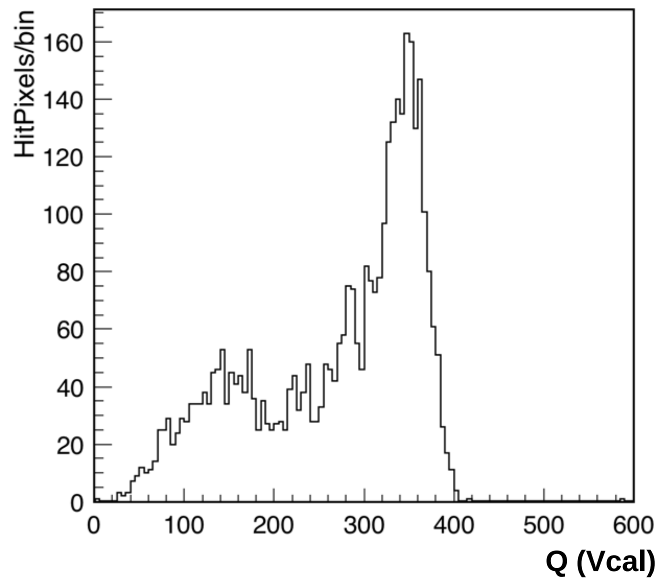


AC-coupled pixel detectors

Trimming



T 65 (3.25 ke$^-$)

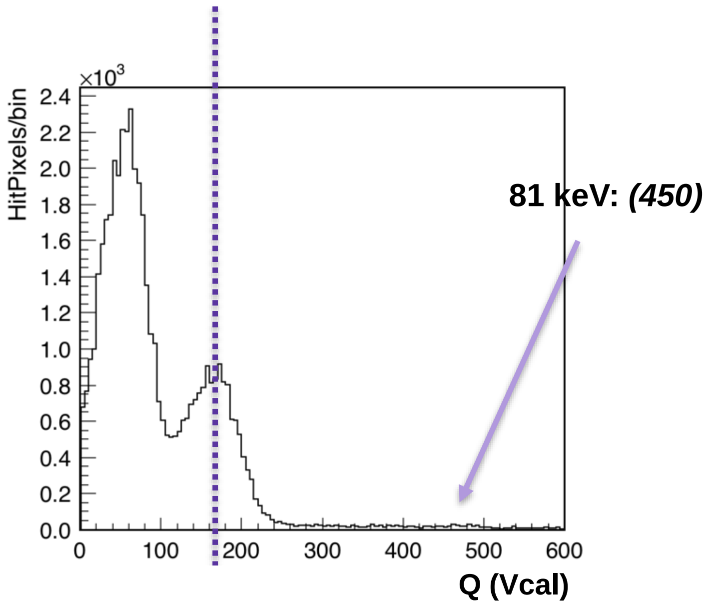


T 100 (5 ke$^-$)

AC-coupled pixel detectors

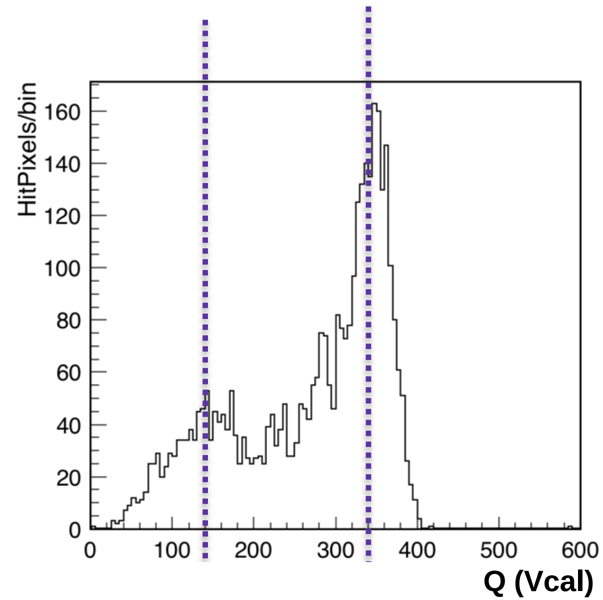
Sources

31 keV: 170 *(172)*



Ba-133

26.3 keV: 140 *(146)* **59.5 keV: 340 *(331)***

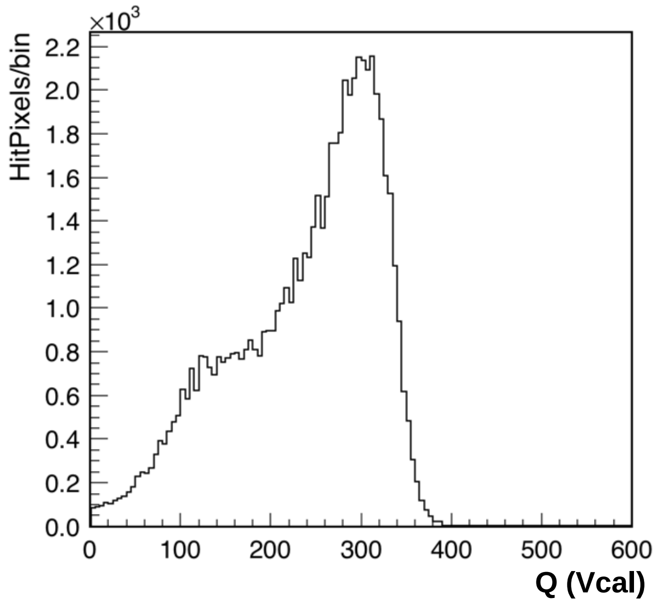


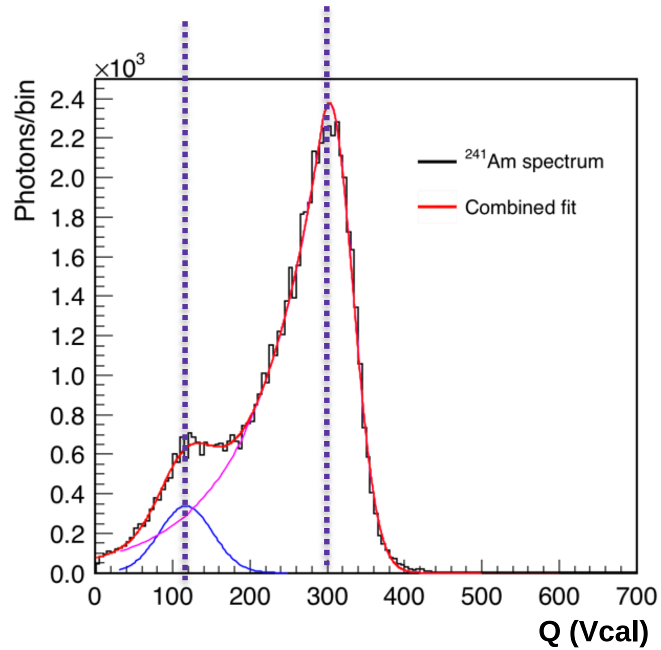
Am-241

AC-coupled pixel detectors

Clustering

26.3 keV: 110 *(146)*   59.5 keV: 300 *(331)*



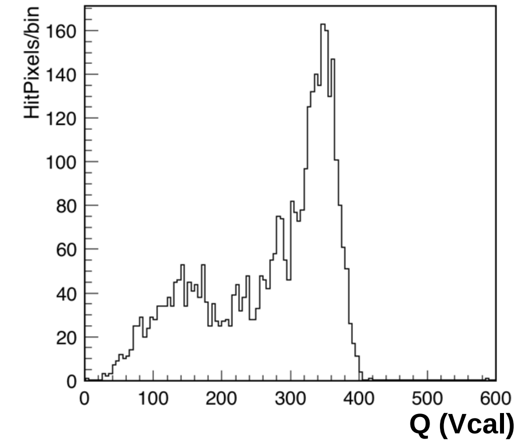


AC-coupled pixel detectors

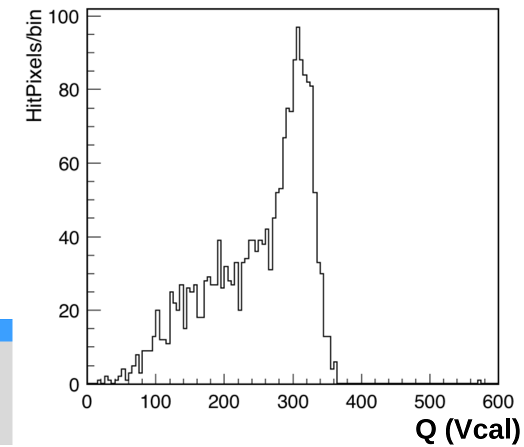
- **De-coupling of (high) current from performance in terms of noise and energy resolution**

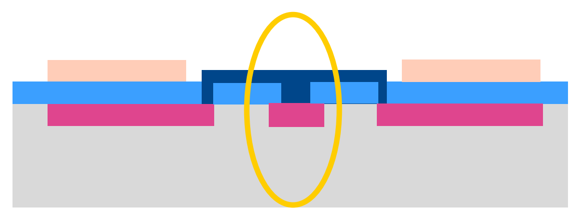
- **Leaking of charge into implanted bias line?**

Sample 2: 8 µA, T 100



Sample 1: 150 nA, T 120





Summary

- **We have fabricated single pad diodes and pixel detectors using aluminium oxide: no SiO_2 left, no p-spray/p-stop**
  - AC-coupling on sensor using Al_2O_3 and nitride biasing resistors
- **Material and basic electrical properties studied with diodes, oxide properties from MOS capacitor measurements**
  - Expected high negative oxide charge, leakage currents okay
- **Functionality of pixel detectors verified by testing with radioactive sources**
  - Testing with existing readout ASIC and test board is convenient, but cannot blindly use the same settings as for DC-coupled CMS Phase-I pixel detectors (need e.g. higher thresholds)

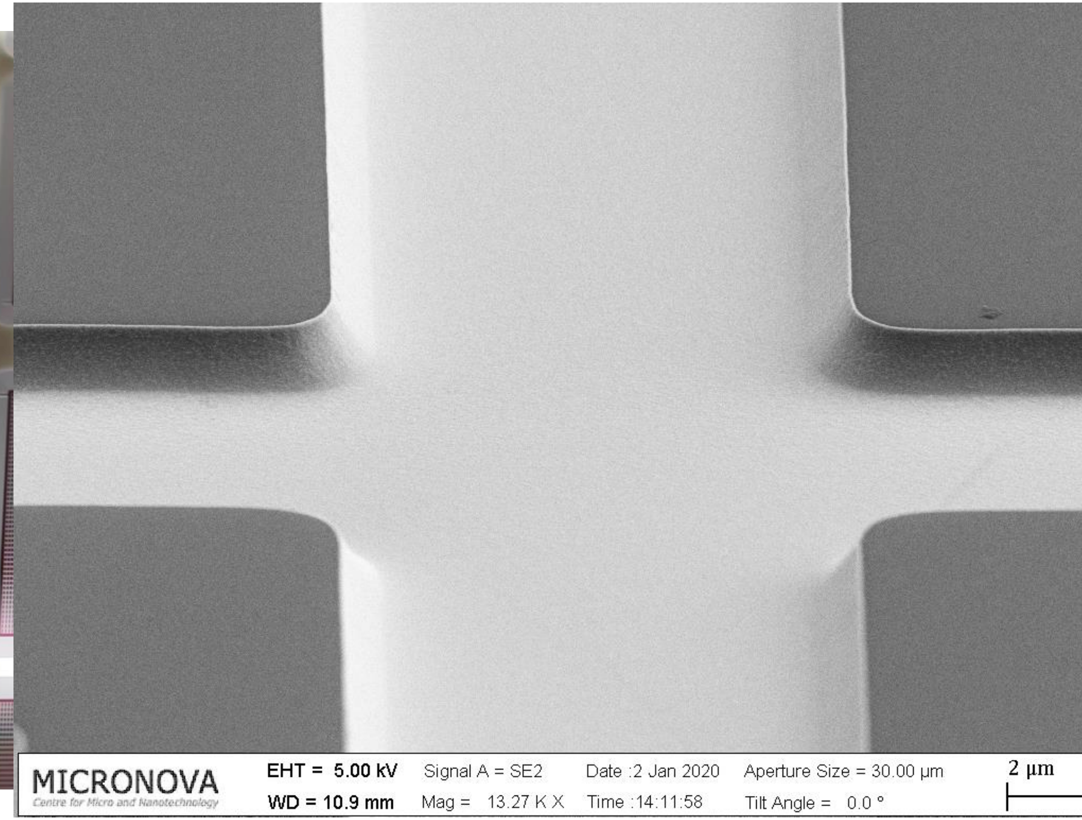
Next steps

- **More statistics with present and additional samples, further optimization of bias and trimming settings**

- **Hit efficiency and charge collection efficiency, spatial resolution from test beam data**
  - Also check for leakage to bias line!

- **Investigate HfO_2 in pixel area for more dielectric strength**
  - Patterning not trivial: investigating chemical-mechanical polishing

HfO_2 patterned by CMP



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LUT University

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Acknowledgements

<u>Micronova Nanofabrication Centre</u>

MICRONOVA
Centre for Micro and Nanotechnology

Helsinki Detector Laboratory

*J. Ott acknowledges the **Vilho, Yrjö and Kalle Väisälä Foundation** of the Finnish Academy of Science and Letters for research funding*

SUOMALAINEN TIEDEAKATEMIA

References

Alumina in strip detectors:

J. Härkönen et al., *Processing of n+/p−/p+ strip detectors with atomic layer deposition (ALD) grown Al2O3 field insulator on magnetic Czochralski silicon (MCz-Si) substrates*, Nucl. Instr. Meth. Phys. Res. A 828 (2016) 46–51

TiN resistors, concepts for ALD in pixel sensors:

J. Ott, *Titanium nitride thin-film bias resistors for AC coupled segmented silicon detectors*, Master's thesis, University of Helsinki, Faculty of Science, Department of Chemistry, Helsinki (2015)

J. Härkönen, J. Ott et al., *Atomic Layer Deposition (ALD) grown thin films for ultra-fine pitch pixel detectors*, Nucl. Instr. Meth. Phys. Res. A 831 (2016) 2–6

Properties and processing of alumina:

J. Ott et al., *Detector processing on p-type MCz silicon using atomic layer deposition (ALD) grown aluminium oxide*, 33rd RD50 Workshop (2018) https://indico.cern.ch/event/754063/contributions/3222806/

J. Ott et al., *Processing of ac-coupled n-in-p pixel detectors on MCz silicon using atomic layer deposited aluminium oxide,* Nucl. Instr. Meth. Phys. Res. A, doi:10.1016/j.nima.2019.162547

A. Gädda, J. Ott et al., *AC-coupled n-in-p pixel detectors on MCz silicon with atomic layer deposition (ALD) grown thin film process*, HSTD12 (2019), https://indico.cern.ch/event/803258/contributions/3582878/

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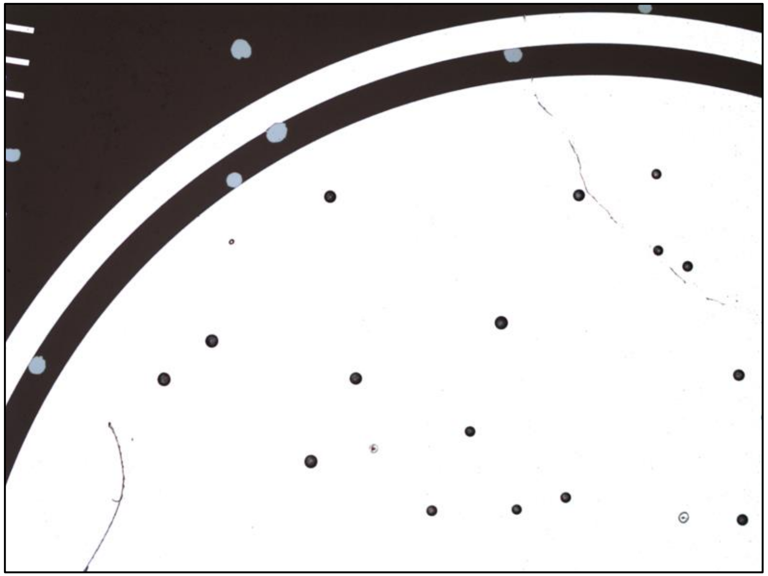
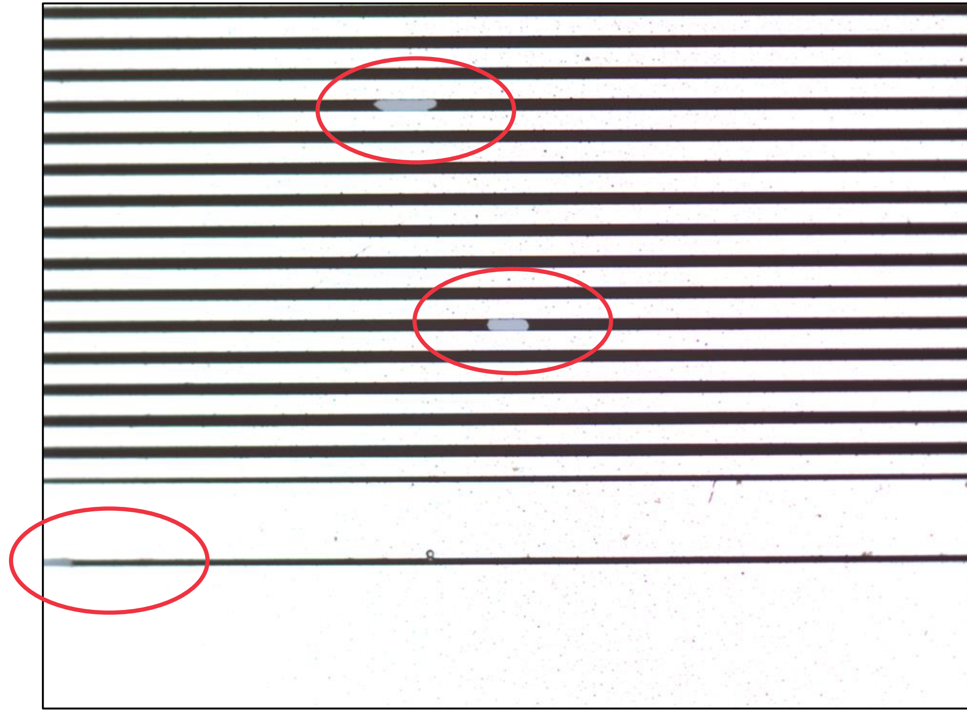
Backup

Considerations on Al_2O_3 in processing

H_2O as precursor:

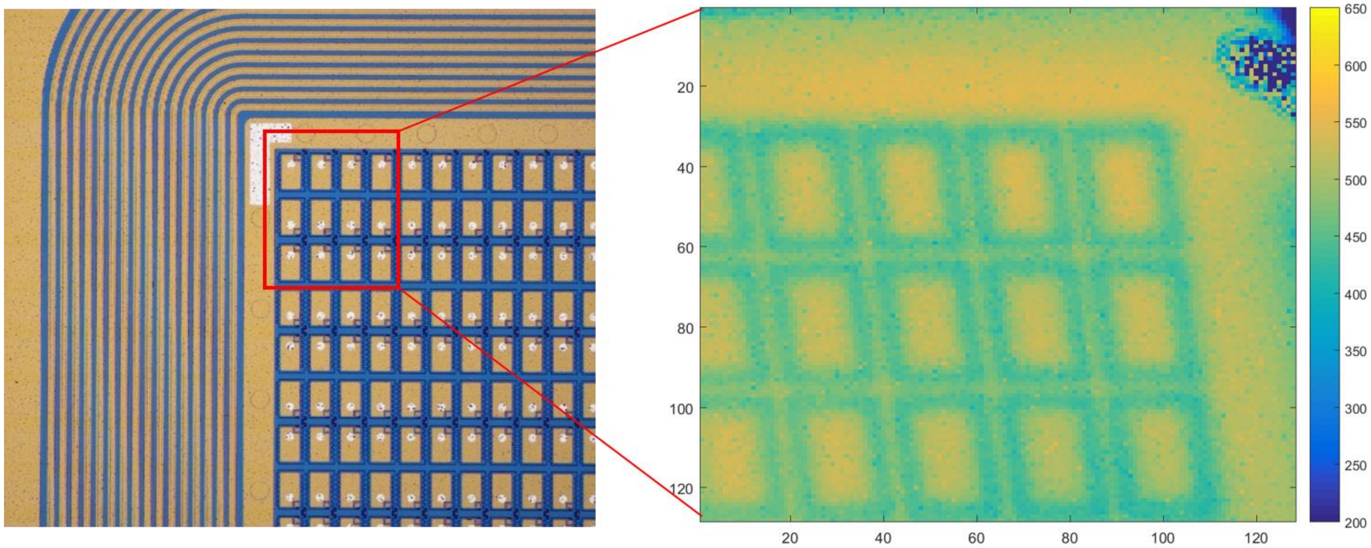




→ **”blistering” of Al_2O_3 film as consequence of H segregation to interface**
→ **blisters can be almost the same size as pixels!**

Proton microprobe

At RBI IBIC facilities, cf. Aneliya's talk



PSI46dig-geometry AC-coupled pixel sensor with Al2O3 insulator

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

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?

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**