The Silicon Electron Multiplier Sensor

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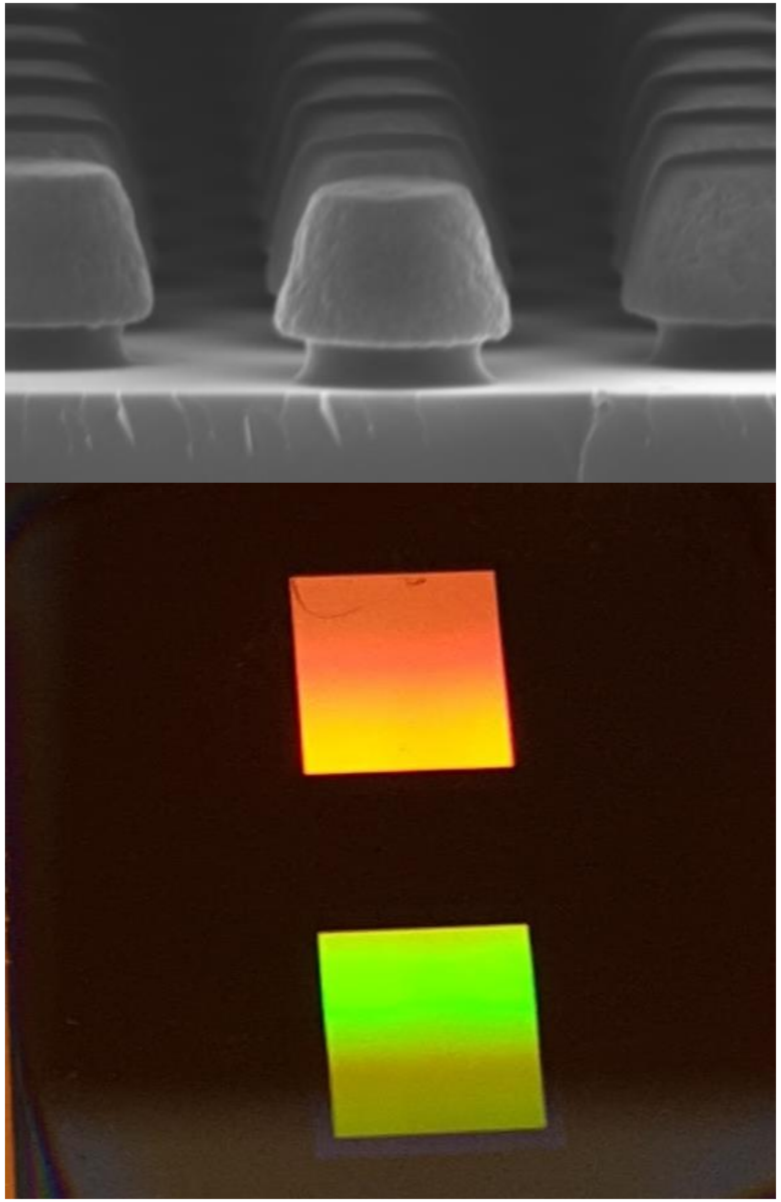
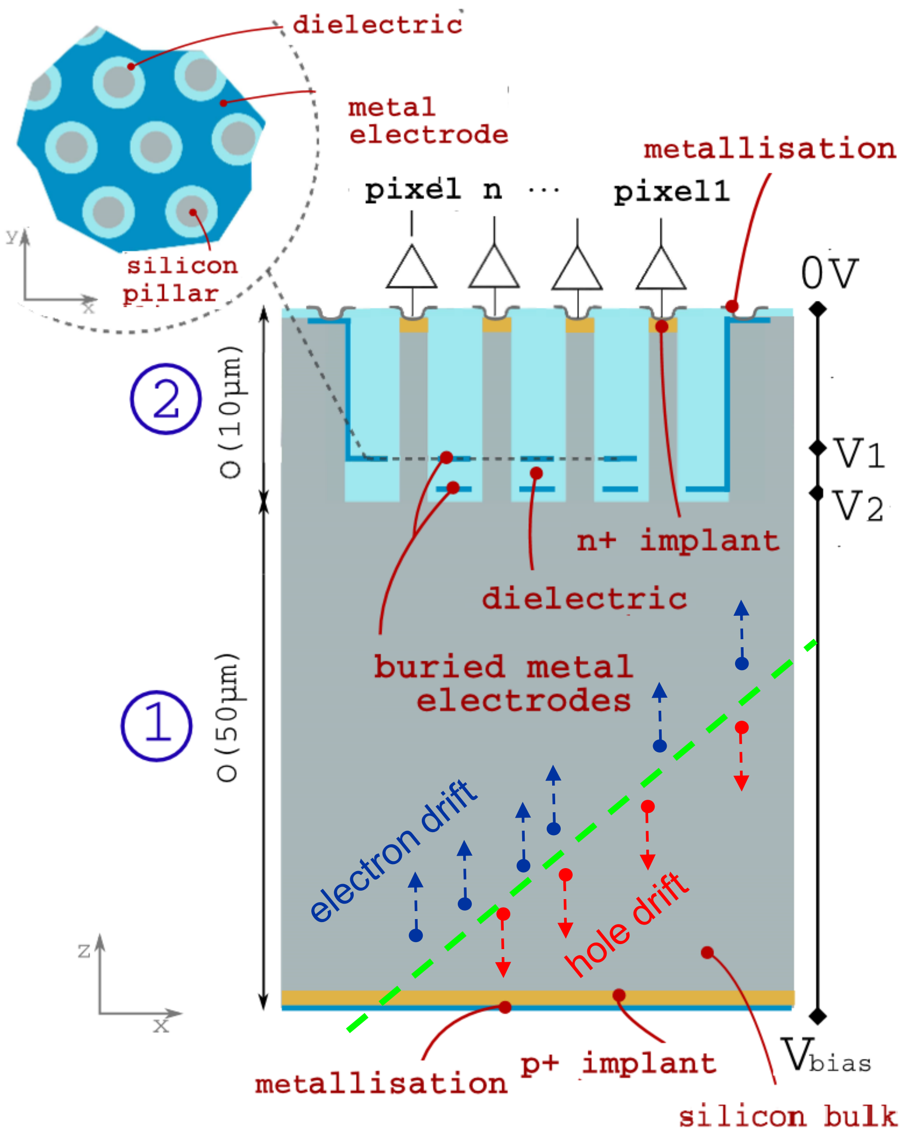
Overview

- Introduction, framework and motivation
- Concept
- Simulation results
- Fabrication study – Metal Assisted Chemical Etching
- Characterisation
- Outlook



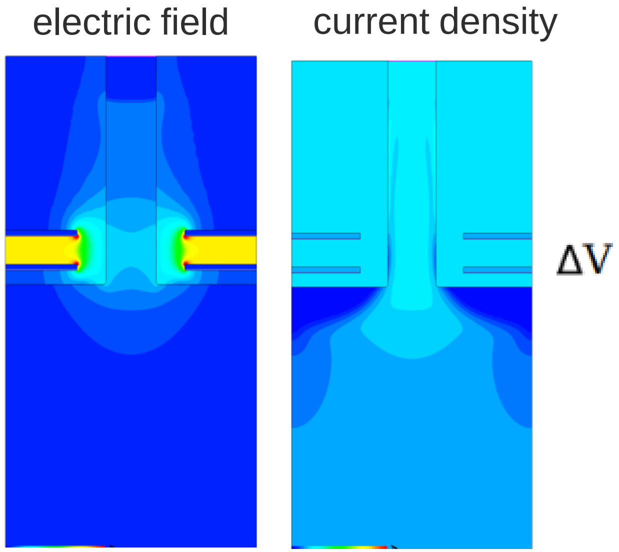
Approach

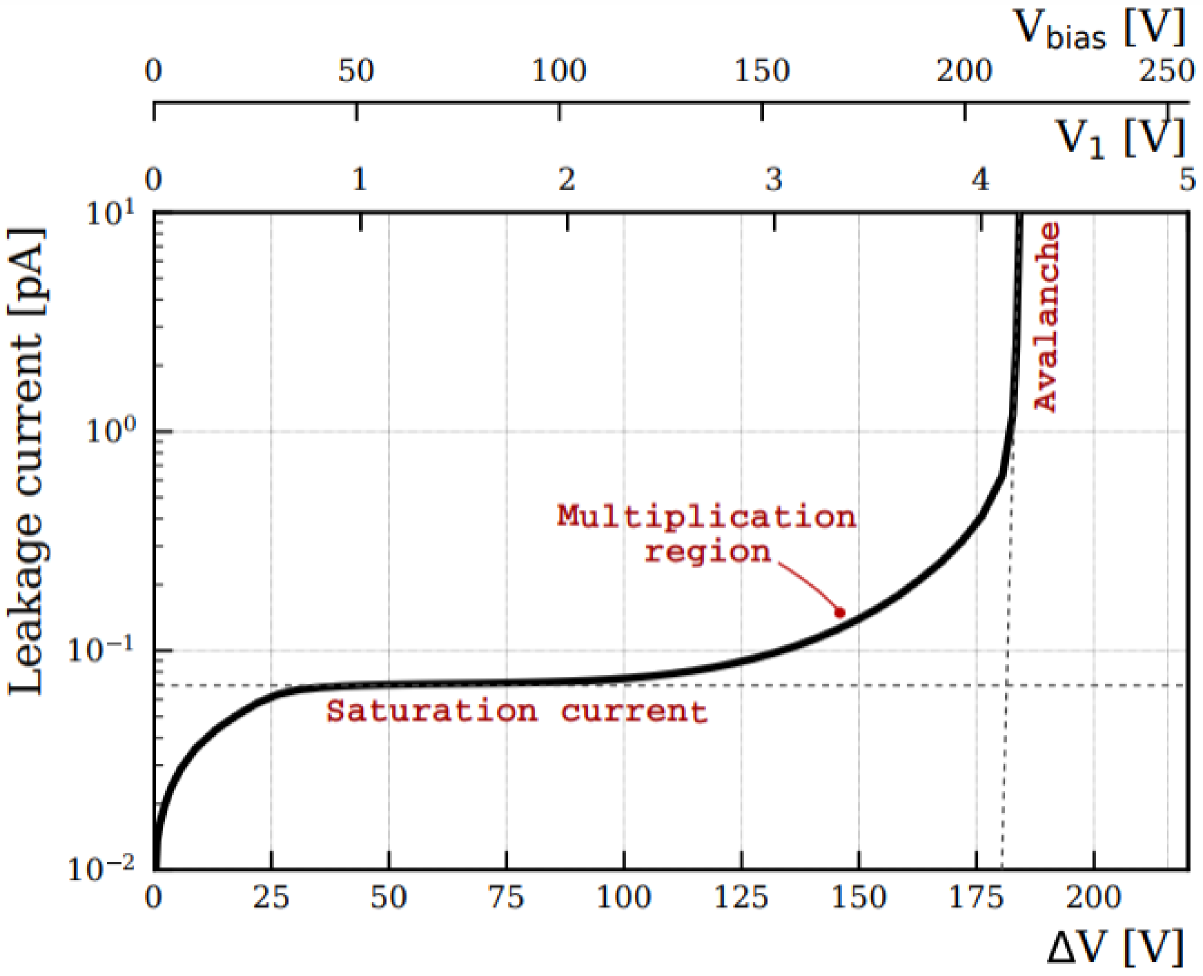
- Additional electrodes in sensor substrate
- Bias to make high field regions for charge multiplication
- Geometry
  - Dense positioned silicon pillars
  - Metallic grids and dielectrics between pillars
- Advantages:
  - Small pitch
  - Good time resolution
  - No gain layer deactivation due to acceptor 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.

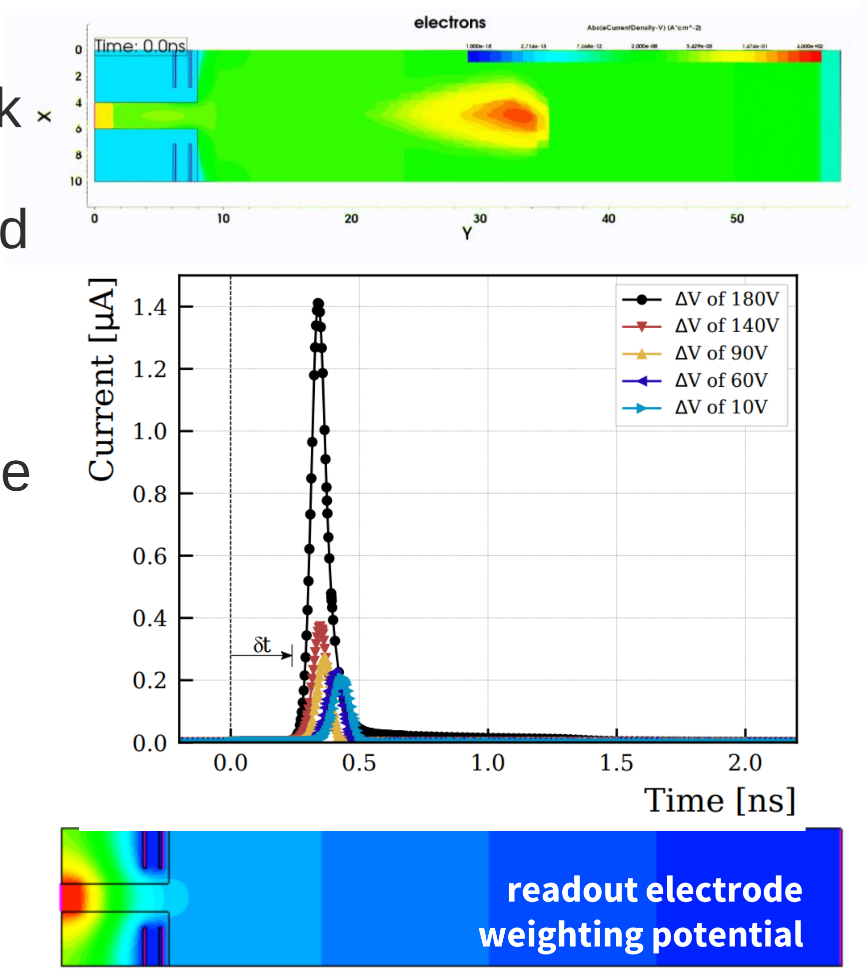




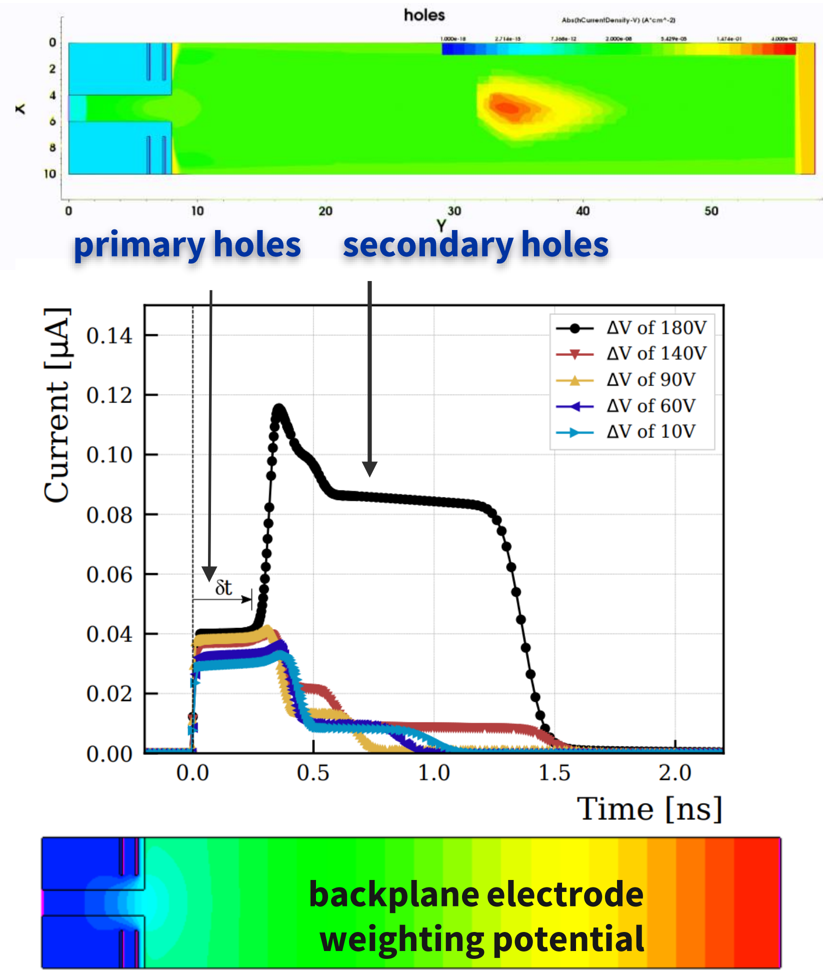
Signal simulations and charge multiplication

- 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”

Electrons

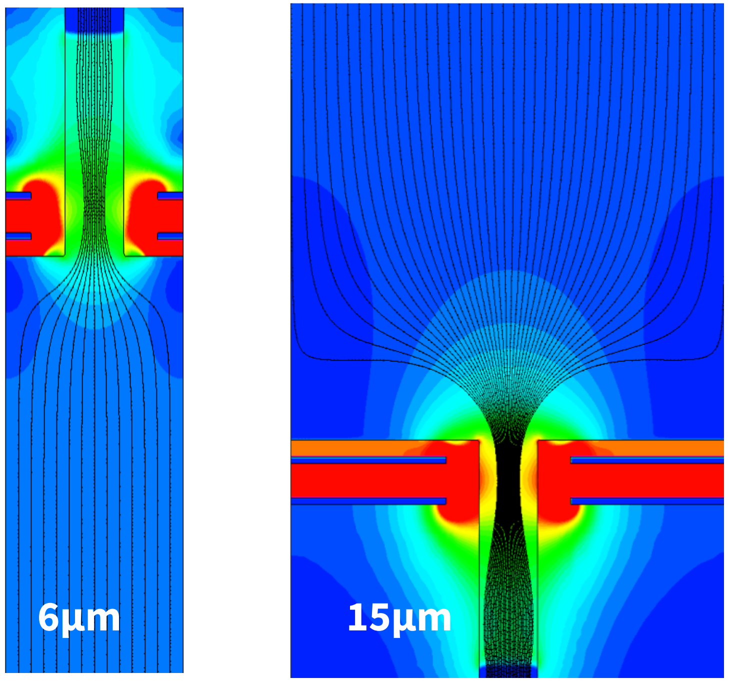


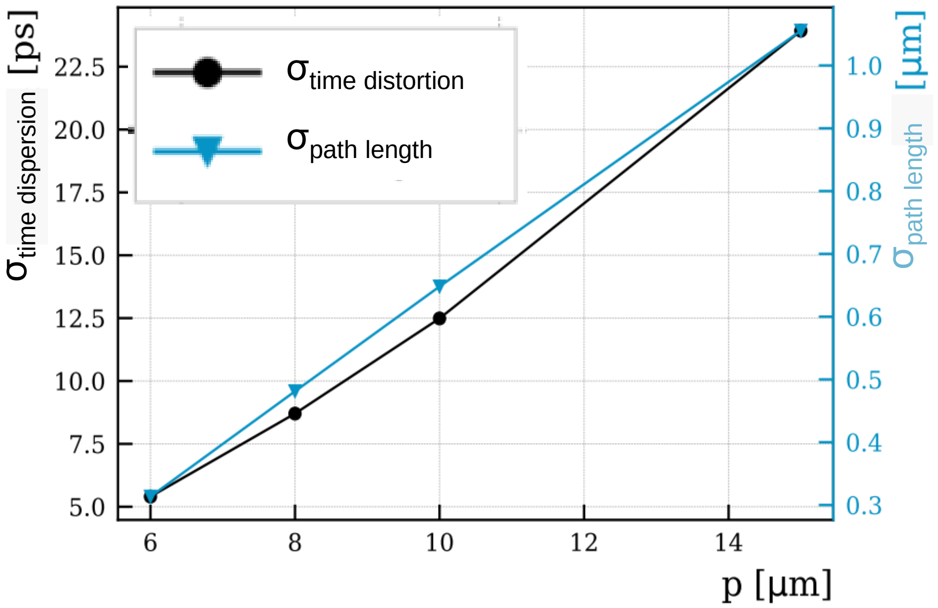
Holes



Optimisation studies

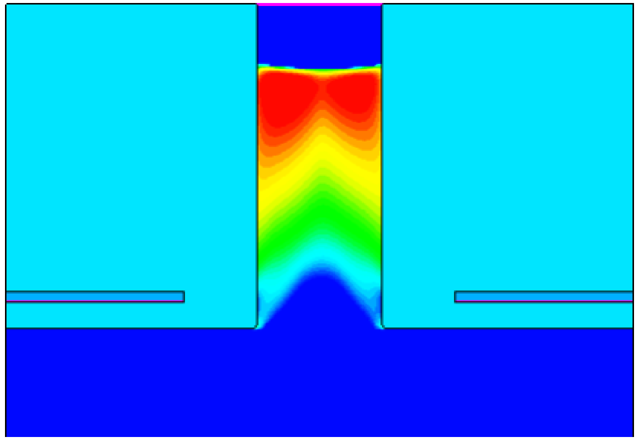
- Explore parameter space
  - Pillar diameter
  - Pillar height
  - Electrode geometries
  - +++
- Pitch
  - Large pitch distorts the drift paths

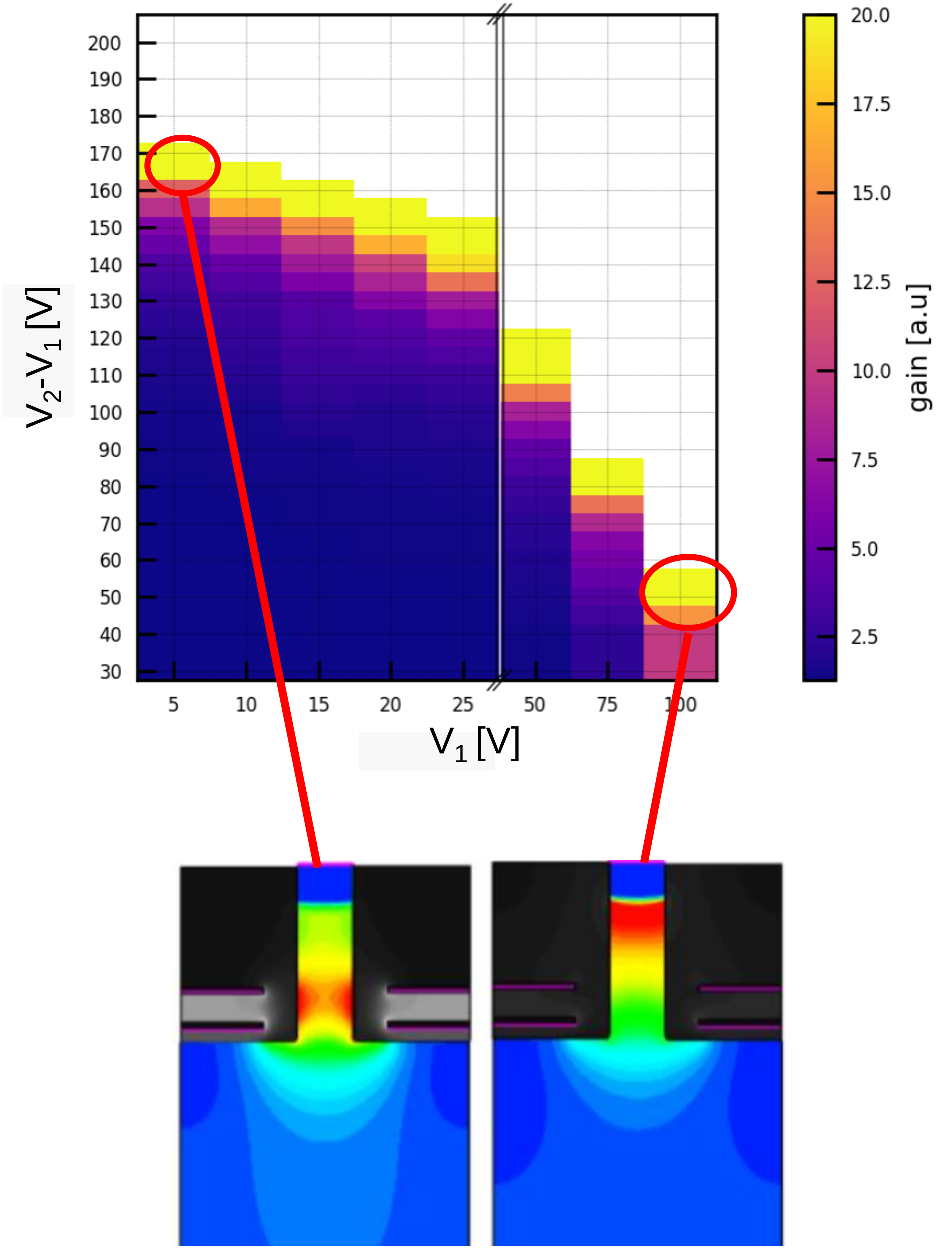




Electrodes

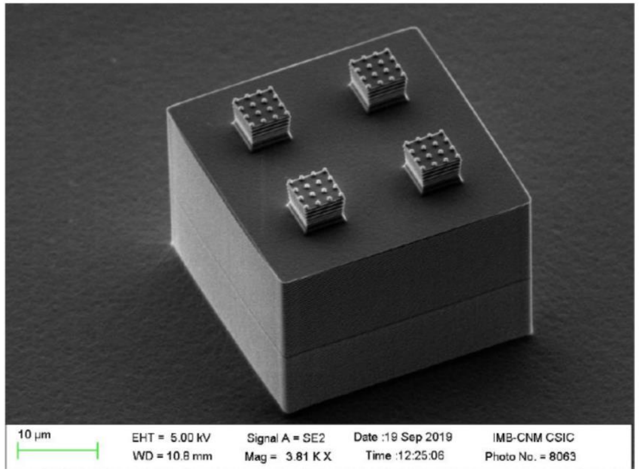
- Biassing scheme
- Electrode geometry
  - Electrode separation
  - Electrode dimensions
  - Number of electrodes
    - Single electrode configurations





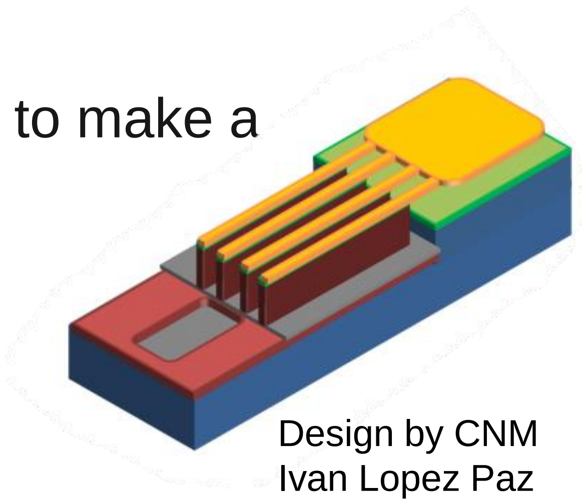
[courtesy of CNM]

Fabrication



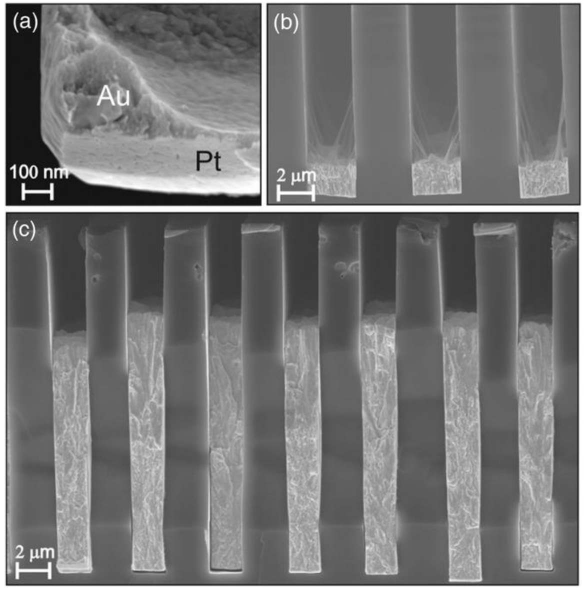
Deep Reactive Ion Etching (DRIE)

- Awarded the AIDA innova blue sky R&D to make a demonstrator with CNM
- Project started
  - Prototype design
  - Simulation tuning
  - Moving towards production



Design by CNM
Ivan Lopez Paz

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



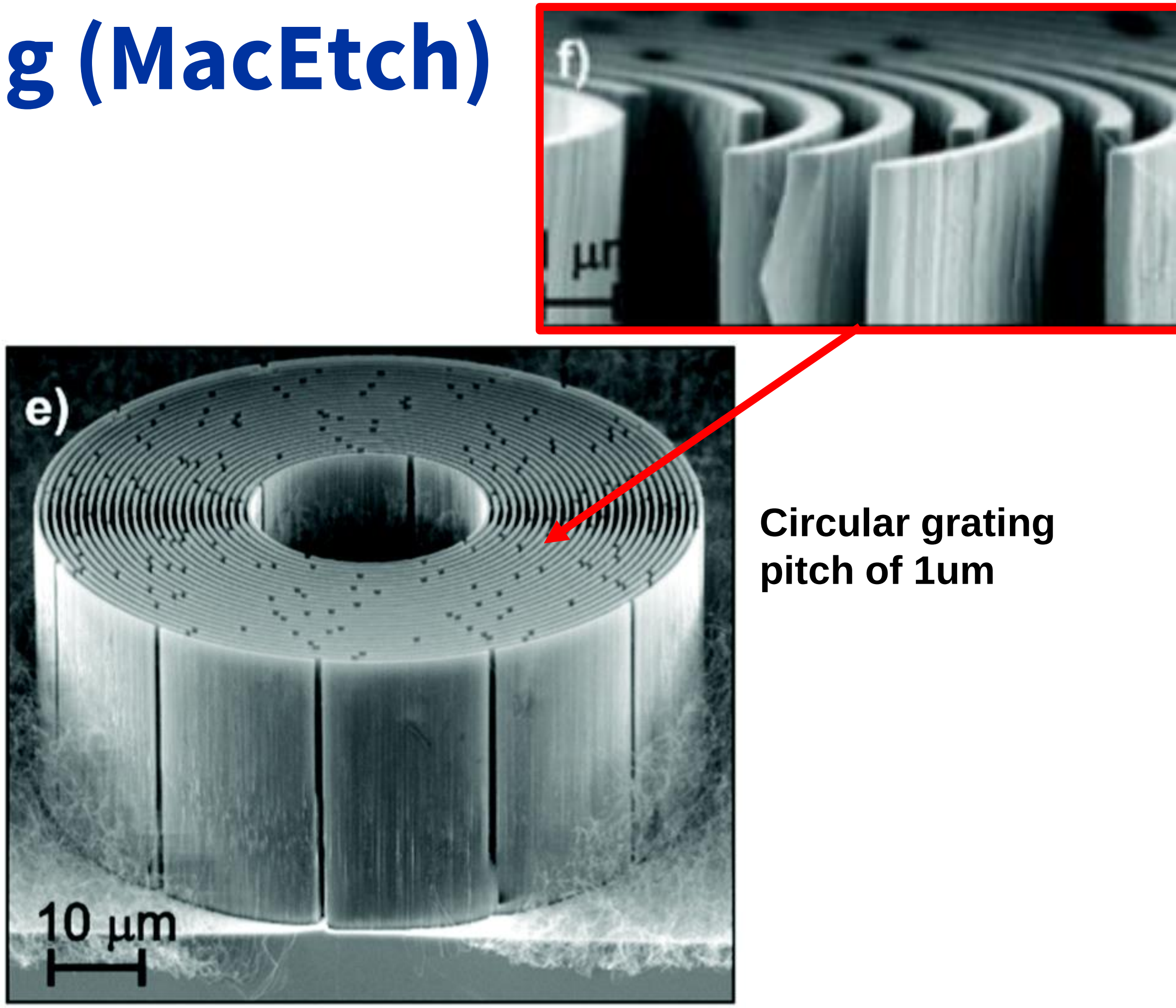
Metal Assisted Chemical Etching (MacEtch)

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

Metal Assisted Chemical Etching (MacEtch)

- 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

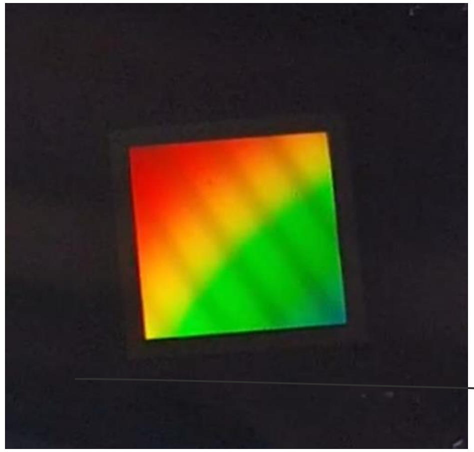


Circular grating pitch of 1um

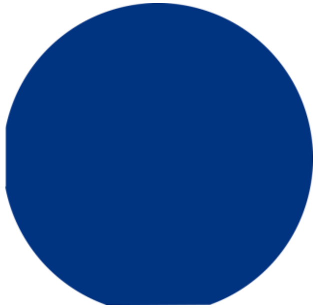
[L. Romano *et al*; https://doi.org/10.1039/C9NH00709A]

Demonstrator production with MacEtch

- Photolithography optimisation
  - Photoresist
  - Direct write laser
    - Heidelberg DWL66+
    - UV laser
    - Feature sizes down to 300 nm
  - Pattern
    - Hexagonal lattice
    - 500 nm circle radius
    - 1.5 µm pitch

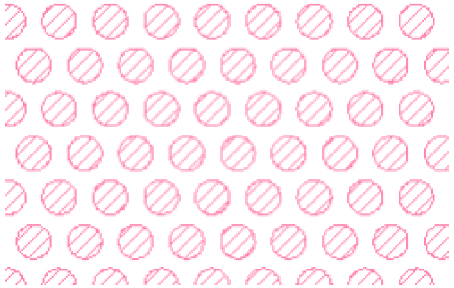


1. Implanted Silicon wafer



2. wafer photoresist

3. Patternise with direct write laser

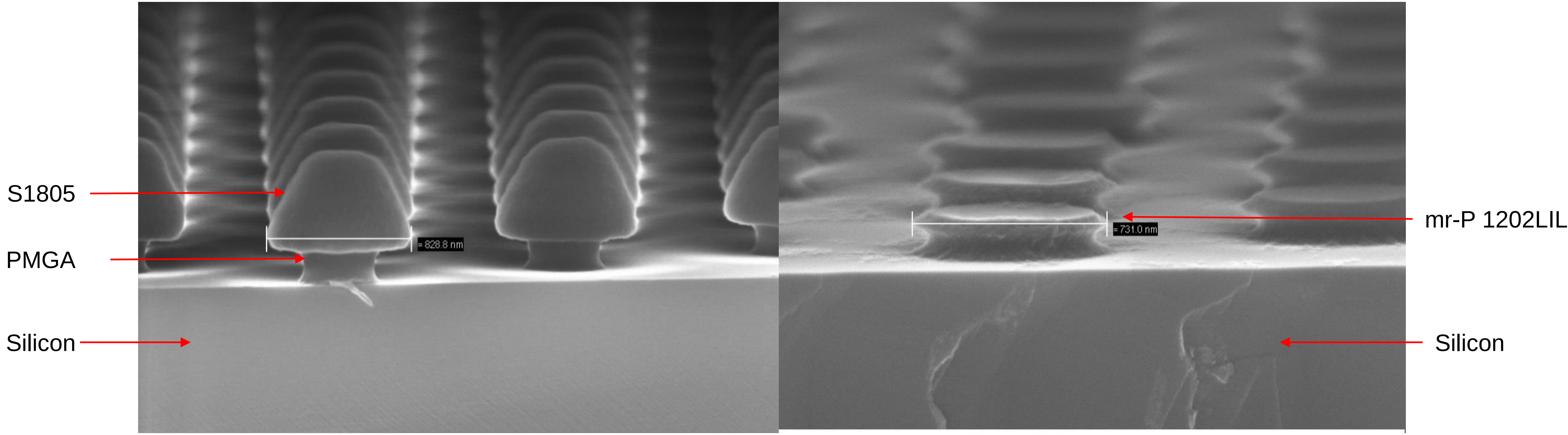


diameter =1 µm
pitch = 1.5 µm

4. Develop

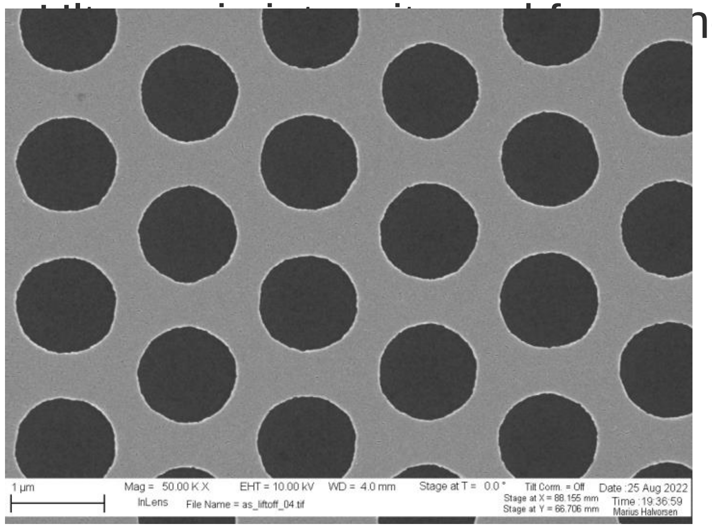
Lithography optimisation

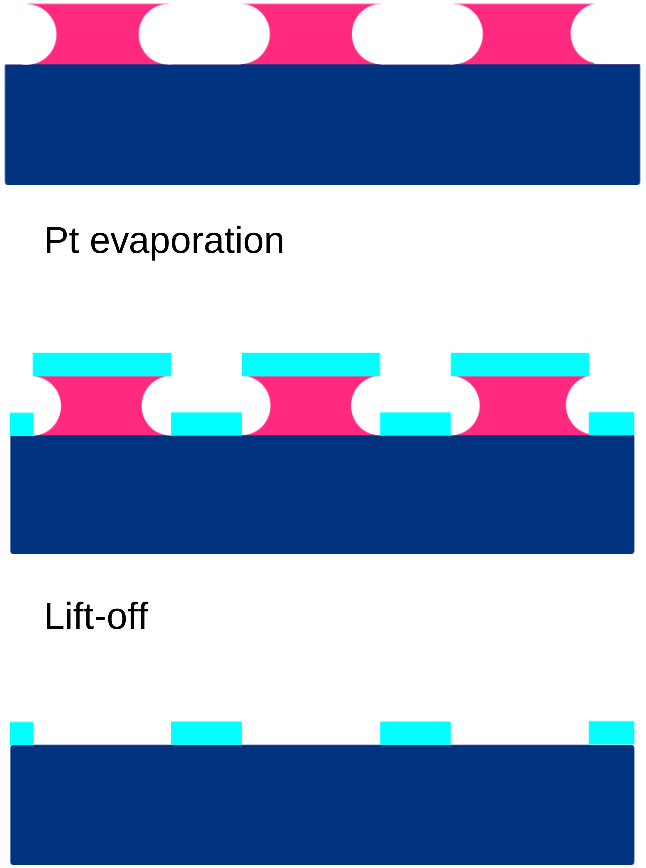
- Tried different photoresists
- Optimise laser exposure parameters
  - Pattern features
  - Laser power
  - Development time



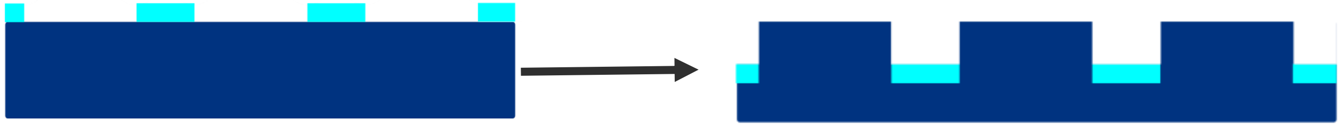
Metal deposition

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



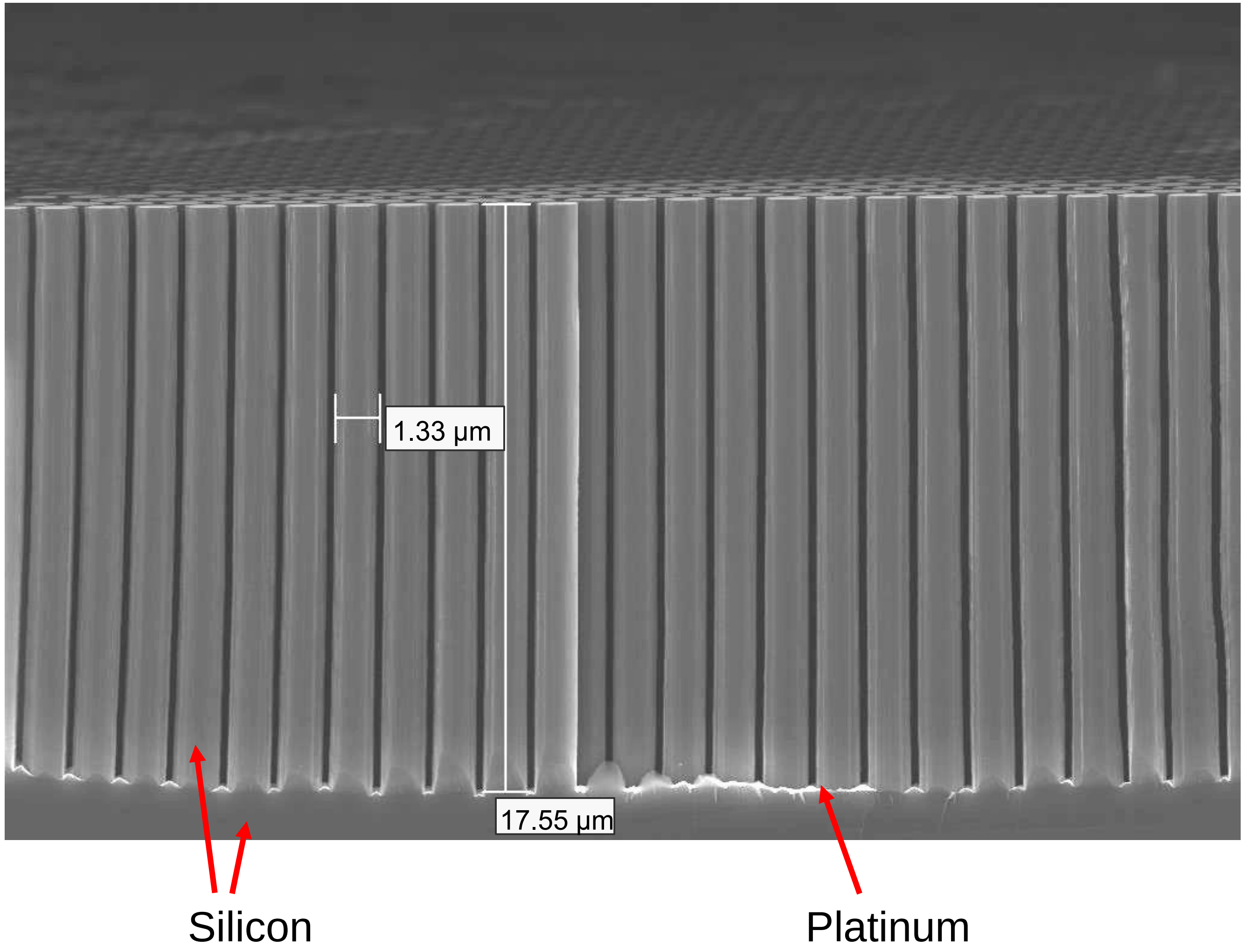


Etching

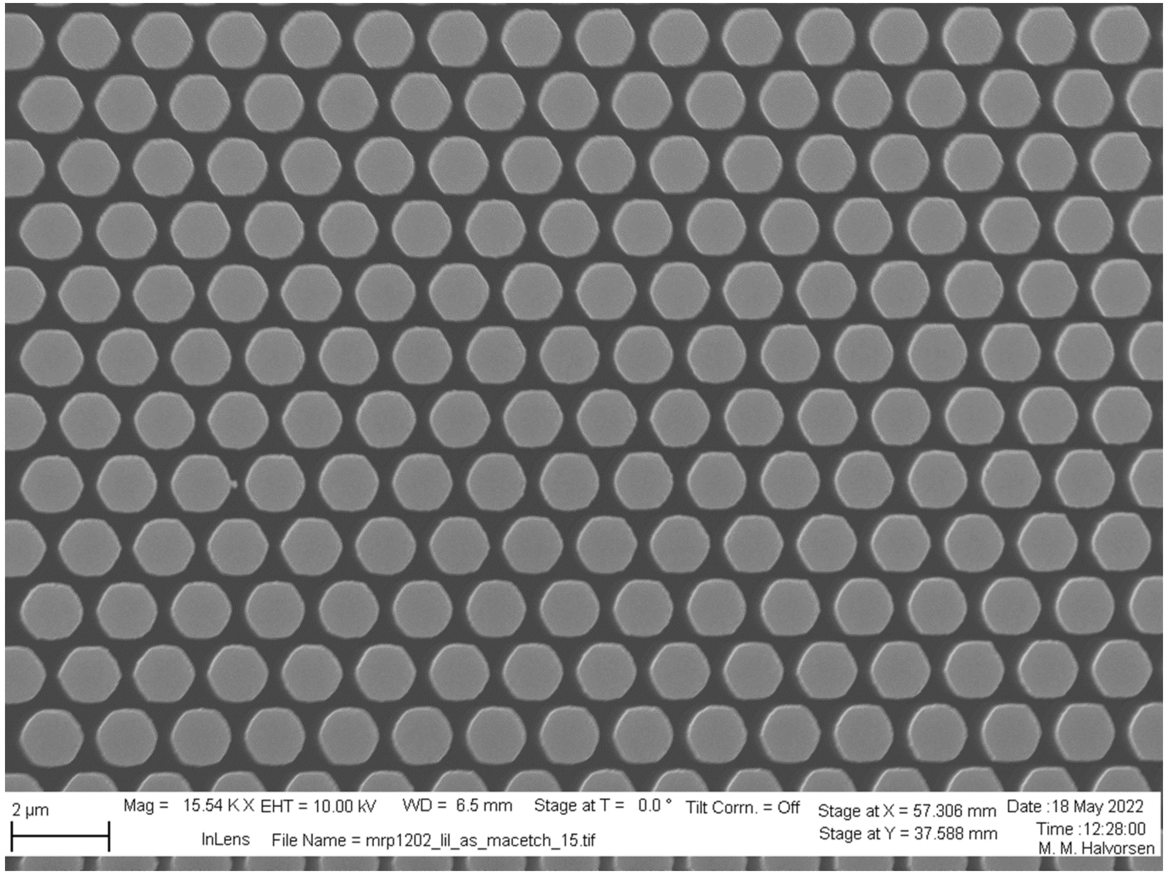


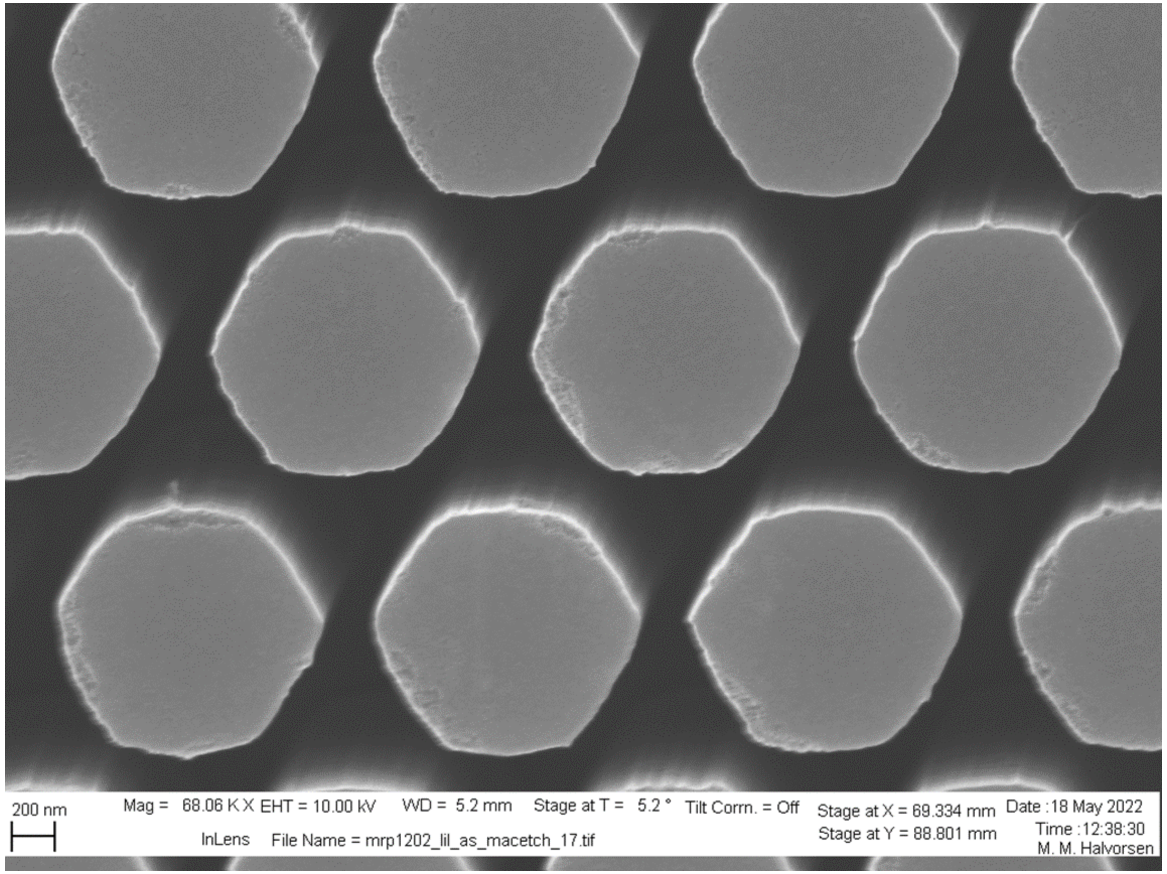
- Expose patter to HF vapor
  - Oxygen reduction at catalyst
    - $O_2+4H^+ \rightarrow 2H_2O+4h^+$
  - Silicon dissolves through two possible paths:
    - $Si+4h^++4HF \rightarrow SiF_4+4H^+$

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



Etching


2 µm
Mag = 15.54 K X EHT = 10.00 kV WD = 6.5 mm Stage at T = 0.0 ° Tilt Corrn. = Off
InLens File Name = mrp1202_lil_as_macetch_15.tif
Stage at X = 57.306 mm
Stage at Y = 37.588 mm
Date :18 May 2022
Time :12:28:00
M. M. Halvorsen

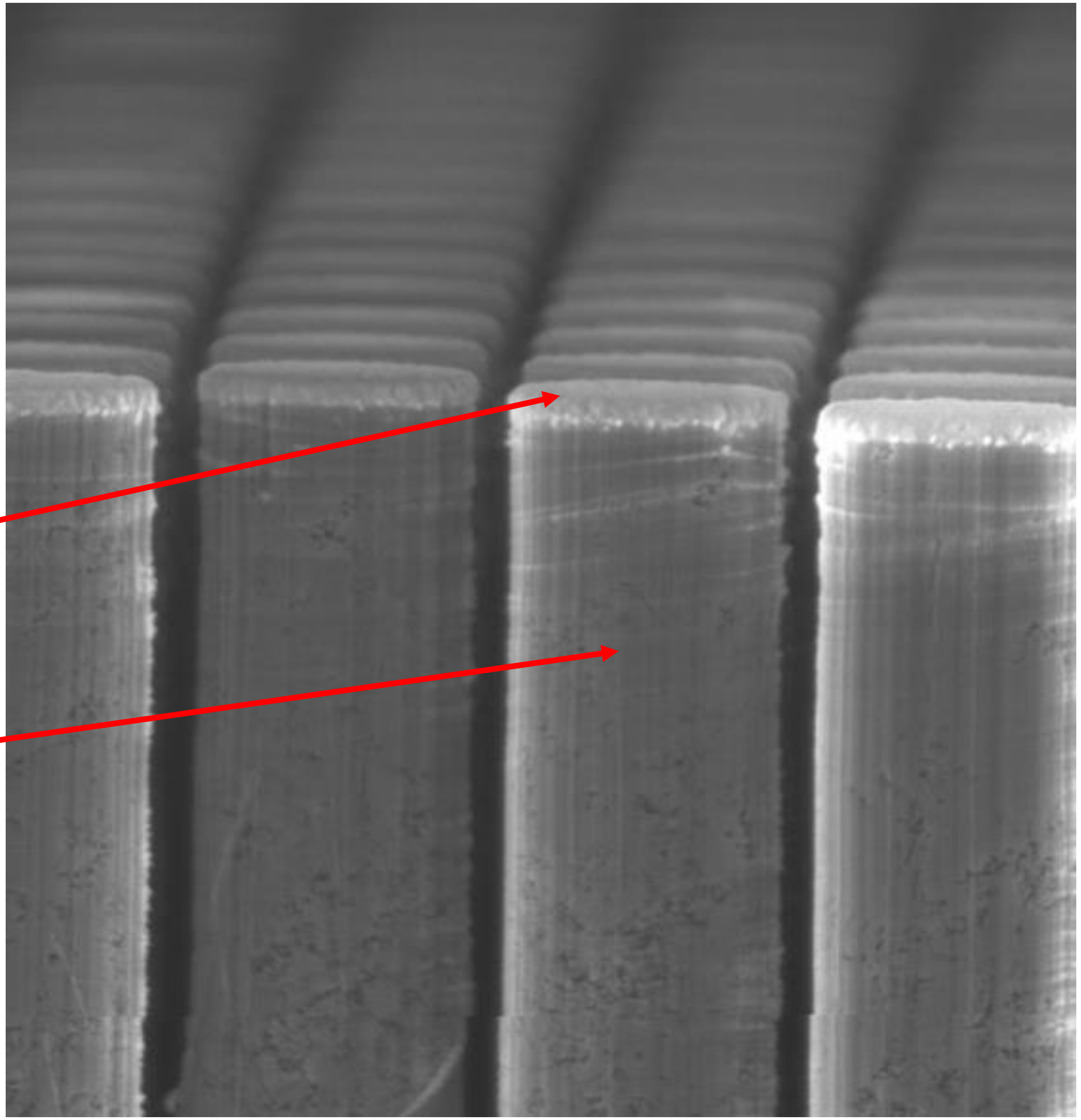

200 nm
Mag = 68.06 K X EHT = 10.00 kV WD = 5.2 mm Stage at T = 5.2 ° Tilt Corrn. = Off
InLens File Name = mrp1202_lil_as_macetch_17.tif
Stage at X = 69.334 mm
Stage at Y = 88.801 mm
Date :18 May 2022
Time :12:38:30
M. M. Halvorsen

Electrical contact

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

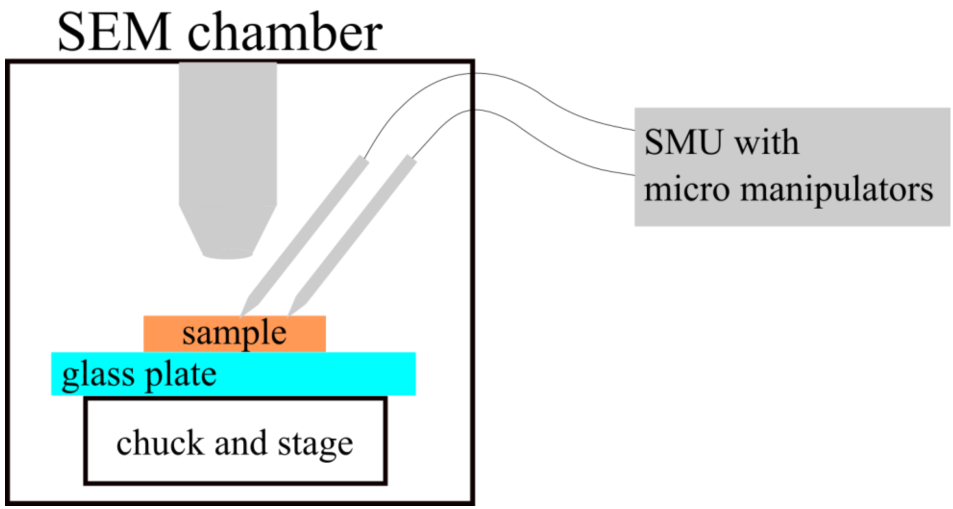
Aluminum

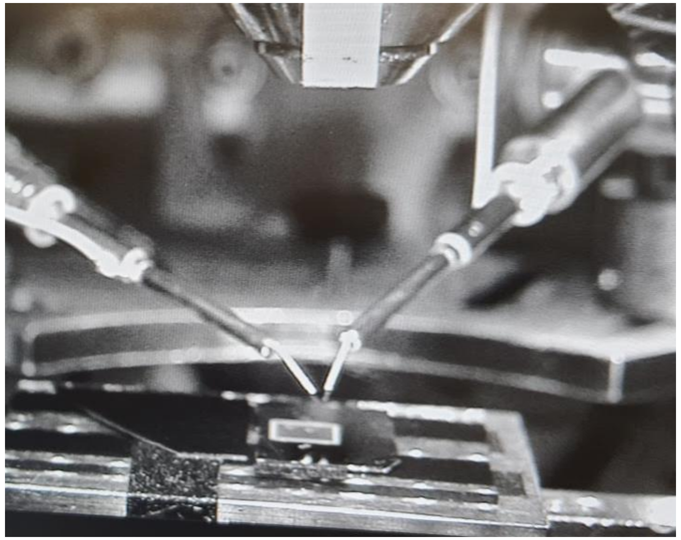
Silicon

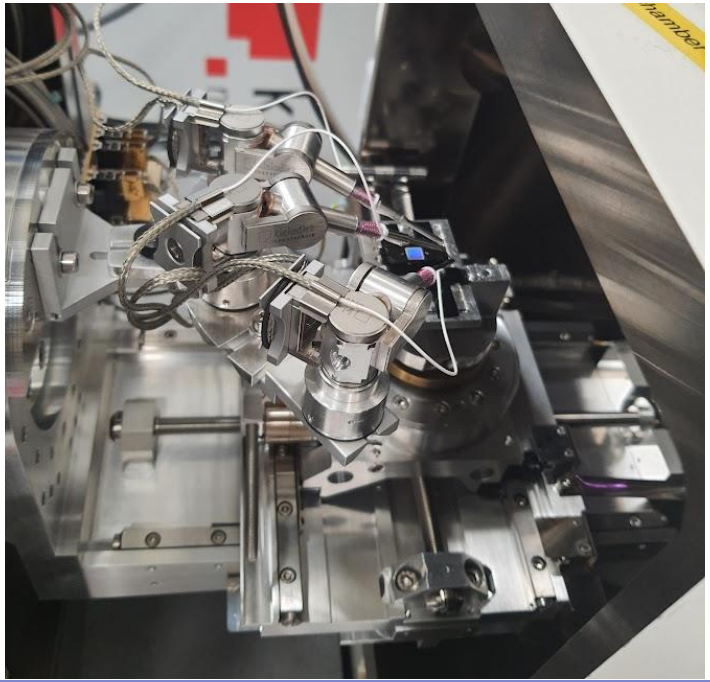


Set-up at PSI

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







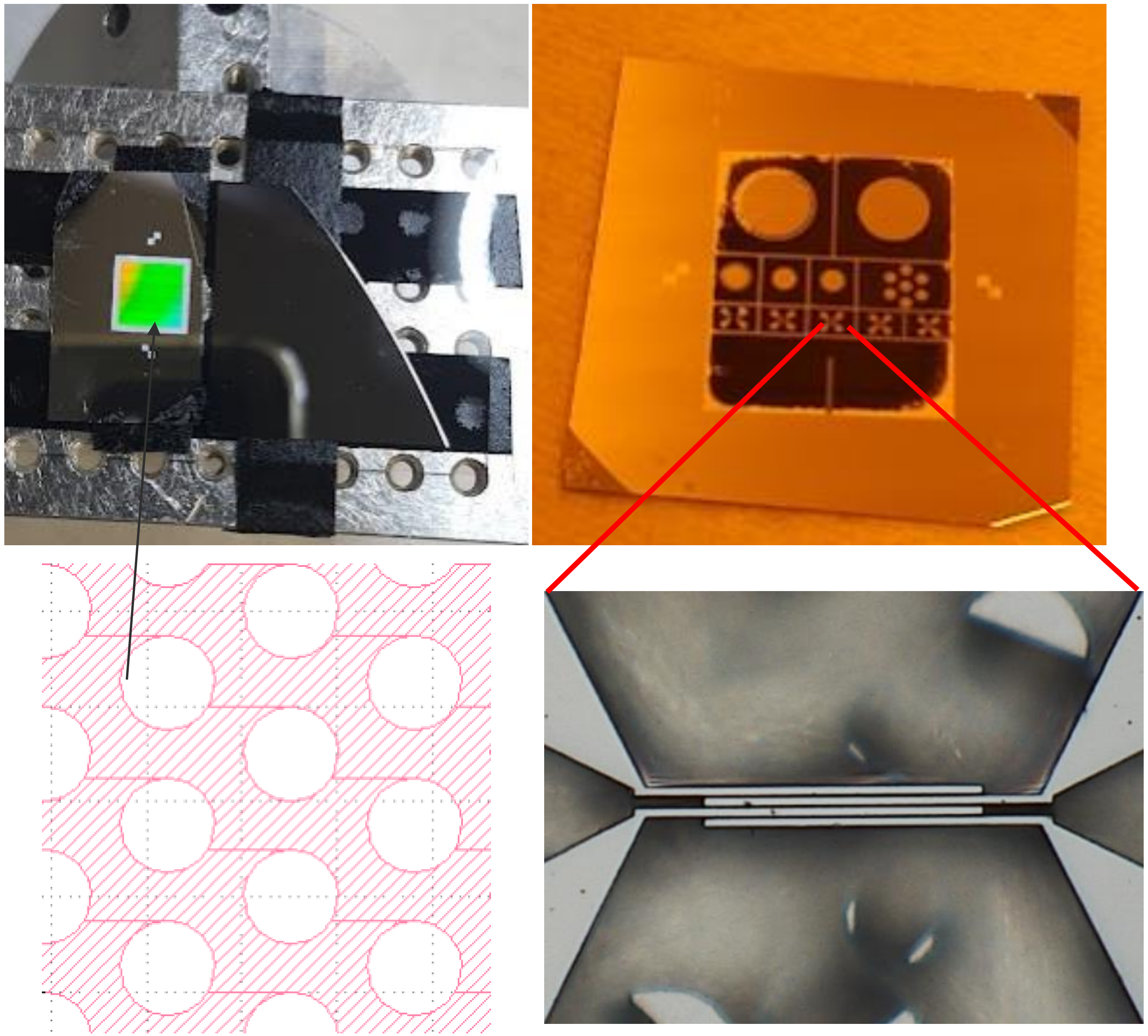
Support from Anja Weber, Dimitrios Kazazis, Lucia Romano, Soichiro Tsujino

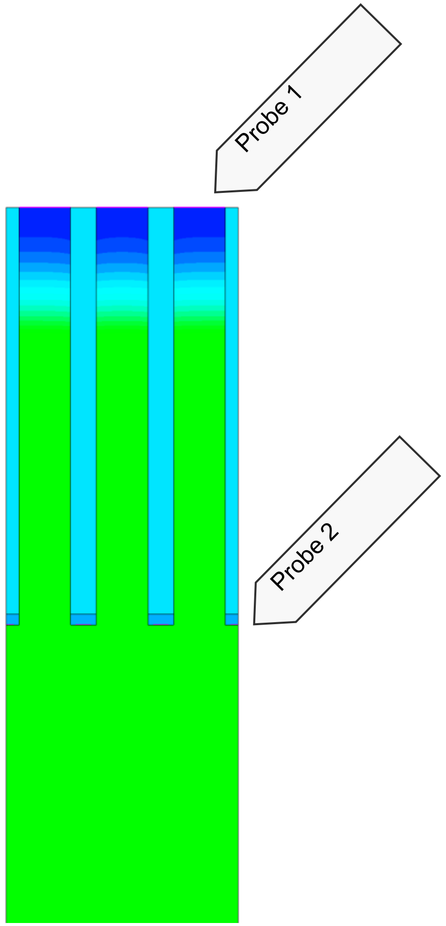
Test structures

Two samples:

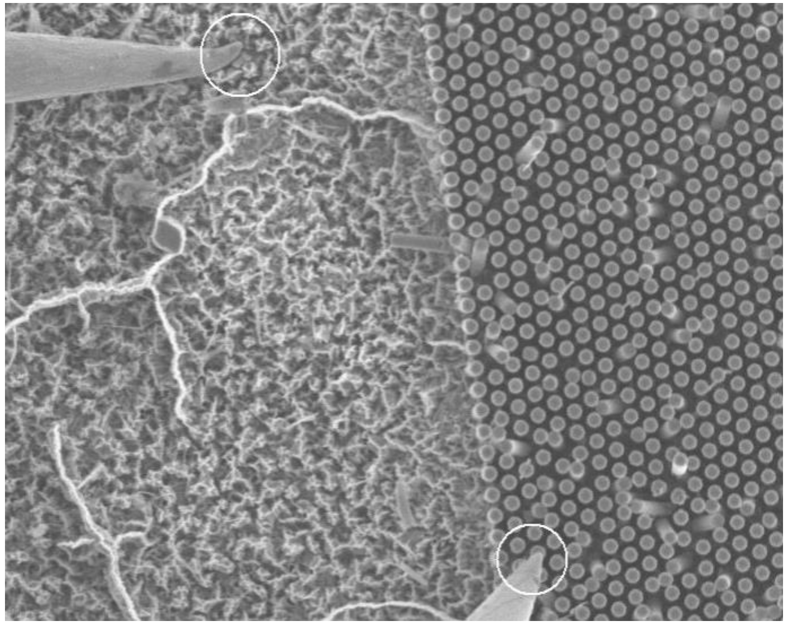
- A)
    - Pillar pattern
    - 1 µm wide pillars, hexagonal lattice with a pitch of 1.5 µm
- B)
    - strip structures
    - same width and pitch as circle pattern

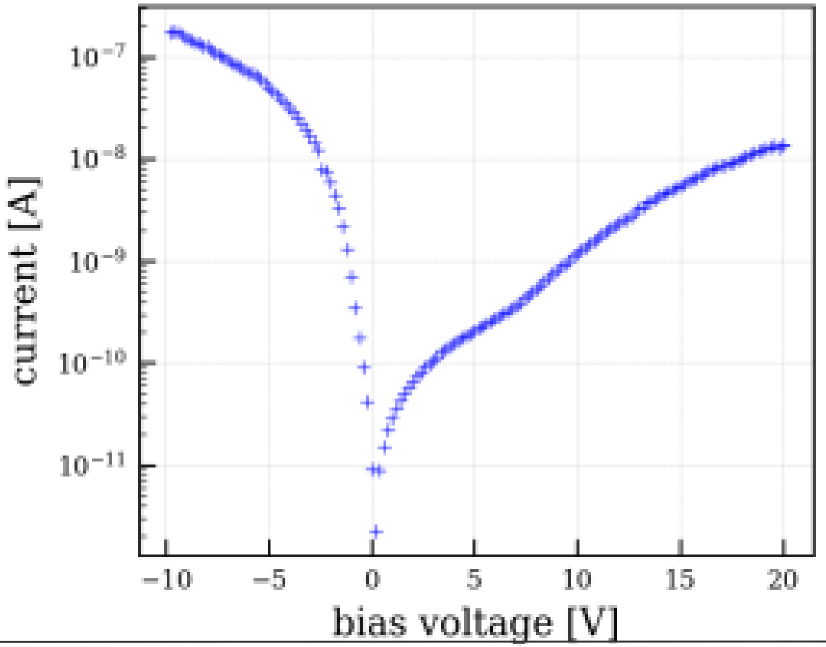
A) B)



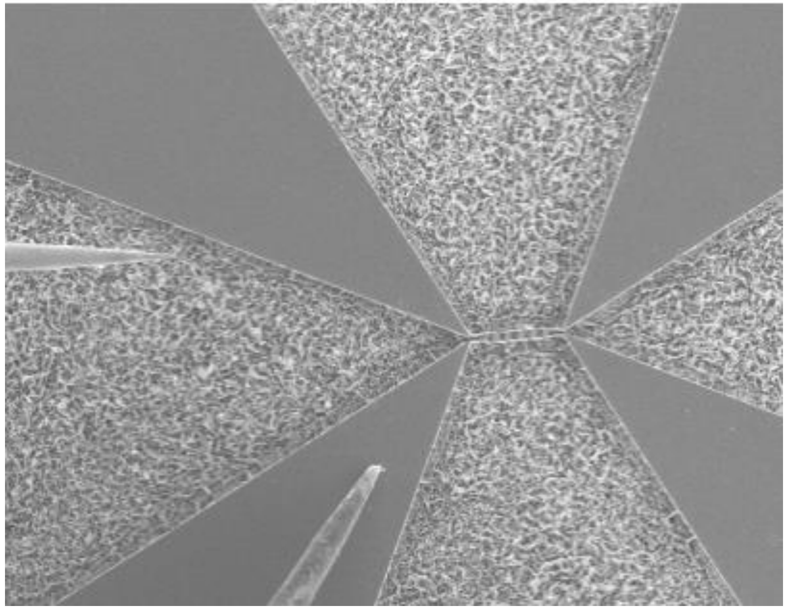


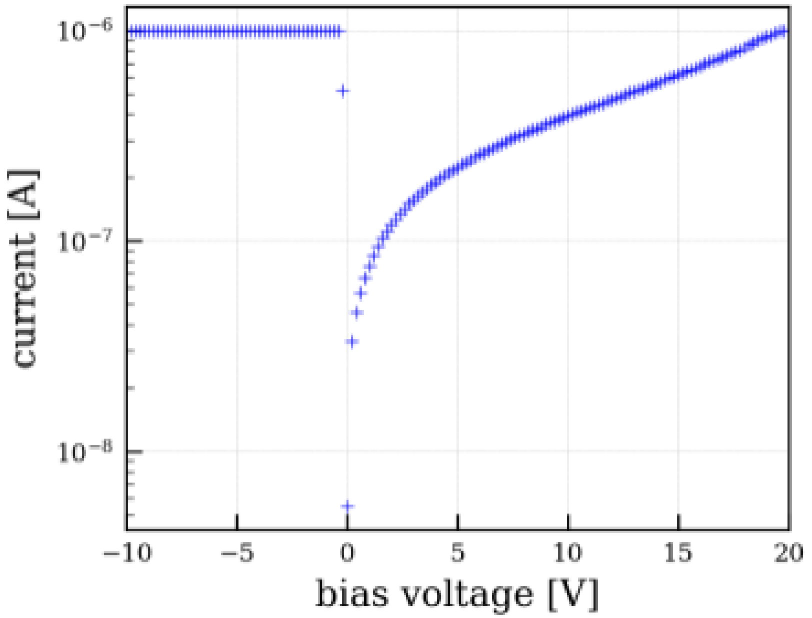
Single pillar

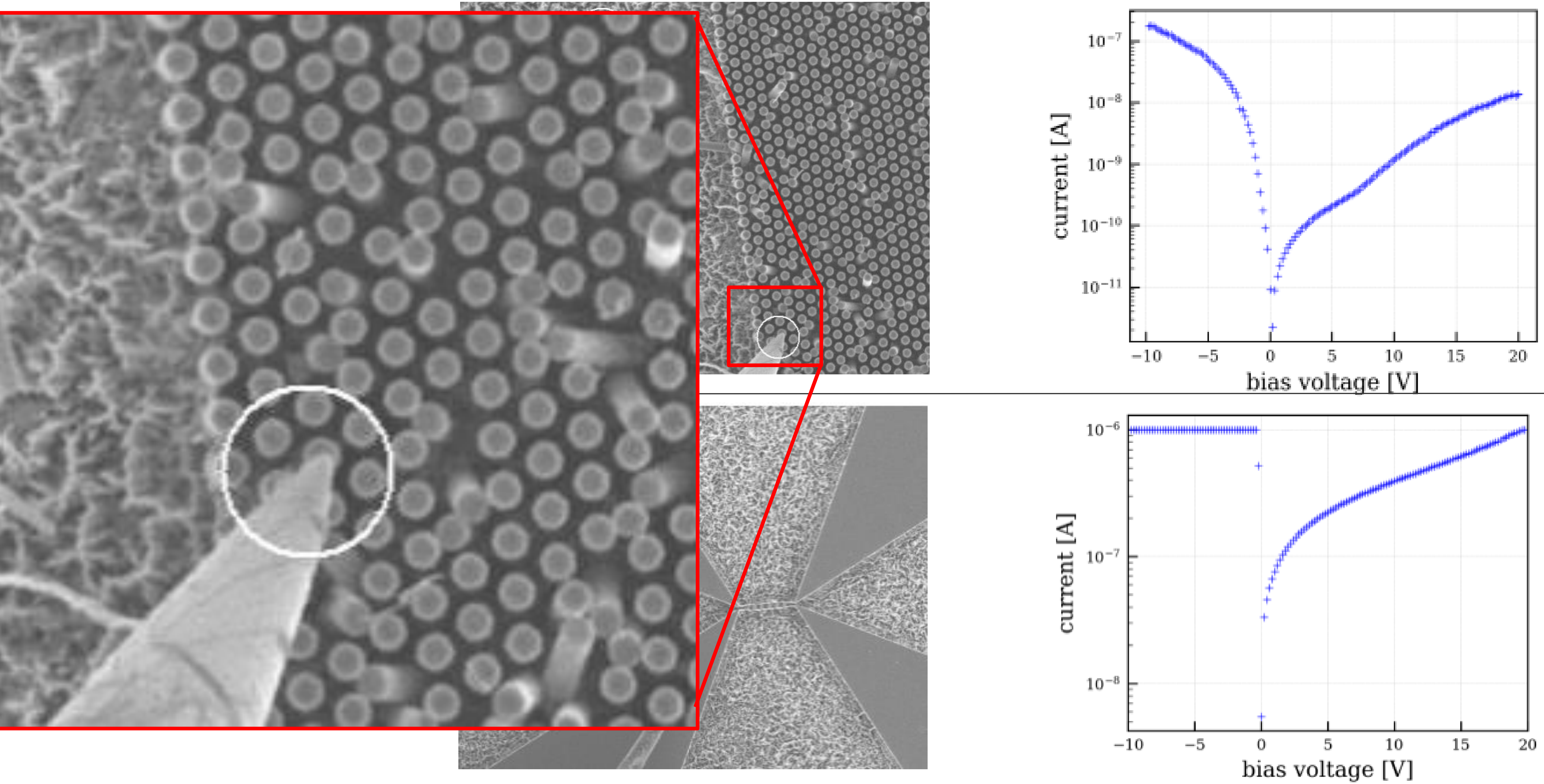




Strip







current [A]
bias voltage [V]
current [A]
bias voltage [V]

Current status

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

Second production
  - Implement lessons learned from first production

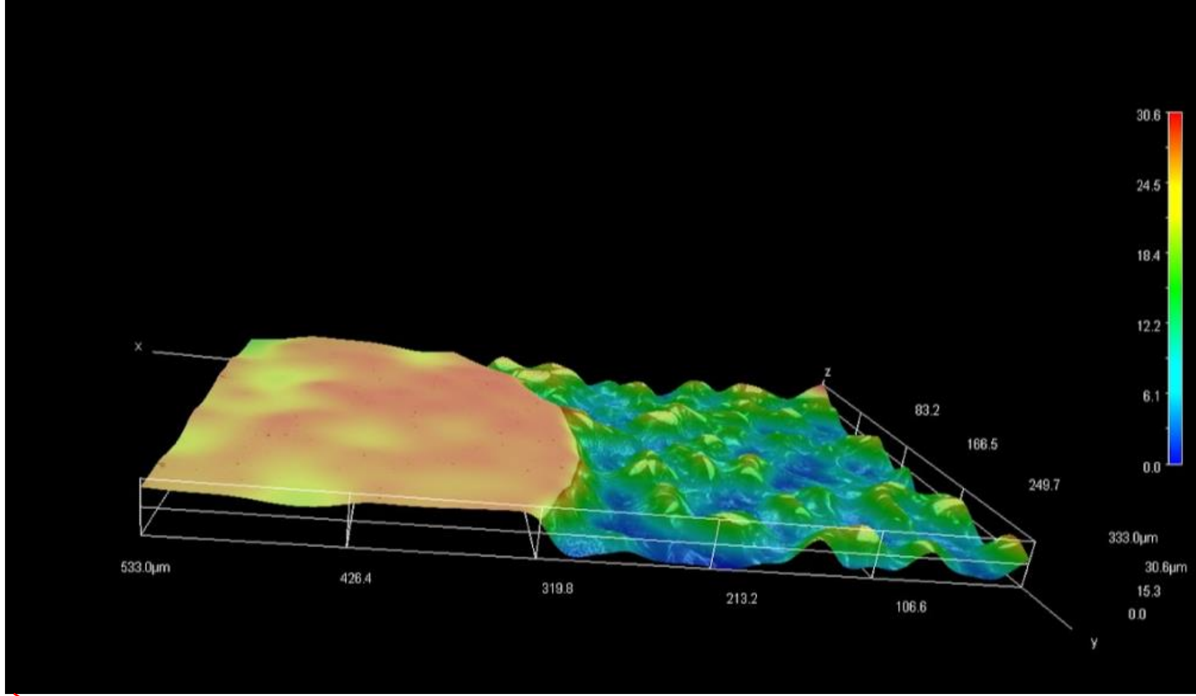
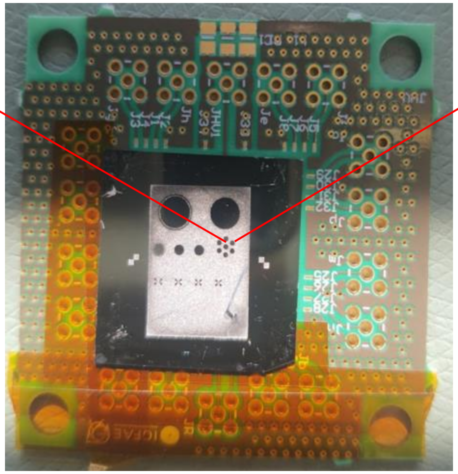


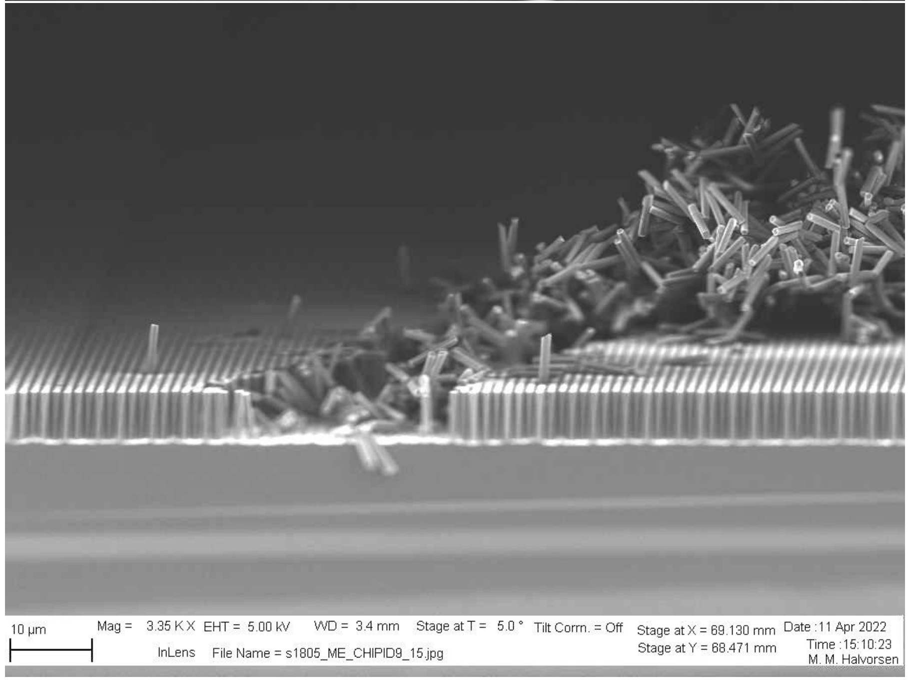
image taken at CERN QARTlab



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
    - Proceed with DRIE production with CNM

Electron storm in nano forrest



“Dramatic” paper cut

Acknowledgments

- **Lucia Romano, Zhitian Shi, Konstantins Jefimov** for microfabrication support
- **TOMCAT** team for guesting at PSI
- **PSI - LNQ** for clean room facilities and technical support
- **Anja Weber, Dimitris Kazazis and Soichiro Tsujino** for IV probe station at SEM

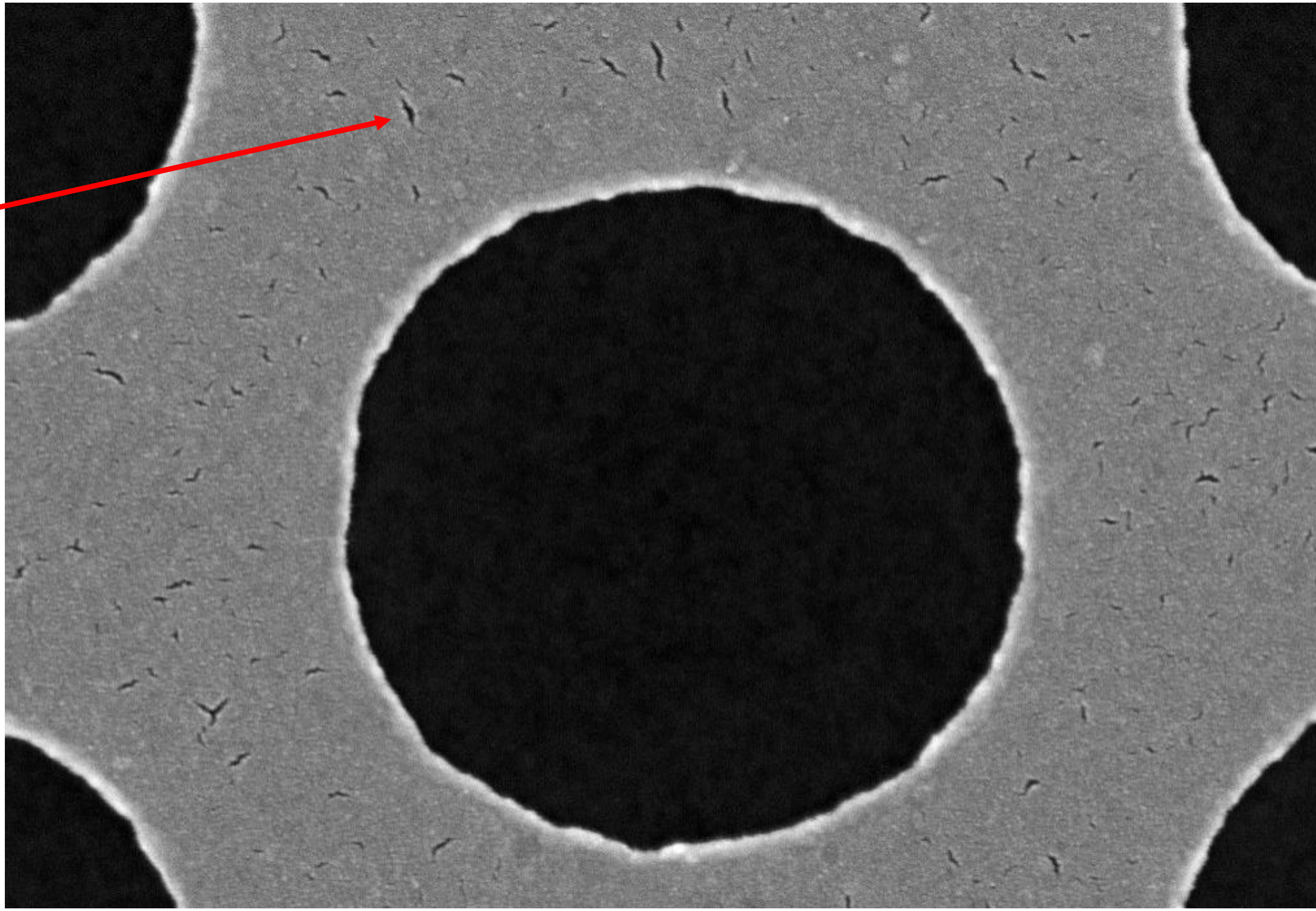
home.cern

Backup

Dewetting

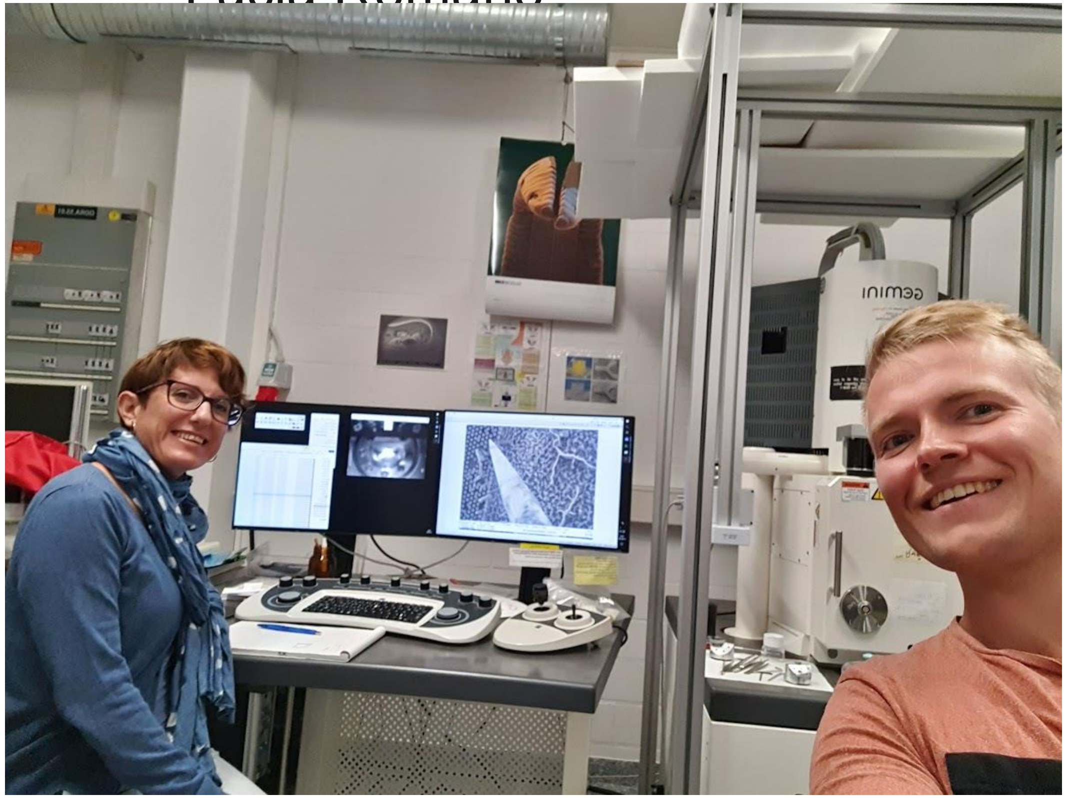
Pt self assembly at 250–300 °C

- Nano-pores
  - Assists mass transport of etchants and oxidants
  - Homogeneous etching
- Platinum-silicide
  - Stabilises metal on semiconductor

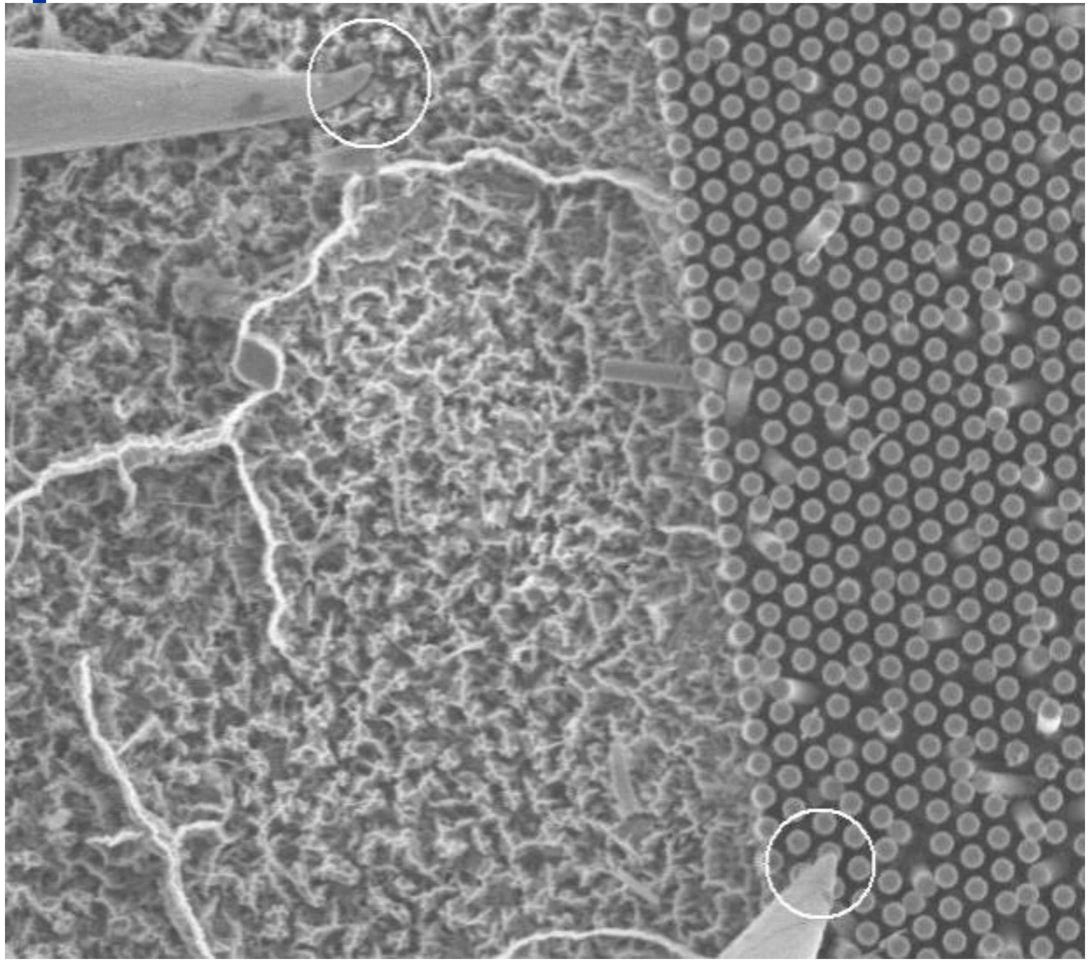


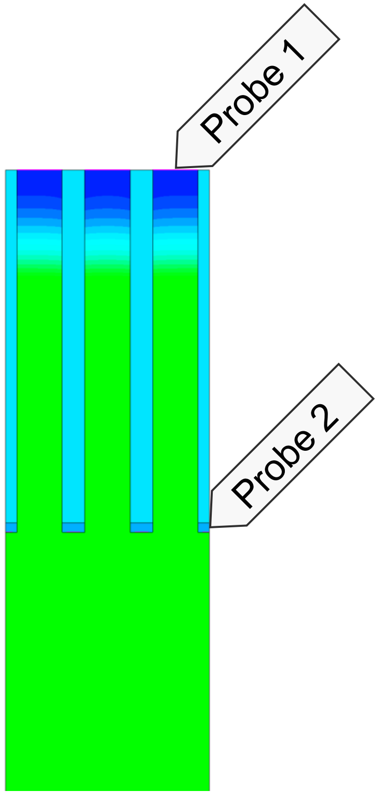
Mounting with

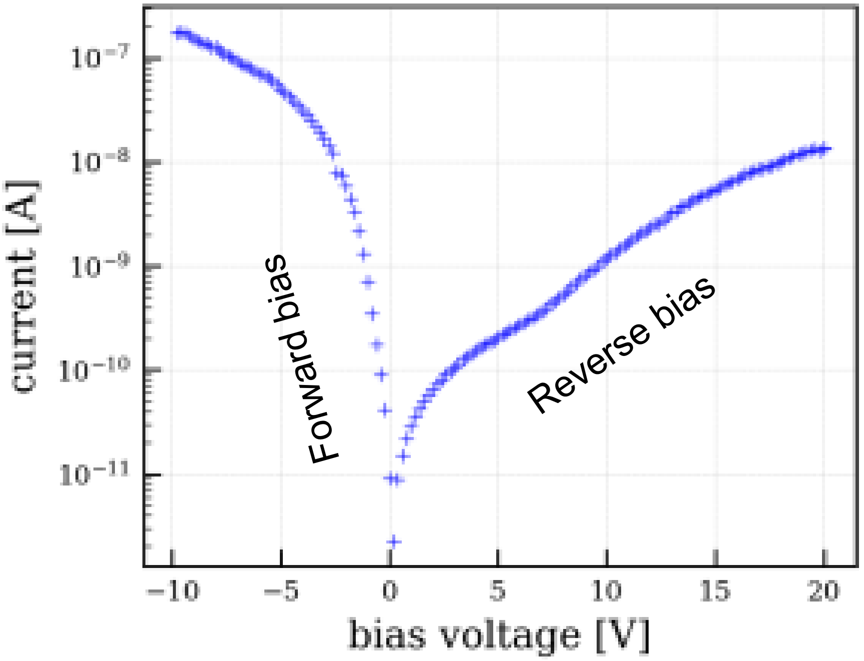
- Anja Weber
- Dimitrios Kazazis
- Lucia Romano



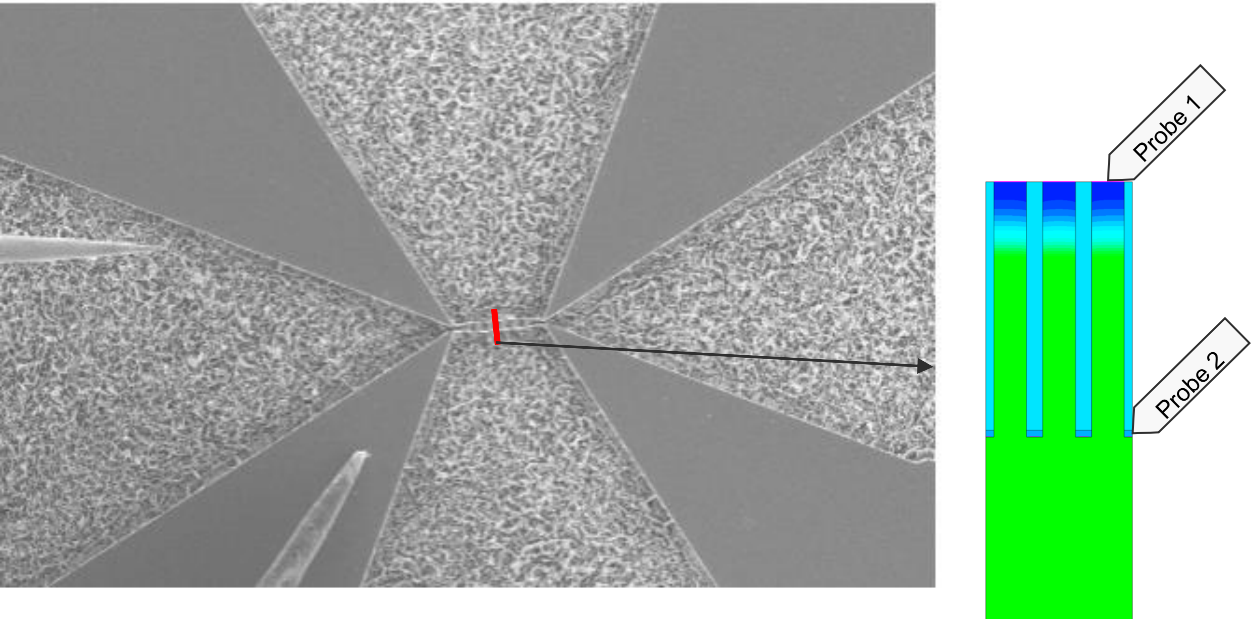
Probe pillars – One single pillar

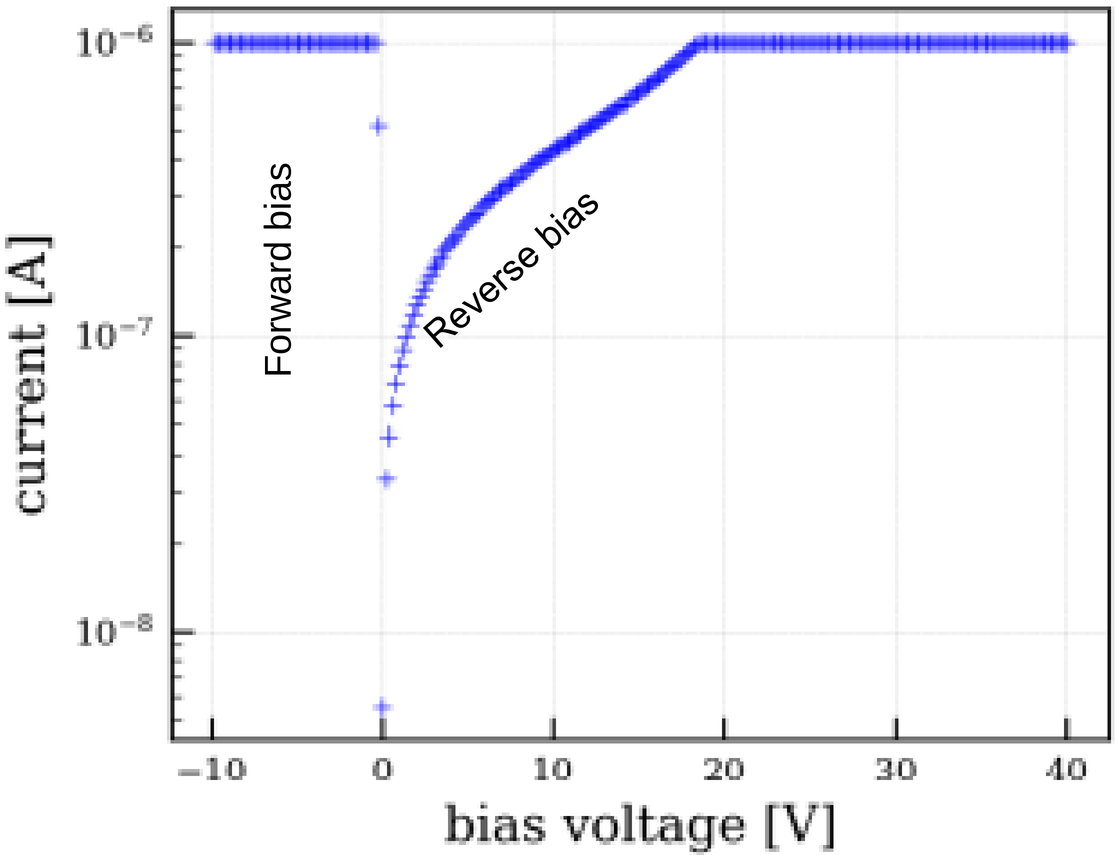






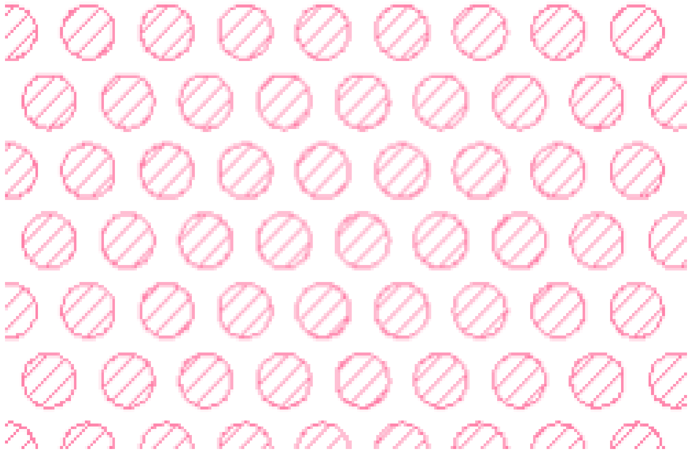
Probe strip structures

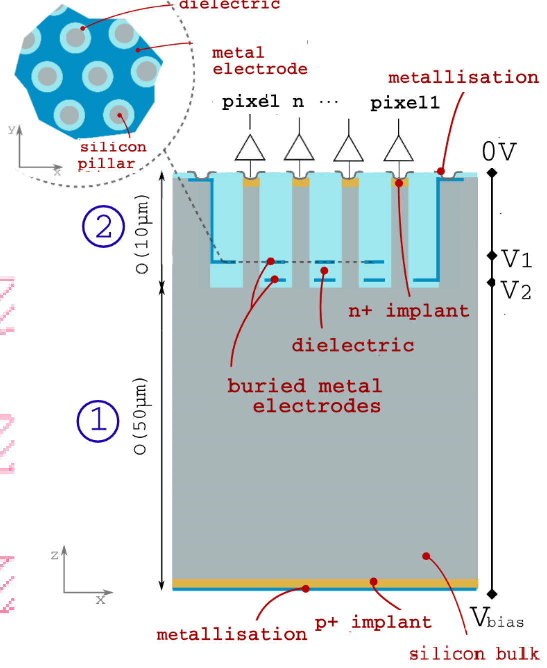


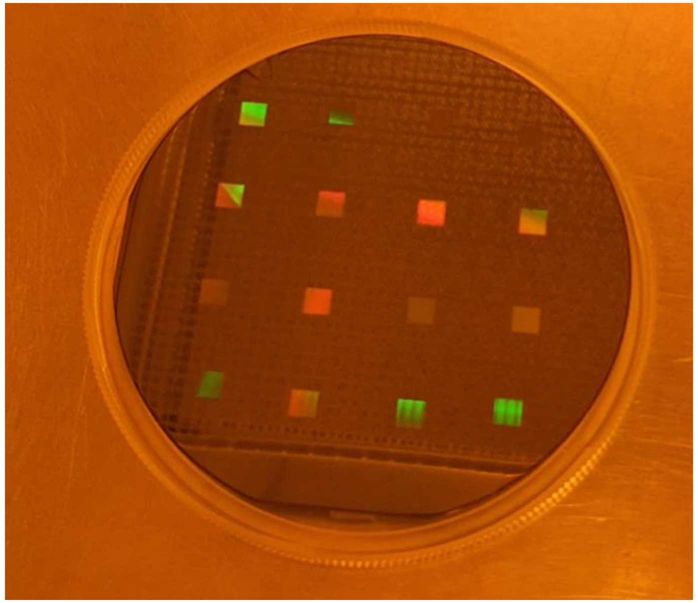


Lithography demands

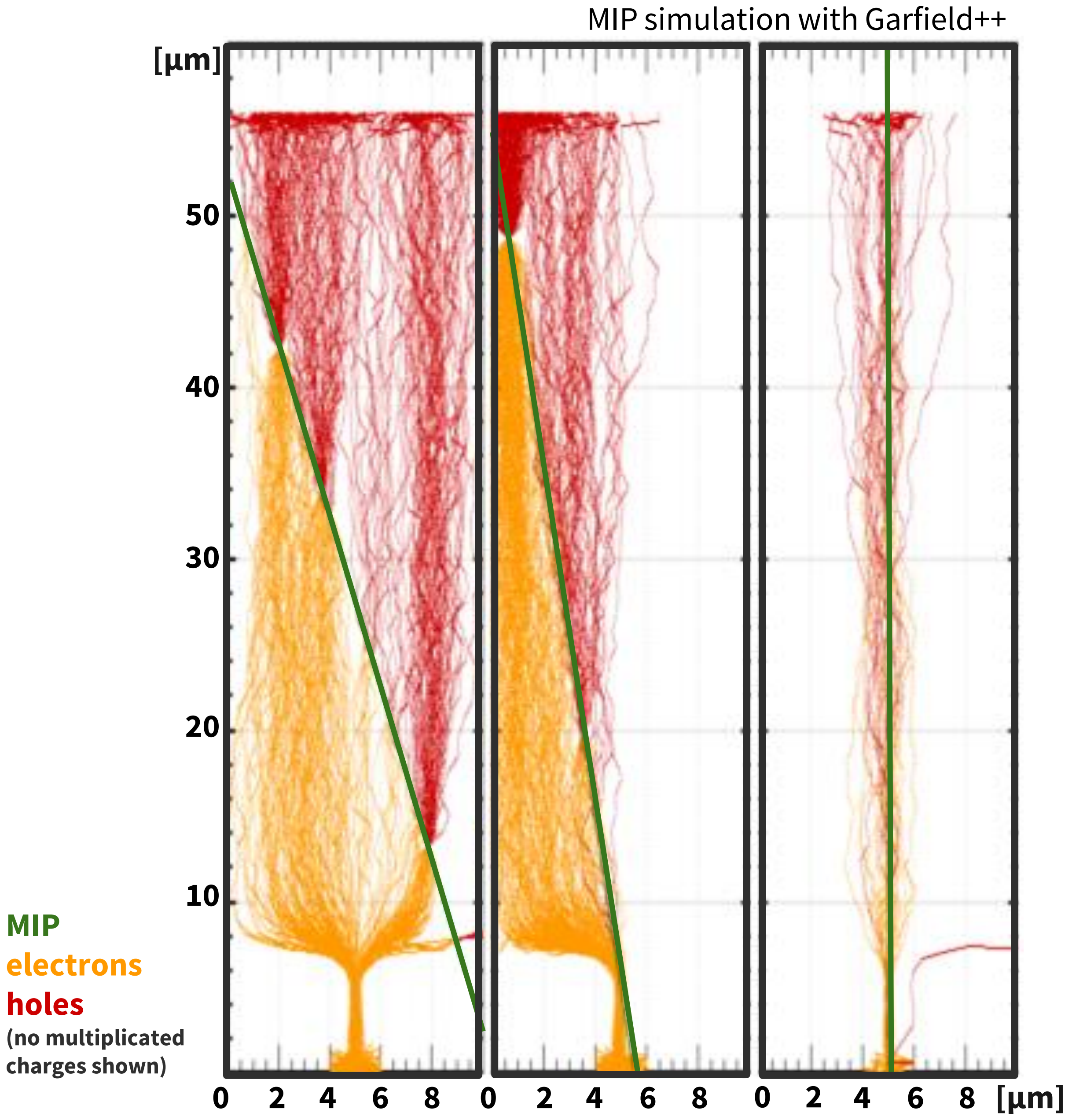
- **Small circles, down to 1.0 µm**
  - To allow electrical field to enter pillar center
  - Utilise small feature size capabilities of MacEtch
- **Small pitch, 1.5 µm**
  - Uniformity of drift path→ time resolution
  - Depletion
- **Heidelberg direct write laser, DWL66+, for prototyping**
  - Dynamically adapt pattern
  - Pattern flexibility, mask free
  - Easier lift-off with respect to e-beam
  - Appropriate resolution, ~300 nm
- **Target pattern**
  - 1.0 µm circle diameter
  - 1.5 µm pitch
  - Hexagonal lattice





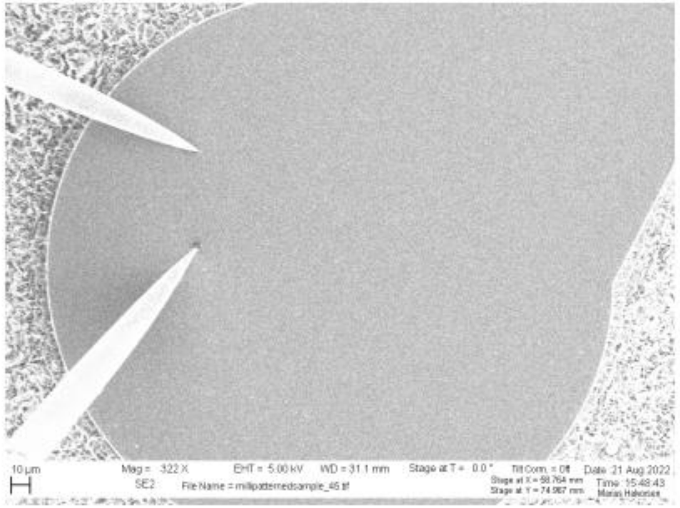


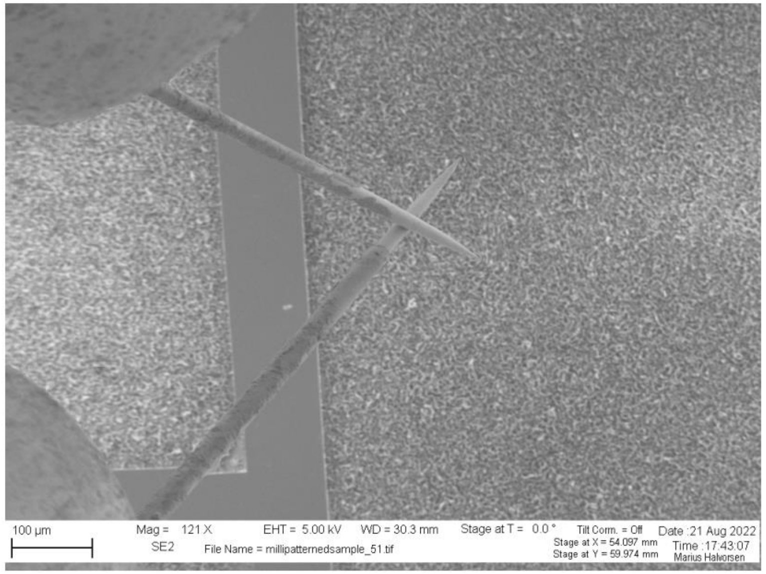
Garfield++ simulations



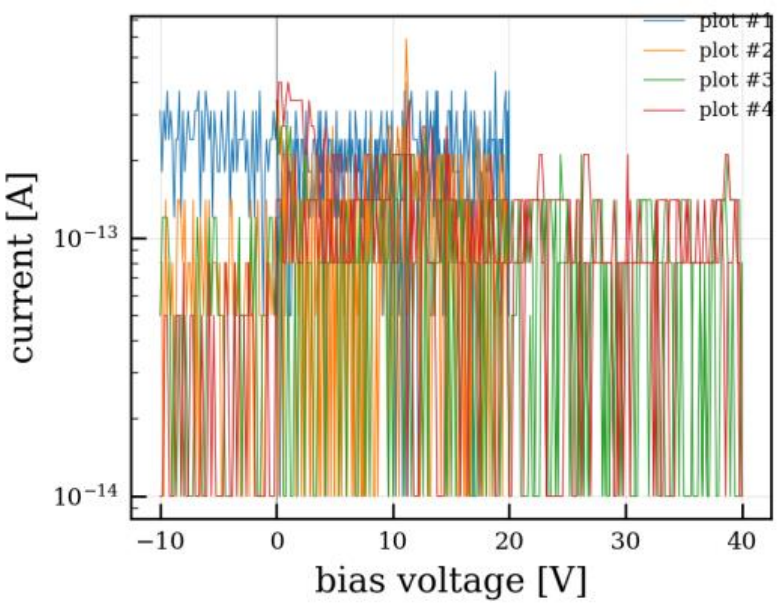
Sanity checks

- Sanity checks to be carried out often. Extremely fragile needles that broke often
- Open circuit
- Short circuits

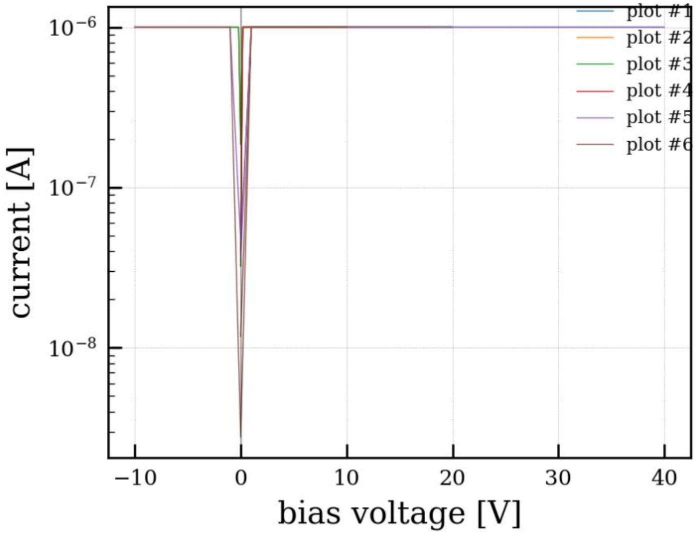




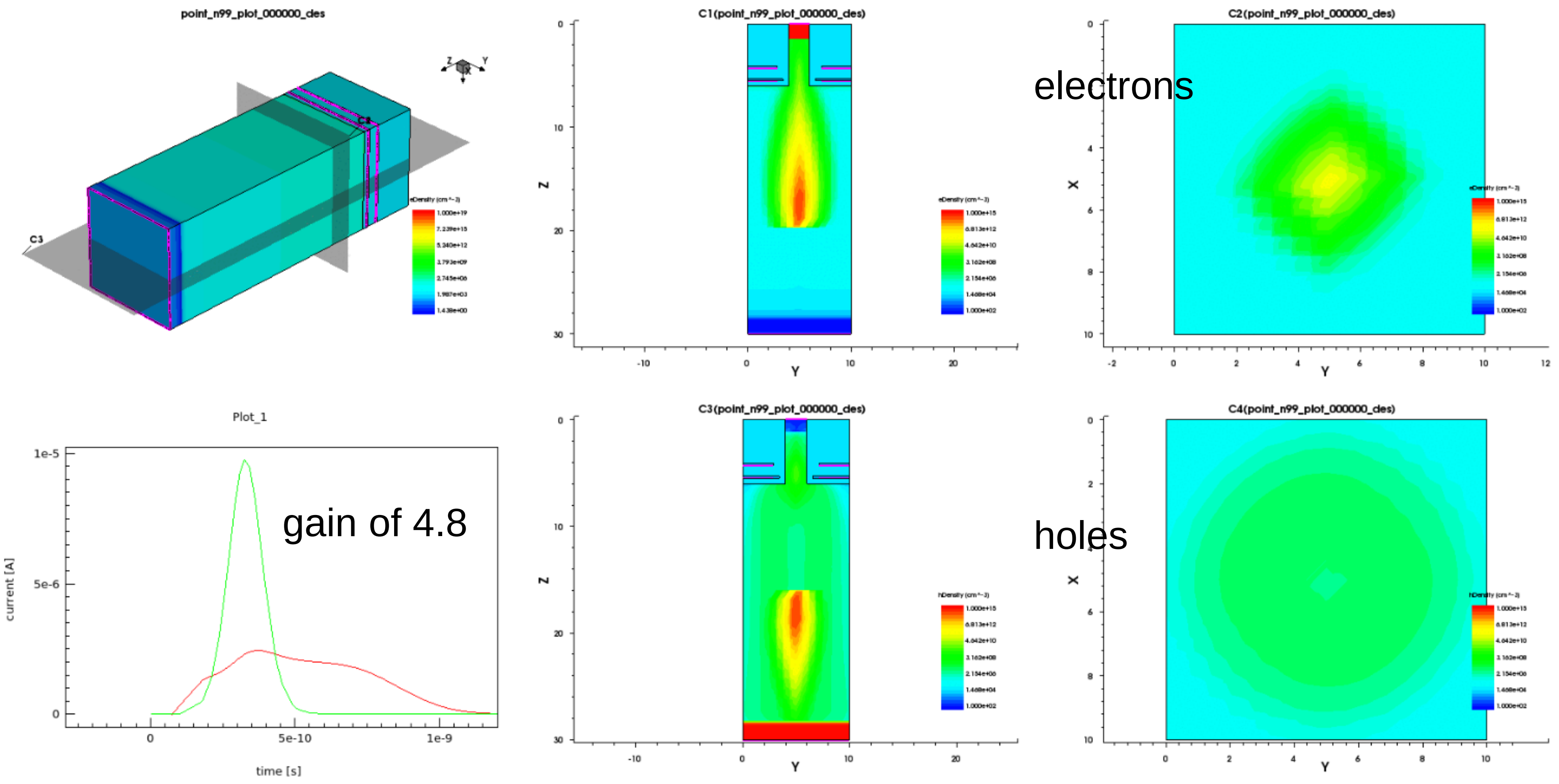
open circuit



short circuit

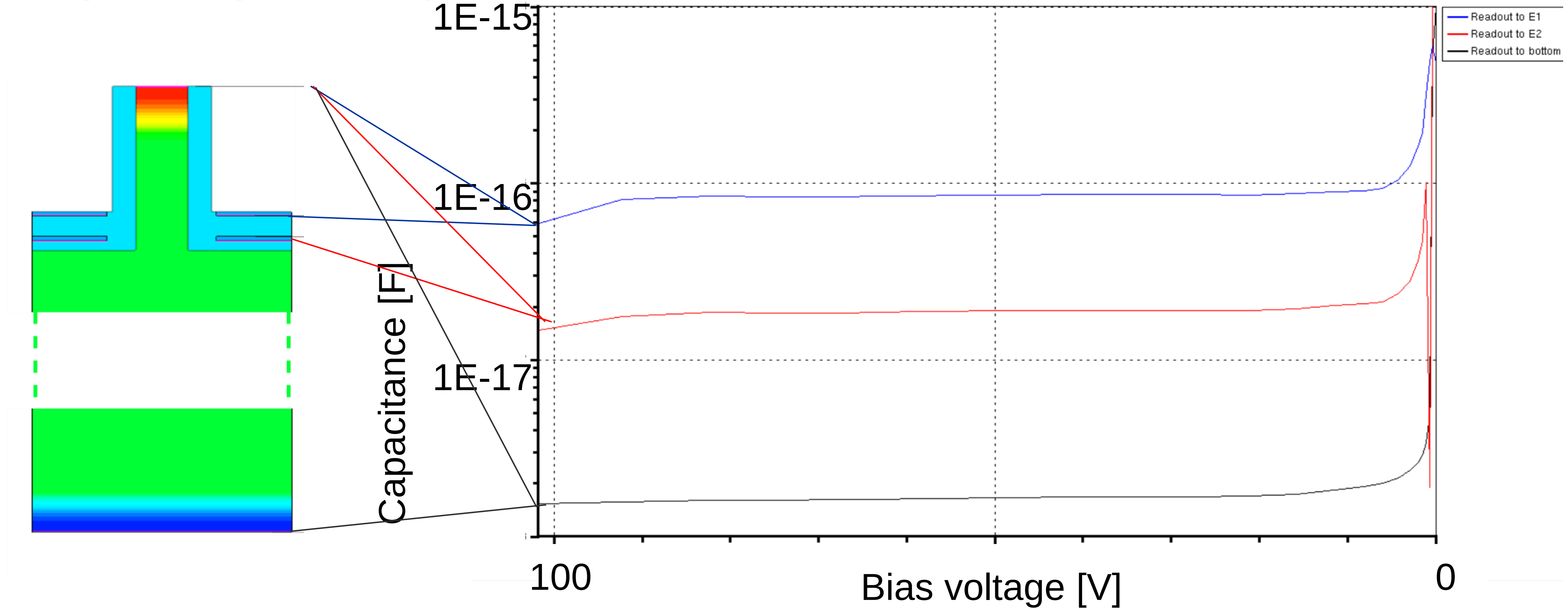


3D simulations



CV curves

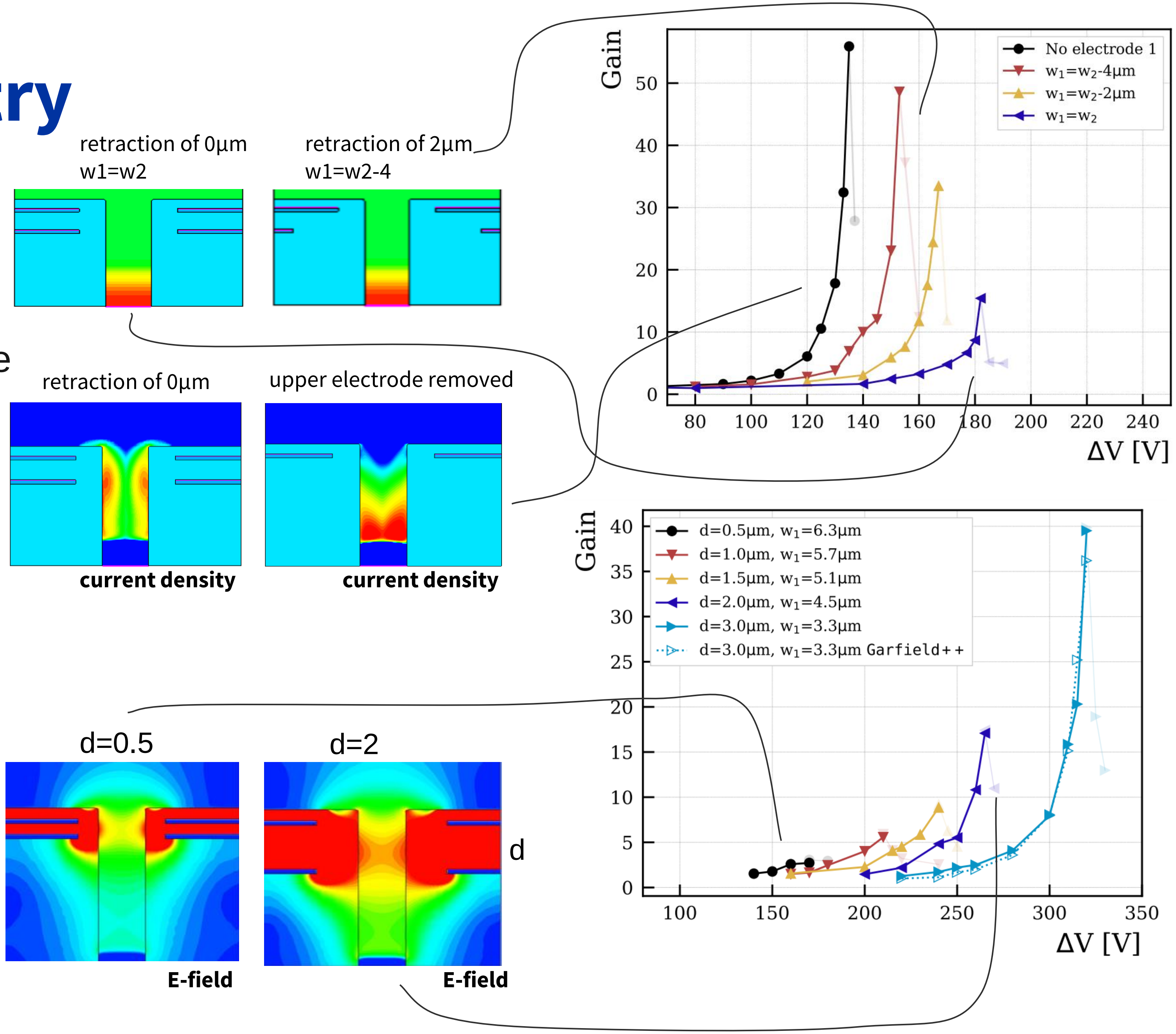
- **Simulation of one unit cell (no inter-pixel capacitance)**



Optimisation –geometry

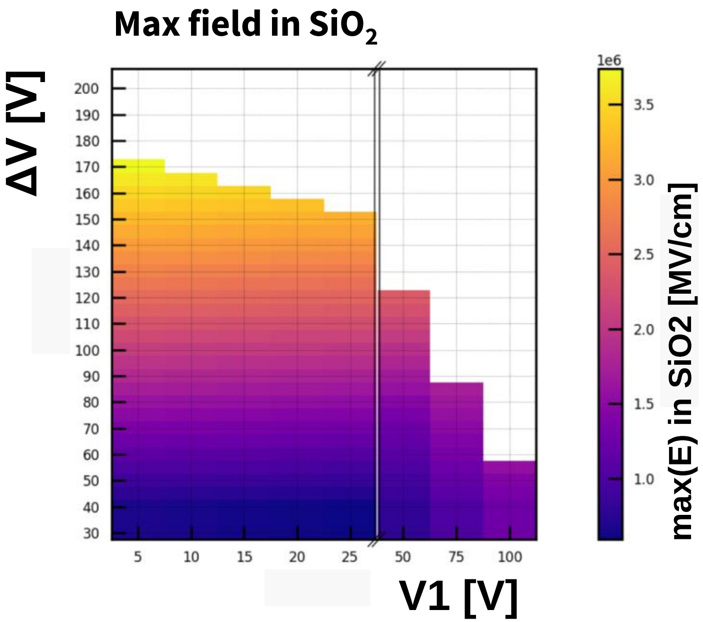
- Electrode geometries and pillar height
  - Retraction of the shallower electrode allow to better fill the pillar with high field
  - Similar effect to rising V_1
- Single electrode configuration
  - Simpler but higher field in the silicon
  - Different breakdown location
- Larger inter-electrode distance
  - Better spreading of the field
  - Less localised high field values

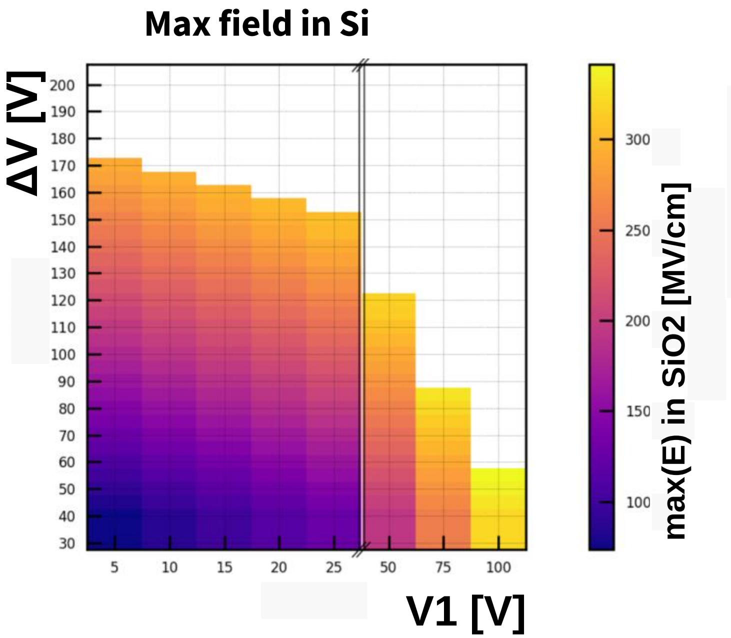
Several degrees of freedom to cope with production process constraints

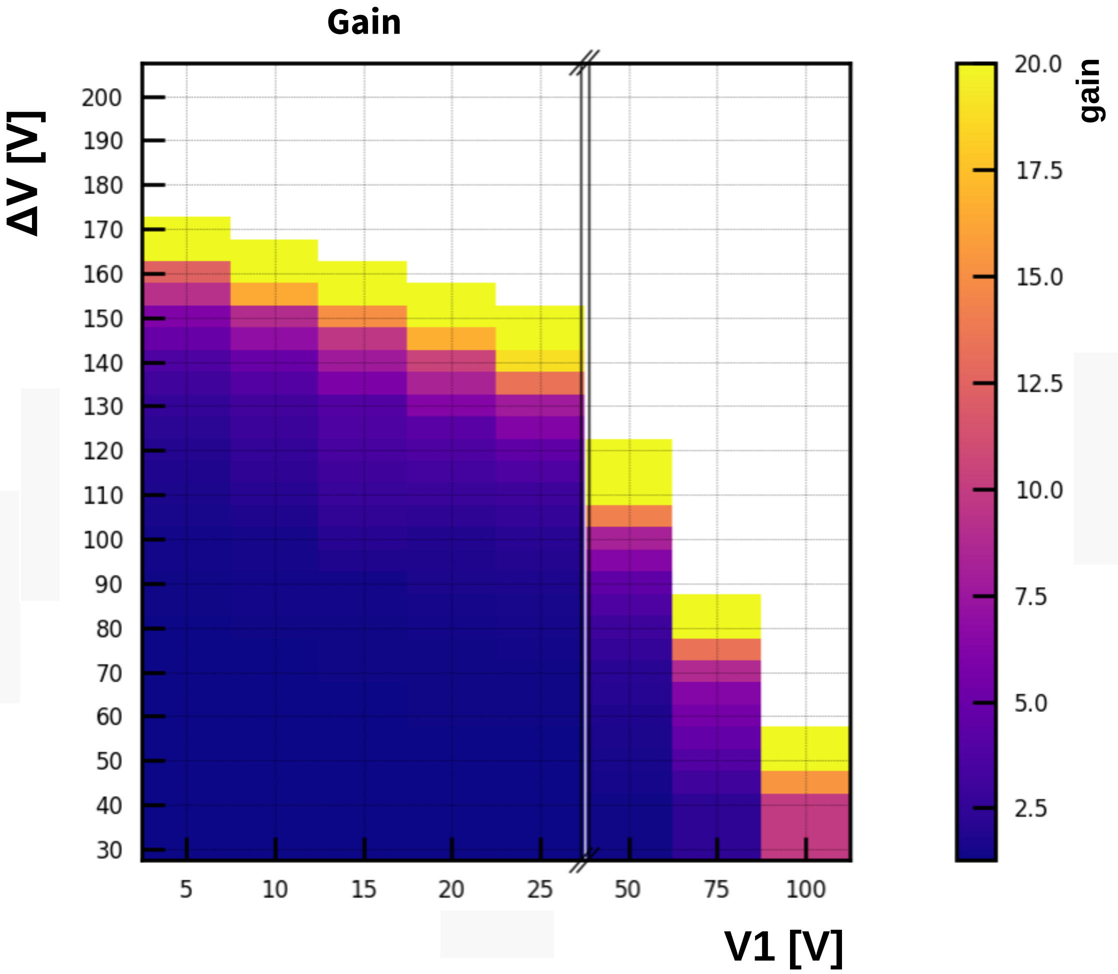


Optimisation – biassing

- Interplay between V_1 and ΔV can be optimised
  - freedom in choice of operation settings
- High V_1 leaves high field in silicon
- High ΔV leaves high field in the oxide



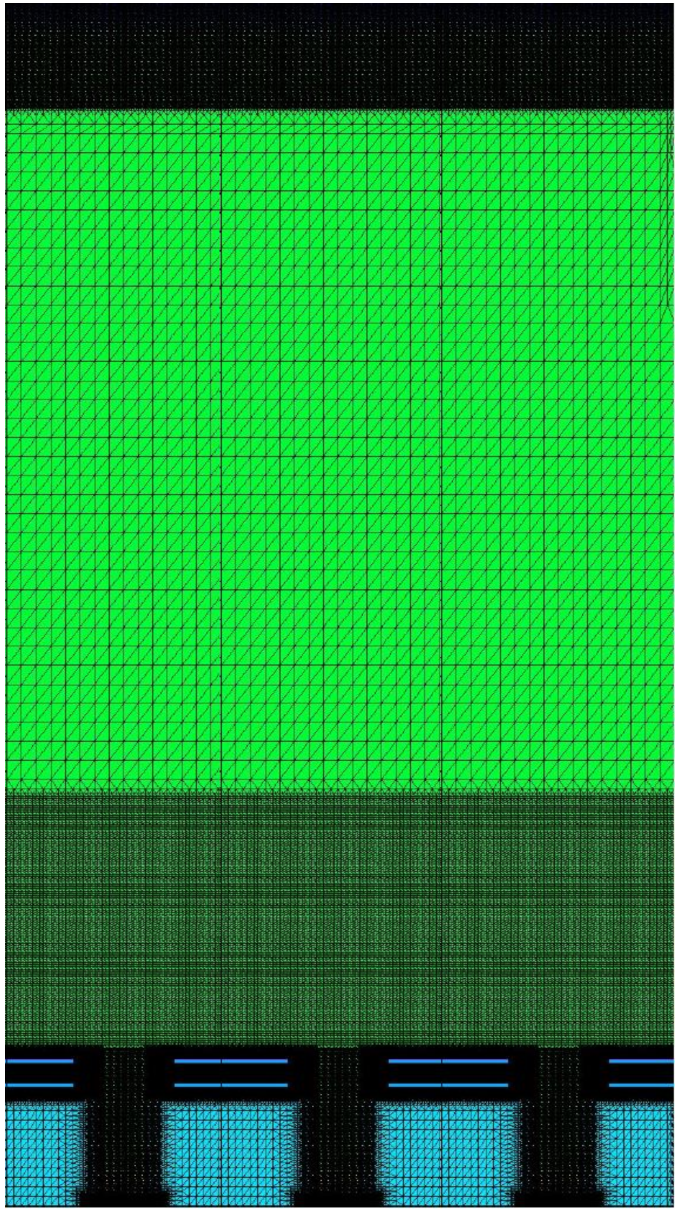




Synopsys TCAD simulations

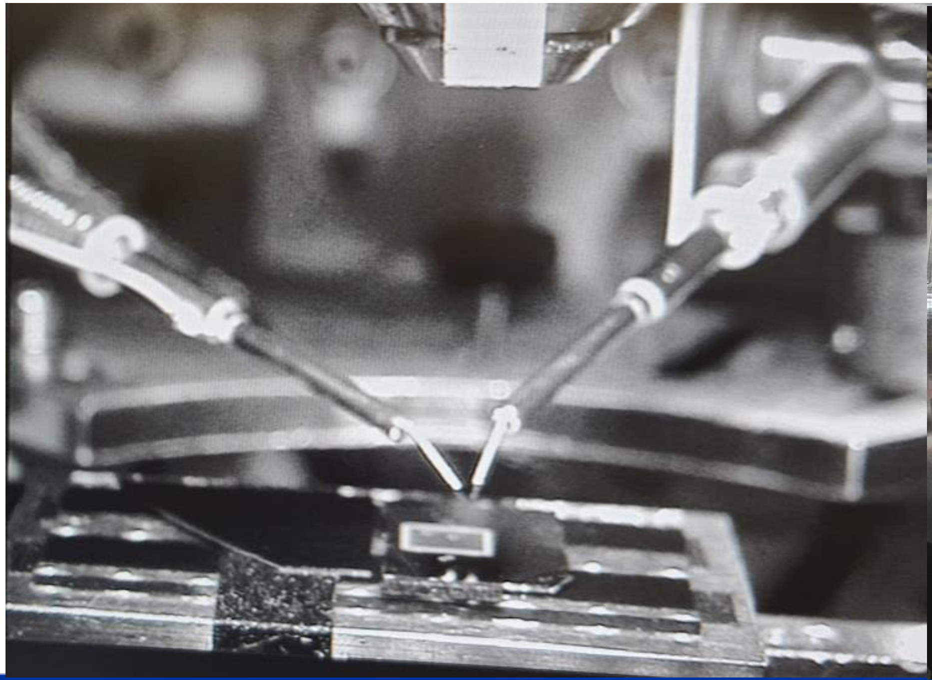
- Synopsys TCAD
  - Version Q-2019.12
  - Version Q-2021.06
- Impact ionization model: vanOverstraeten
  - Tested other models
- Mobility model: Canali
- Solver: PARDISO
- Recombination: Shockley-Read-Hall
- Transient model: HeavyIon
- Band gap model: Slotboom

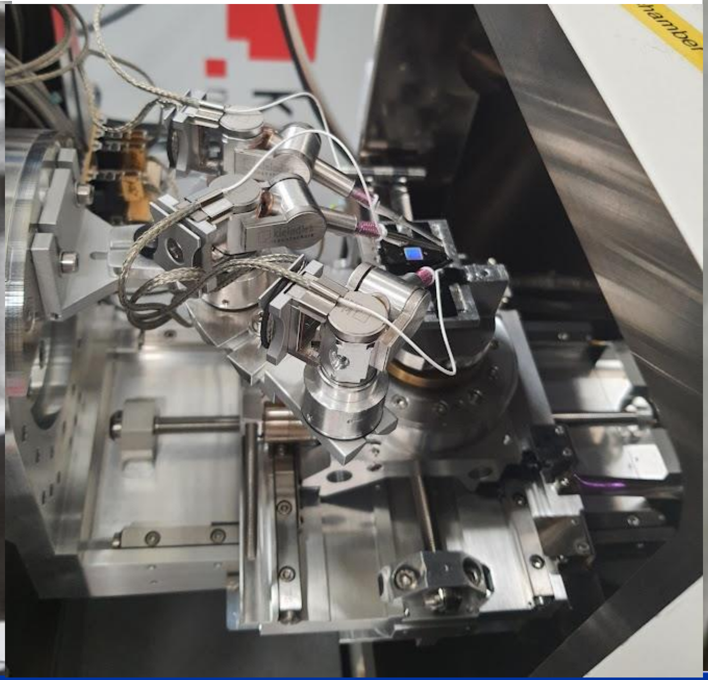
- SiEM simulation study summarized in a NIM-A article



Needles

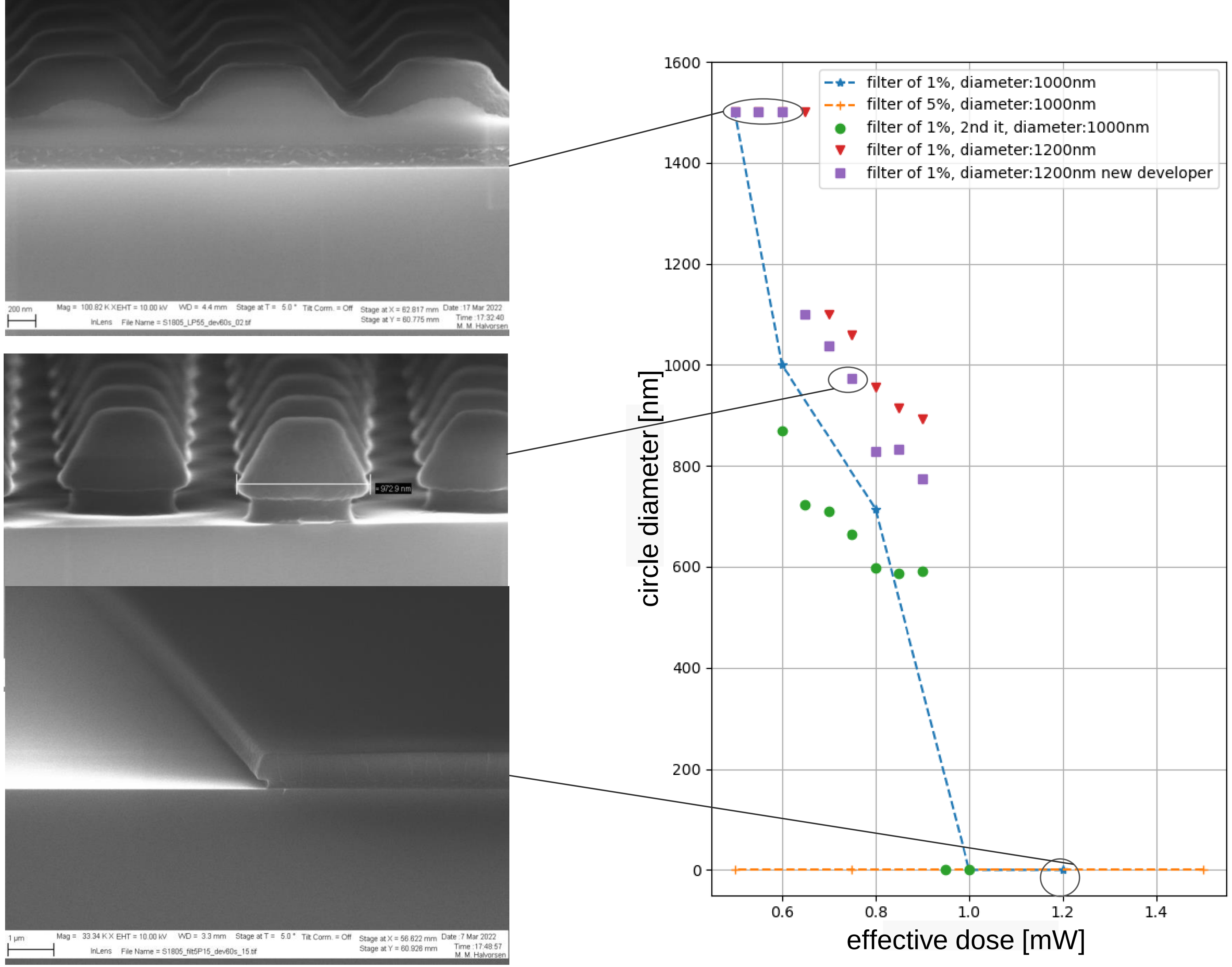
Final tungsten tip in sub-micrometer range





Optimisation

- Exposure parameters must be tuned
- Effective dose delivery
- Laser focus point



Lift-off

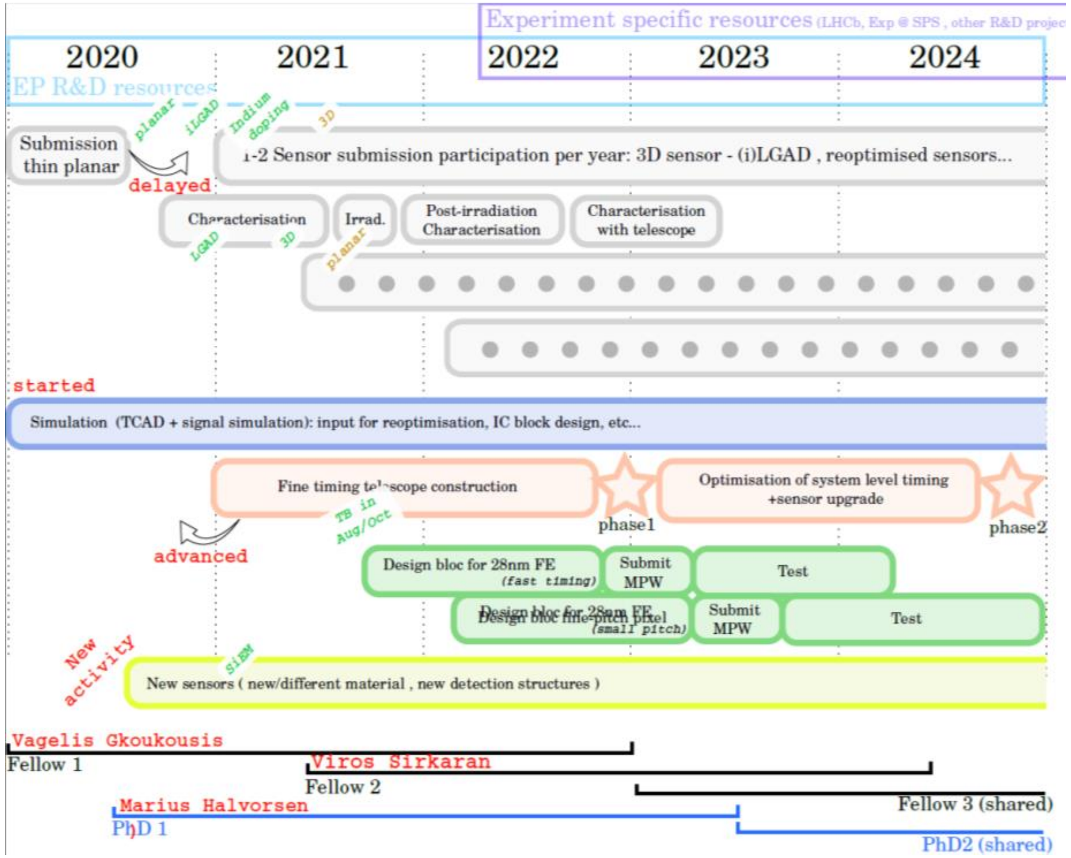
- testet EBR, Acetone, DMSO

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)
  - Test beam
- 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}