The Silicon Electron Multiplier Sensor

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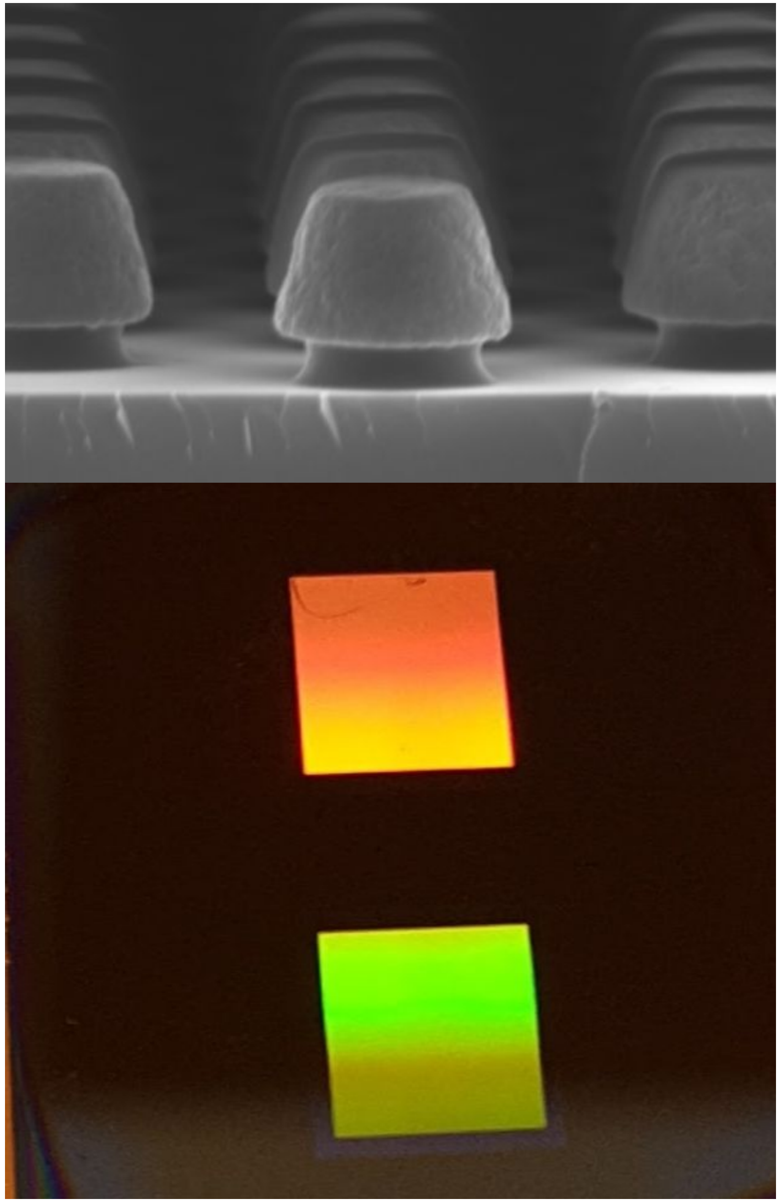
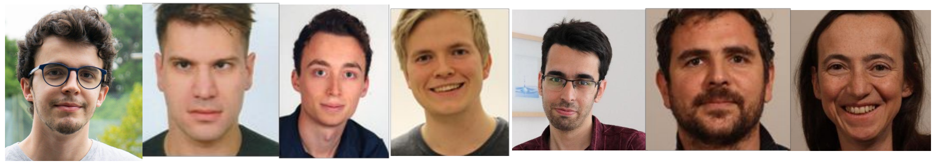
Overview

- Introduction, framework and motivation
- Concept
- Simulation results
- Fabrication study
- Characterisation
- Outlook

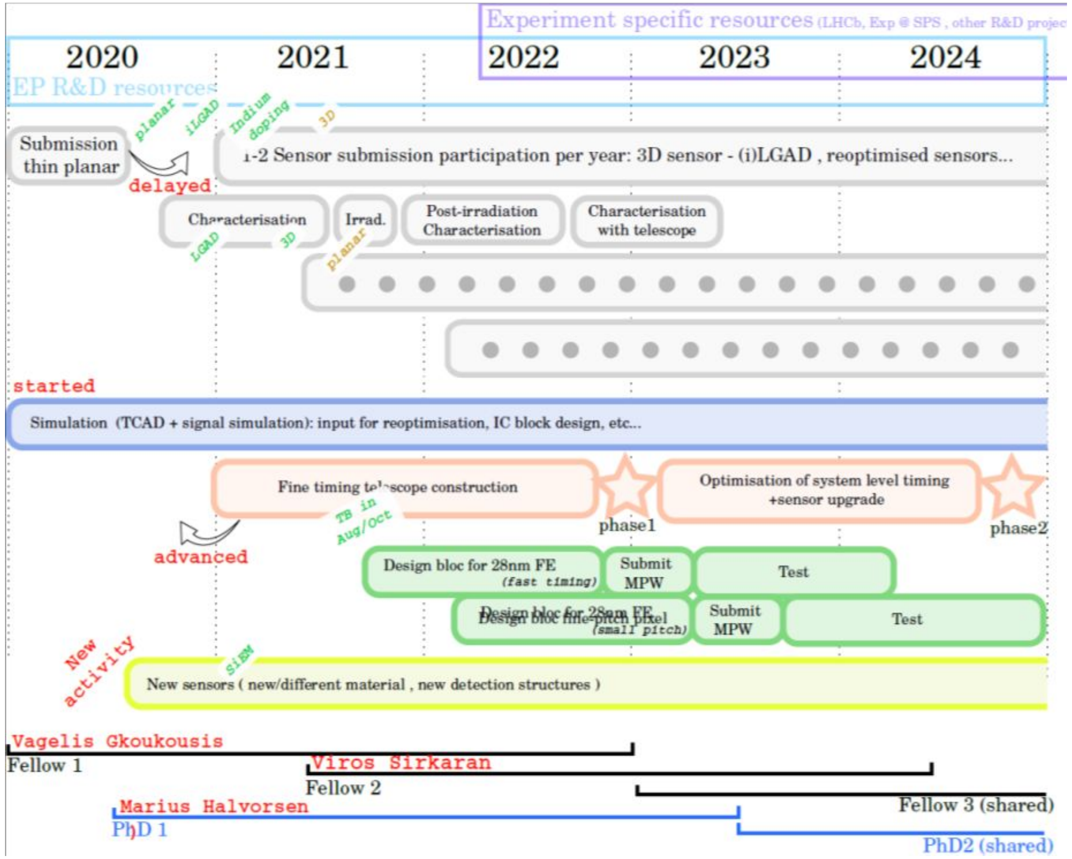


Introduction to EP – R&D WP1.1 Hybrid sensors



Eloi Pazos Rial, Vagelis Gkougkousis, Jakob Haimberger, Marius Mæhlum Halvorsen, Mohammadtaghi Hajheidari, Victor Coco, Paula Collins

- Planar sensors
  - Radiation damage and trapping model validation through TCAD
  - Timing and efficiency at <10^{17} n_{eq}/cm^2 using fast neutrons and PS protons(thicknesses 50, 100, 200, 300 μm)
- LGADs
  - Radiation damage mechanisms and modelling on different doping types (TIPP)
  - Arxiv preprint
  - Indium–Lithium gain layer radiation hardness investigations (Trento2021)
  - Process simulations and SiMS-Carbon/Boron (Trento2022)
- Silicon Electron Multiplier Sensor
  - Structure optimisation and electrostatic simulations
  - Timing and transient simulations
  - Processing iterations (Metal Assisted Chemical Etching)
  - NIM-A article
  - RD50 november 2021, Trento2022
- Small Pitch 3Ds for tracking and timing (Trento2022)
  - β particle timing studies on irradiated and unirradiated devices
  - Test beam with SPS Pions (Tracking +Timing)
  - Proton and neutron irradiations >10^{17} n_{eq}/cm^2
  - New small pitch production optimised for gain at the electrode region
- ASIC design
  - small pitch, fast timing



Motivation

from the CERN Strategic R&D Programme on Technologies for Future Experiments [CERN-OPEN-2018-006]
and CEPC Conceptual Design Report: Volume 2- Physics & Detector [IHEP-CEPC-DR-2018-02]

[fineprint in CERN-OPEN-2018-006]	HL-LHC	SPS	FCC-ee	FCC-hh	CEPC
Fluence [$n_{eq}/cm^2/y$]	$5x10^{16}$	10^{17}	10^{10}	10^{17}	$6x10^{12}$
Max Hit rate [$cm^{-2}\ s^{-1}$]	2-4 G	8 G	20 M	20 G	11M
Material budget per layer [X_0]	0.1-2%	2%	0.3%	1%	0.15%
Pixel size [μm^2] inner trackers	50x50	50x50	25x25	25x25	16x16
Temporal hit resolution [ps] inner trackers	~50	~40	-	~10	-

Future inner tracker detectors will require

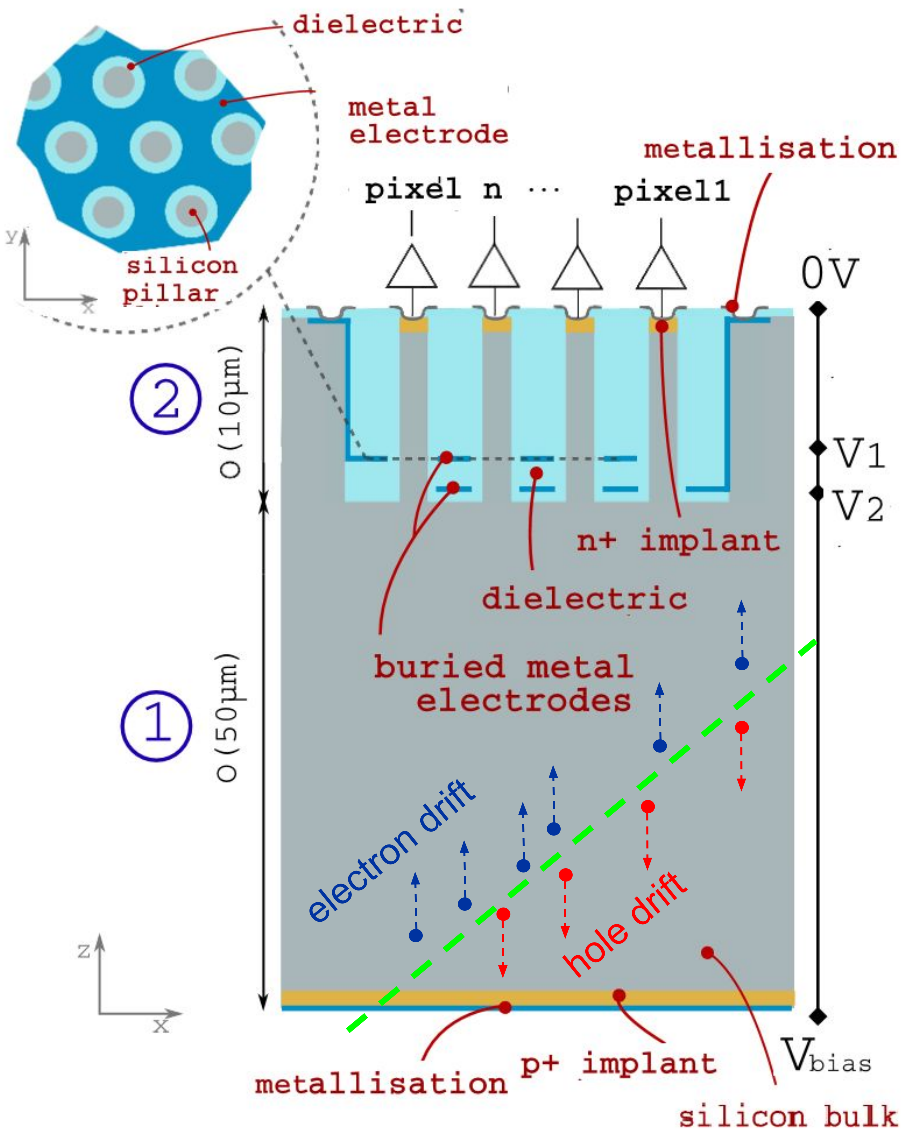
- Time resolutions below 50 ps
- Pixel pitch down to 25 µm
- Radiation hardness up to 10^{17} n_{eq}

Our approach

- Gain, doping independent
- Small pitch
- Small thickness, radiation hardness

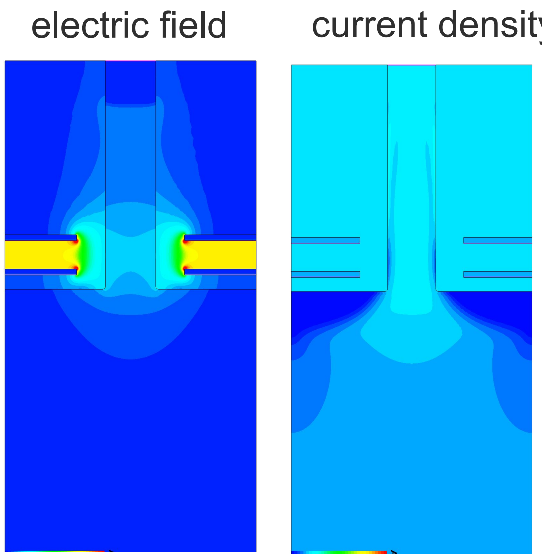
Approach

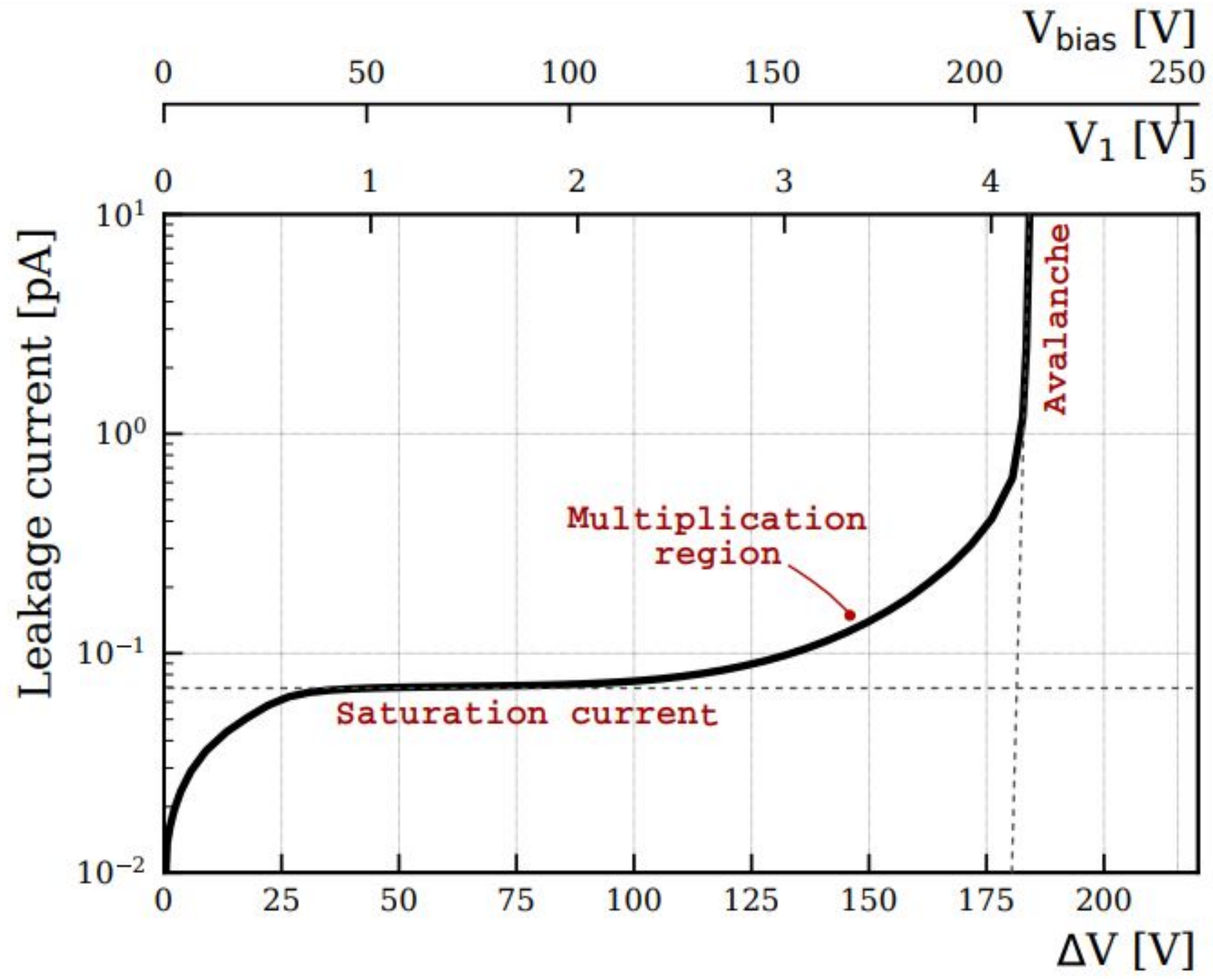
- Additional electrodes in sensor substrate
- Bias to make high field regions for charge multiplication
- Geometry
  - Dense positioned silicon pillars
  - Metallic grids and dielectrics between pillars
- Advantages:
  - Small pitch
  - Good time resolution
  - No gain layer deactivation due to acceptor removal
- Simulations using Synopsys TCAD
  summarised in article 10.1016/j.nima.2022.167325



Quasi-stationary simulations

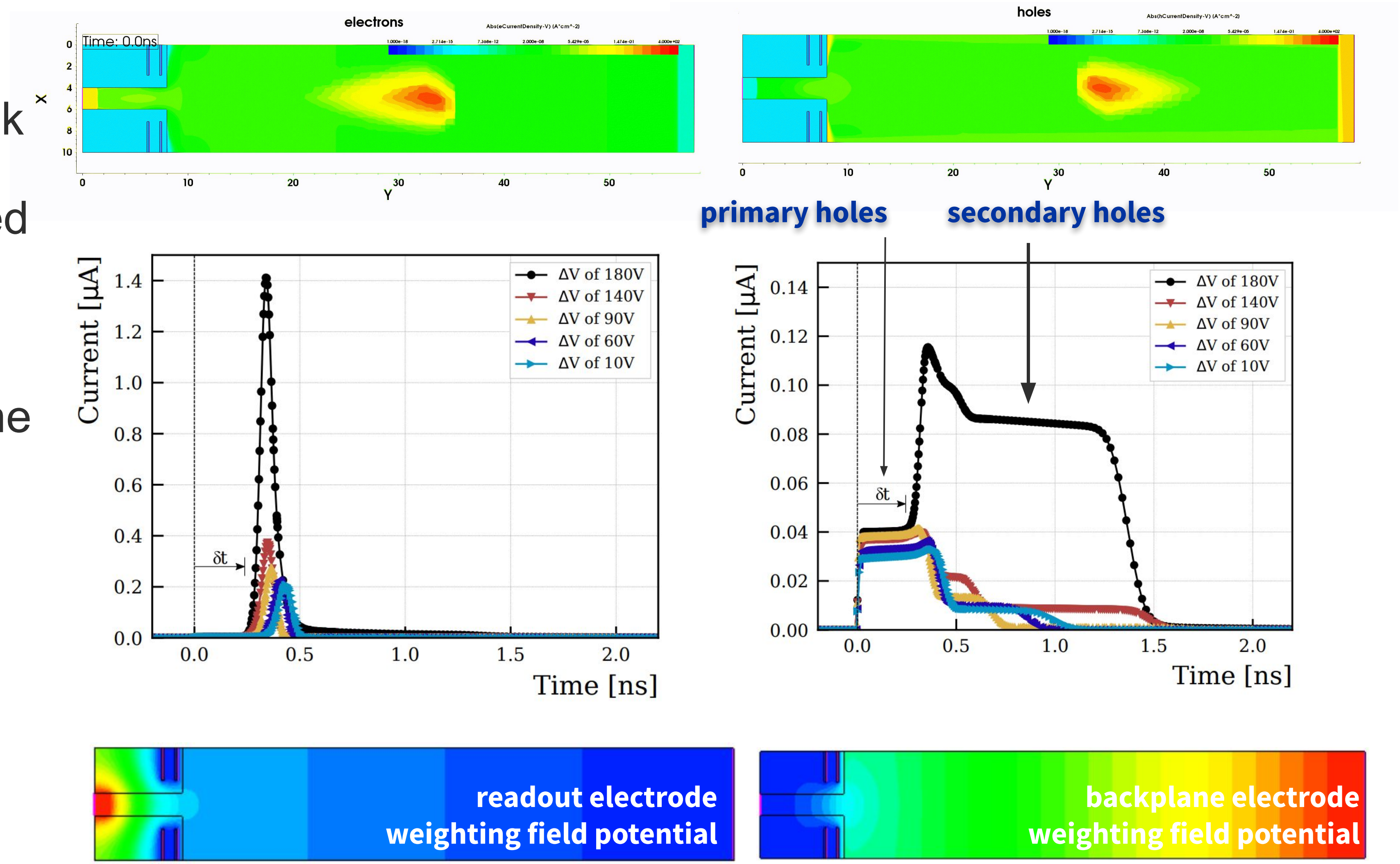
- Evaluate electric field and leakage current
- Pillar and bulk depletes
- High electric field in the pillars can be reached
  - Above 15 V/µm
  - Multiplication region.





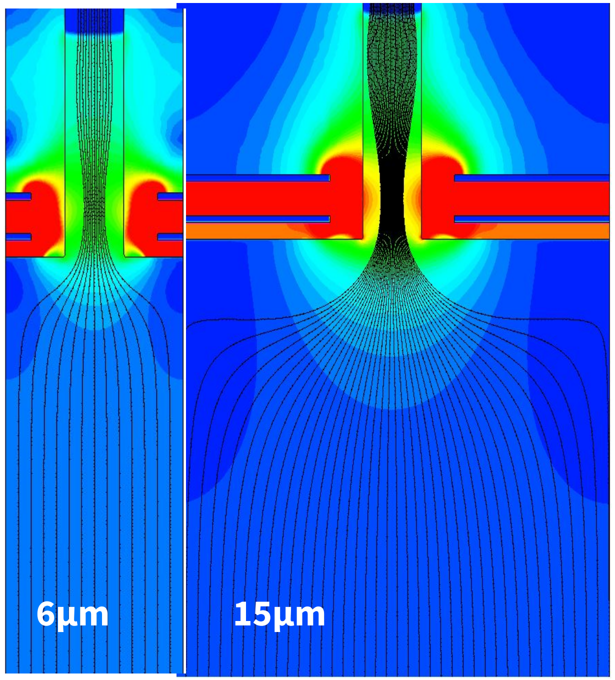
Signal simulations and charge multiplication

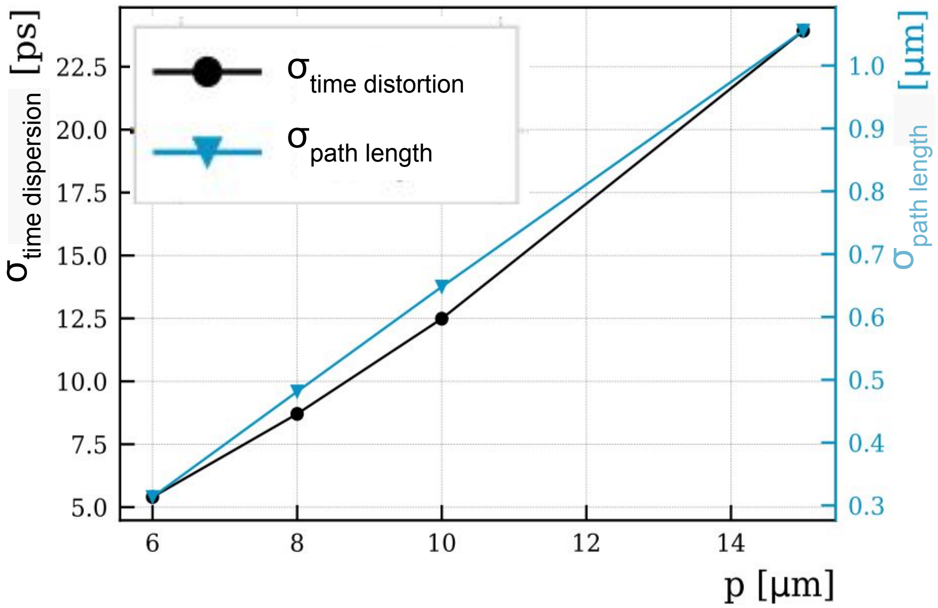
- Charge cloud deposited in bulk center
- Charges drift and get multiplied in pillars.
  - Gain= $Q_{collected}/Q_{injected}$
- Weighting field of readout electrode is concentrated in the pillar
  - Shielded by multiplication electrode
- Weighting field of backside electrode
  - “Pad like”



Optimisation studies

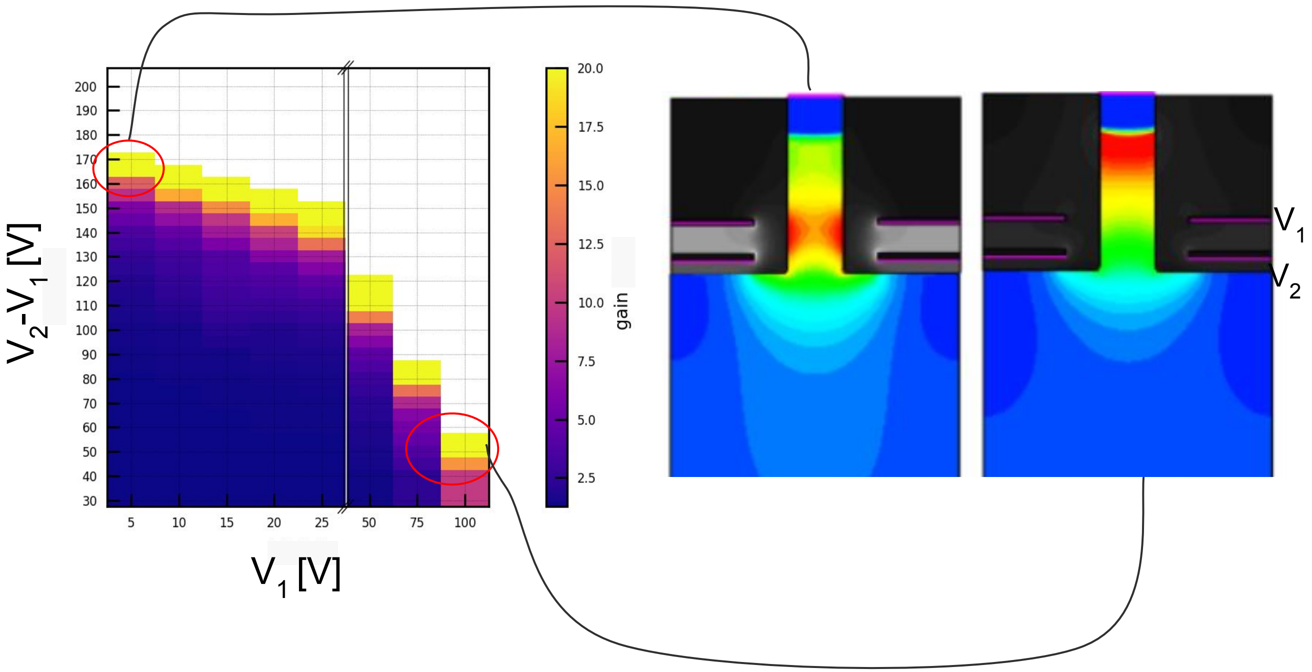
- Explore parameter space
  - Pillar diameter
  - Pillar height
  - Electrode geometries
  - +++
- Pitch
  - Large pitch distorts the driftpaths

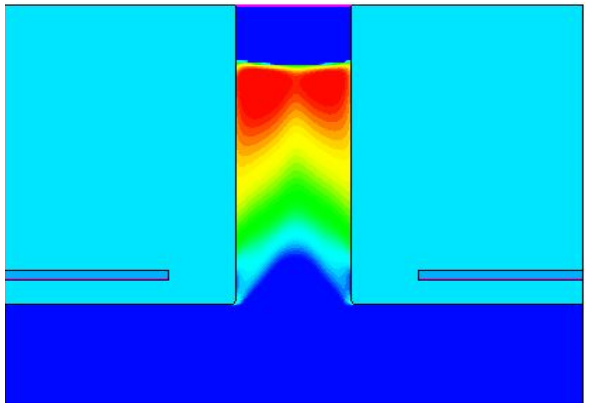




Electrodes

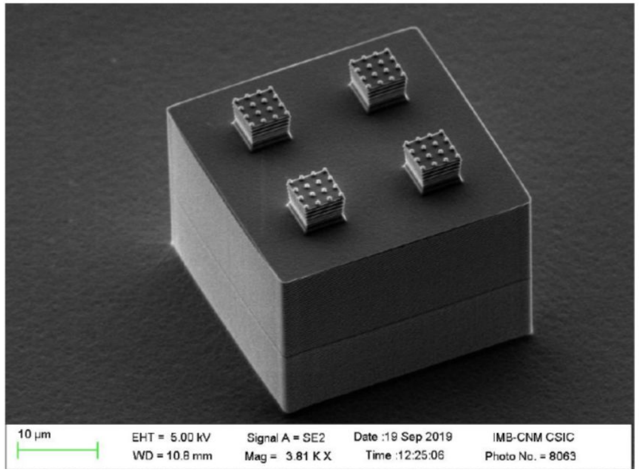
- Biassing scheme
- Electrode geometry
    - Electrode separation
    - Electrode dimensions
    - Number of electrodes
        - Single electrode configurations





Fabrication

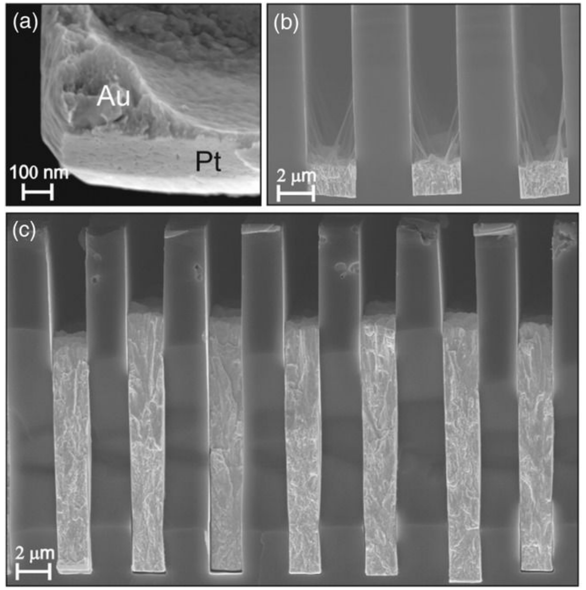
[courtesy of CNM]



Deep Reactive Ion Etching (DRIE)

- Awarded the AIDA innova blue sky R&D to make a demonstrator with CNM
- Properties to explore in and after production
  - Feasibility of geometry
  - Electrode/wall guard, thickness of oxide, corner shapes…
  - SiO_2/Si interface, scalloping, ...
  - Electrical properties

[L. Romano *et al*; AdEM 22 (2020) 2000258]



Metal Assisted Chemical Etching (MacEtch)

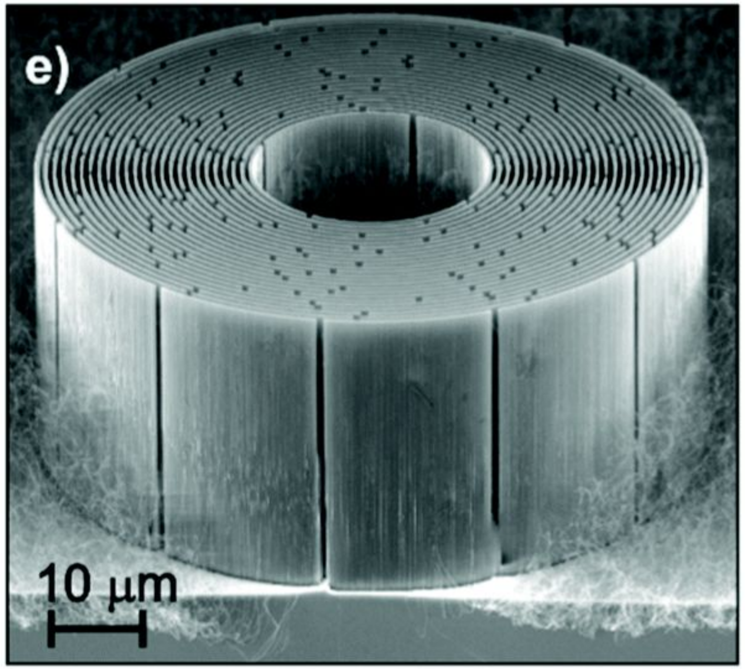
- Demonstrator production with PSI
- Never tested on active media
  - Compatability with active media

Metal Assisted Chemical Etching

- The MacEtch process
  - Metal pattern used as a catalyst for HF etching.
  - Recipe for X-ray optics developed at PSI
    - Romano,L (2020). Metal assisted chemical etching of silicon in the gas phase: a nanofabrication platform for X-ray optics, https://doi.org/10.1039/C9NH00709A

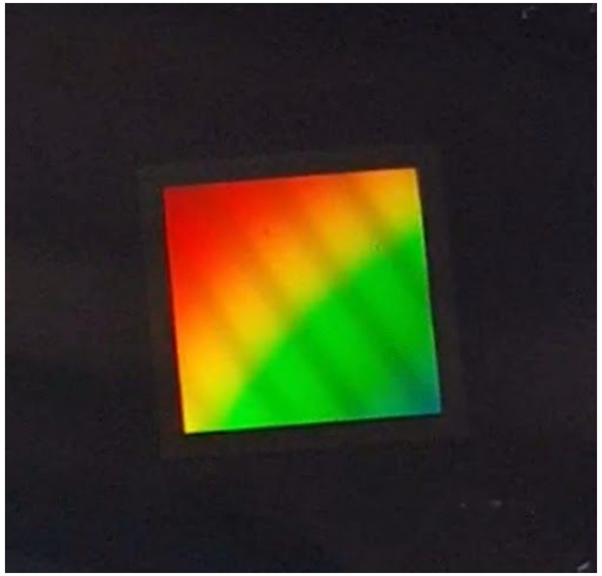
- MacEtch for prototyping
  - Single multiplication electrode structures
  - Allows dense pillars

[L. Romano *et al*; https://doi.org/10.1039/C9NH00709A]

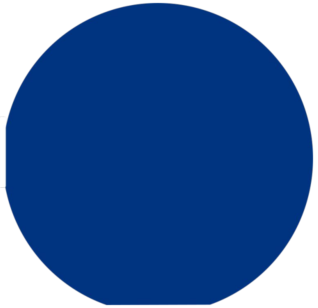


Demonstrator production with MacEtch

- Photolithography optimisation
  - Photoresist
  - Direct write laser
    - Heidelberg DWL66+
    - UV laser
    - Feature sizes down to 300 nm

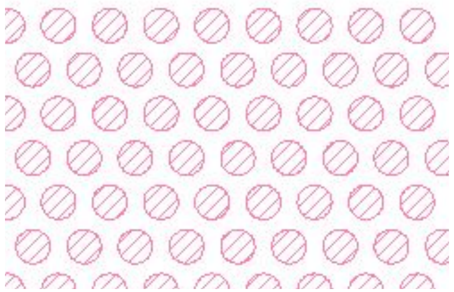


1. Implanted Silicon wafer



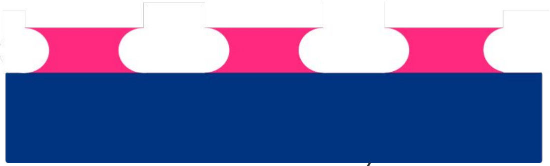
2. wafer photoresist

3. Patternise with direct write laser



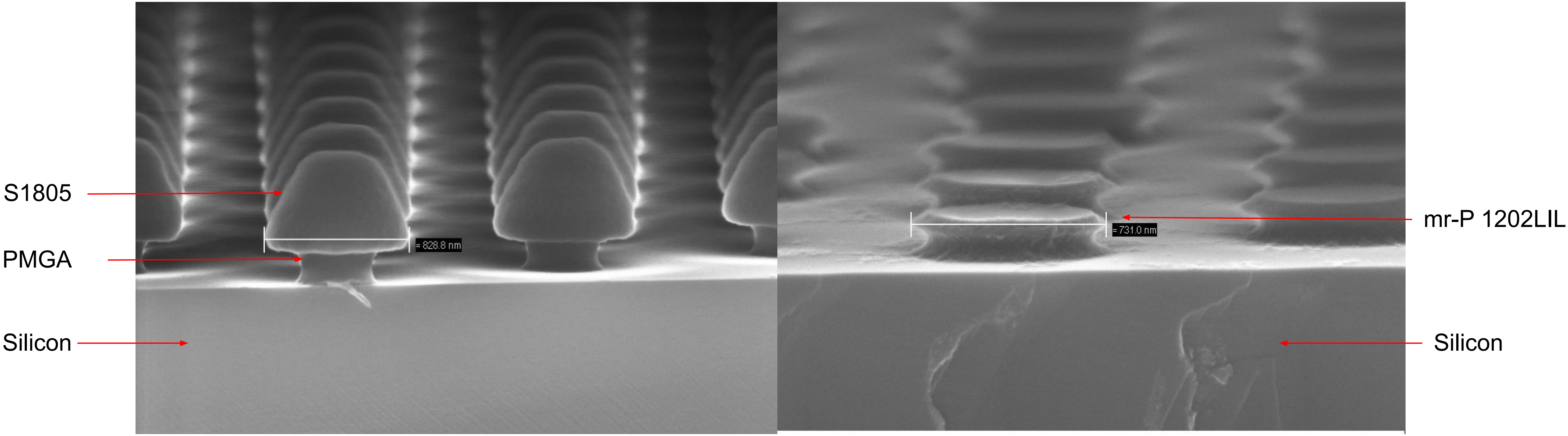
diameter =1 μm
pitch = 1.5 μm

4. Develop



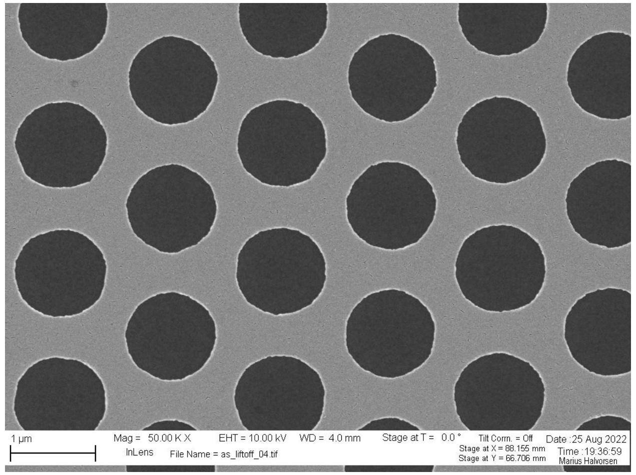
Lithography optimisation

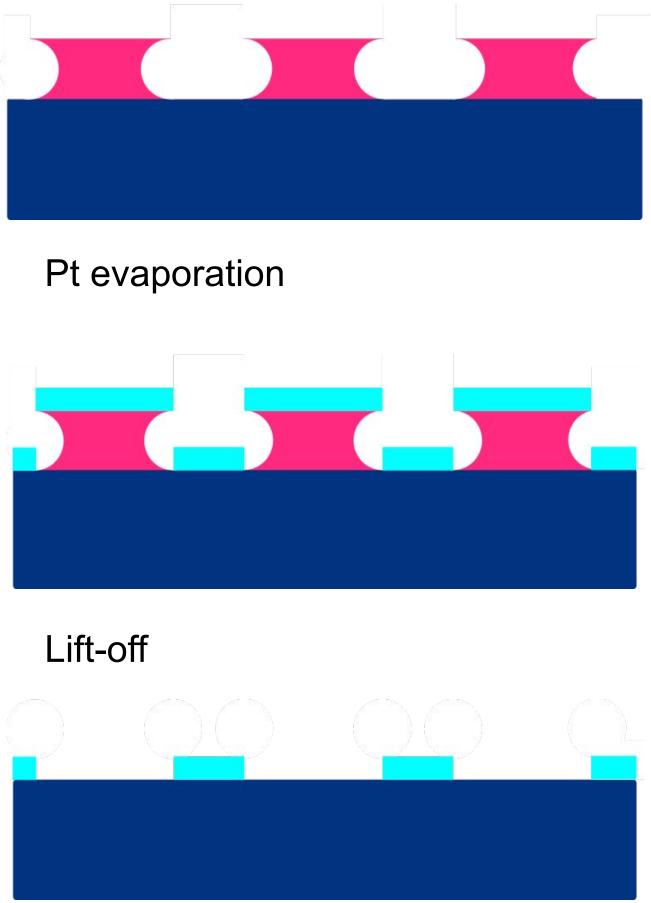
- Tried different photoresists
- Optimise laser exposure parameters
  - Pattern features
  - Laser power
  - Development time



Metal deposition

- Metal deposition
  - e-beam evaporation, 12 nm Pt.
- Lift-off
  - Remove photoresist and excess metall
  - Optimise method
    - Solvent
    - Temperature
    - Ultrasonic intensity and frequency



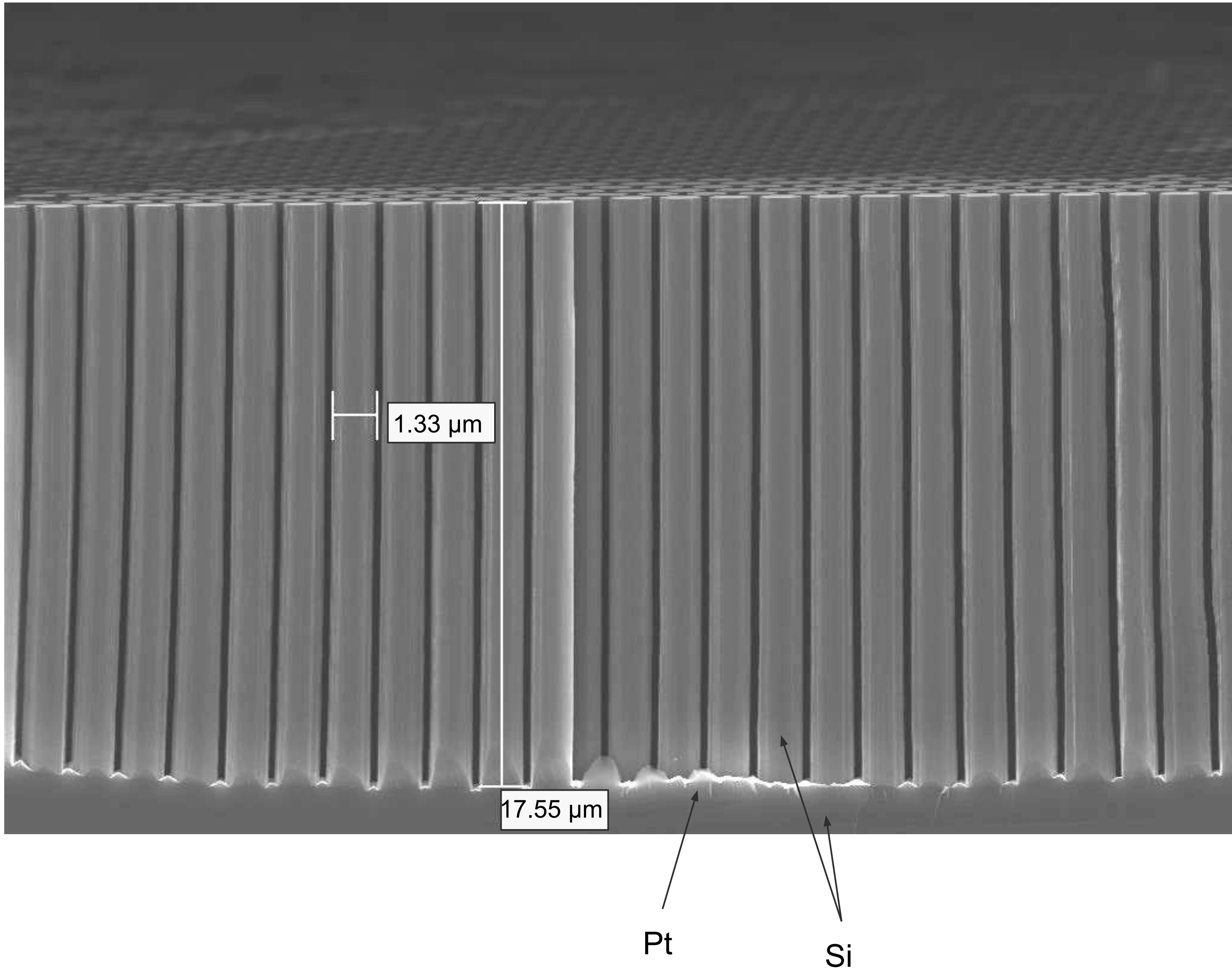


Etching

- Expose patter to HF vapor
  - Oxygen reduction at catalyst
    - $O_2+4H^+\rightarrow 2H_2O+4h^+$
  - Silicon dissolves through two possible paths:
    - $Si+4h^++4HF\rightarrow SiF_4+4H^+$

      or

    - $Si+2H_2O+4h^+\rightarrow SiO_2+4H^+$
      - $SiO_2+2HF^-_2+2HF\rightarrow SiF_6^{2-}+2H_2O$

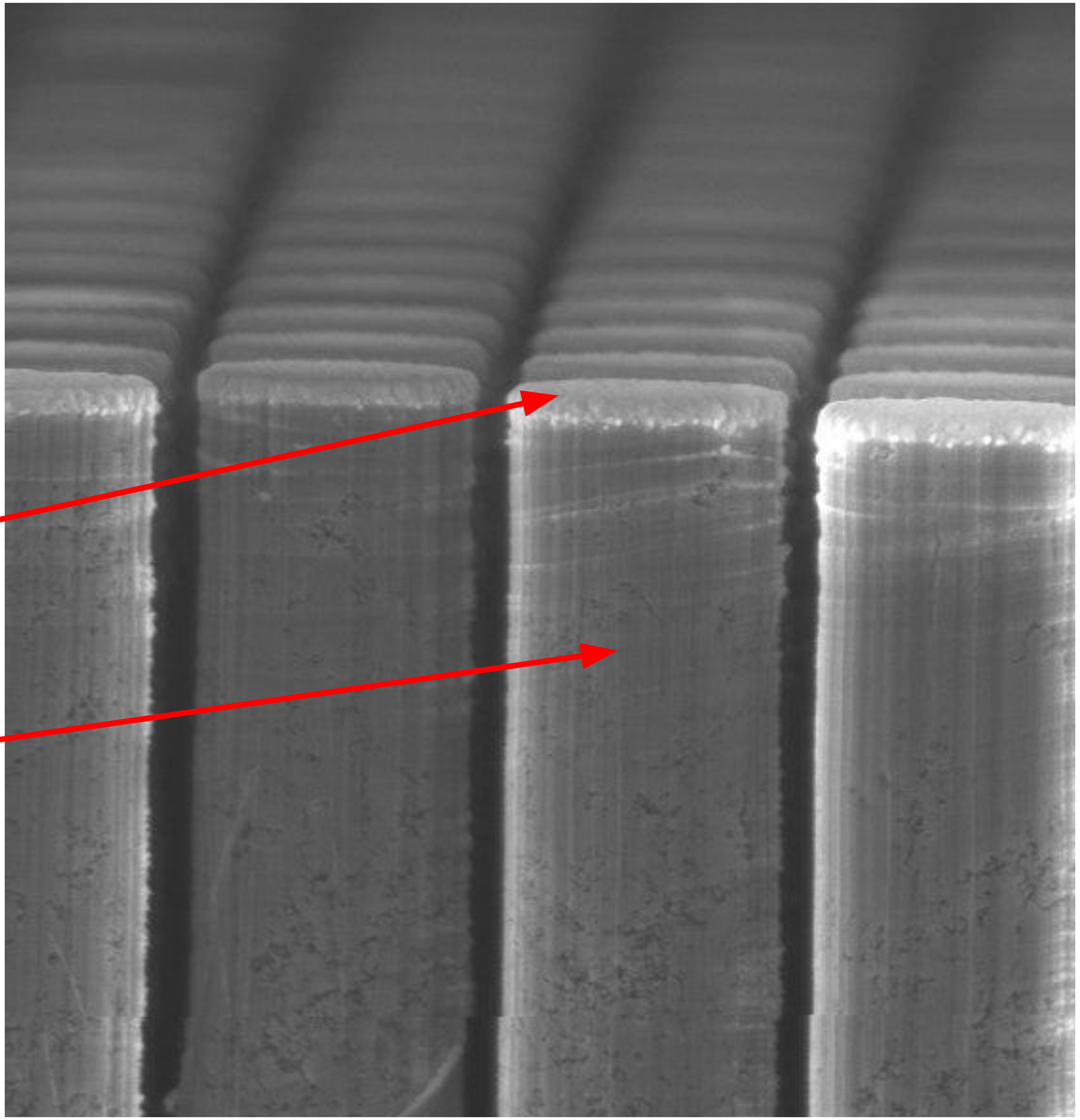


Electrical contact

- Native oxide removal
- Evaporation of 100 nm aluminum
    - Front side and back side

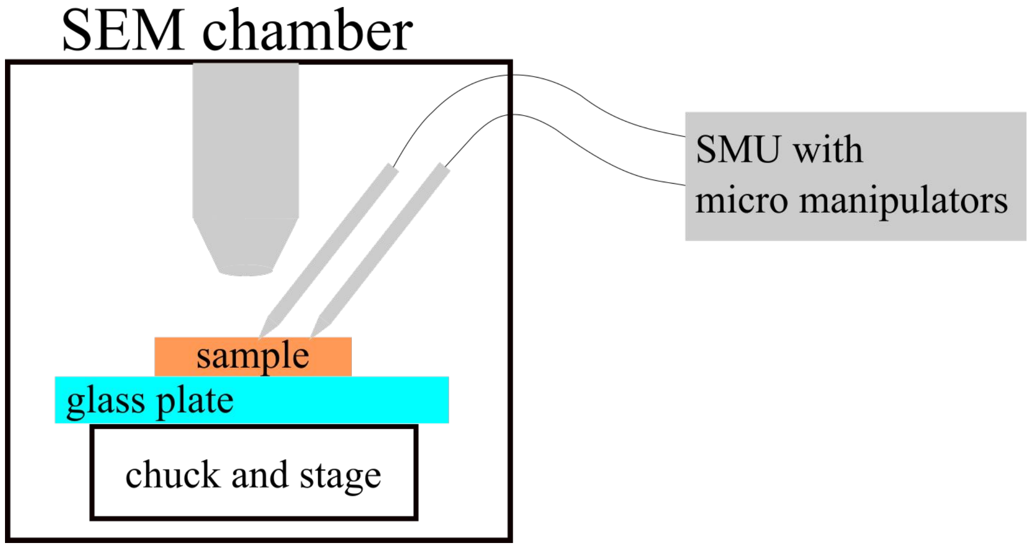
Aluminum

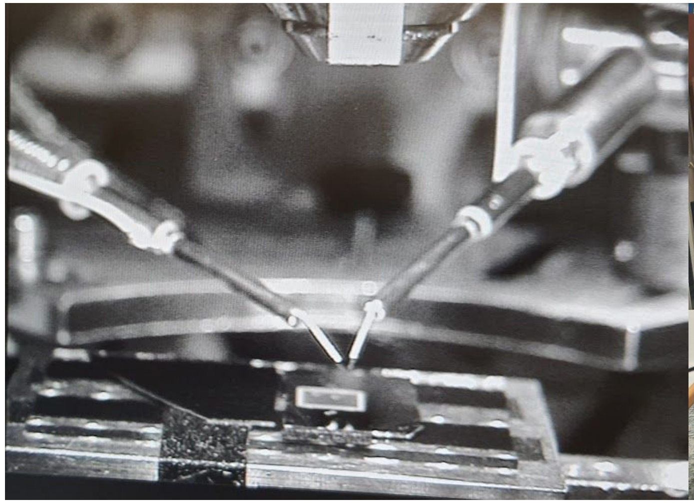
Silicon

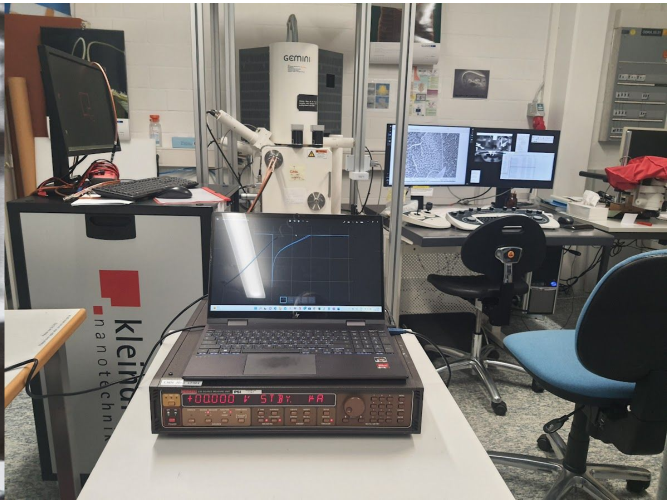


Set-up at PSI

- Current–Voltage (IV) characteristics
- Supra Zeiss SEM
- Kleindiek nanotechnik micromanipulators
  - Sub-micrometer tungsten needles
- Keithley 236 Source Measure Unit
  - Triax cables to micro manipulators







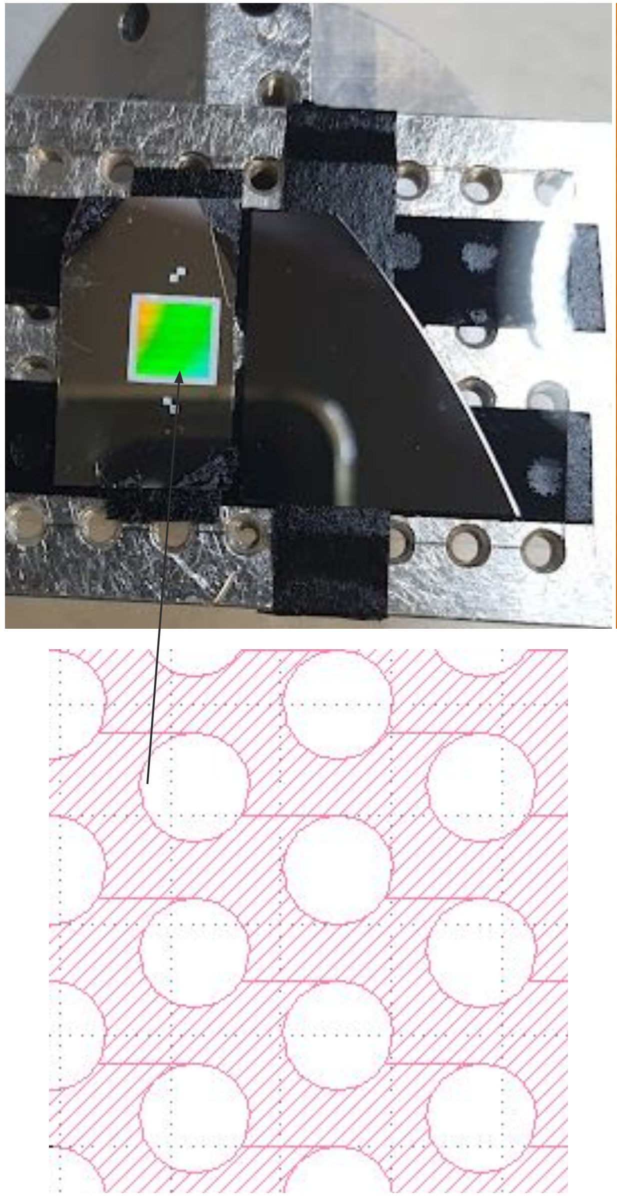
Support from Anja Weber, Dimitrios Kazazis, Lucia Romano, Soichiro Tsujino

Tested structures

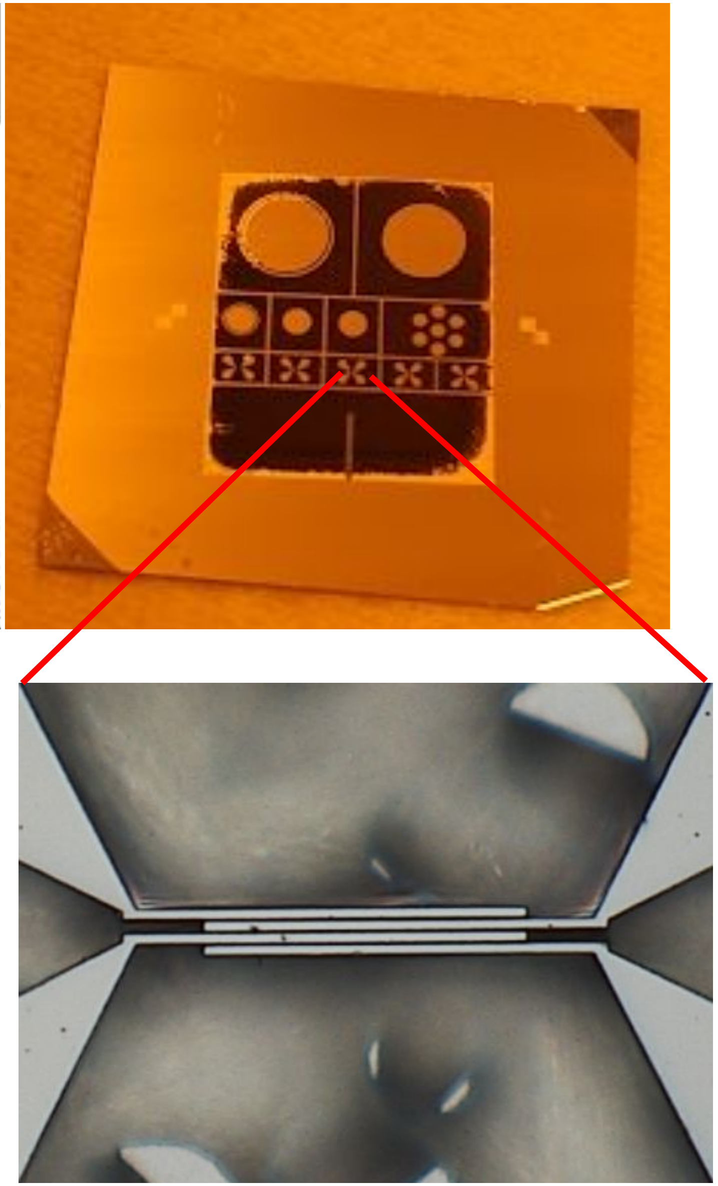
Two samples:

- A)
  - Pillar pattern
  - 1 µm wide pillars, hexagonal lattice with a pitch of 1.5 µm
- B)
  - strip structures

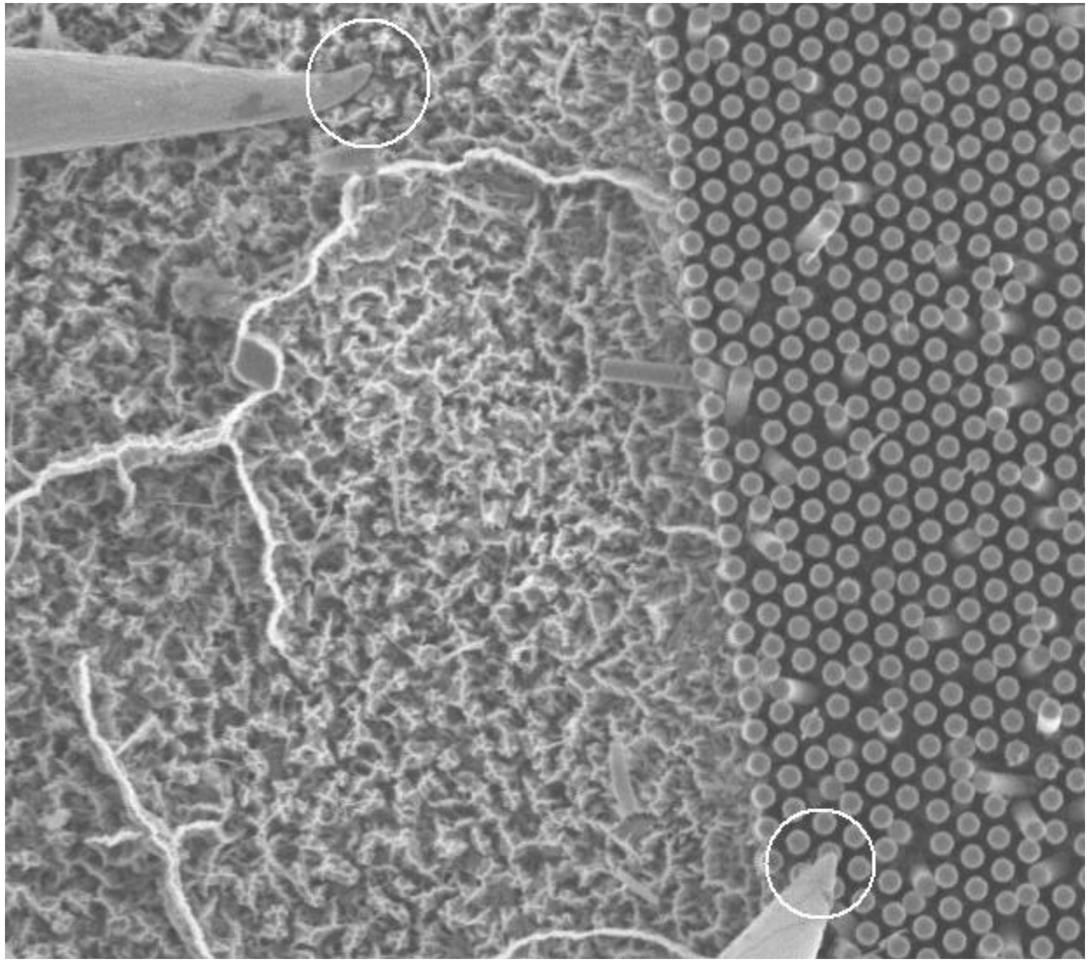
A)

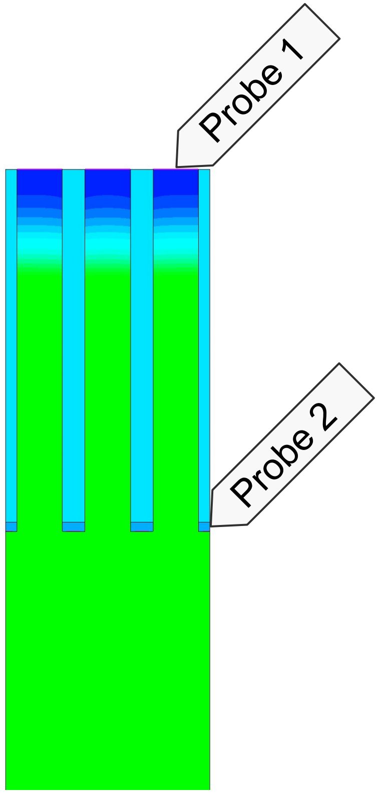


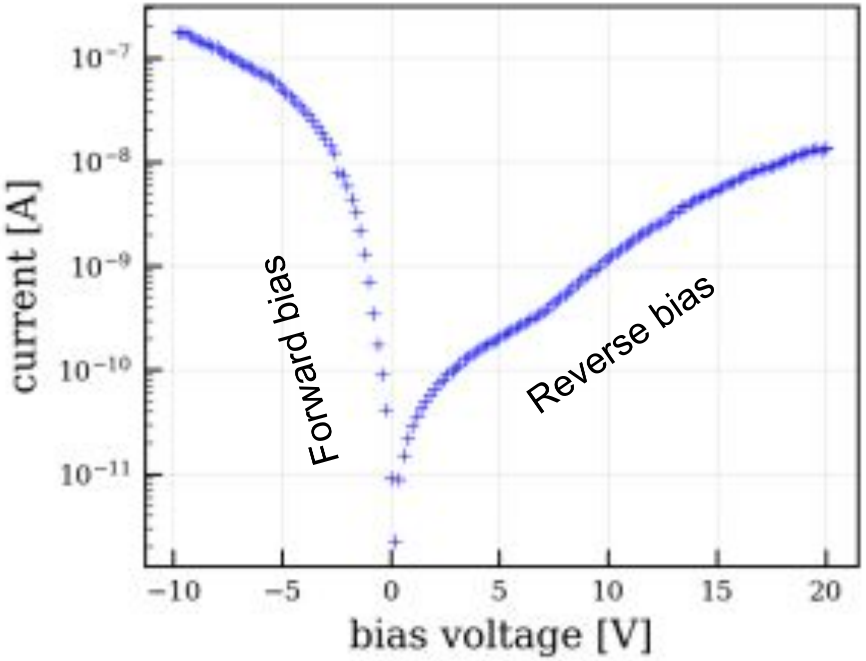
B)



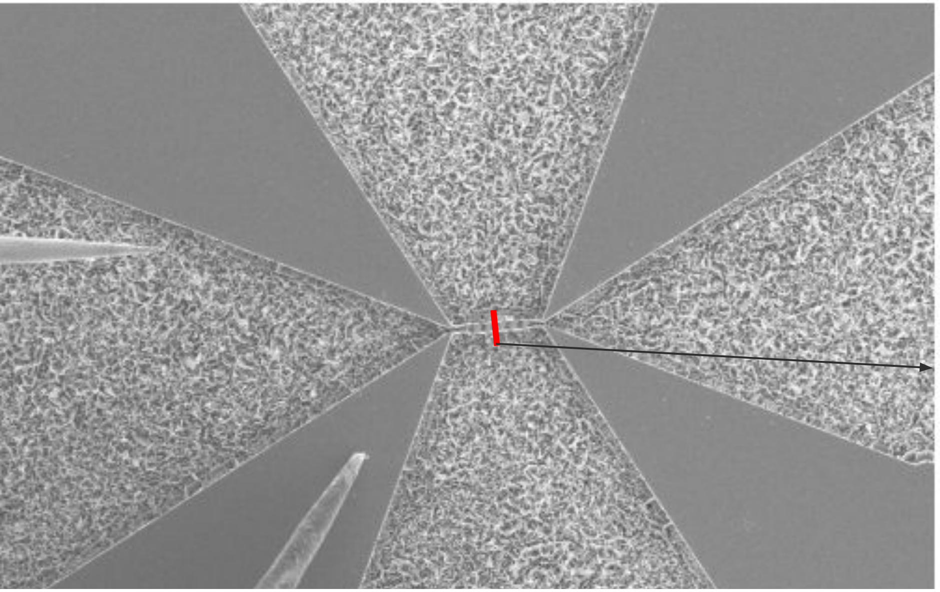
Probe pillars – One single pillar

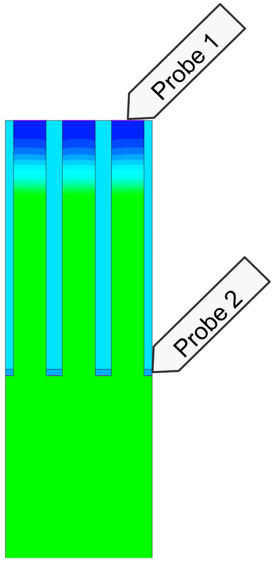


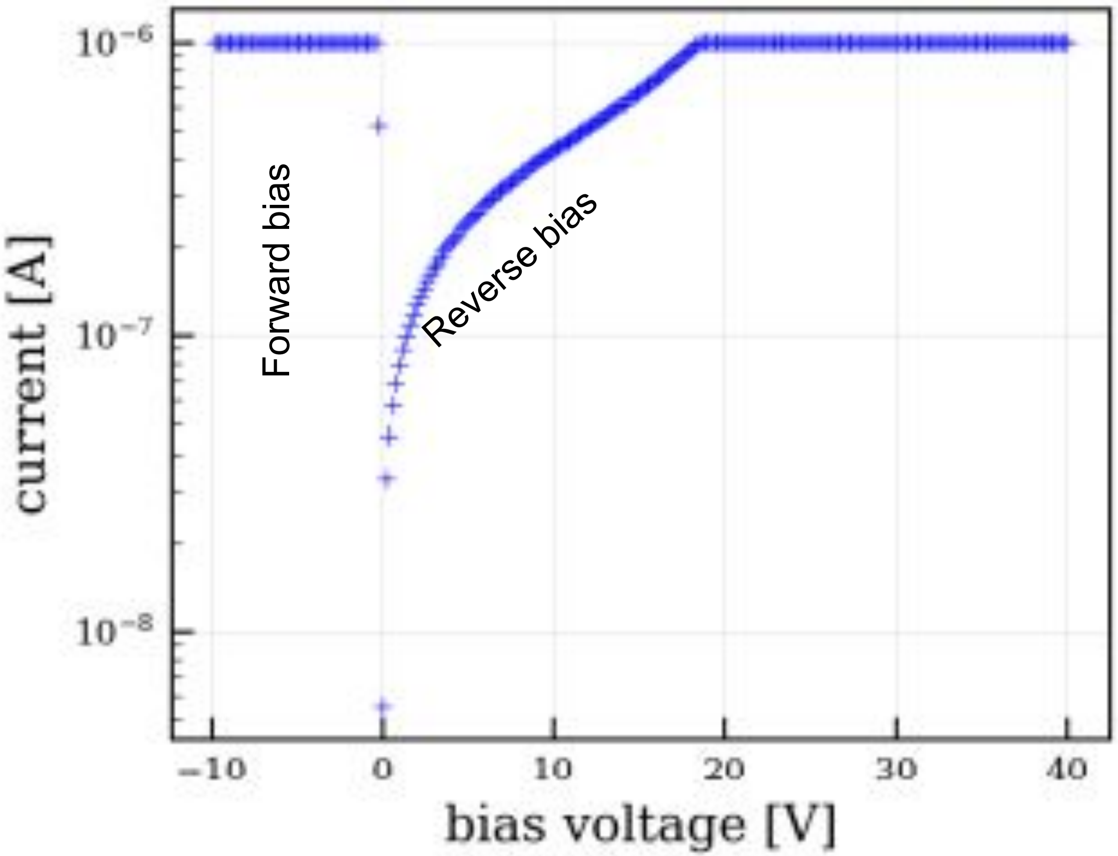




Probe strip structures







Current status

- Wire bonding of test structures
    - IV–measurements
- TCAD simulations to compare with measurements

Second production
- Implement lessons learned from first production

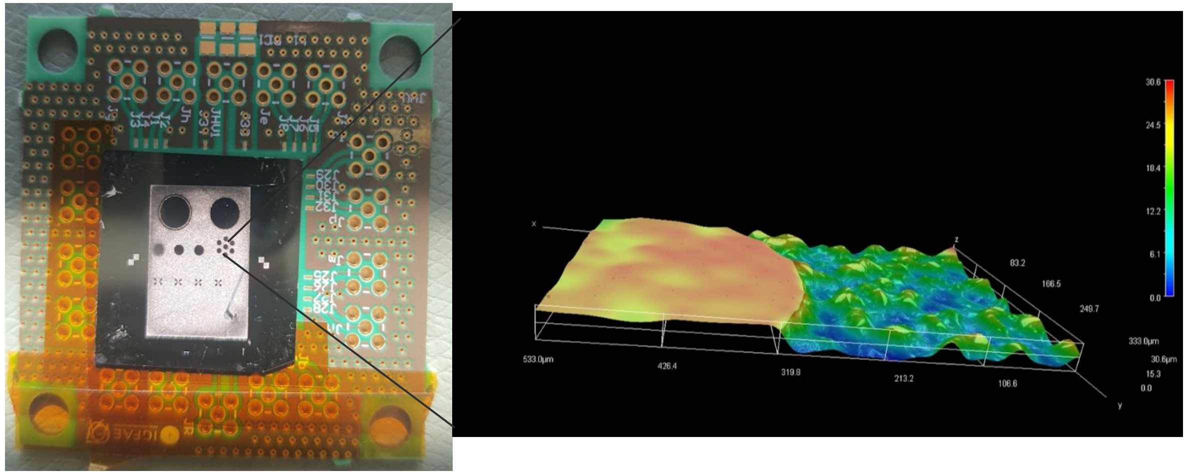


image taken at CERN QARTlab

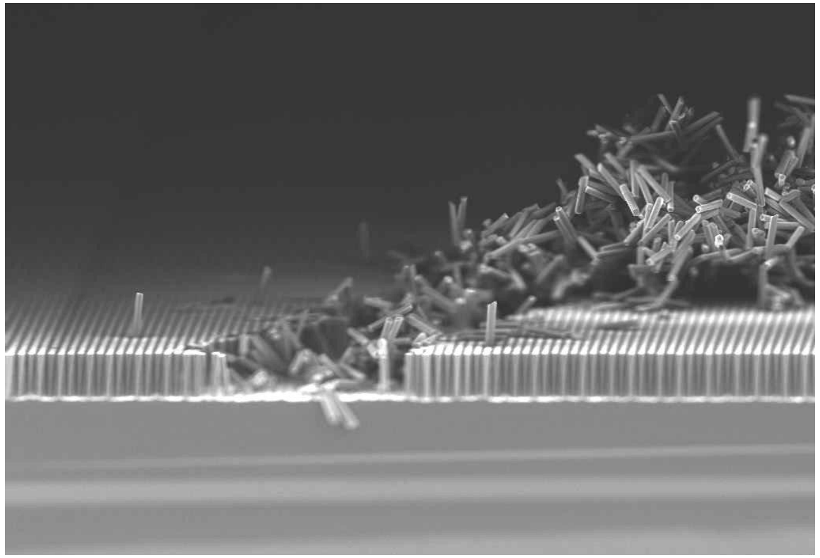
Summary and Outlook

- A new solid state radiation detector concept has been presented along with results from the production study.

- It has been shown that MacEtch is compatible with pn-junctions and active media

- Next steps
  - Complete IV-characterisation of first production.
  - TCT-measurements
    - IR-laser
    - Mimic traversing particles
  - Beta source measurements
  - Second production

Electron storm in nano forrest



Overdramatic paper cut

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