Development and production of advanced 3D pixel sensors @ FBK

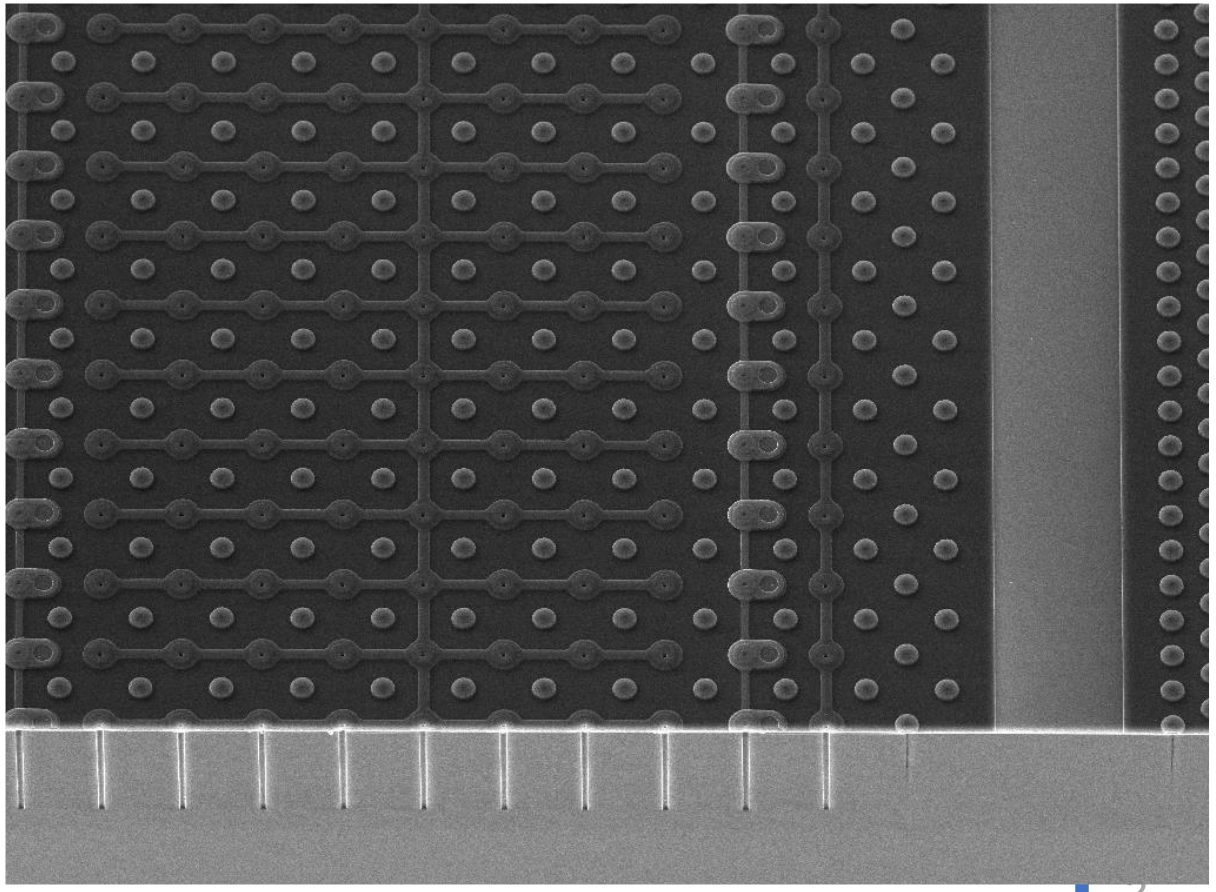
M. Boscardin[1,2], M. Centis Vignali [1,2], G. F. Dalla Betta [2, 3],
F. Mattedi [1], L. Parellada Monreal [1,2], S. Ronchin [1,2]
[1]Fondazione Bruno Kessler; [2] TIFPA INFN;
[3] Università degli Studi di Trento

Outline

Semiconductor detectors, to keep up with the trends in high-energy physics, must have:

- good spatial resolution,
- good time resolution,
- resistance to radiation damage.

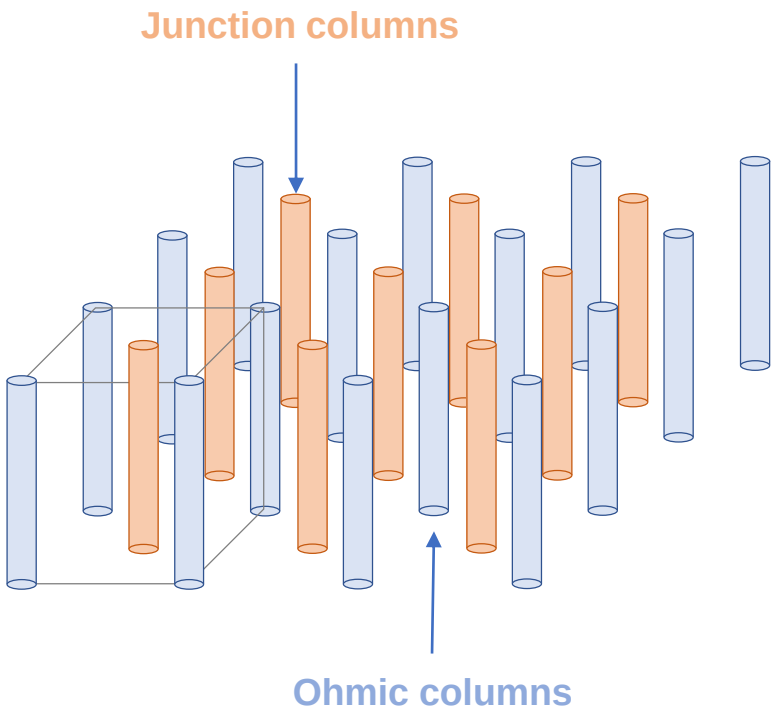
Si 3Ds fulfill these requests



Outline

- ATLAS ITK : background
- Si 3D technologies
  - Columnar Tech: ATLAS & CMS
  - Trench Tech: timing
- Next steps

Si 3D introduction



Parker et al., NIMA 395 (1997) 328 - 343

ADVANTAGES:

- Low depletion voltage (low power diss.)
- Short charge collection distance:
  - Fast response (timing)
  - Less trapping probability after irr. (radiation resistance)
- Lateral drift → cell "shielding" effect:
  - Lower charge sharing
  - Low sensitivity to magnetic field
- Active edges

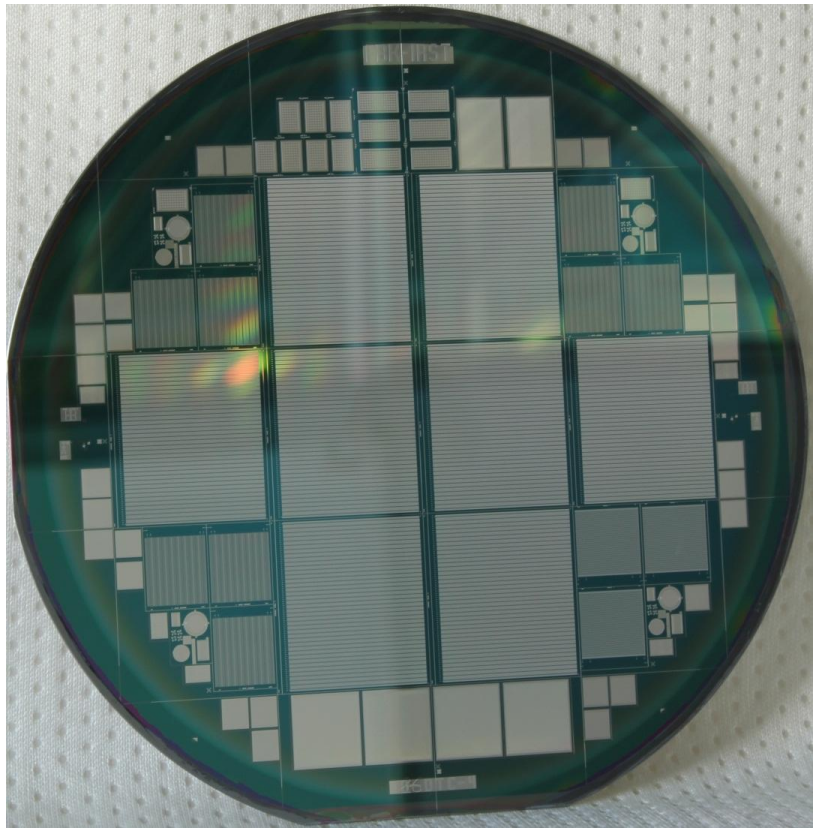
DISADVANTAGES:

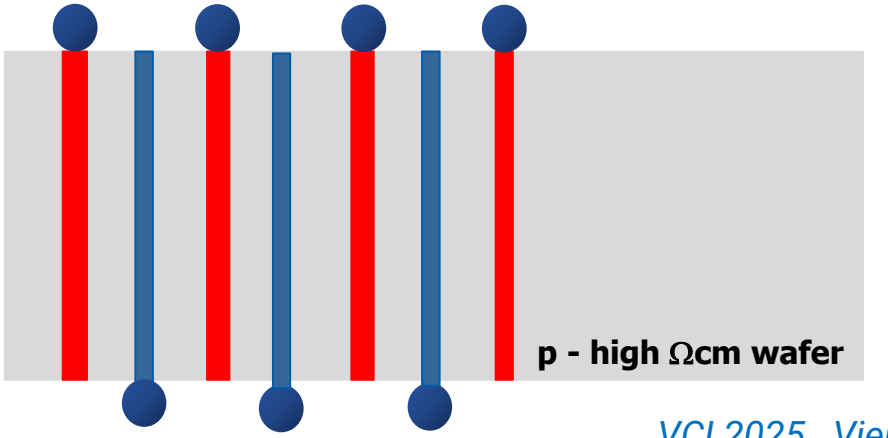
- Non uniform spatial response (electrodes and low field regions)
- Higher capacitance with respect to planar (~3x for ~ 150 μm thickness)
- More complex manufacturing than a planar device

Si 3D: FBK Background

G. Darbo 2015 *JINST* **10** C05001
The ATLAS IBL collaboration 2012 *JINST* **7** P11010

- FBK has been involved in the development of 3D sensors since 2004 in partnership with INFN
- **Main achievement: ATLAS IBL**
  - 4 inch wafers
  - Double-side technology
  - 230 um thick wafers
  - fully through holes
  - Electrode diameter: 12 um

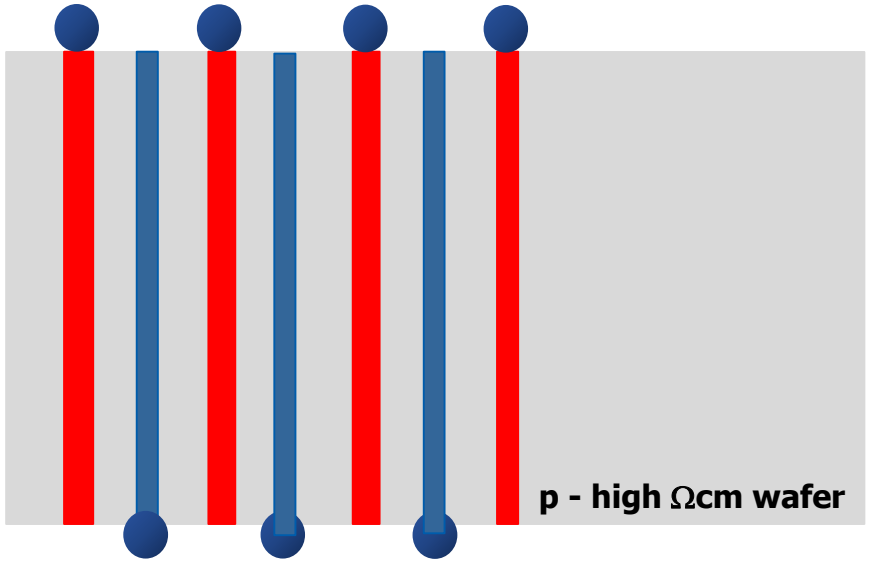




Thin Si 3D (on 6-inch wafers) : double sided vs. single sided

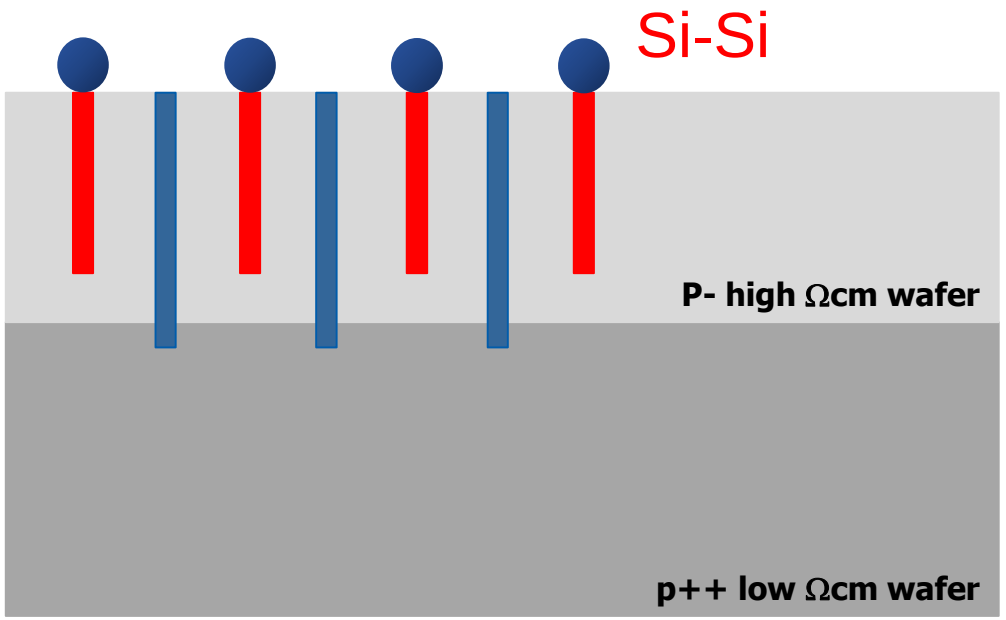
Double-side 3D technology

- 275 µm thick Fz wafers
- fully through holes
- Electrode diameter: 12 µm



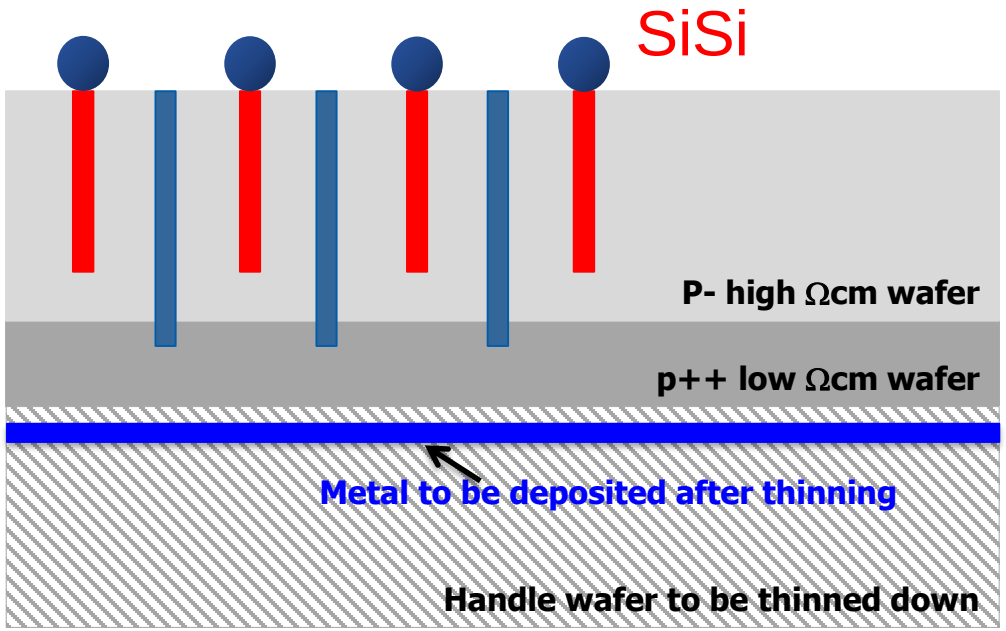
Single-side 3D technology

- Si-Si and SOI wafers = thinner sensors (100-150 µm)
- narrower electrodes (5 µm)
- reduced inter-electrode spacing (~30 µm)

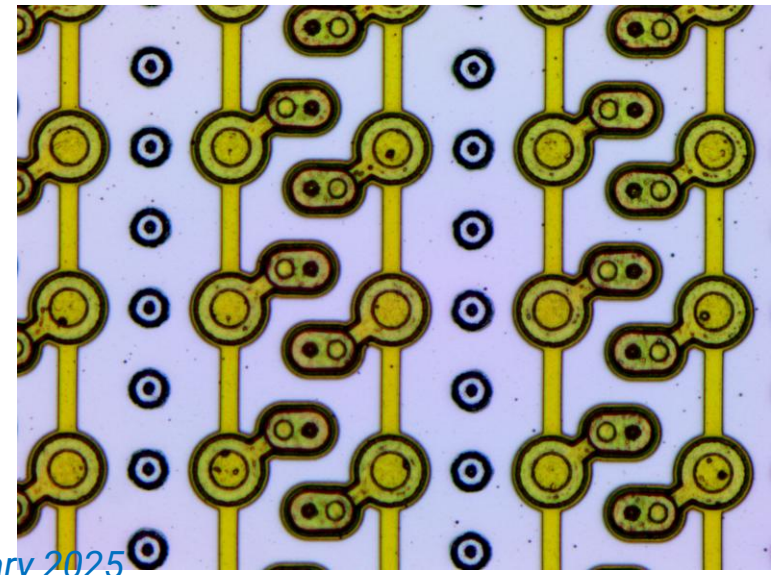


Si3D Tech @ FBK

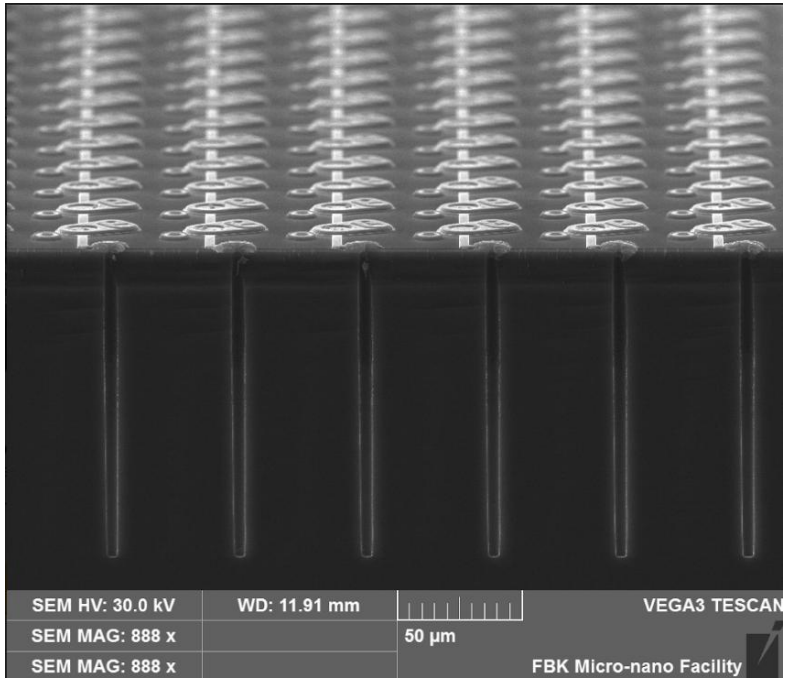
- 6 inch wafers
- p-spray isolation
- thin sensors on support wafer: SiSi or SOI
  - *150 µm of active wafers (FZ p-type, ρ= 5000-10000 Ωcm)*
  - *500 µm of support wafers (CZ)*
- **Ohmic columns/trenches depth** > active layer depth (for bias)
- **Junction columns depth** < active layer depth (for high V_{bd})
- Reduction of hole diameters to ~5 µm
- Holes (at least partially) filled with poly-Si
- Temporary metal
- **SINGLE SIDED PROCESS**

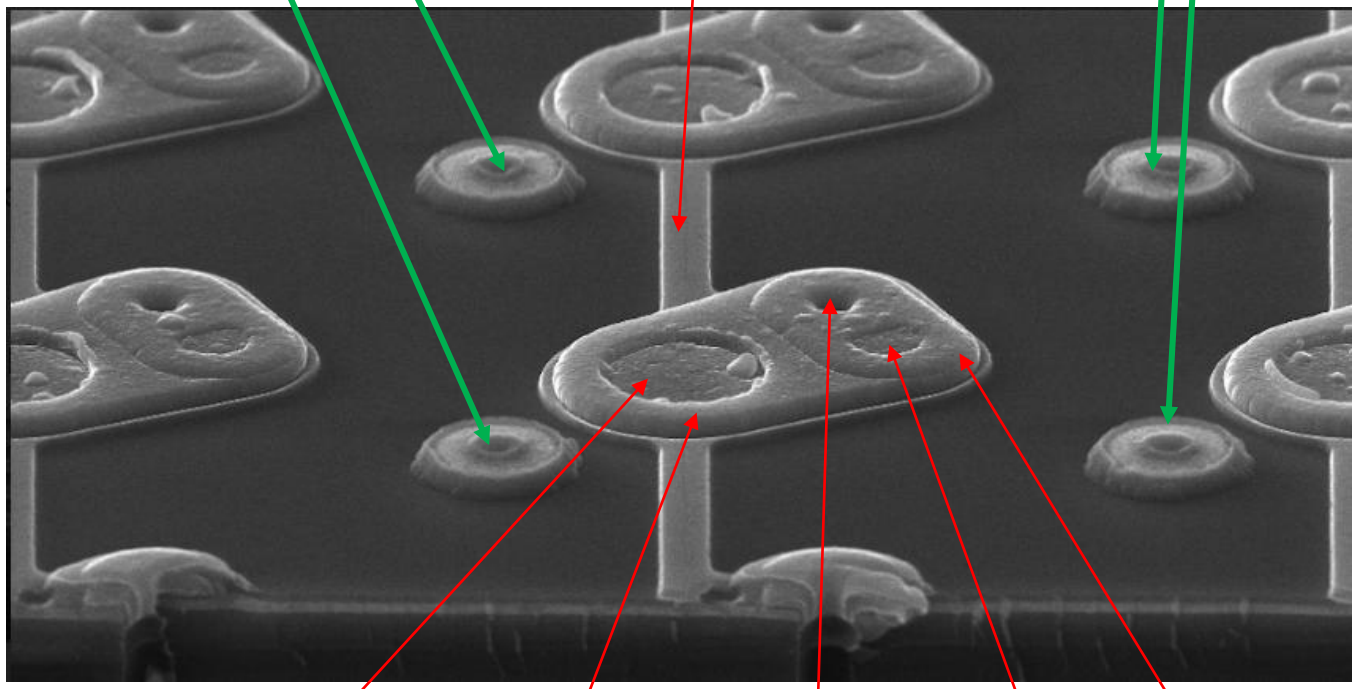


Temporary metal



3D ATLAS 50x50: SEM images

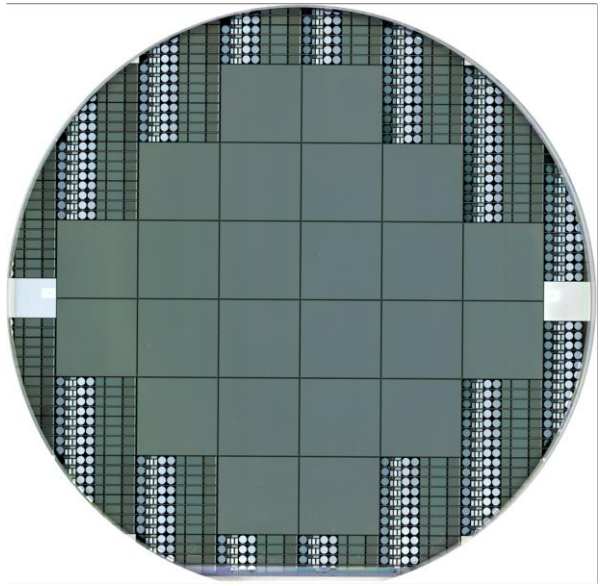




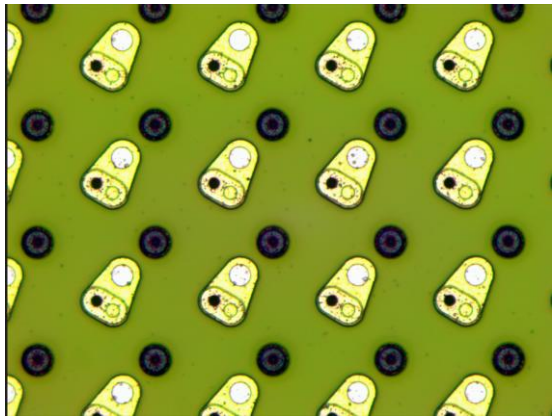
Si-3D production for CERN

ATLAS

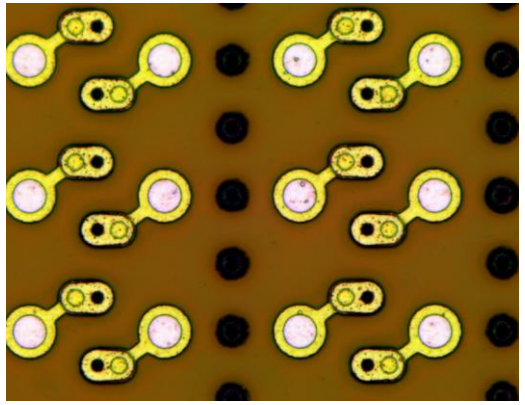
Wafer layout 24 sensors
20.4 x 19.5 mm^2



RD53B 50 x 50 µm^2



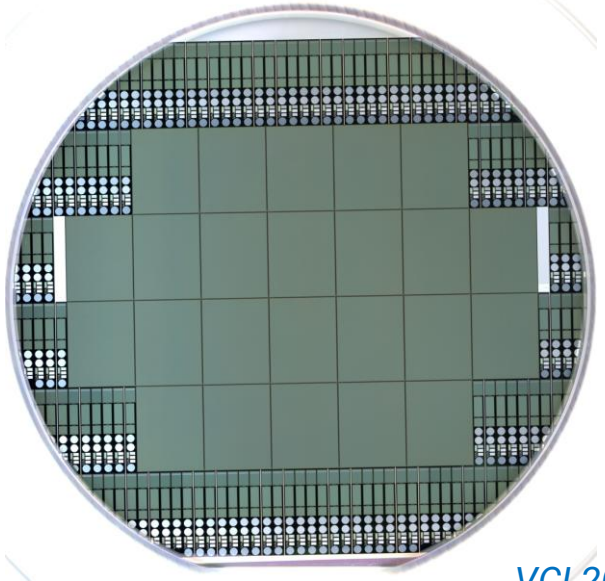
RD53B 25 x 100 µm^2



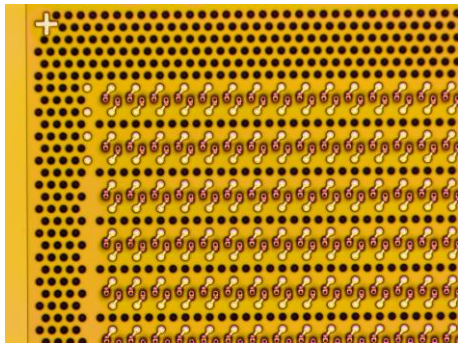
Total Good Devices produced up now:
Atlas 50x50 ~700
ATLAS 25X100 ~ 320

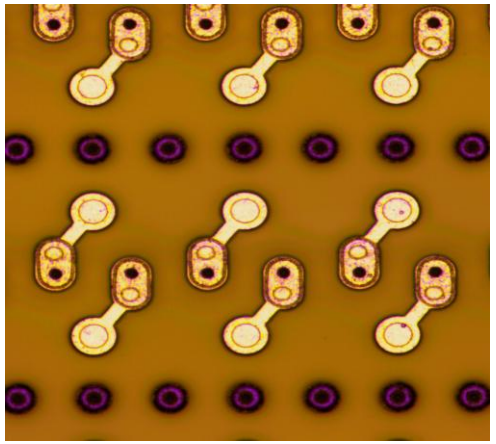
CMS

Wafer layout 24 sensors
17.2 x 22.0 mm^2



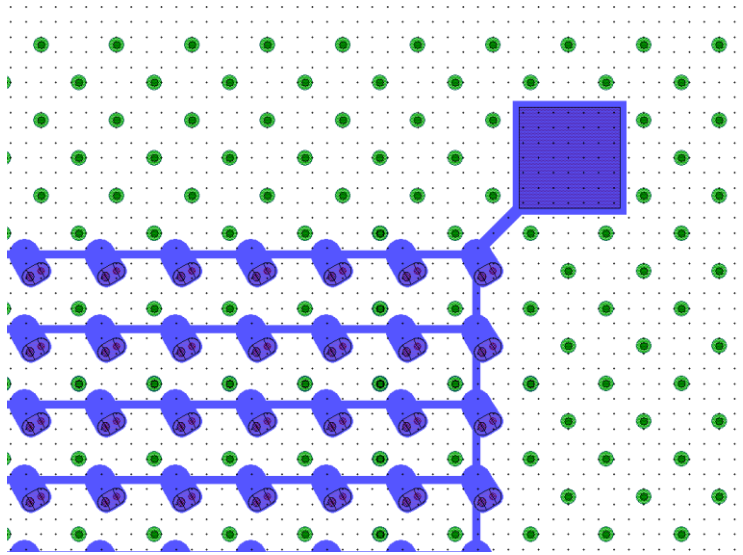
CROC 25 x 100 µm^2

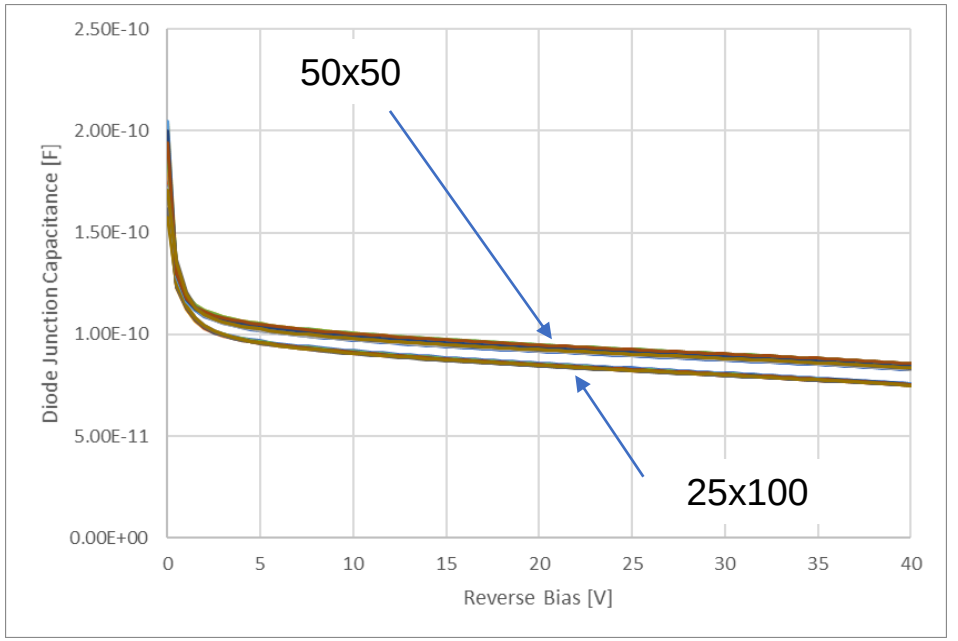


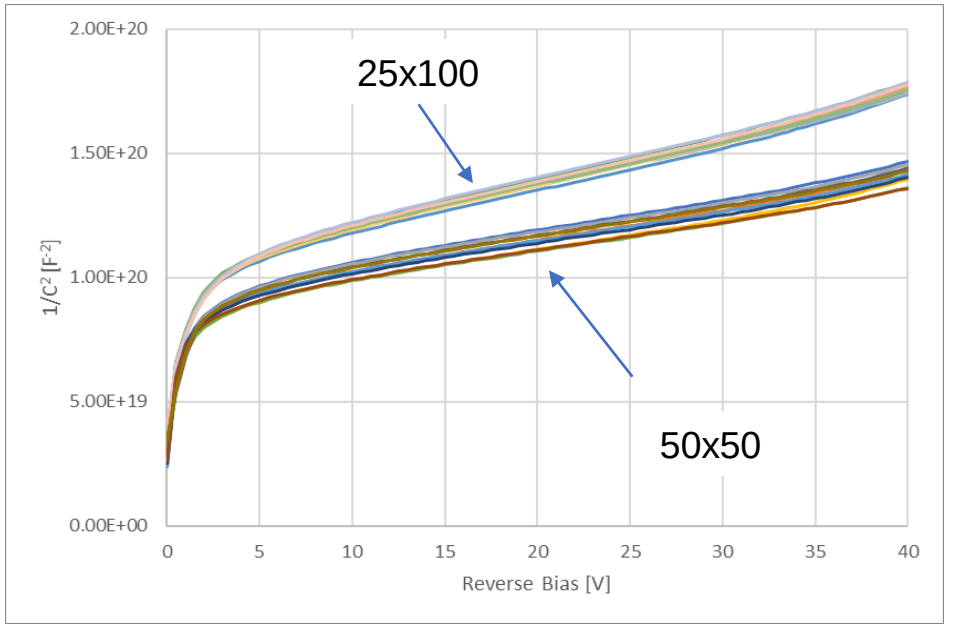


Total Good Devices produced up now:
CROC 25 x100 ~ 525

CV on Si 3D diode





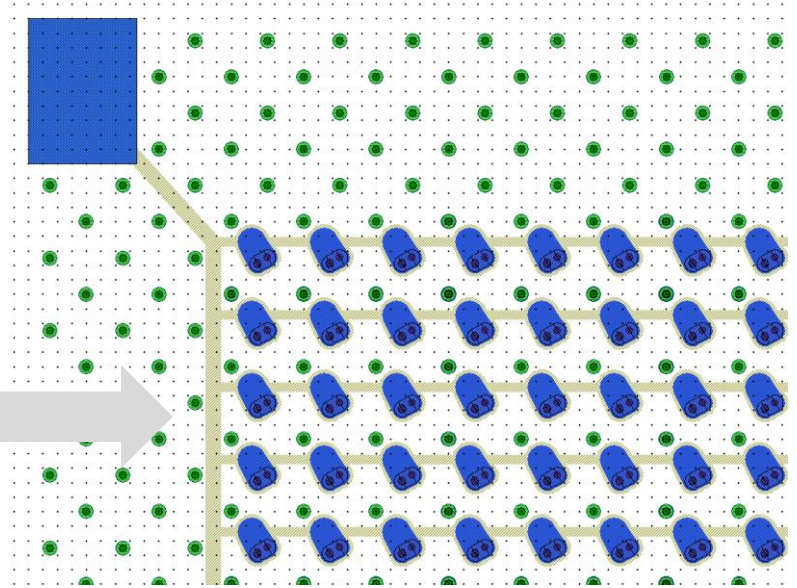


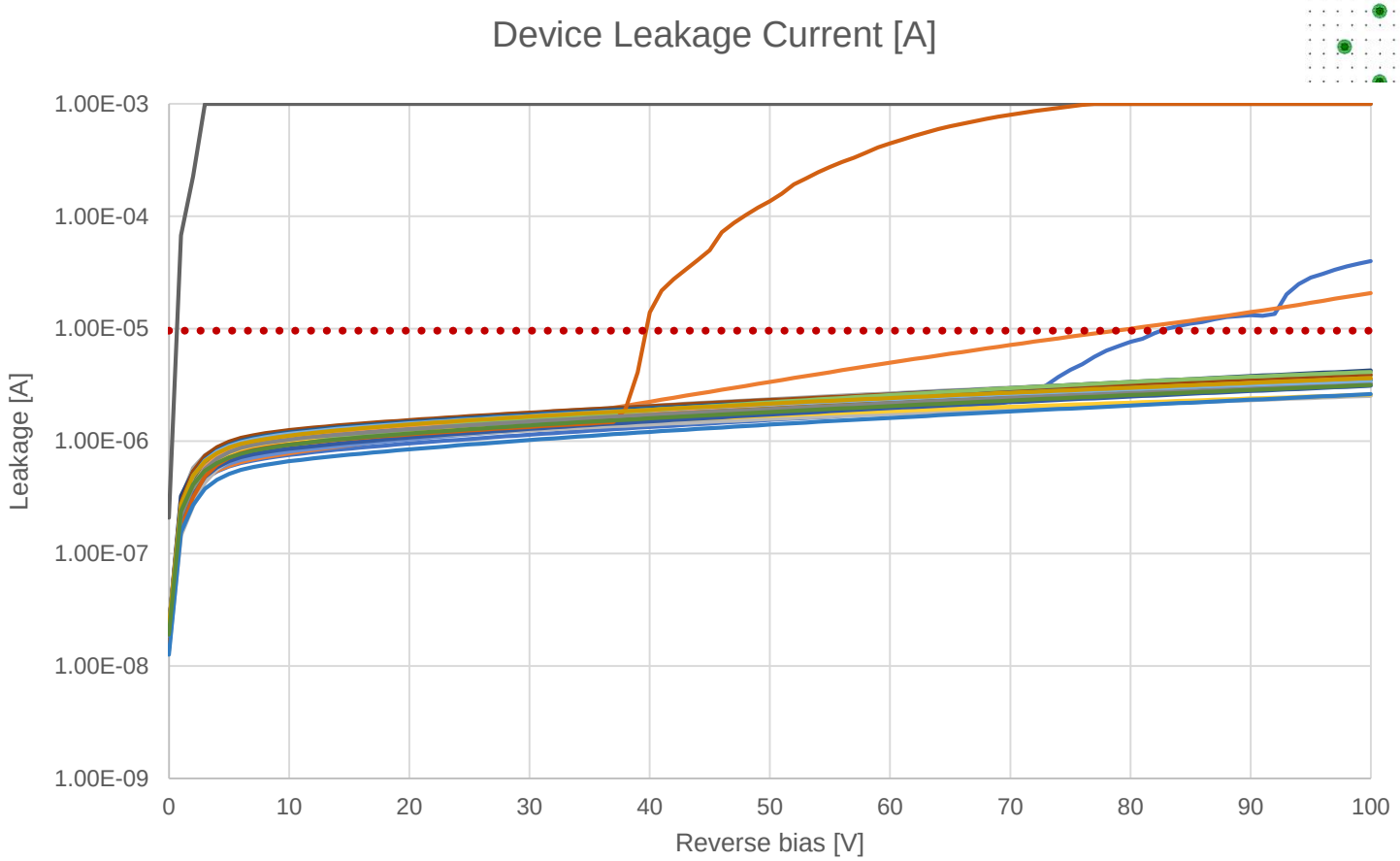
- $V_{depletion}$ less than 5 V
- C per column ~ 50 fF (including contribution from metal grid)
- $C_{50x50} > C_{25x100}$

FONDAZIONE BRUNO KESSLER
SENSORS AND DEVICES

IV on Si 3D full detector

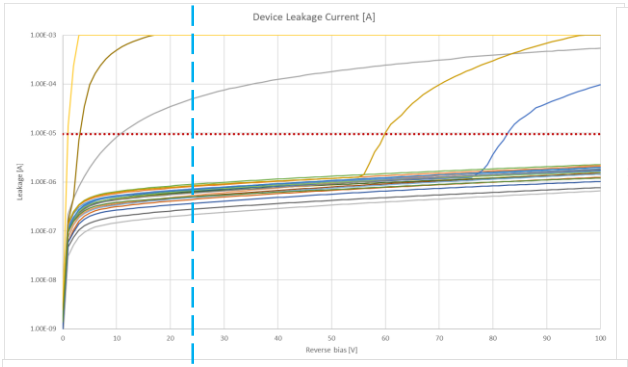
- IV on ATLAS 3D pixel
- 20.4 x 19.5 mm2
- Measured on Temporary Metal: all pixel shorted

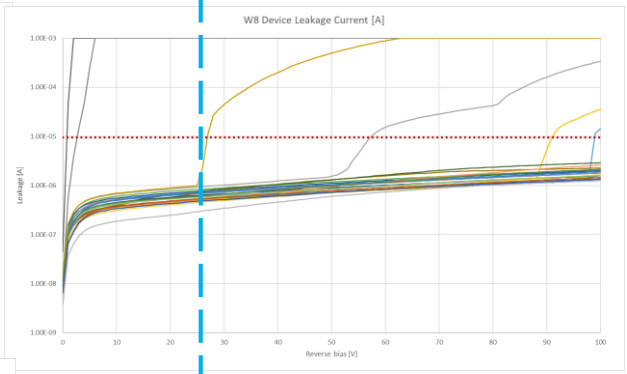


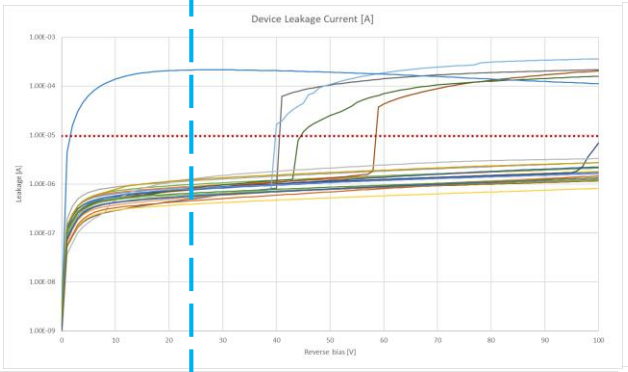


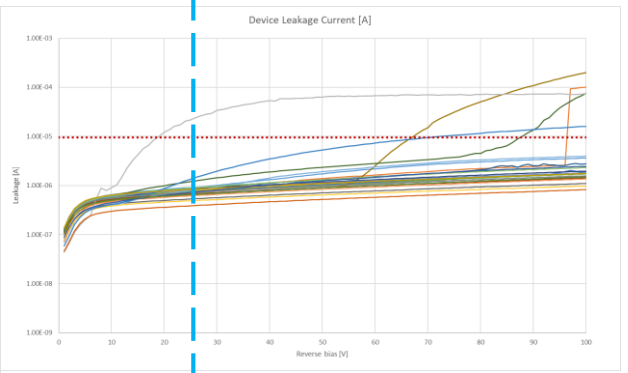
IV on Si 3D full detector

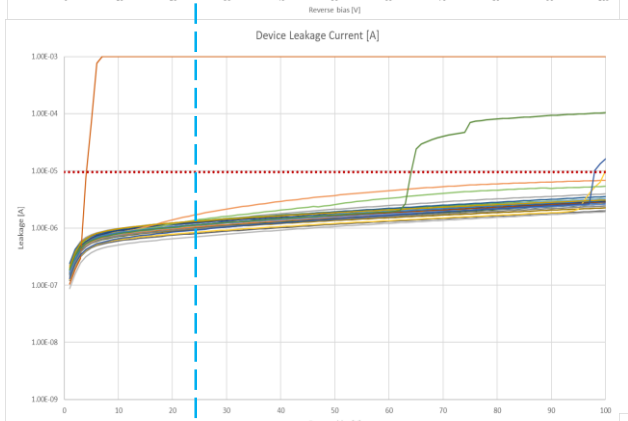
I_{leak}<9.6E-6A IV_{BD}>25V

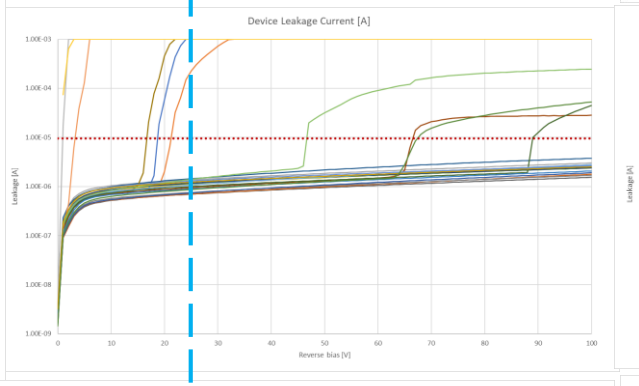


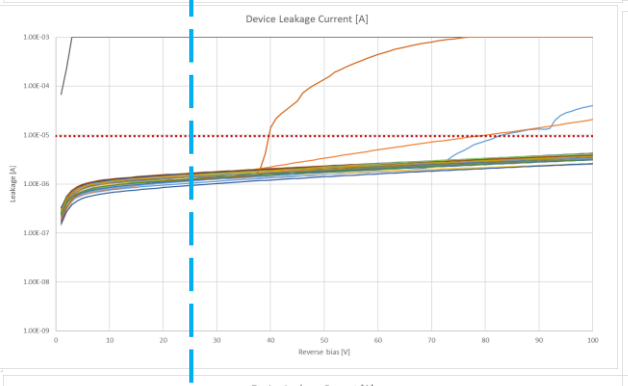


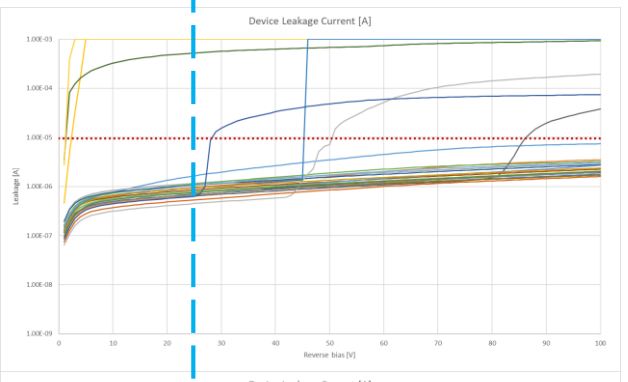


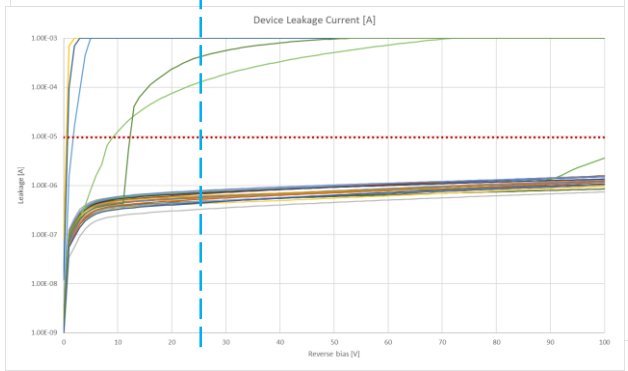


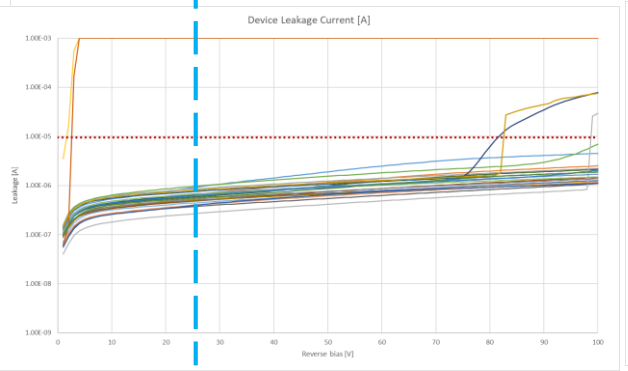


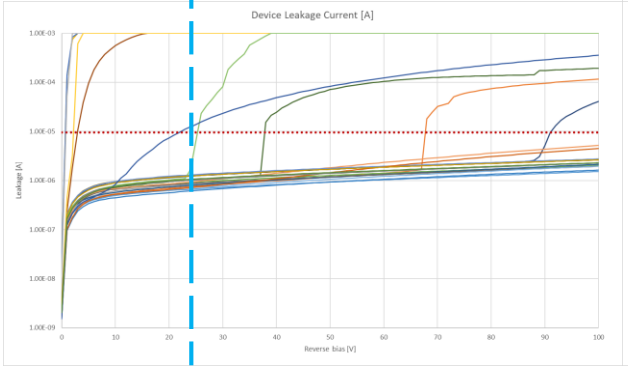


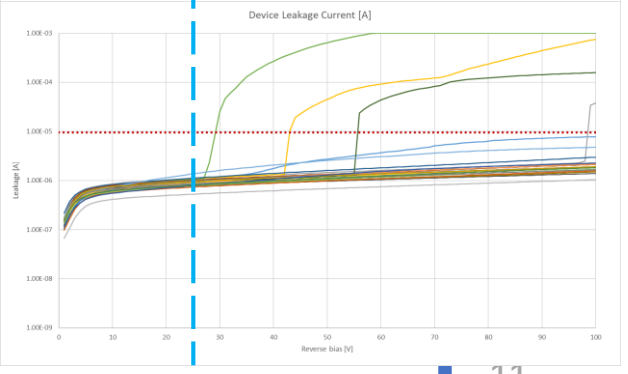








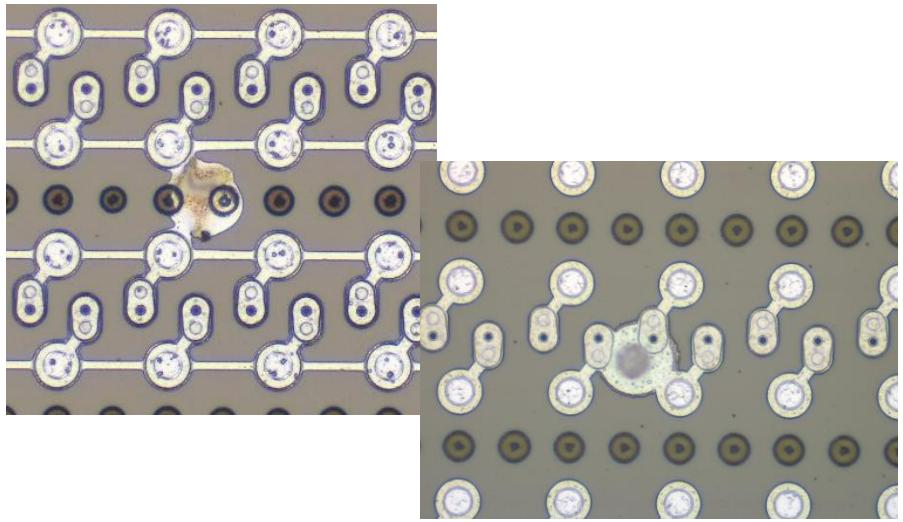


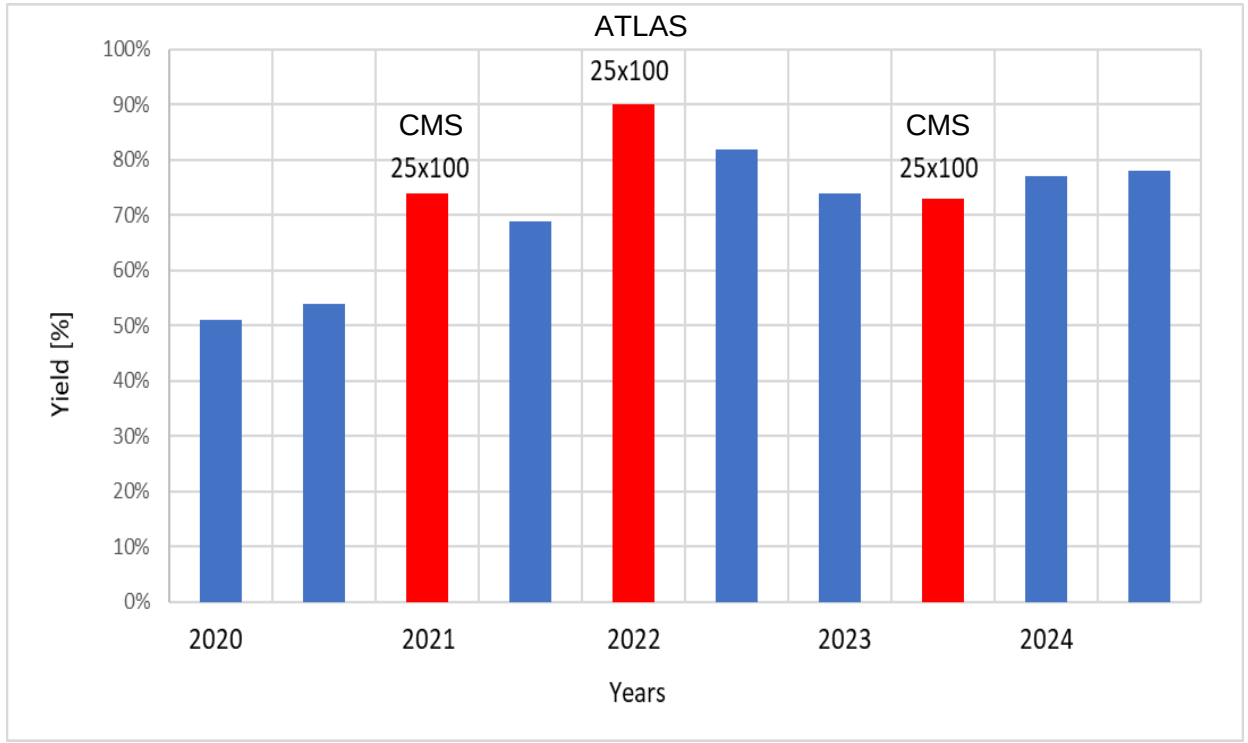


Si 3D : production yield

Devices Selection

- I leak less than 9.6E-6A
- V_{BD} more than 25V
- Optical inspection (mainly for shorts)

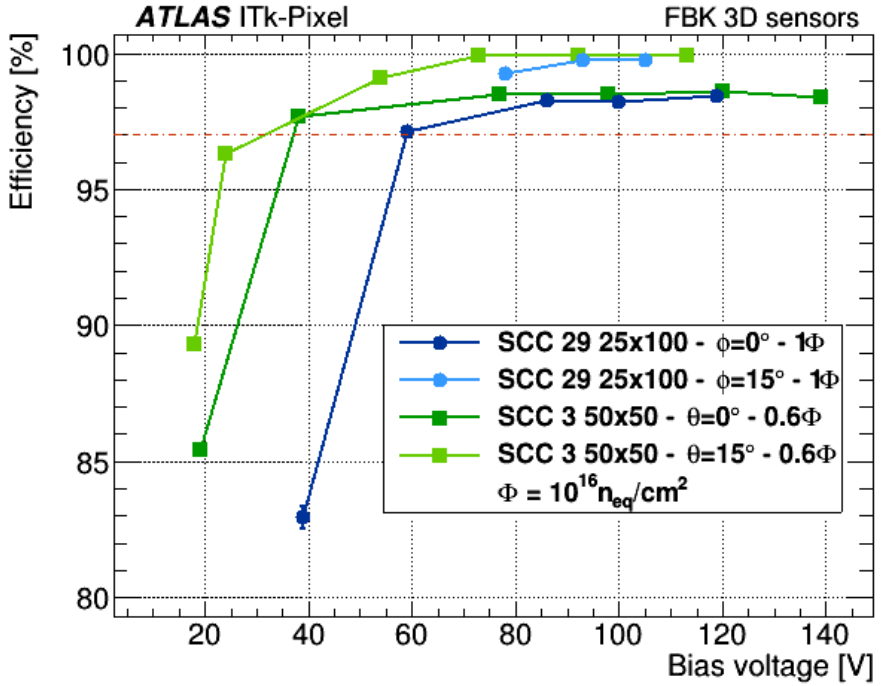




Increasing the number of batches → Increasing yield

Irradiated FBK 3D sensors ATLAS pre production

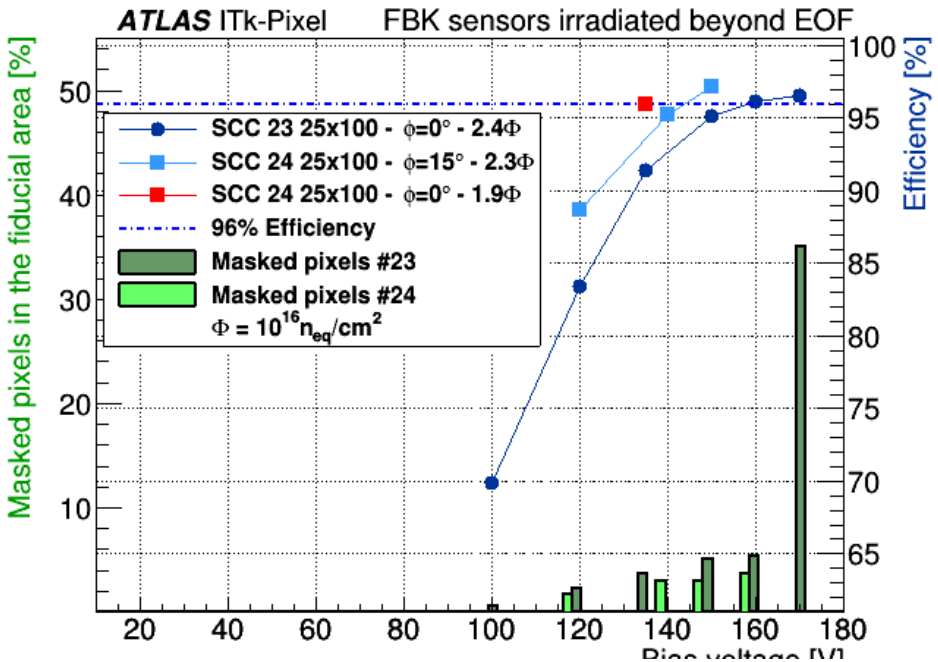
Irradiation in Bonn (13Mev proton) and KIT (23 MeV proton)
fluences is 1.0E16 n_{eq}/cm^2



- Efficiency higher than 97% with inclined sensors
- 50x50 reaches 97% at lower bias in comparison at 25x100

Irradiated @IRRAD in 2023

- Mean fluences is 1.7E16 n_{eq}/cm^2
- Peaks up to 2.5 E16 n_{eq}/cm^2



Efficiency

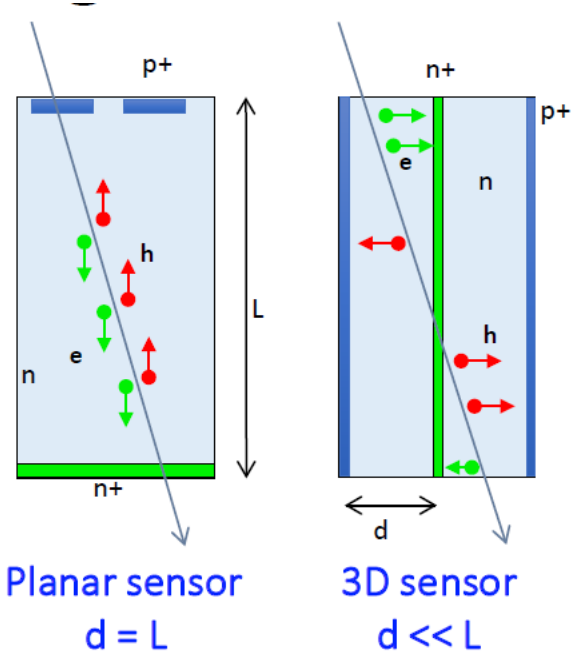
- 96% at normal incidence
- close to 97% at 15

The number of disabled pixel is lower than 5% up to 160V then increase

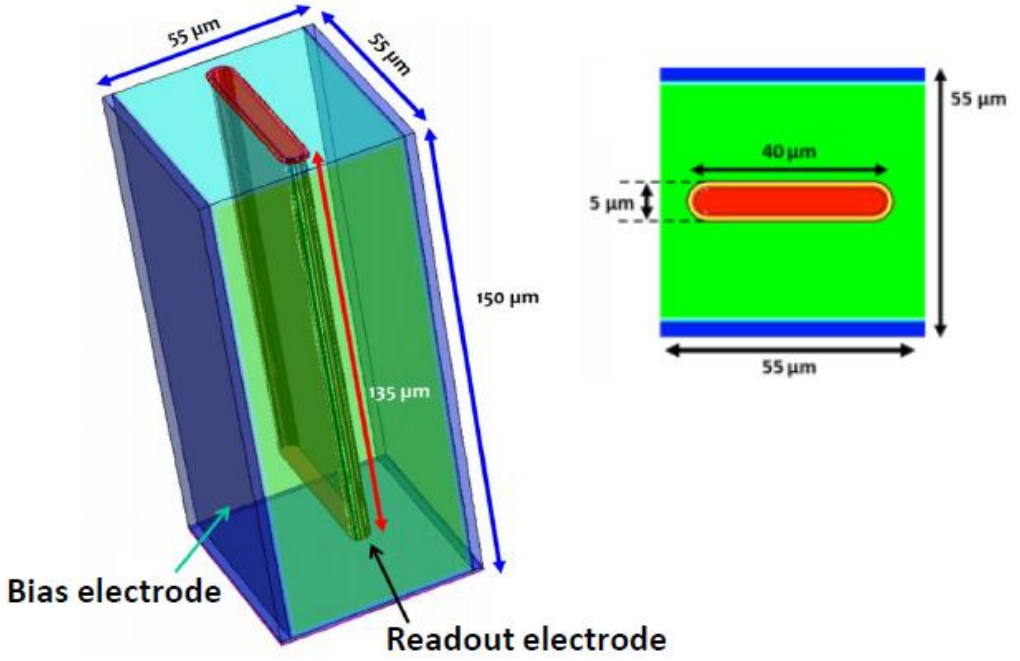
3D @FBK timing: from columns to trenches

Short inter-electrode distance (d<<L)

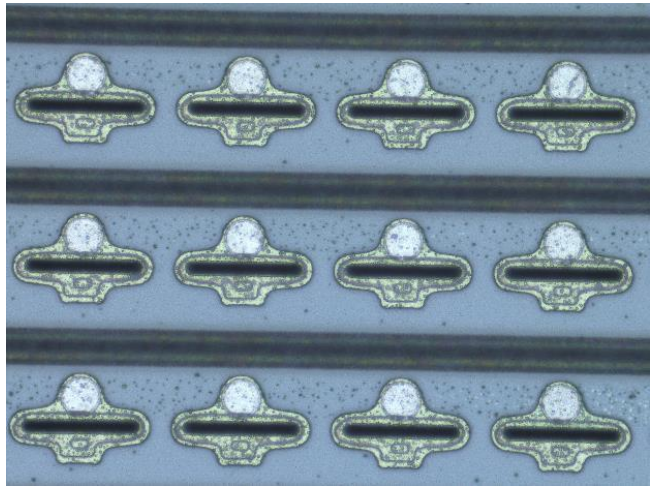
extremely fast signals



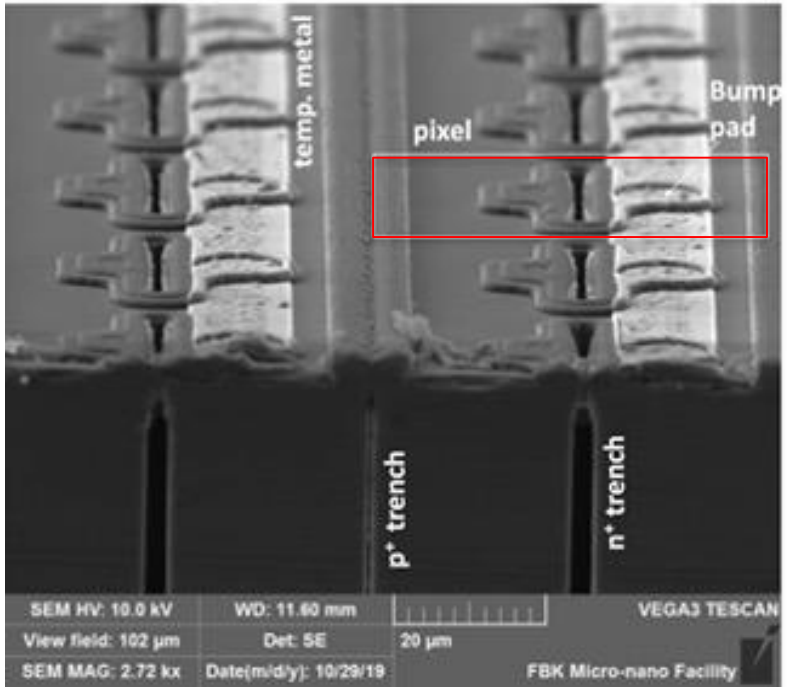
- The idea is to use a 3D based on trenches instead of columns in order to obtain a more uniform electric/weighting field between electrodes
- This reduces the dependence of timing on the impact position of particles

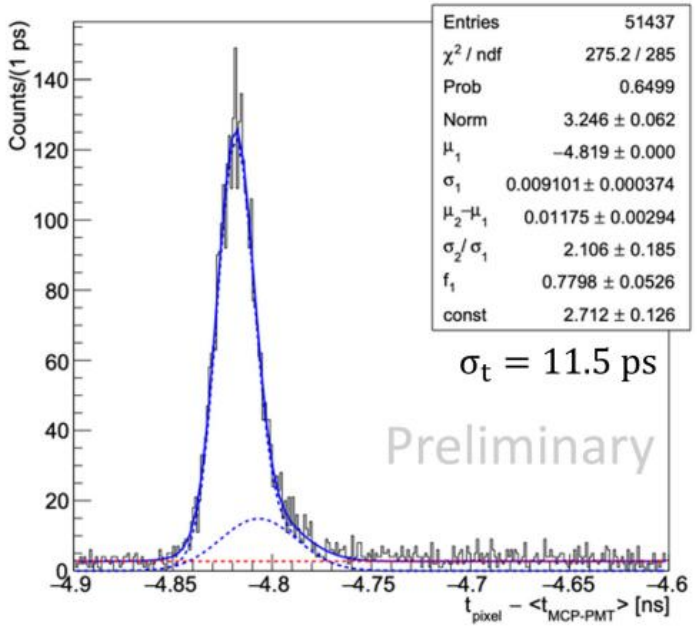


TIMESPOT
trench Si 3D sensors



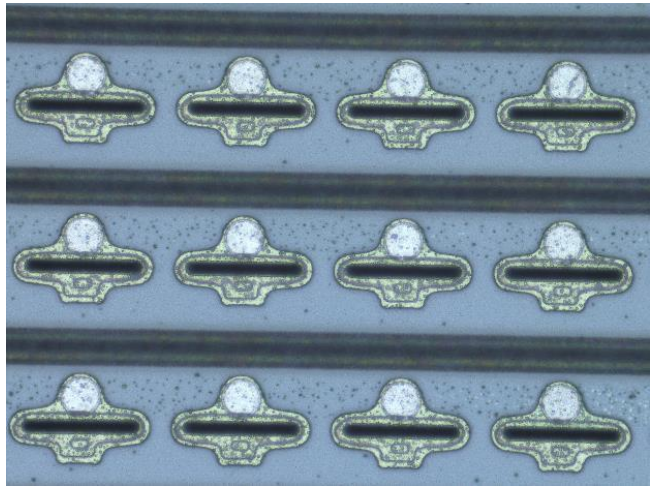
G. Forcolin et al., NIMA 981 (2020) 164437



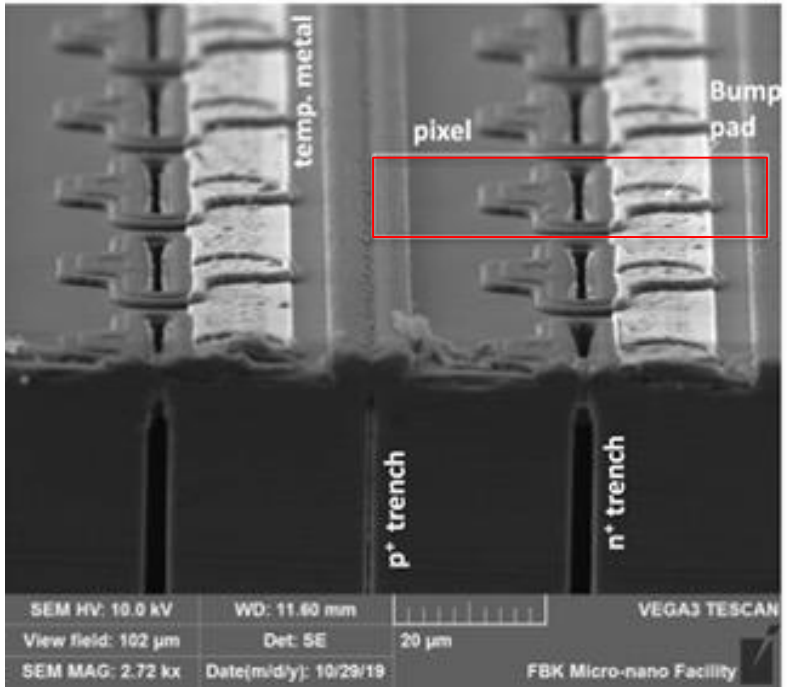


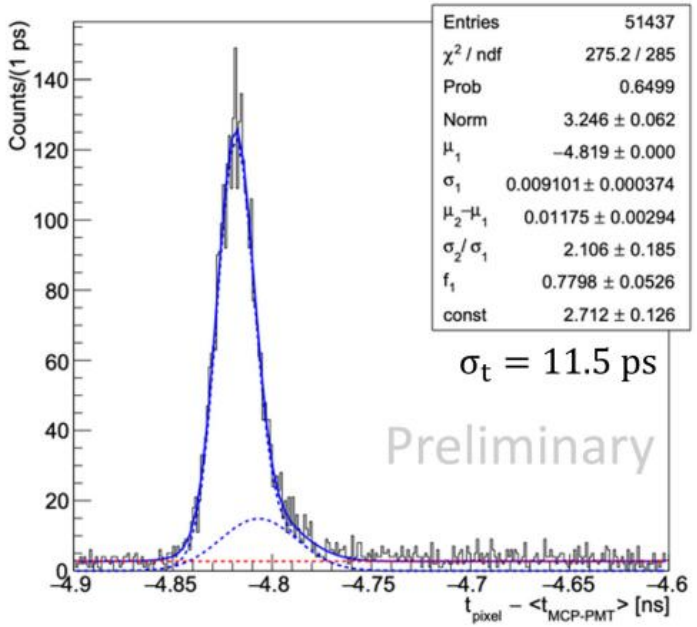
A. Lampis et al., “10 ps timing with highly irradiated 3D trench silicon pixel sensors”, JINST 18, C01051, 2023

TIMESPOT
trench Si 3D sensors



G. Forcolin et al., NIMA 981 (2020) 164437





A. Lampis et al., "10 ps timing with highly irradiated 3D trench silicon pixel sensors", JINST 18, C01051, 2023

Next talk by Adriano Lai " Could we efficiently operate 3D silicon pixel-based tracking detectors irradiated with neutron fluences up to 1E+18 1MeVneq/cm^2 ?"

Si-3D @ AIDAinnova

Lesson learned from TimeSPT batches

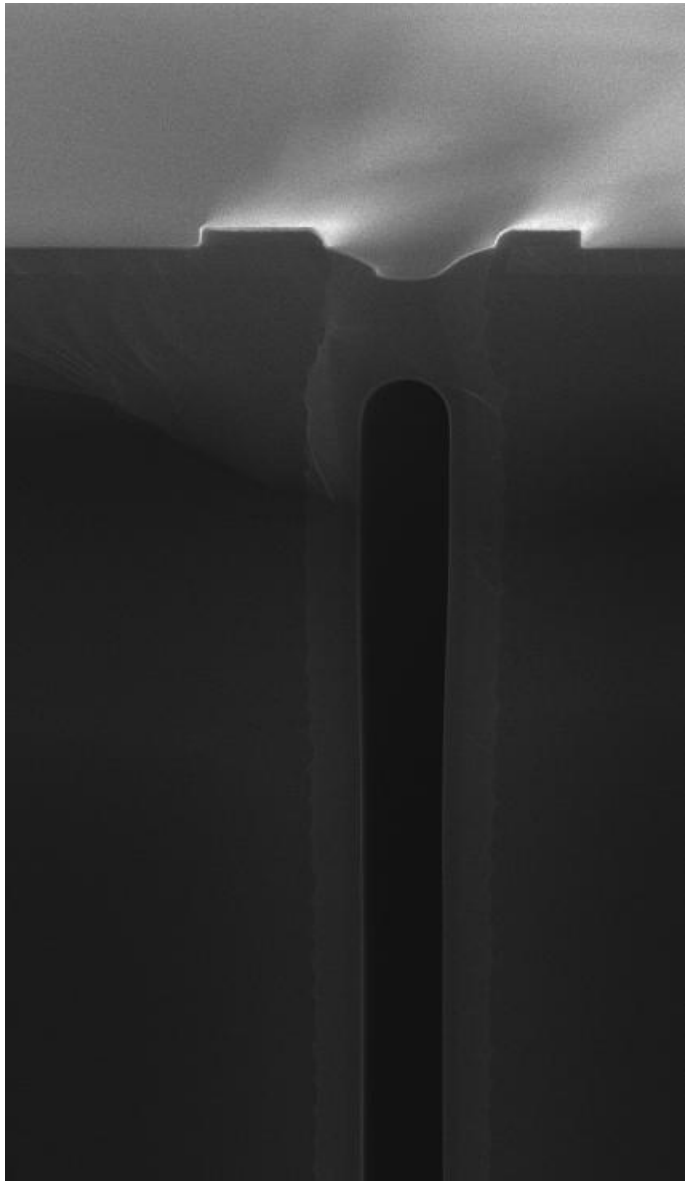
- Reduce wafer bow (increase the device density)

Main Process split: trench filling

- Trench filling (two poly thickness 2 or 3 µm)
- Planarization (BPSG doped oxide)

The goal is to

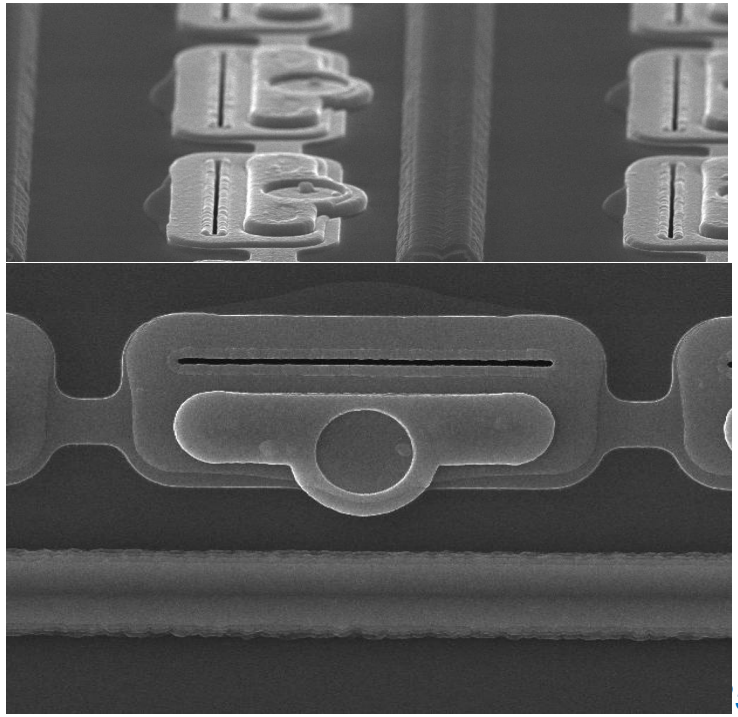
- Reduce defects
- Increase device area
- Increase density



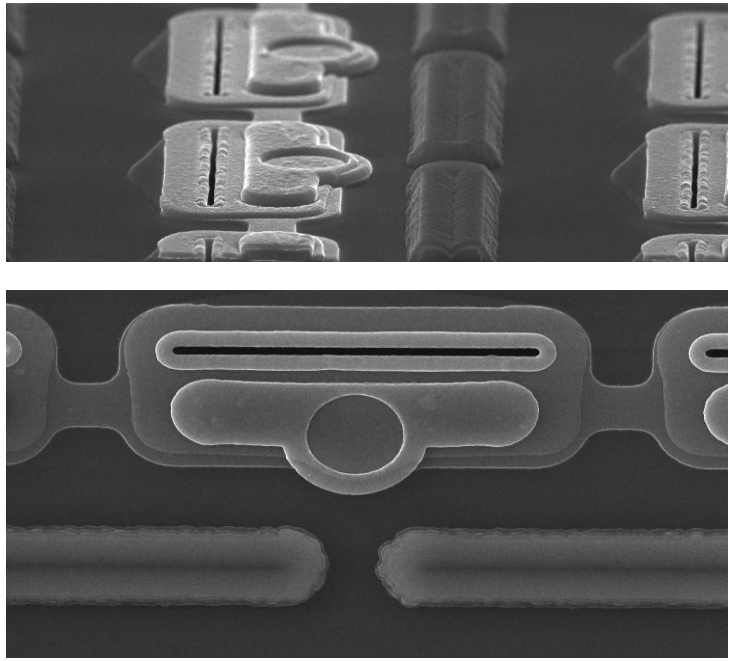
Si-3D @ AIDAinnova: electrode design

- Continuous ohmic trenches
- Dashed ohmic trenches

Long continuous ohmic trenches in the standard design.

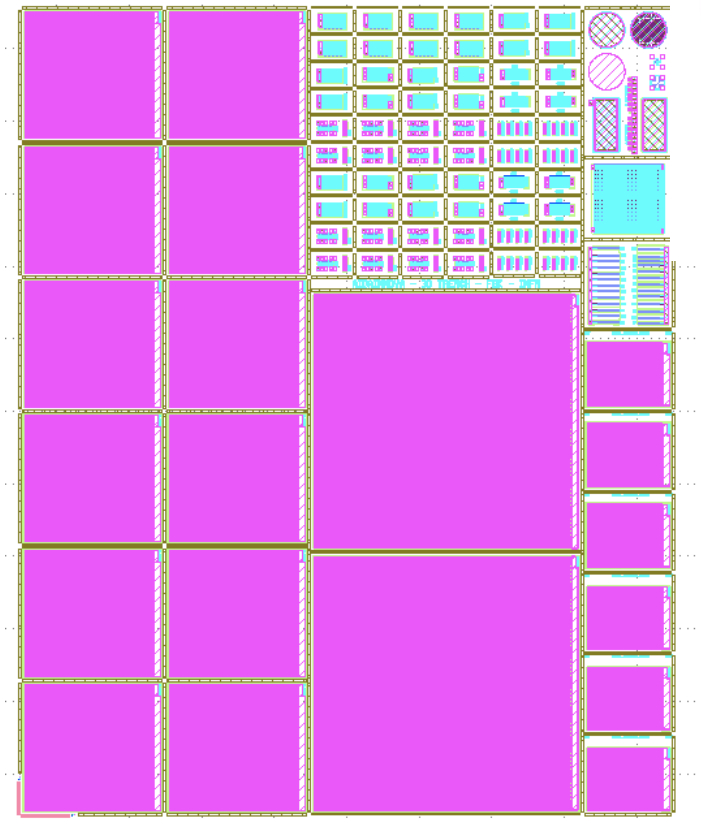


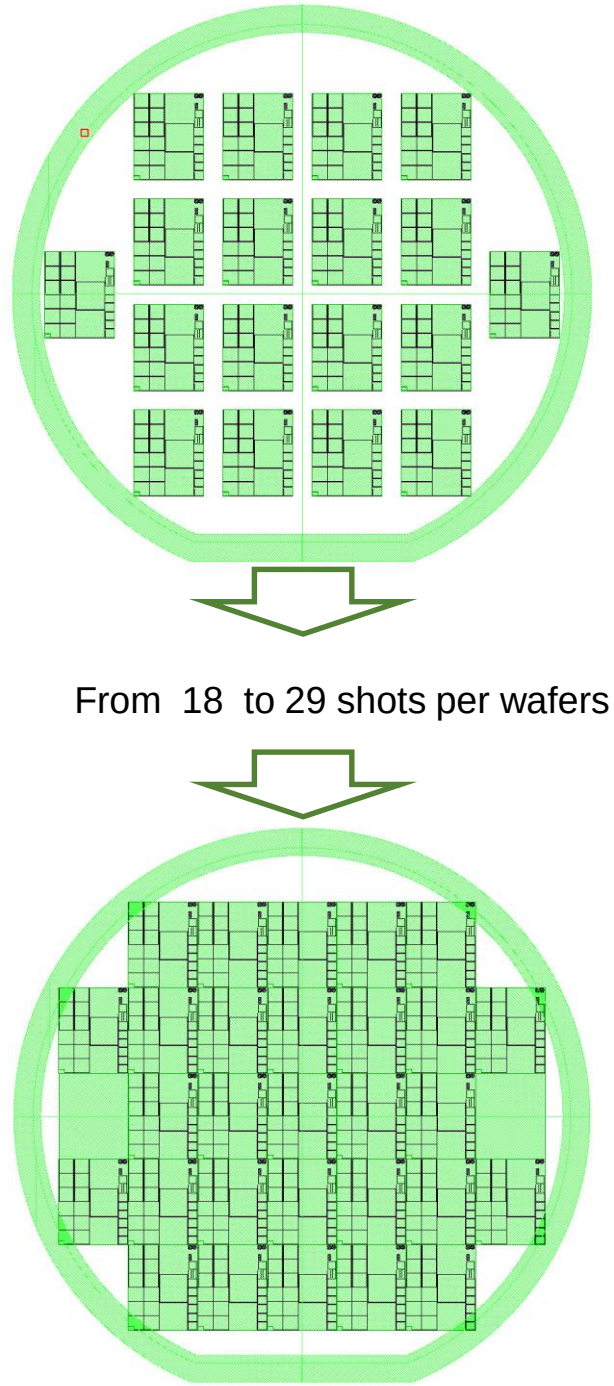
Dashed ohmic trenches in the new design.



Si-3D @ AIDA innova Layout

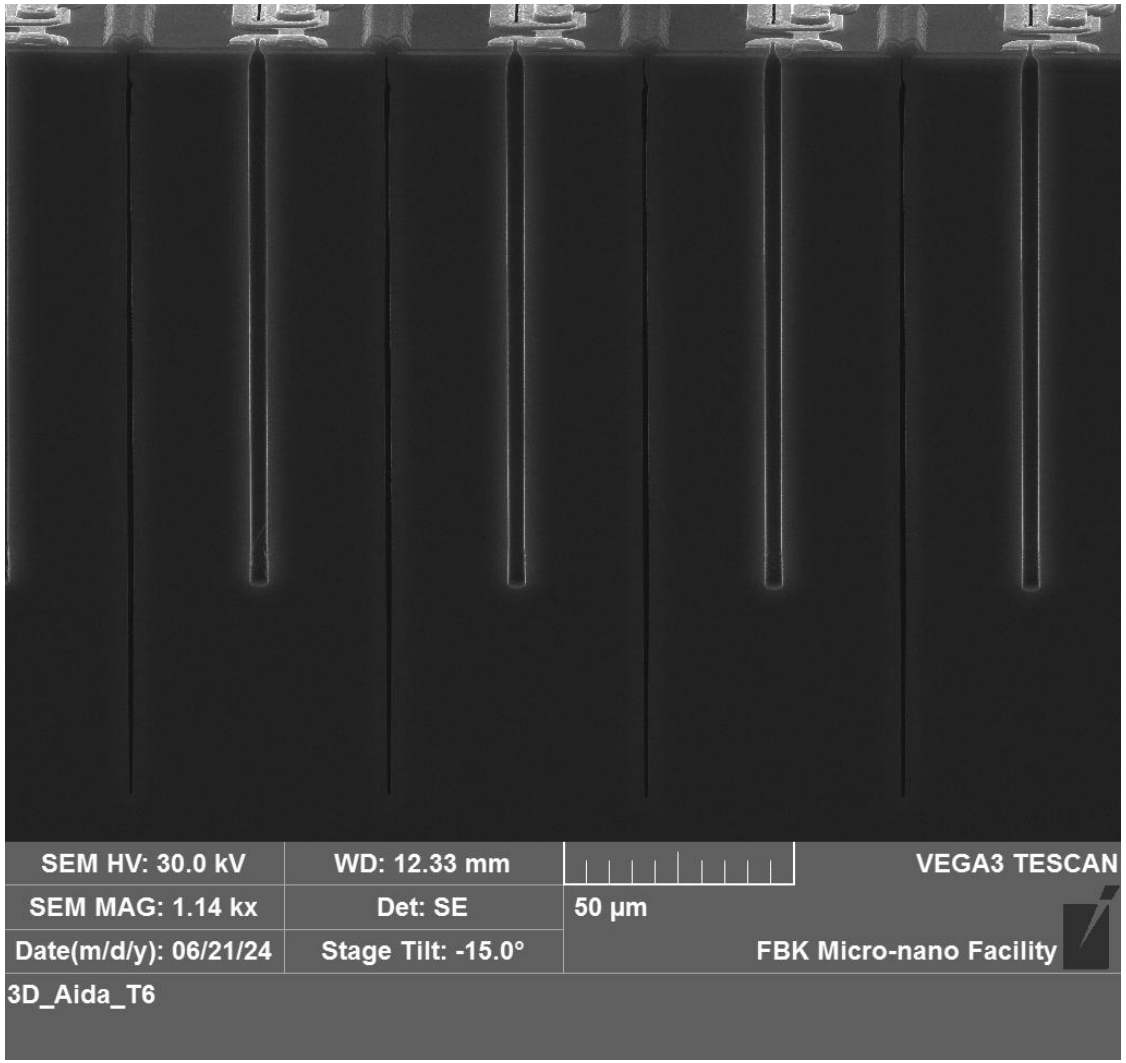
- **Pixel sensors (55 mm pitch)**
  - 32x32 pixels, (3 std, 3 dashed)
  - 64x64 pixels, (6 std, 6 dashed)
  - 128x128 pixels, (1 std, 1 dashed)
- **Device test structures (55 µm pitch and 42 µm pitch, std and dashed)**
  - Groups of individual pixels
  - Strips
  - Diodes
- **Technological test structures**

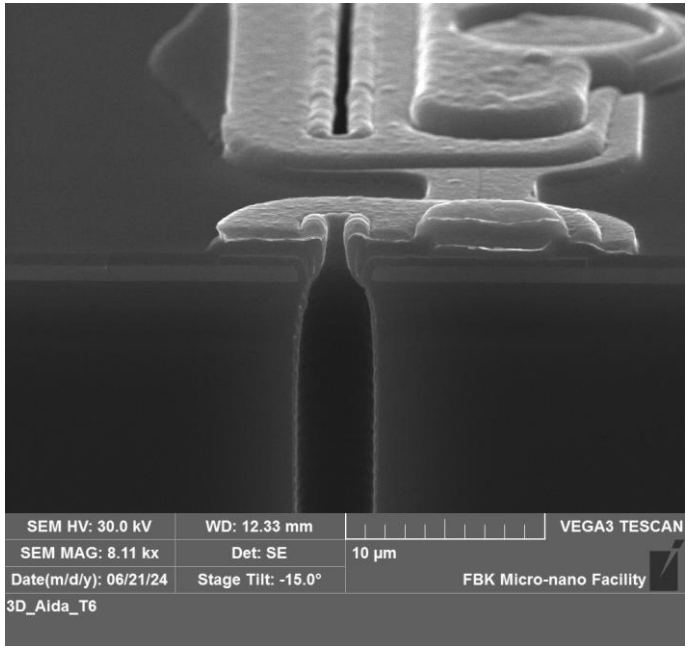


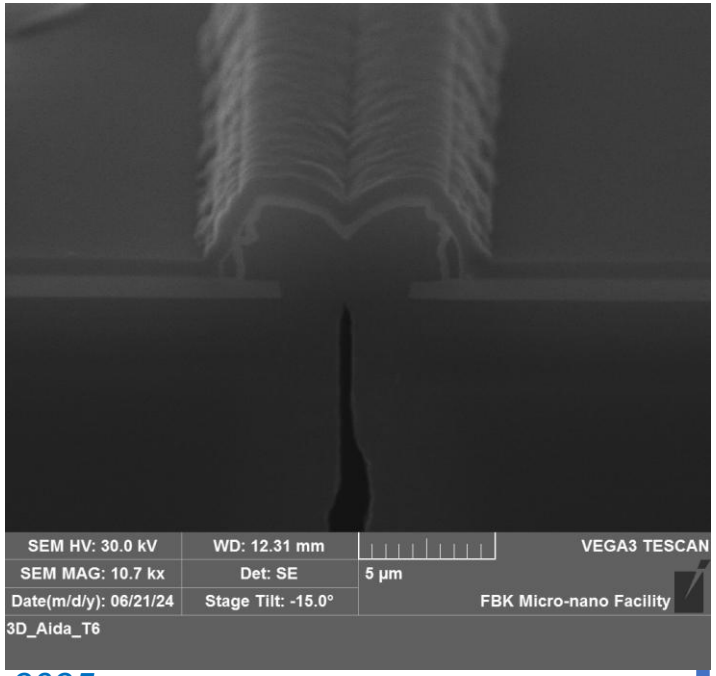


SENSORS AND DEVICES
FONDAZIONE BRUNO KESSLER

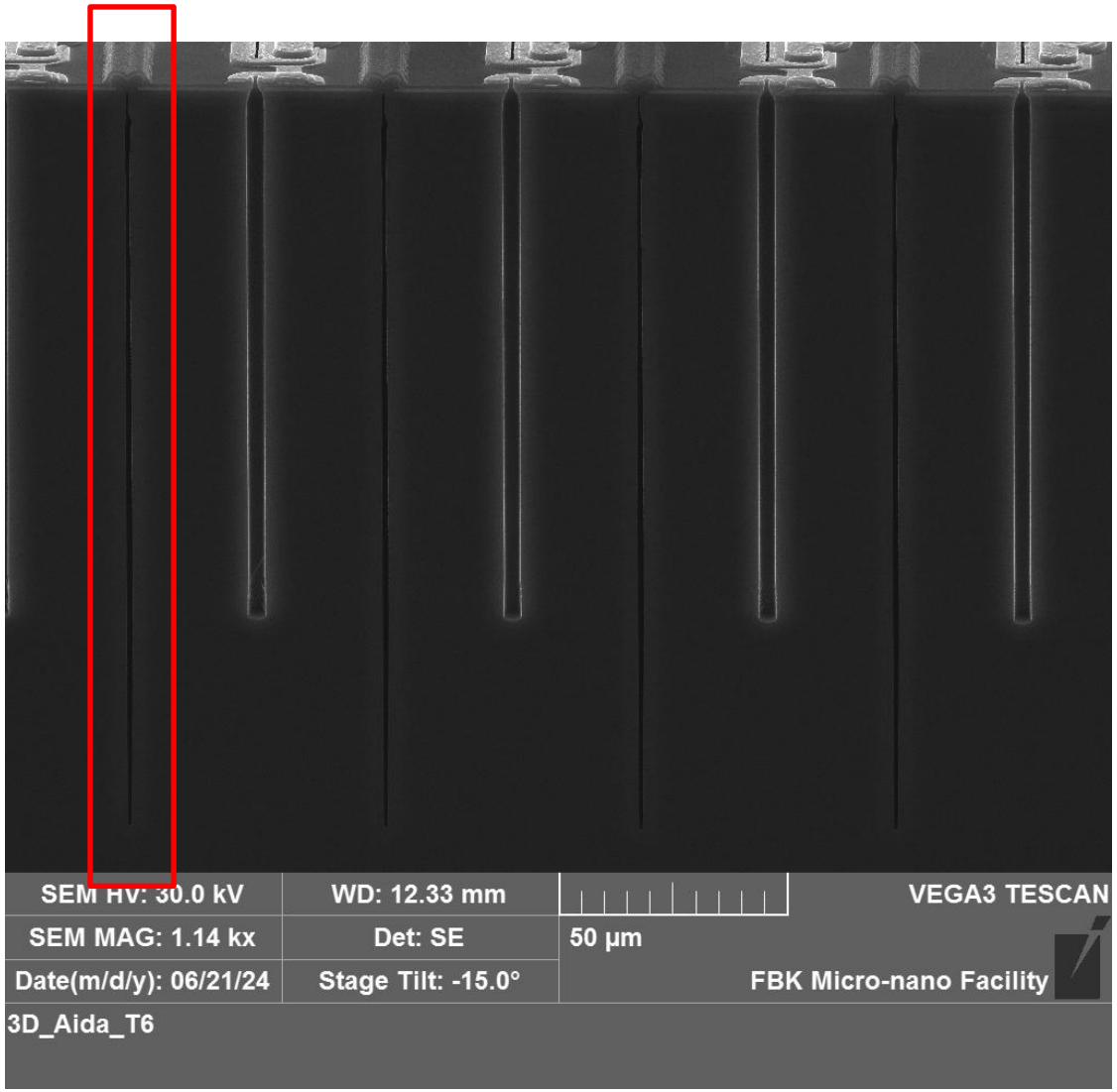
AIDA innova : SEM

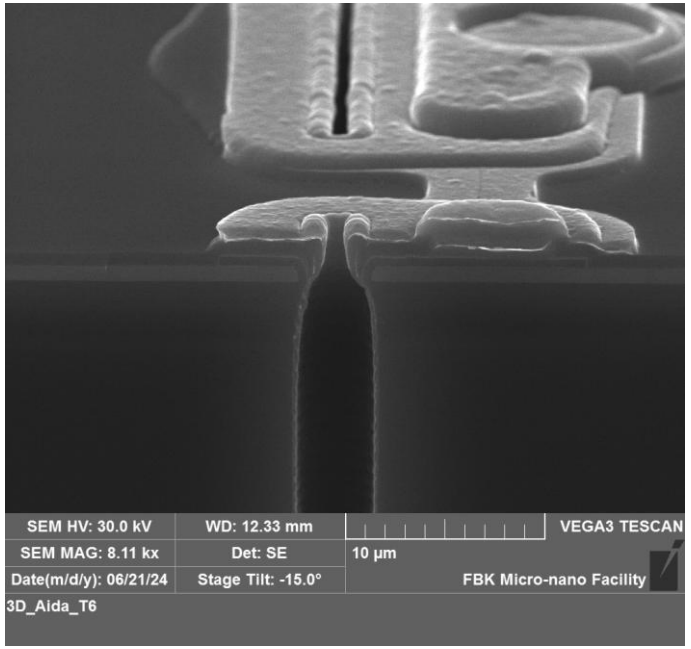


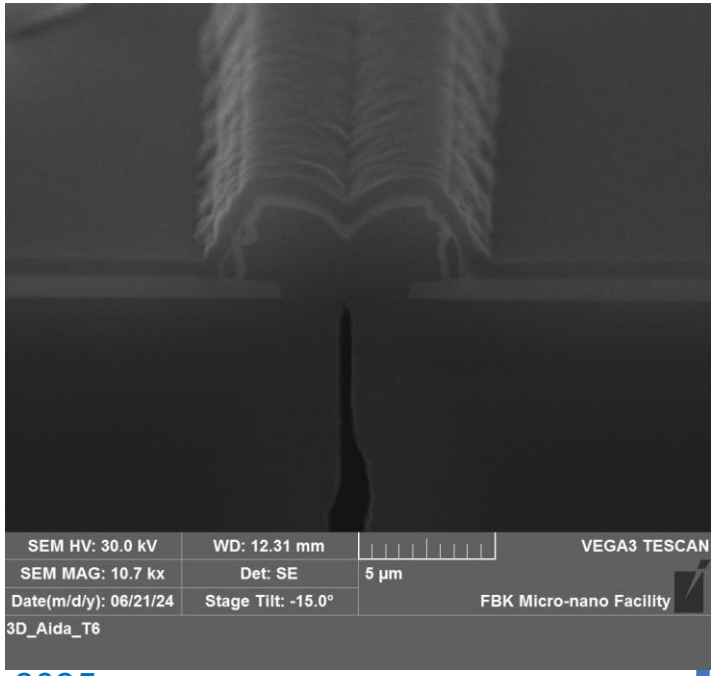




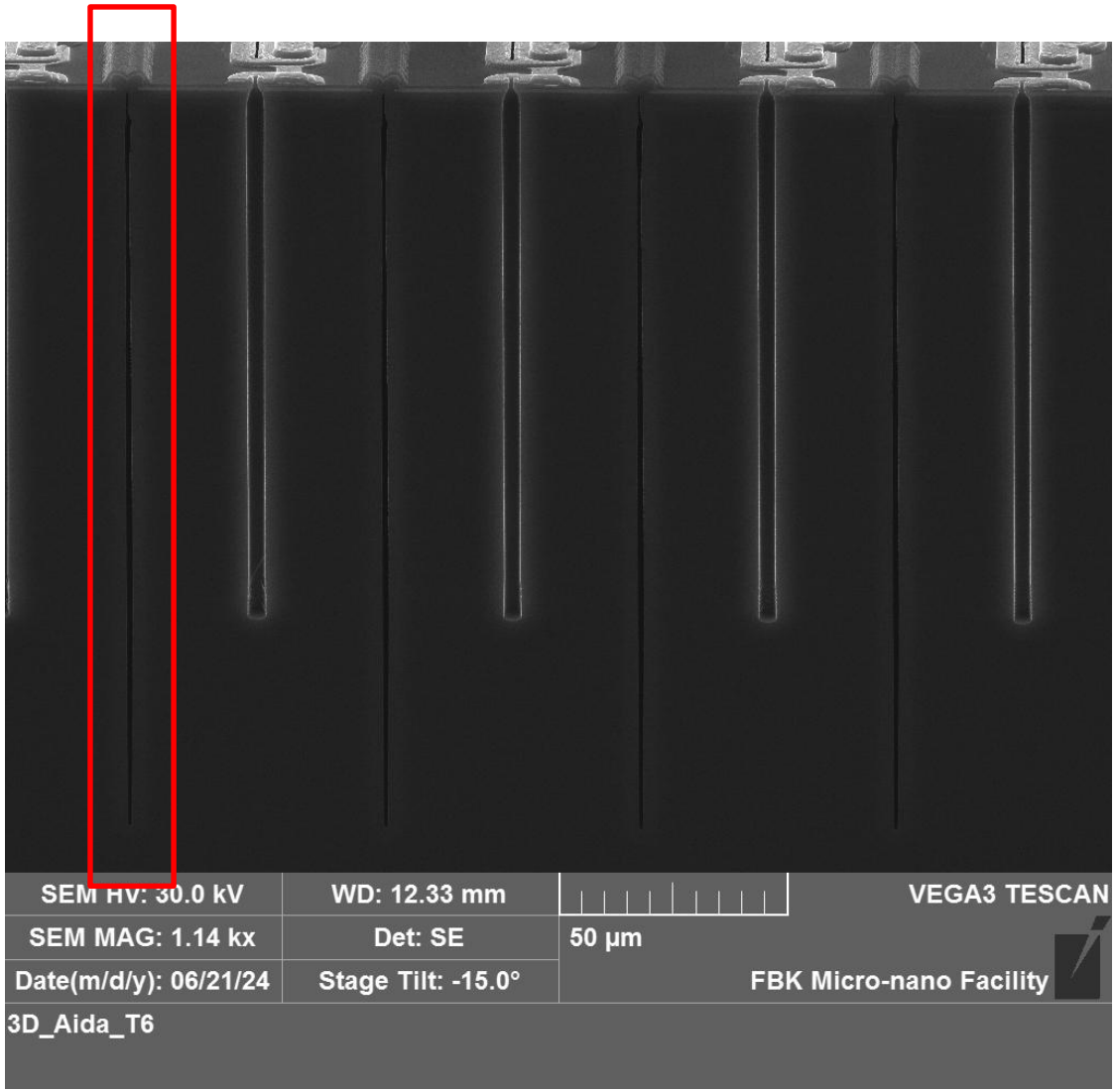
AIDA innova : Ohmic trenches

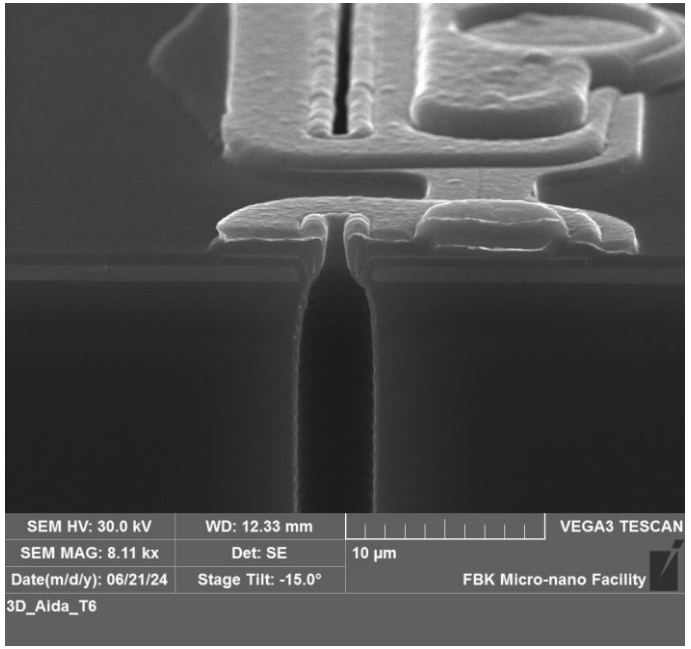


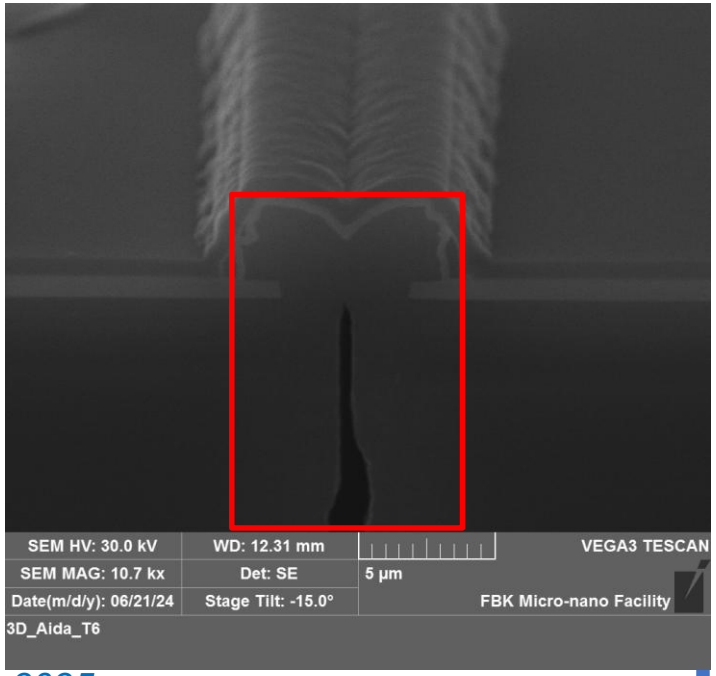




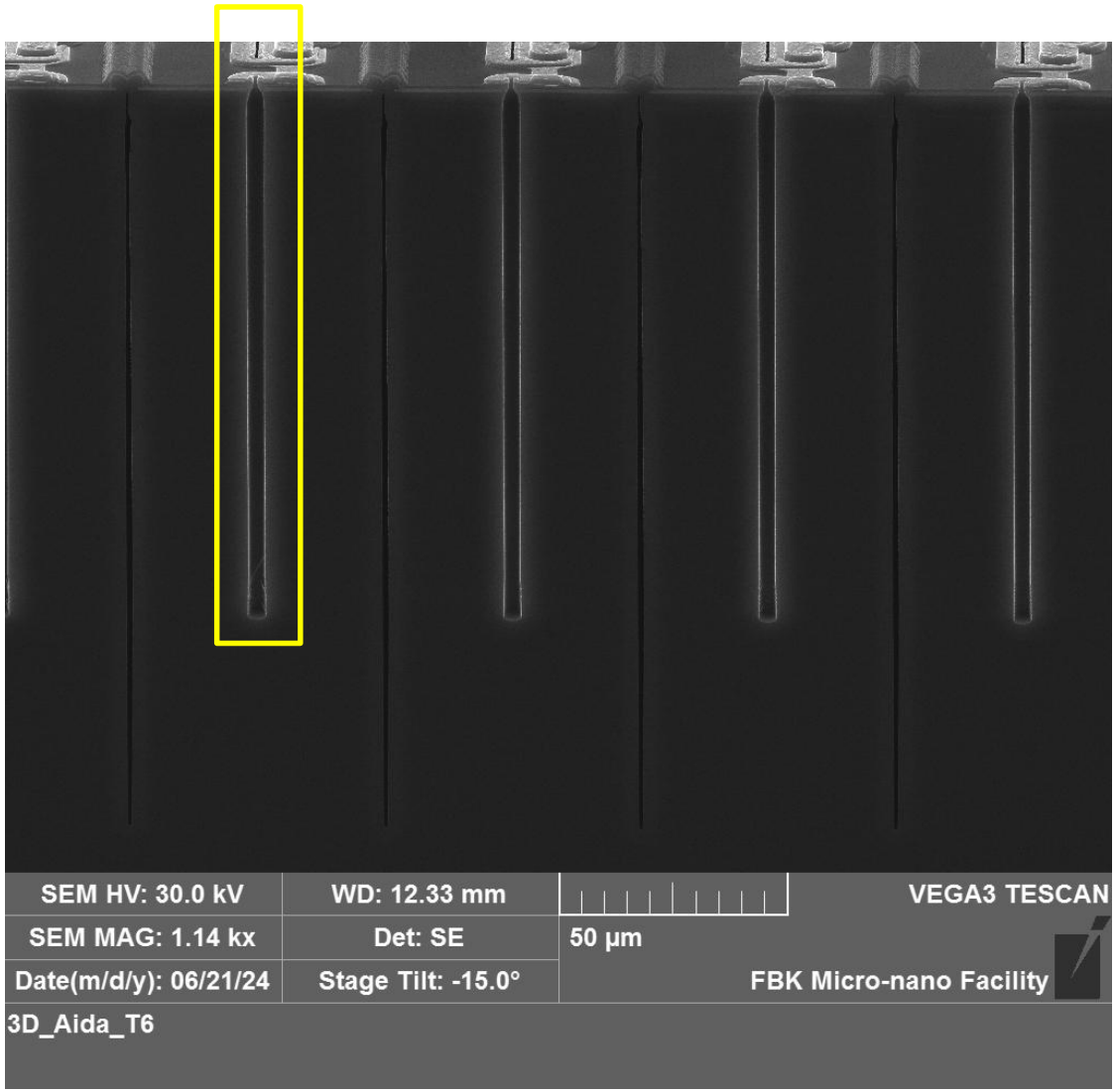
AIDA innova : Ohmic trenches

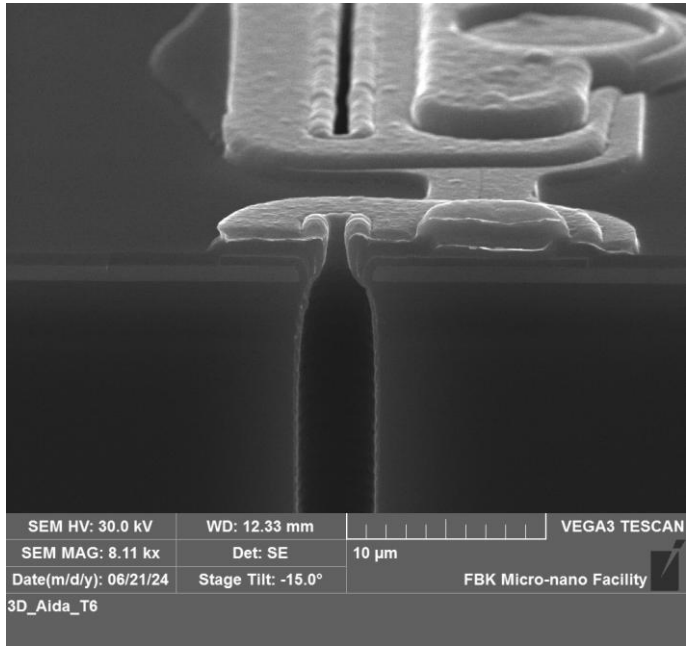


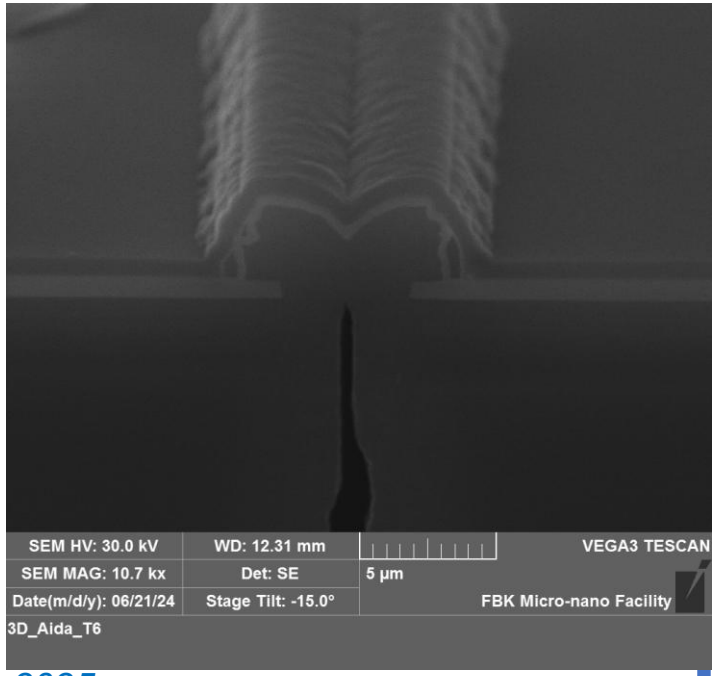




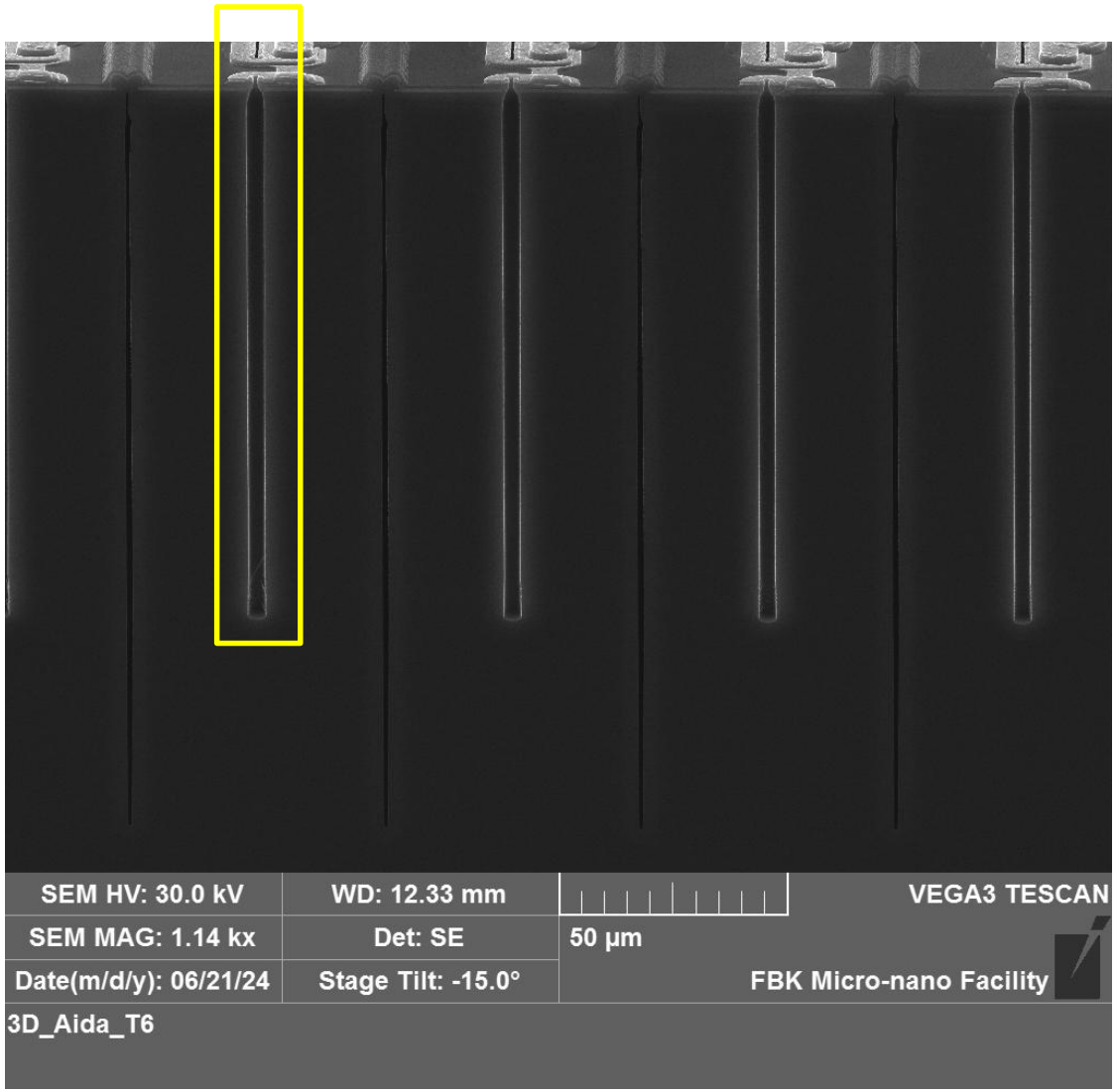
AIDA innova : Junction trenches

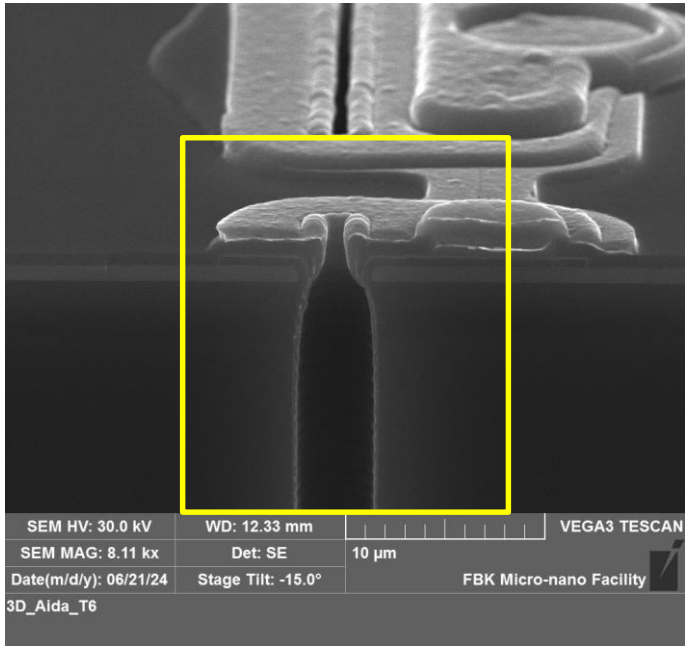


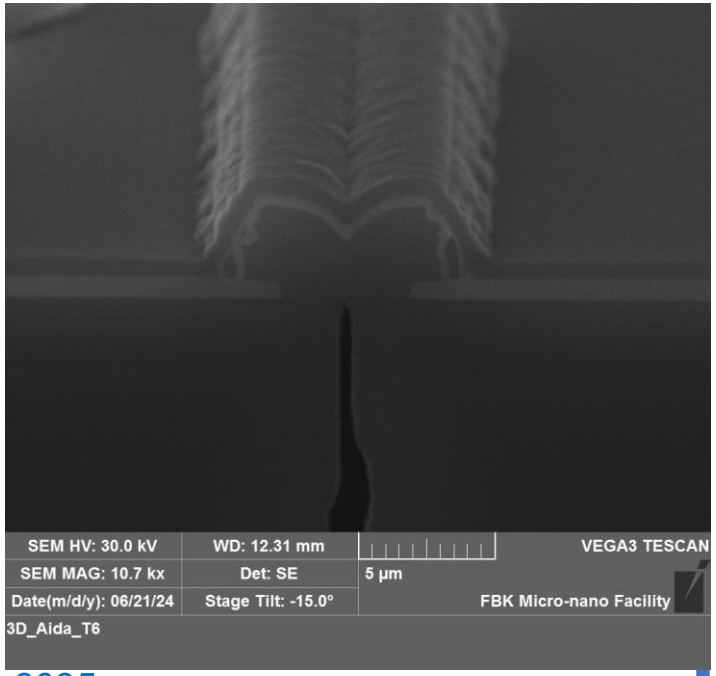




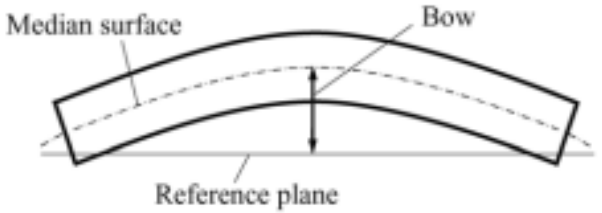
AIDA innova : Junction trenches

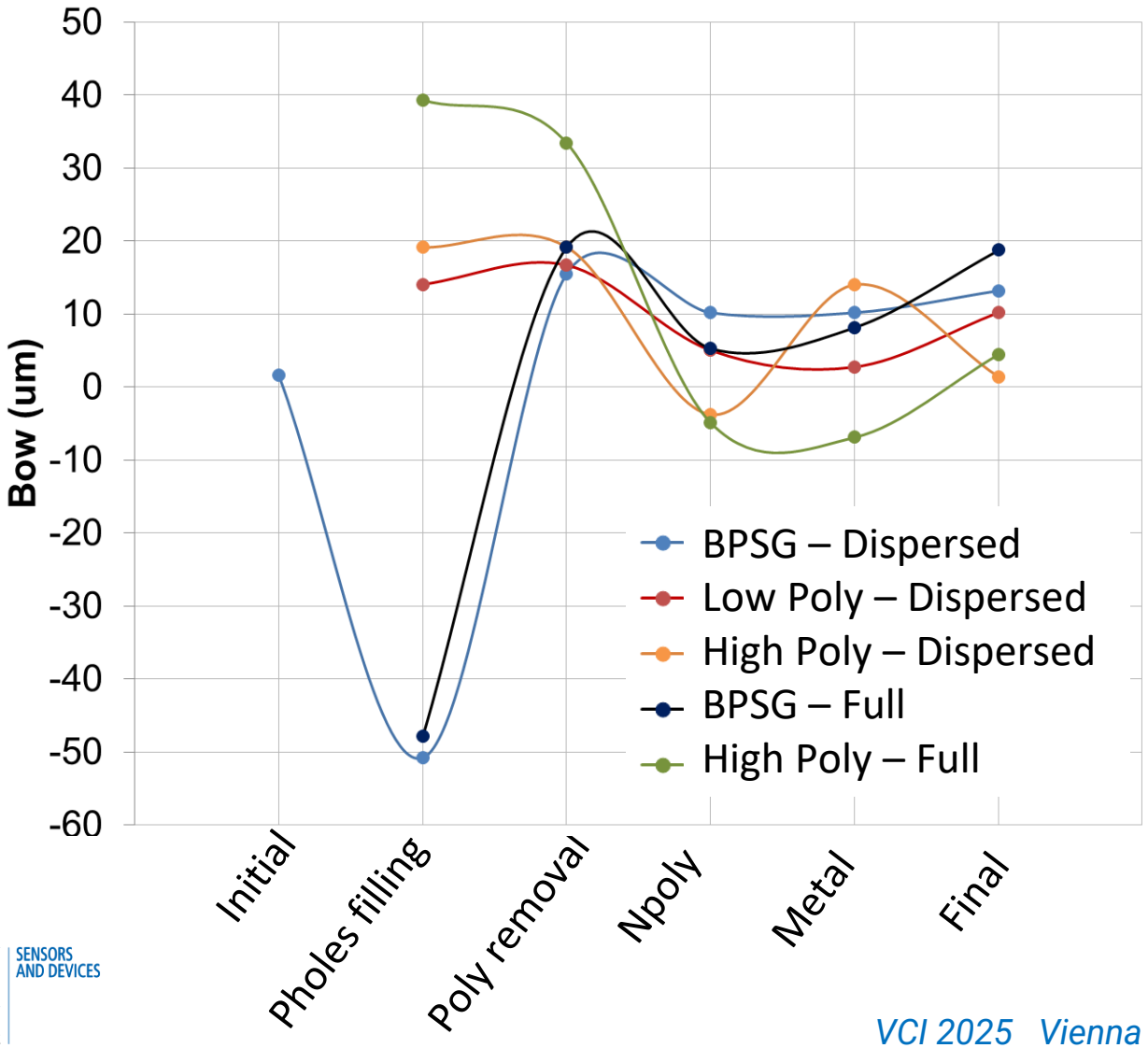




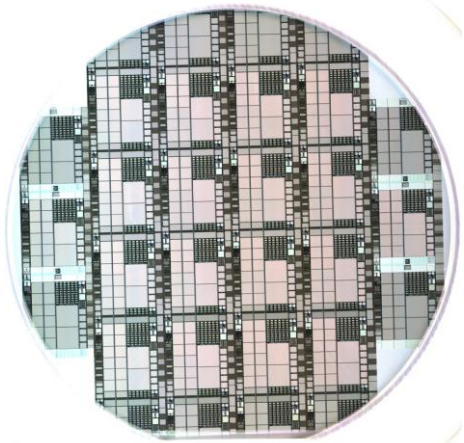


Bow

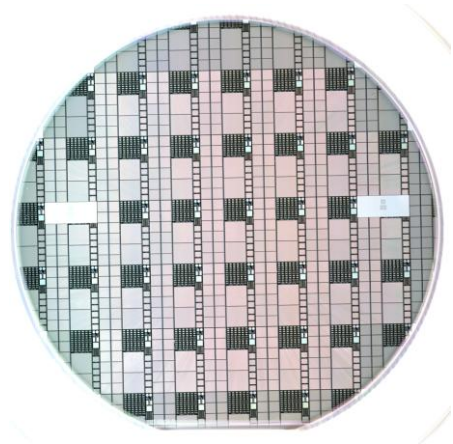




Dispersed
18 shots



Full
29 shots

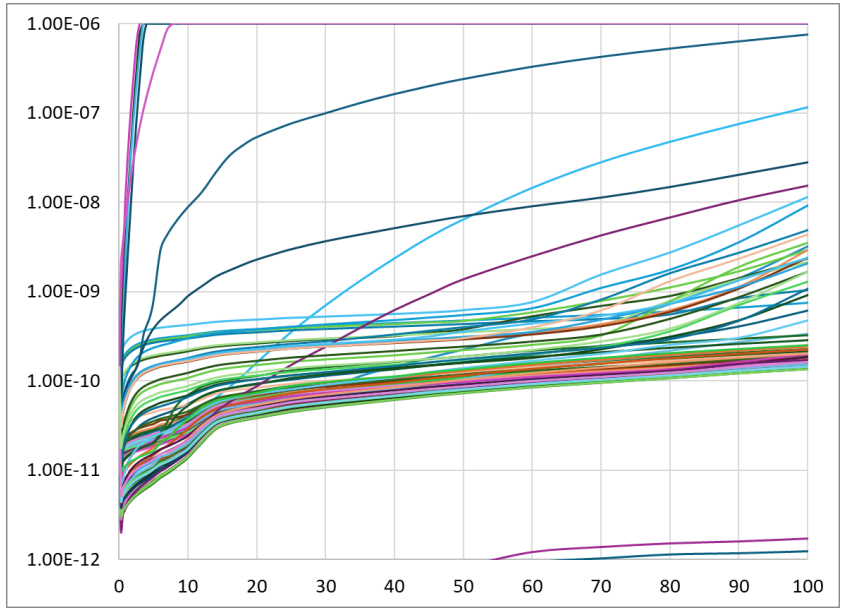


	BOW
BPSG sparse	20,2±2,2
BPSG full	24,0±5,3
POLY 2000 sparse	7,8±2,2
POLY 3000 sparse	5,3±4,0
POLY 3000 full	4,5 *

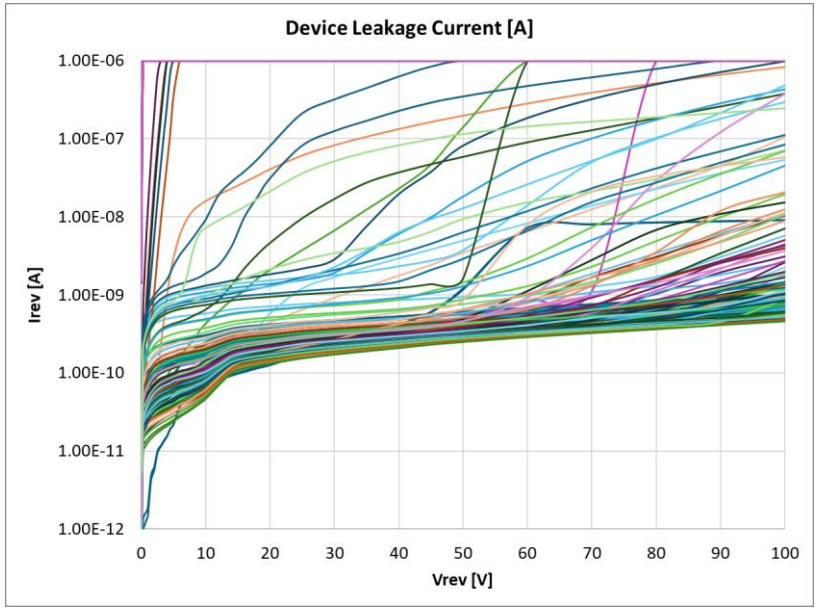
*only one wafer

AIDA Innova:
IV on Temporary Metal on pixel sensors

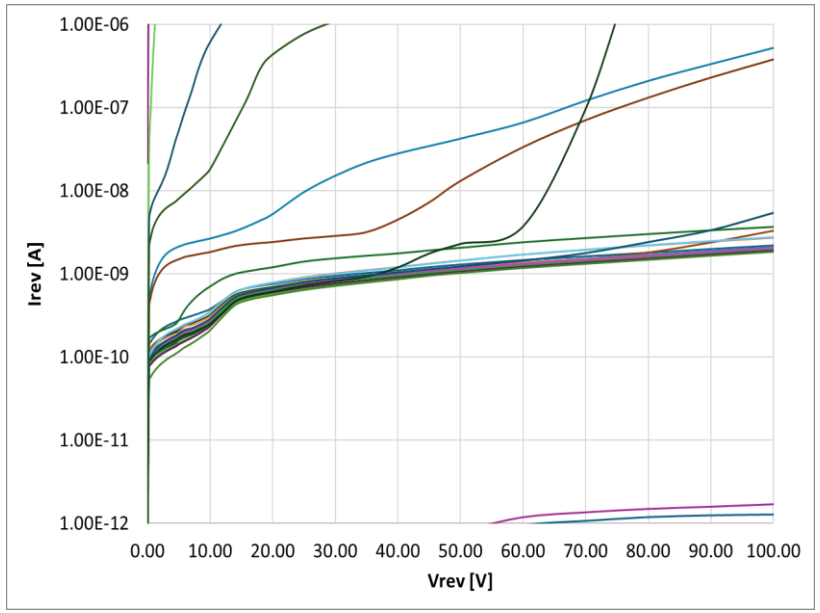
32 x 32 pixel



64 x64 pixel



128 x128 pixel



	32x32	64x64	128x128
Yield %	80 -90%	70-80%	35% (on best wafer 78%)

Activity Status

AIDA innova (trenches)

- UBM deposited @ IZM
- Wafers dicing @ FBK

Next batch in partnership with INFN CA and Univ TN

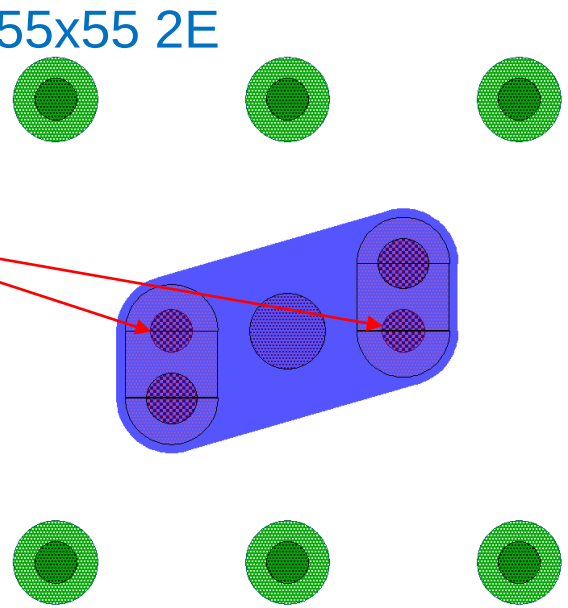
- Explore different **3D-column** layouts for optimal timing
- Pixel pitch down to 45 μm (process modification needed)
- Introduce process optimization to increase the process robustness
- Layout almost completed
- Process will be started asap

See Angelo Loi poster “3D silicon sensors with columnar shaped electrode geometry for fast timing tracking detectors”

In progress: DRD3 Project

- Two batches in the next 3 years

Next Si 3D batch



Pitch reduction

- From 55 µm to 45 µm (maybe less it's feasible ⇒ fill factor decrease)

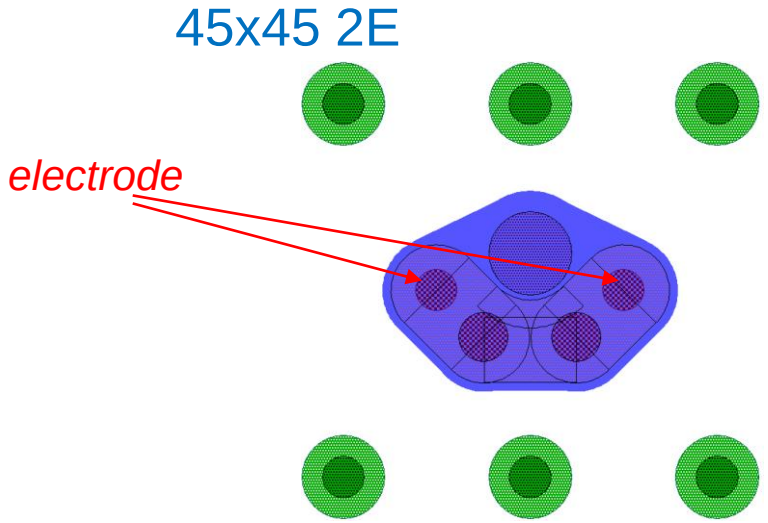
Layout

- Fix a hole of 6 µm diameter ⇒ increase breakdown voltage

J. Ye et al., MDPI Sensors, 23, article 4732, 2023.

Process optimization

- Filling n & p columns
- Increase the planarization performance using BPSG
- Bump on columns
- No poly cap



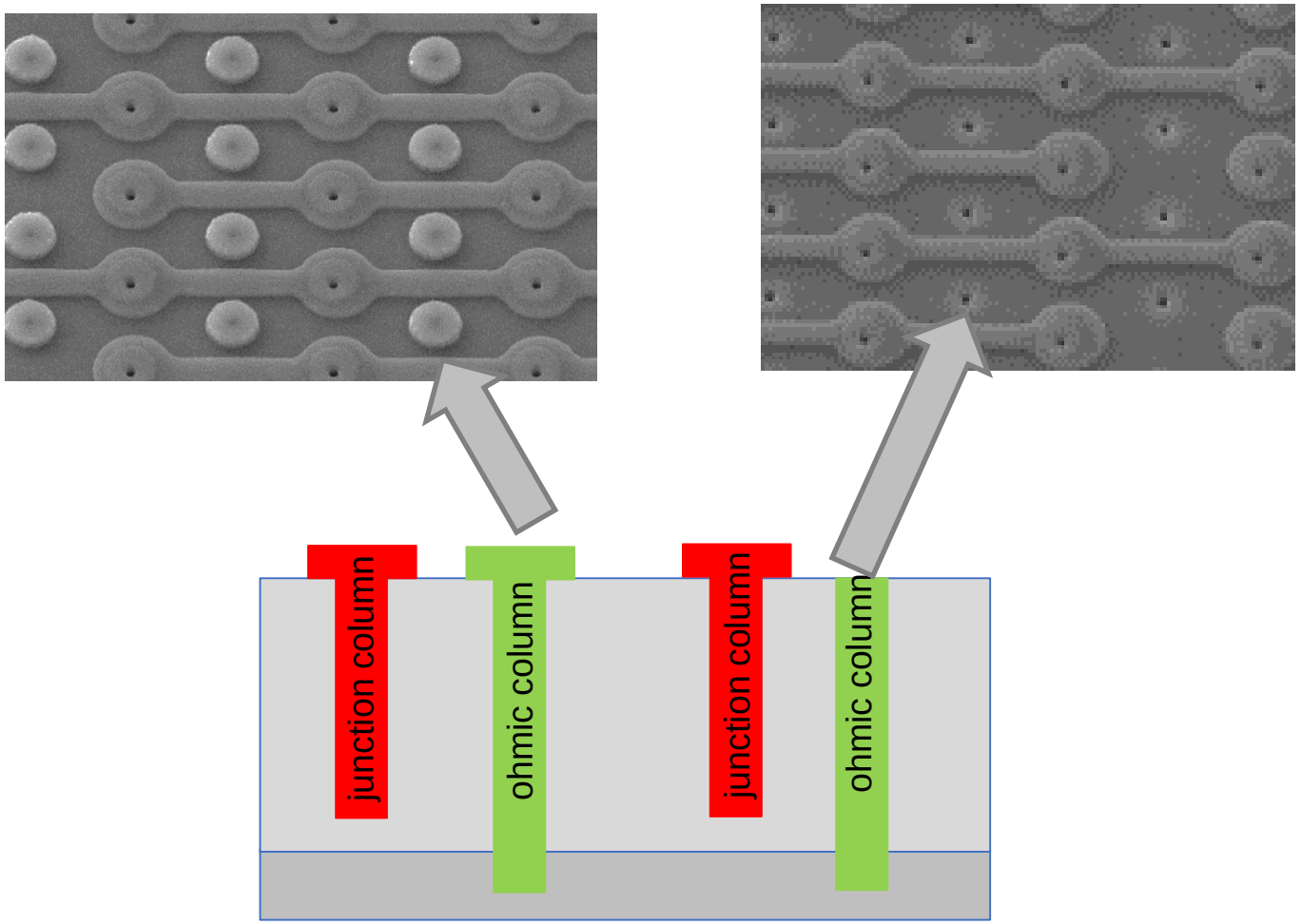
Next steps: no poly cap

Preliminary «old» test

NO poly cap

- More distance between structures
- Planarization
- Reduction of one mask

- Simplify process
- Increase yield



Summary

FBK has been active on 3D sensors since 2004

Currently in production: ATLAS and CMS

- Increase of yield during pre-production

Development of trench detectors

- Timespot collaboration and AIDA innova
- Optimization of process/geometry
- Pitch of 55 µm scalable to 45 µm
- Control of the wafers bow = full wafer layout

Ongoing development to reduce the pitch

- with INFN, DRD3

Acknowledgements

This work has received funding from:-

- *the Italian National Institute for Nuclear Physics (INFN) through the Projects FASE2_ATLAS and FASE2_CMS (CSN1) and TIMESPOT (CSN5)*
- *INFN and FBK through the Framework Agreement MEMS4*
- *the European Union's Horizon 2020 Research and Innovation programme under GA no. 101004761 (AIDAInnova)*

Thanks