The Silicon Electron Multiplier Sensor

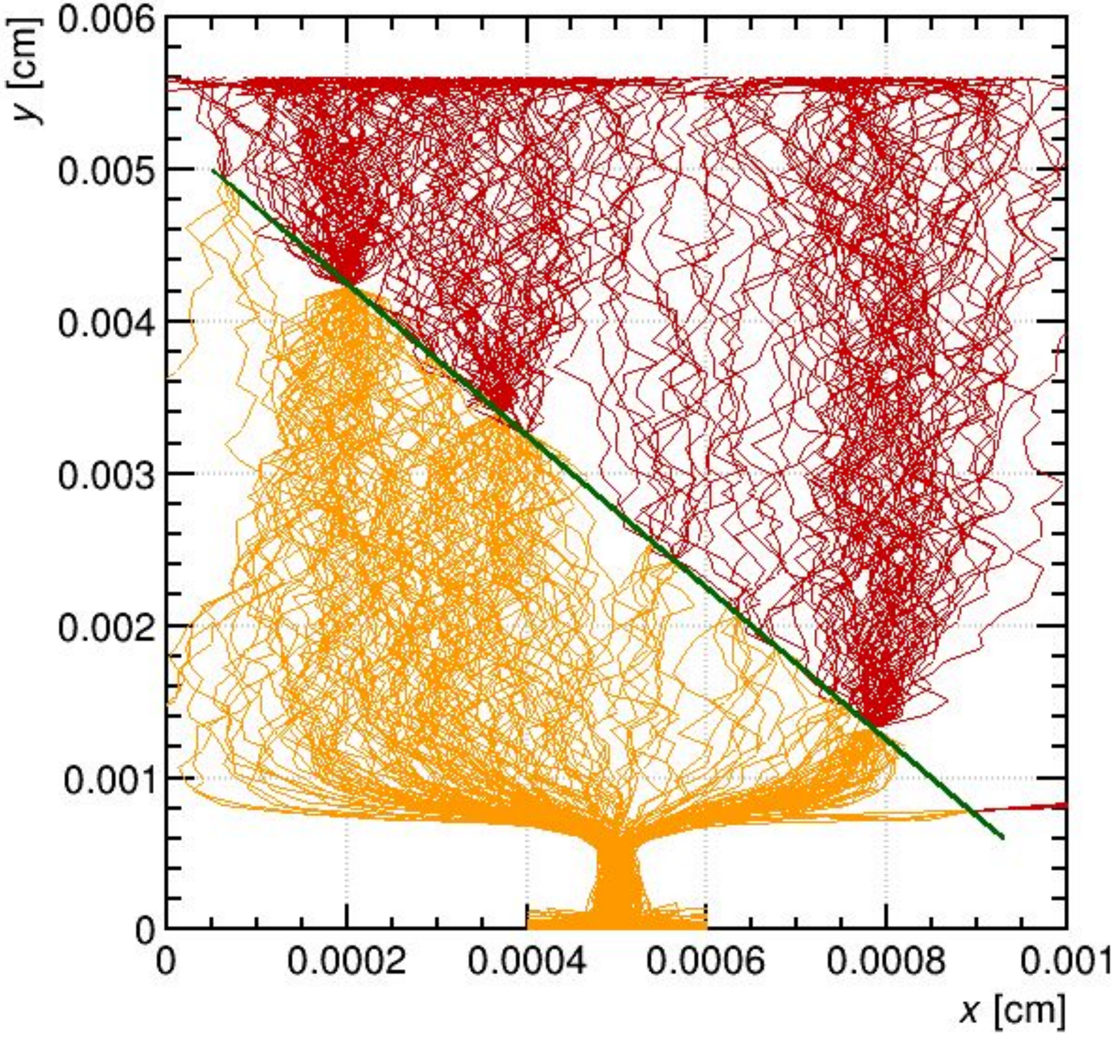
Victor Coco[1], Evangelos Leonidas Gkougkousis[1], Marius Mæhlum Halvorsen[1,2]

The 17th Trento Workshop, Freiburg (Virtual), March 3rd 2022

[1]CERN, [2]University of Oslo

Overview

- Introduction, framework and motivation
- Concept
- Simulation results
- Fabrication progress
- Outlook



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

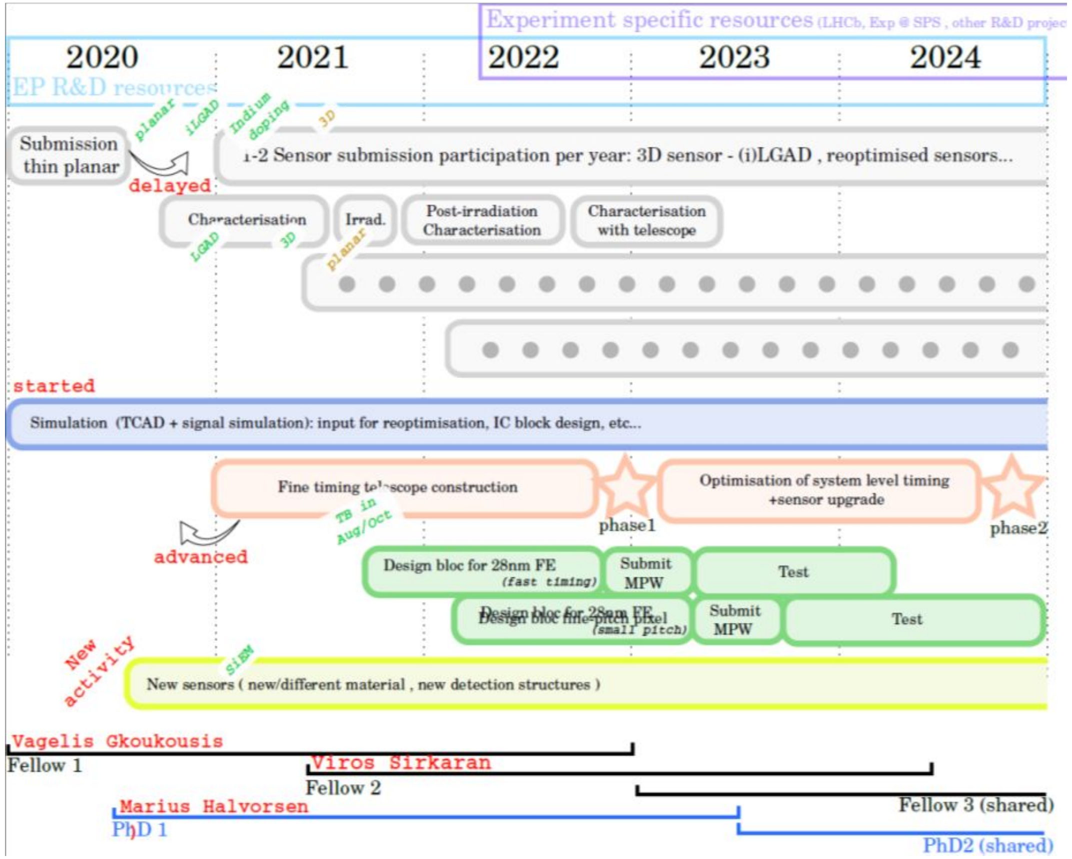
- Planar sensors (J. Haimberger, V. Gkougkousis)
  - Radiation damage and trapping model validation through TCAD
  - Timing and efficiency at $<10^{17} n_{eq}/cm^2$ using fast neutrons and PS protons(thicknesses 50, 100, 200, 300μm)
- LGADs (V. Gkougkousis)
  - Radiation damage mechanisms and modelling 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)
  - Arxiv preprint
  - RD50 november 2021
- 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


Vagelis Gkougkousis


Jakob Haimberger


Marius Mæhlum Halvorsen


Victor Coco



Motivation

from the CERN Strategic R&D Programme on Technologies for Future Experiments [CERN-OPEN-2018-006]

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

Future inner tracker detectors will require

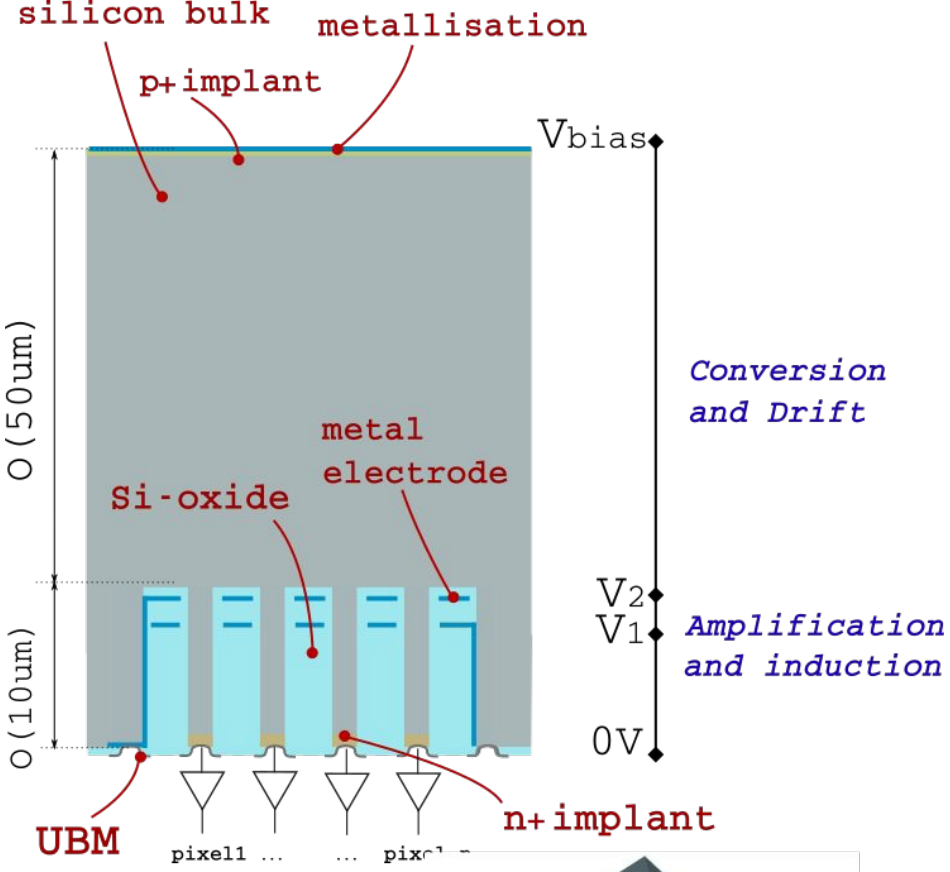
- Time resolutions below 50ps
- Pixel pitch down to 25µm
- Radiation hardness up to $10^{17}n_{eq}$

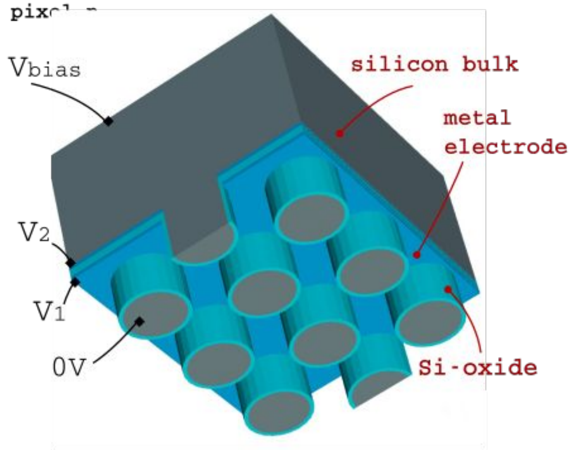
Our approach

- Gain
- Small thickness, doping independent gain

Approach

- Make a radiation hard sensor with good timing capabilities
  - Avoid doping dependent gain regions
- Approach:
  - Implement additional electrodes in sensor substrate to create high electric field regions to promote charge multiplication
- Inversely etch pillar structures
  - Silicon, diamond, SiC …



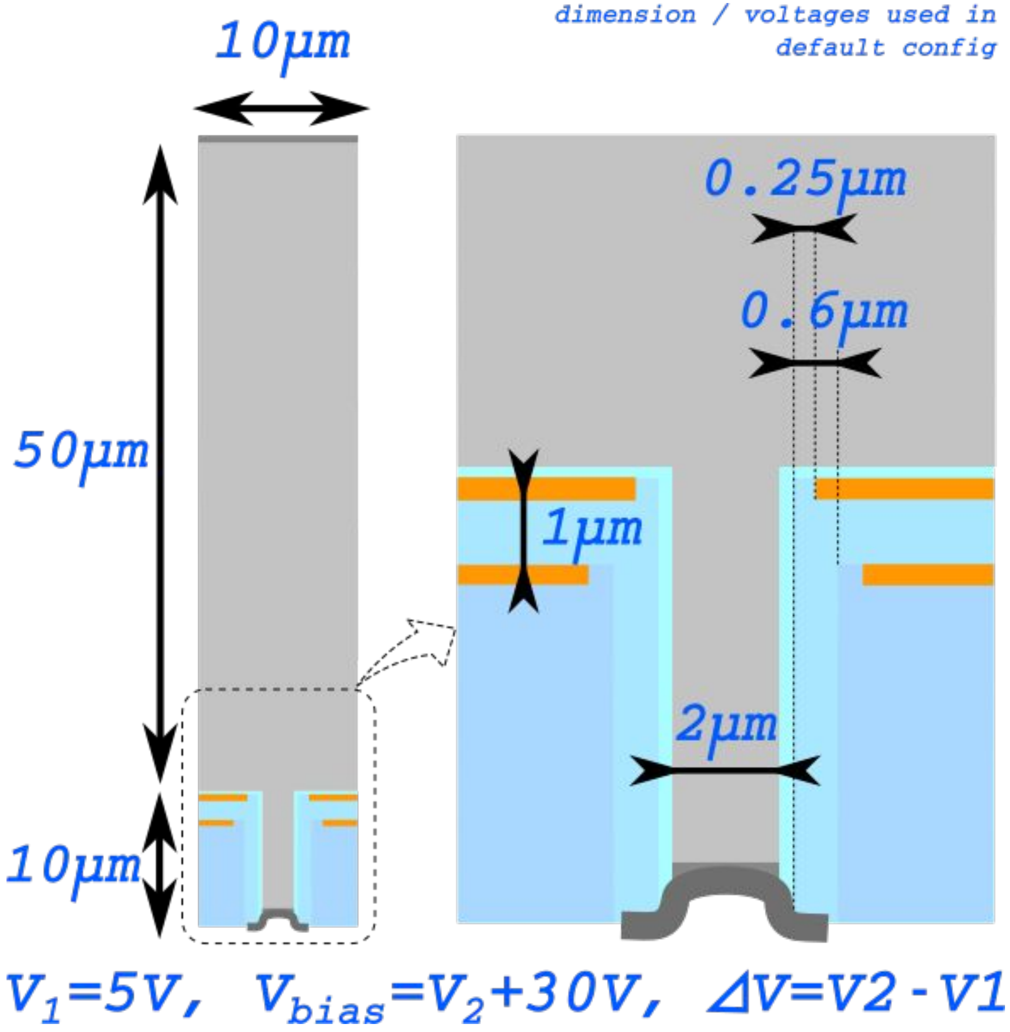


oxide in between pillar and UBMs not shown here

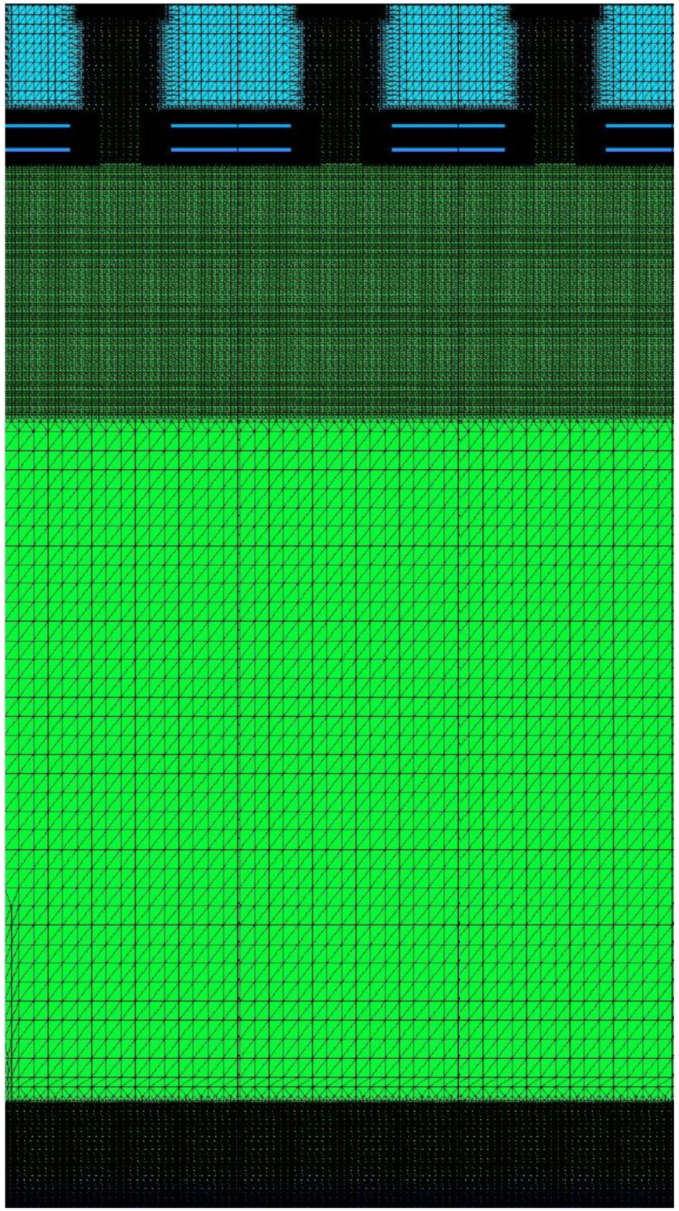
Geometry

- First consider DRIE based processing
  - Etching of pillars and consecutive deposition of metal and oxide
- Process related constraints:
  - Guard and height of pillar
  - Sufficient guard around pillars to not get metal on pillar walls
- Impact on geometry
  - Pillar height 4-15μm,
  - Pillar width 1-4μm
  - Inter pillar distance more than 6μm

- Other fabrication techniques have different geometrical constraints



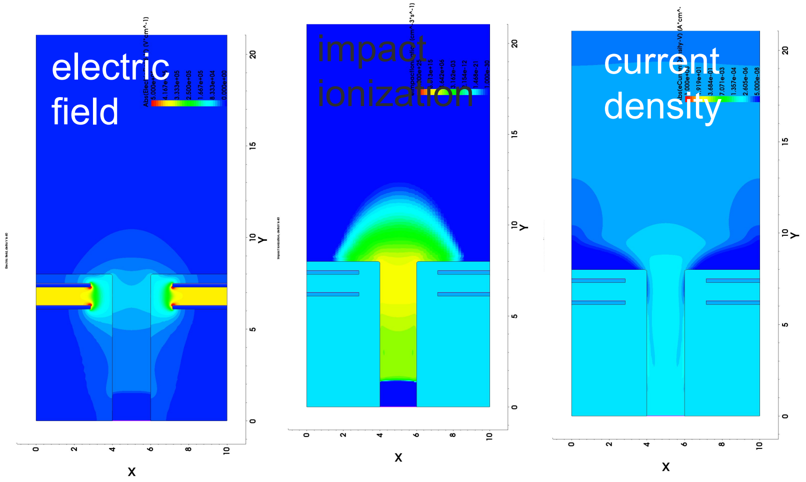
Synopsys TCAD simulations

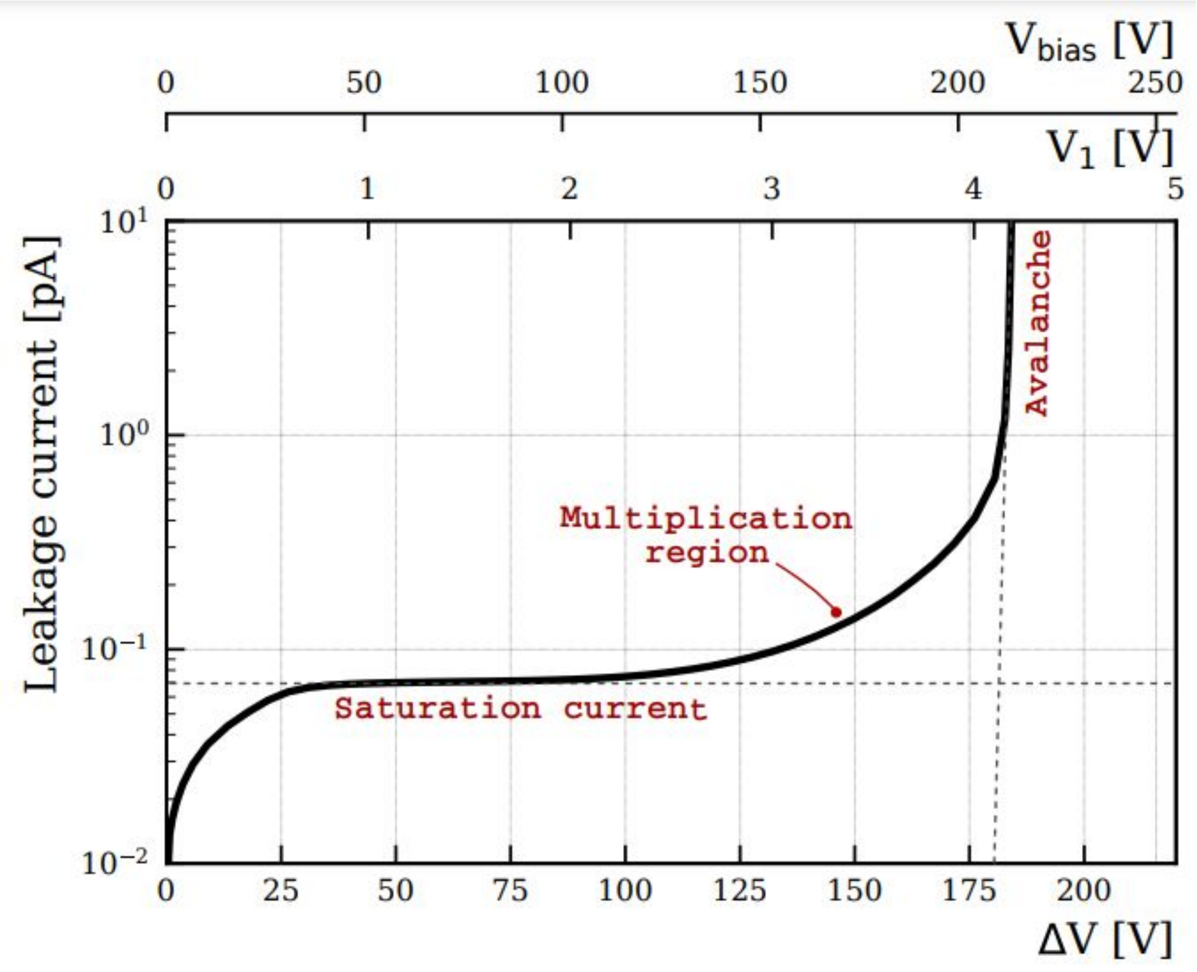


- Synopsys TCAD
  - Version Q-2019.12
  - Version Q-2021.06
- Impact ionization model: vanOverstraeten
  - Tested other models
- Mobility model: Canali
- Solver: PARDISO
- Recombination: Shockley-Read-Hall
- Transient model: HeavyIon
- Band gap model: Slotboom

Quasi-stationary simulations

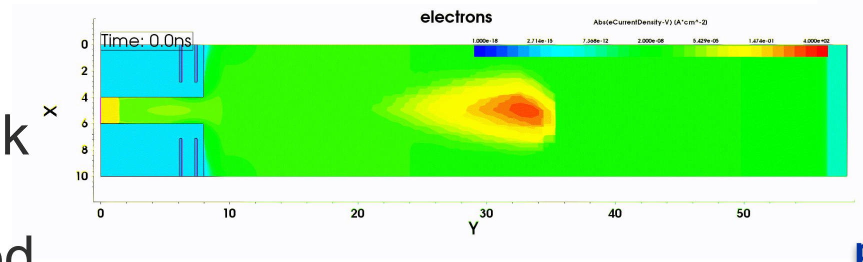
- Evaluate electric field and leakage current
  - Breakdown position depends on biasing configuration
- Pillar and bulk depletes
- High electric field in the pillars can be reached
  - Above 15V/µm

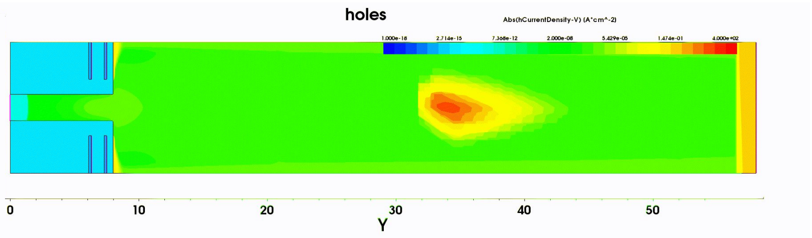


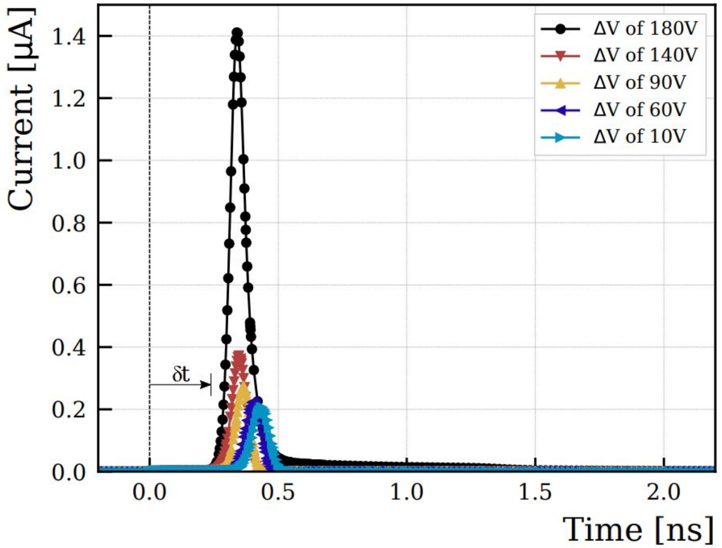


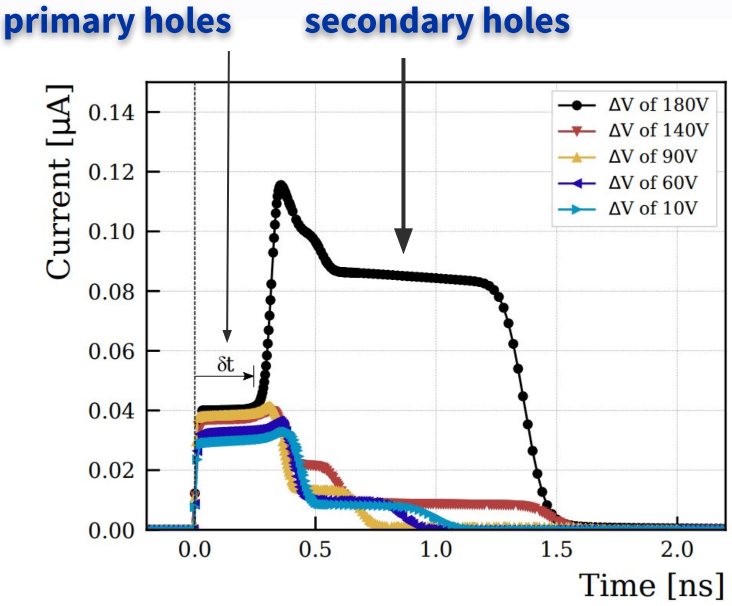
Signal simulations and charge multiplication

- Charge cloud deposited in bulk center
- Charges drift and get multiplied in pillars.
  - Gain= $Q_{collected}/Q_{injected}$
- Gain achieved for ΔV>100V
  - above 10 has been simulated
- Weighting field of readout electrode is concentrated in the pillar
  - Shielded by multiplication electrode
- Weighting field of backside electrode
  - “Pad like”



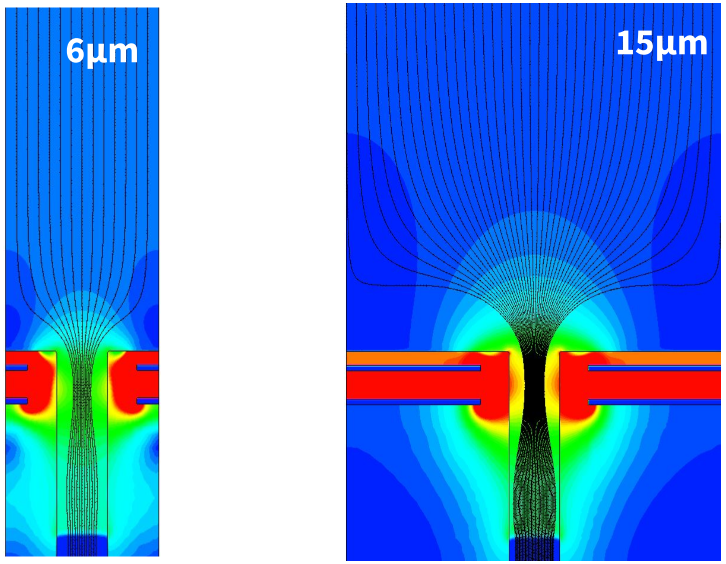


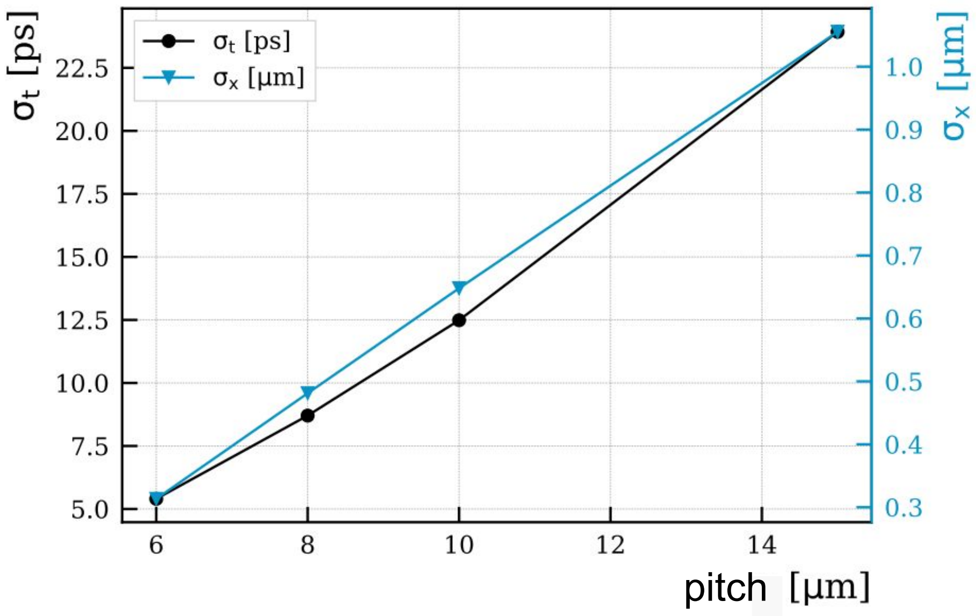




Optimisation
Pillar pitch and timing performances

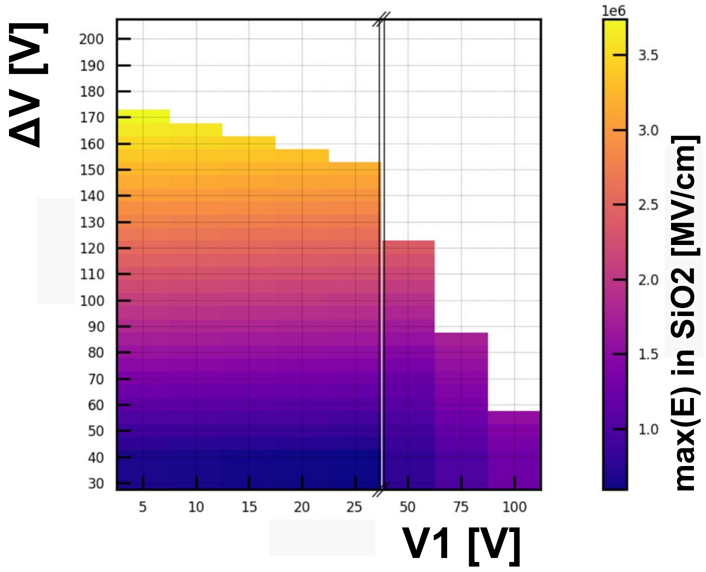
- Arrival time distribution at the gain layer will play a large role on the final time resolution
  - See [Riegler,Windischhofer; NIM A (2021) 165265]
- Inhomogeneity in path
  - Can be reduced by reducing the inter-pillar distance
  - Down to 5ps for 6µm
- Can expect similar time resolution as LGADs, to be confirmed with full MIP simulations

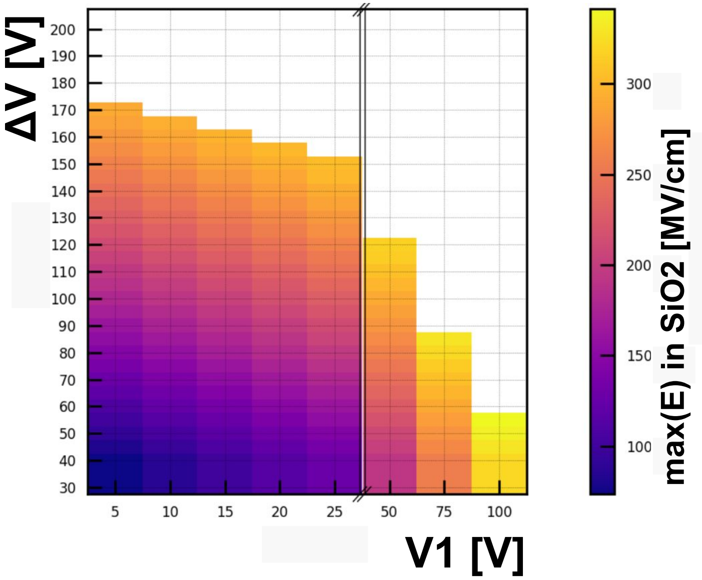


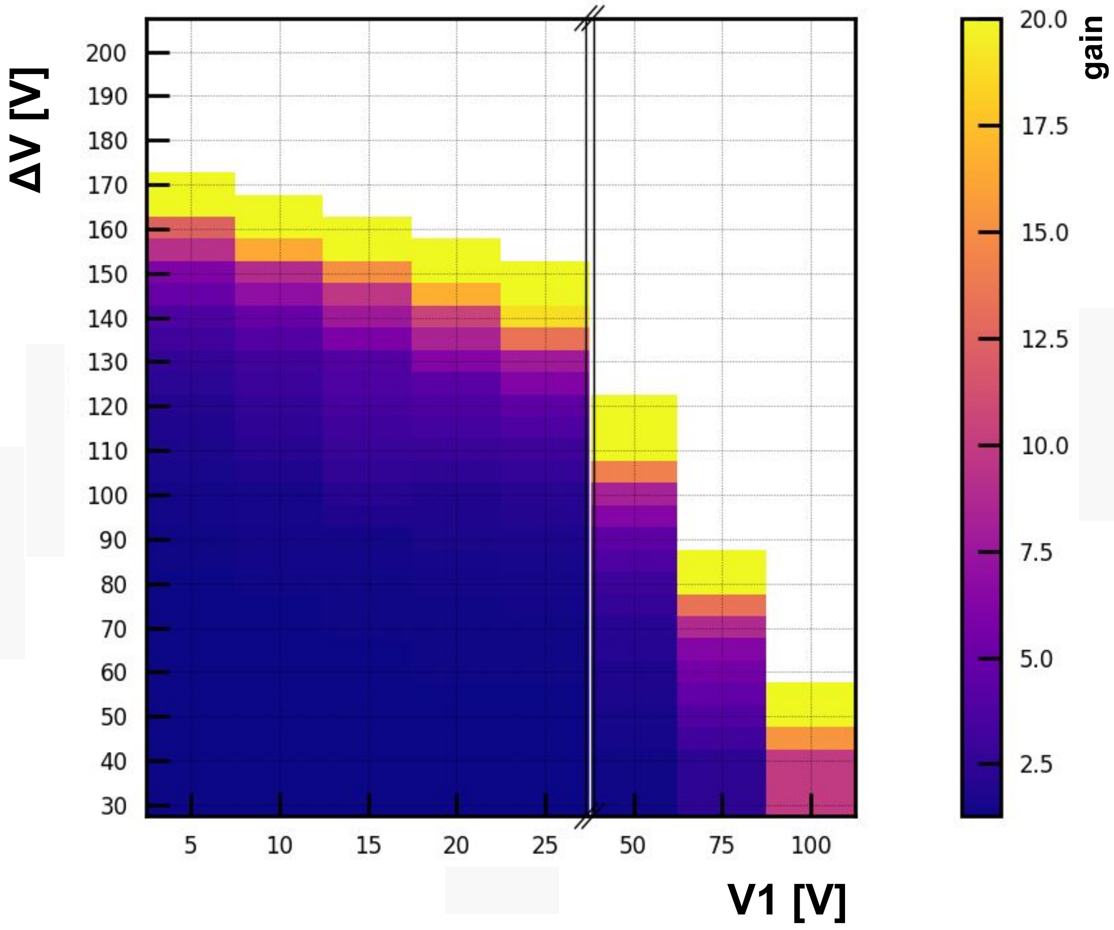


Optimisation – biassing

- 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



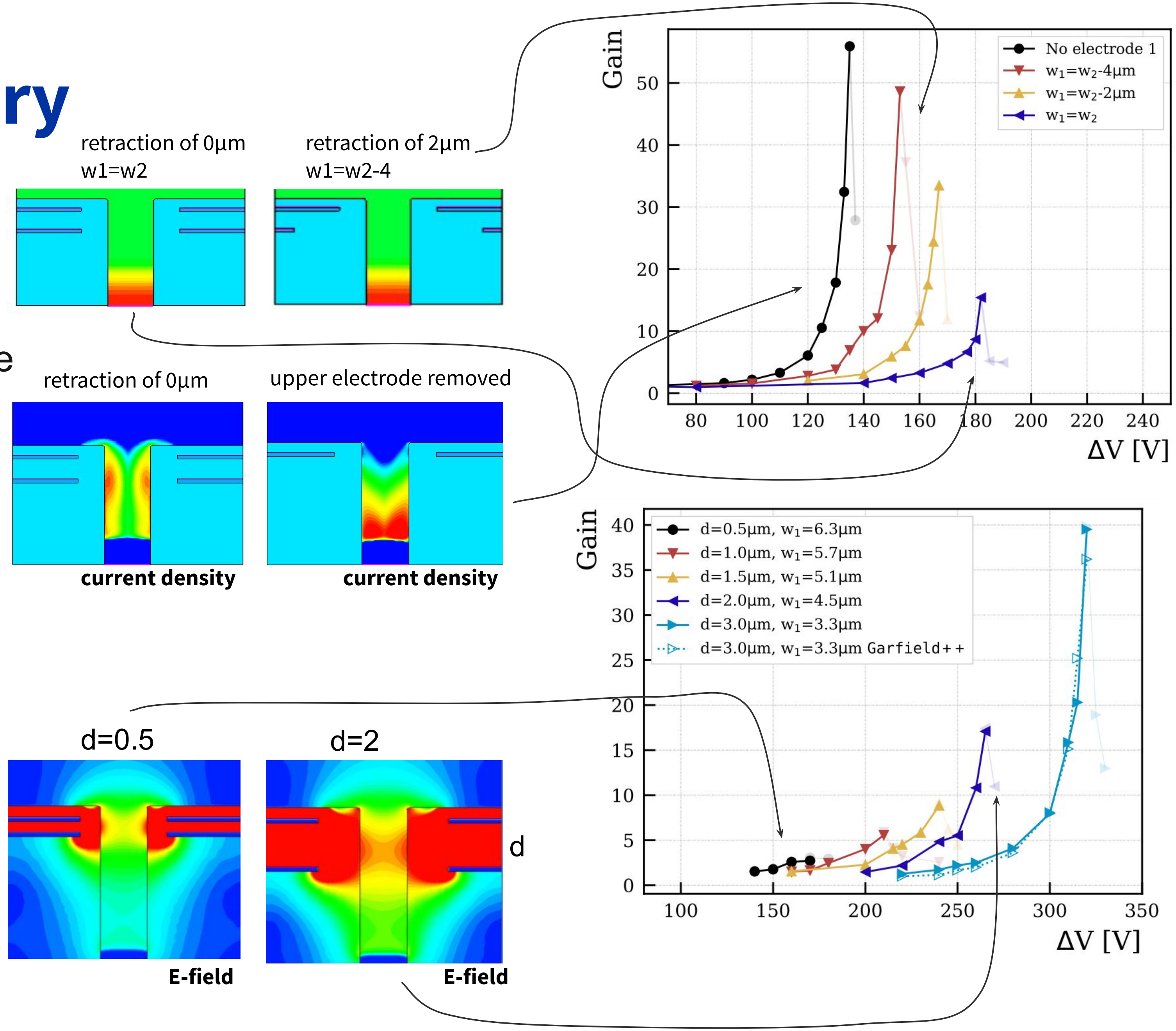




Optimisation –geometry

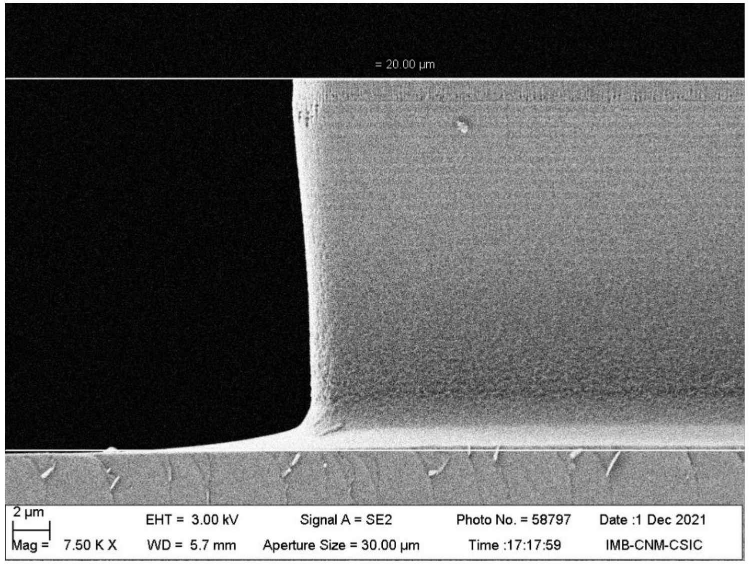
- Electrode geometries and pillar height
  - Retraction of the shallower electrode allow to better fill the pillar with high field
  - Similar effect to rising V_1
- Single electrode configuration
  - Simpler but higher field in the silicon
  - Different breakdown location
- Larger inter-electrode distance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

Several degrees of freedom to cope with production process constraints



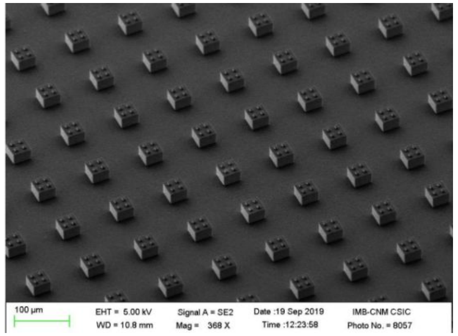
Production processes

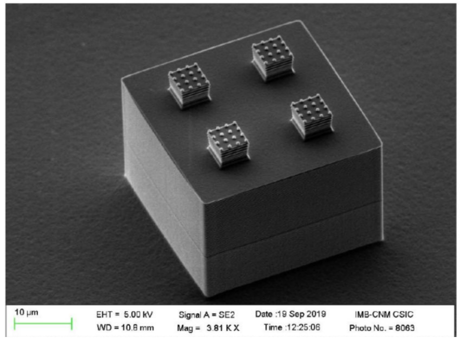
[courtesy of CNM]



DRIE based

- Discussions about the process and its constraints with LeTI and CNM
- Awarded the AIDA innova blue sky R&D to make a demonstrator with CNM
  - Will start this year
- 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
  - Sensor performance

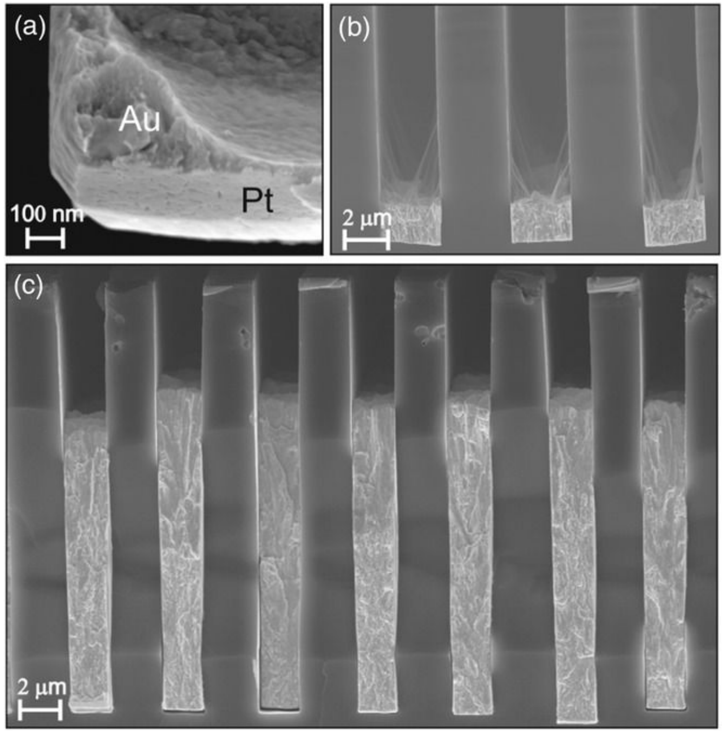




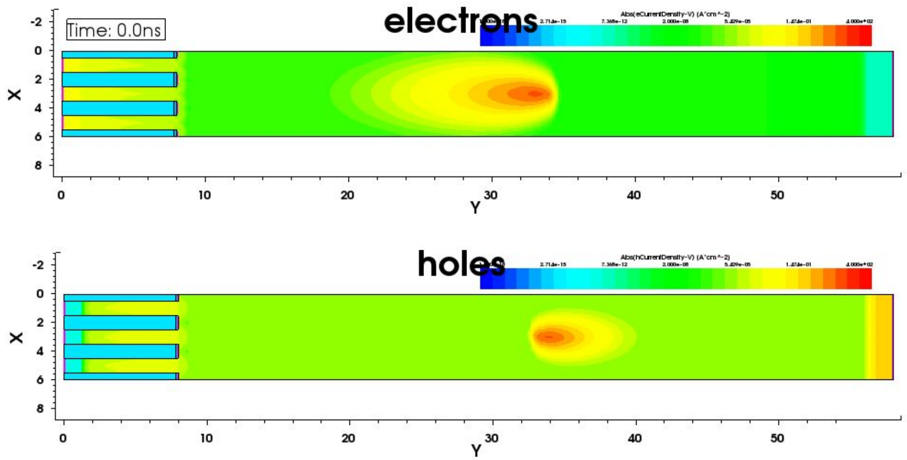
[courtesy of CNM]

Metal Assisted Chemical Etching

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



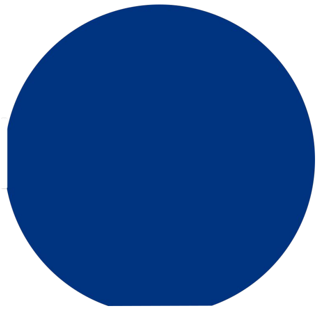
- The MacEtch process
  - Metal pattern used as a catalyst for HF etching.
  - Electroplating with gold
- Metal pattern can be used as multiplication electrode
- More appropriate for single electrode structures
- Denser pillars
- No more constraints on the guard



Demonstrator production with MacEtch

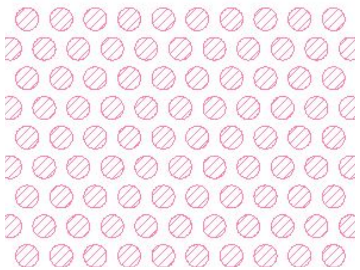
- An ongoing feasibility study and demonstrator production together with PSI started this february.
- A multistep process
  - Lithography
    - Coating
    - Direct write laser

1. Implanted Silicon wafer

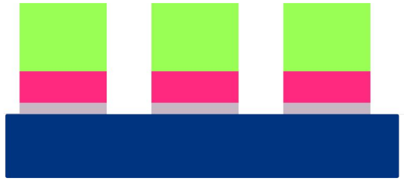


2. wafer + coating, photoresist

3. Pattern with direct write laser



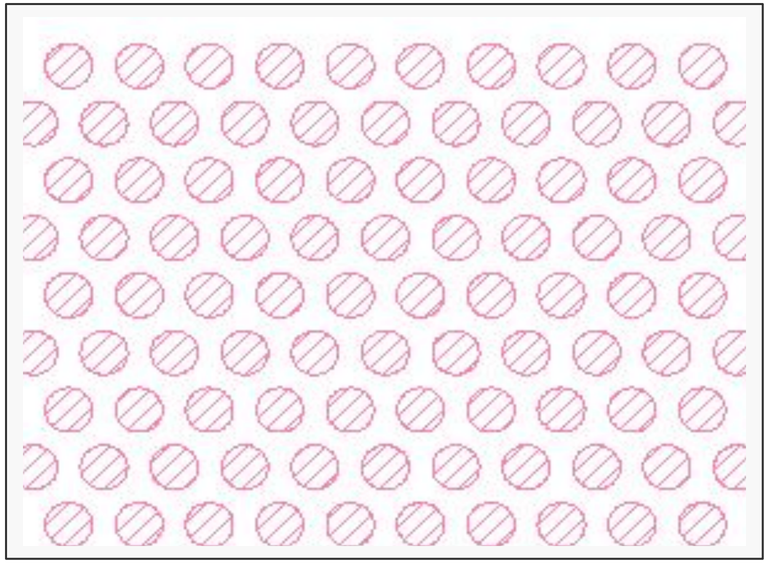
4. Develop



Demonstrator production with MacEtch

Current status

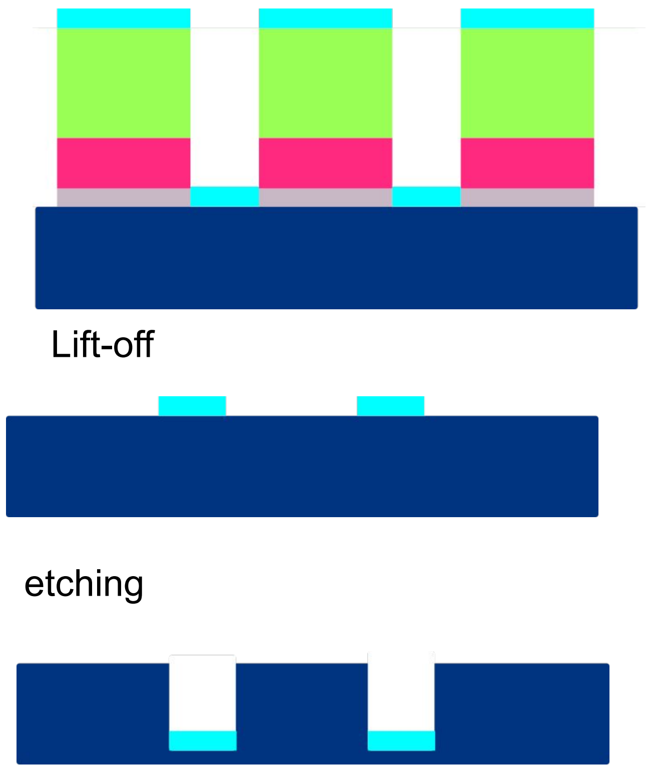
- Fine tuning of laser exposure
- Together with Lucia Romano and Zhitian Shi the first pattern exposure and development was done last week.
    - 1µm diameter circles separated by 0.5µm



after development
optical microscope
bright is photoresist

Next steps of MacEtch

- Metal (Pt) deposition
    - e-beam evaporation
- Lift-off
- HF etching
    - gas phase
- Electroplate multiplication electrode
- Fill trenches with oxide
- Electrically characterise sensor

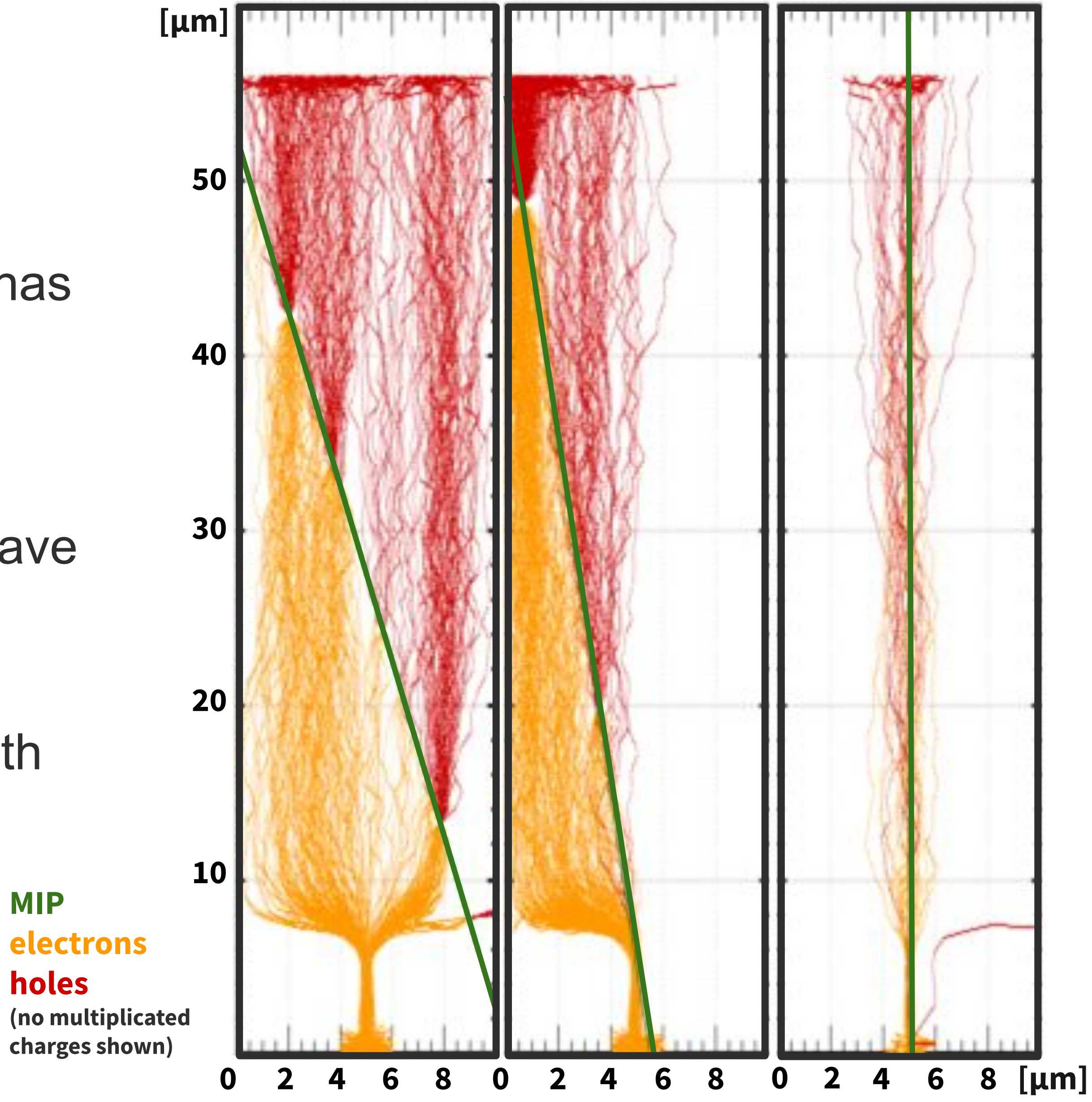


Summary and Outlook

- A new solid state radiation detector concept has been presented.
    - Small pitch
    - Expected time resolution similar to LGADs
    - Gain is not doping dependent
- Two demonstrator studies and productions have been initiated

- Next steps
    - Finish simulations full MIP simulations with Garfield++
    - Produce demonstrators and electrically characterise them.

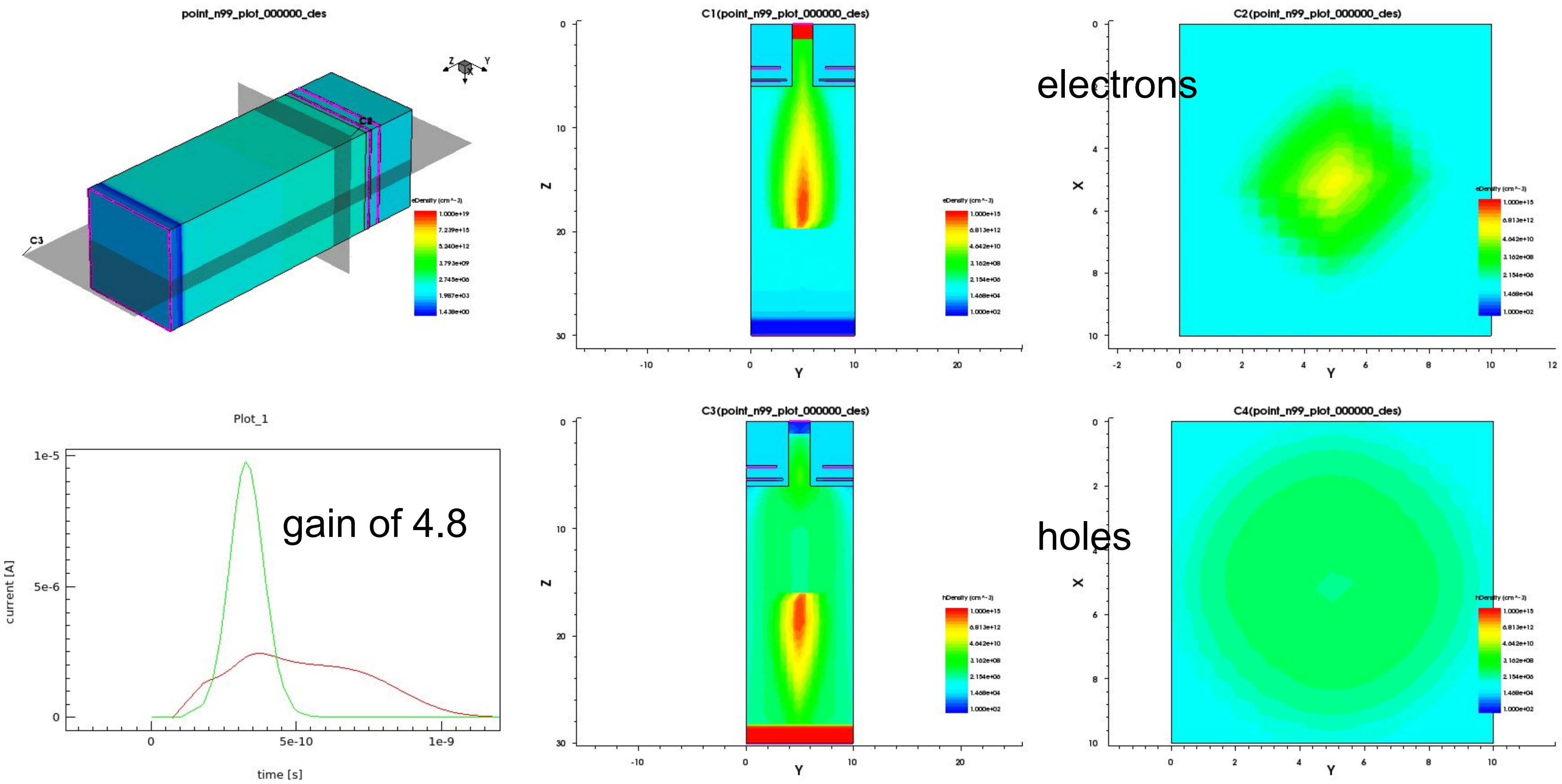
MIP simulation with Garfield++



home.cern

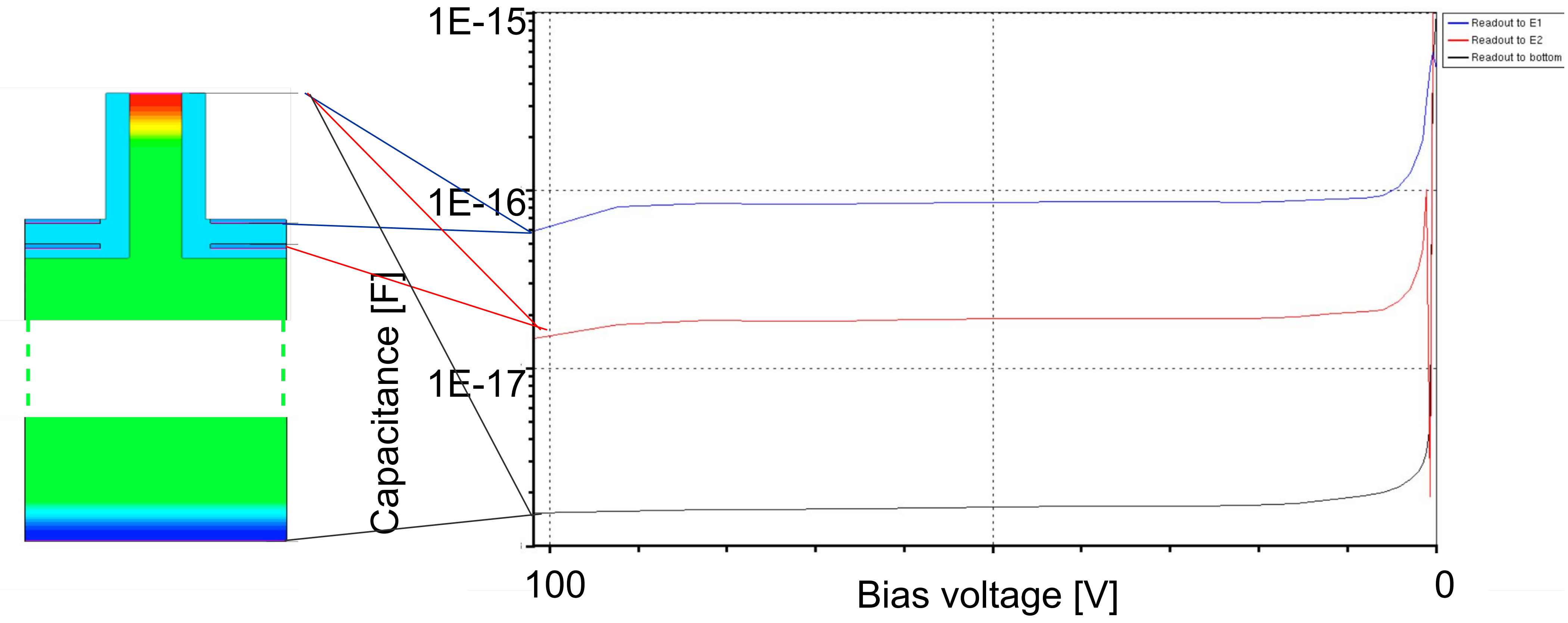
Backup

3D simulations



CV curves

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



HF vapor for etching

- **Reaction**
  - Reduction of oxygen at metal surface
    - holes injected to silicon
    - $O_2 + 4H^+ + 4e^- > H_2O$
  - Silicon can be dissolved through two paths[1]:
    - $Si + 4h^+ + 4HF \rightarrow SiF_4 + 4H^+$
    - $Si + H_2 + 4h \rightarrow SiO_2 + 4H^+$
      - $SiO_2 + 2HF_2 + 2HF \rightarrow SiF_6^{2-} + 2H_2O$