Status of the 3D Silicon Detectors activities @ FBK

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Outline

- Si 3D production for both ATLAS and CMS experiments.
  - The latest developments and parametric measurements with Temporary Metal.
  - Process yield over the years
- Continuing development of 3D sensors based on trenches:
  - Past experience on 3D sensors with trenches for Timespot
  - New 3D trenches batch for AIDA Innova project
- 3D Optime: further 3D detectors developments

Si3D Production @ FBK

ATLAS
Production:

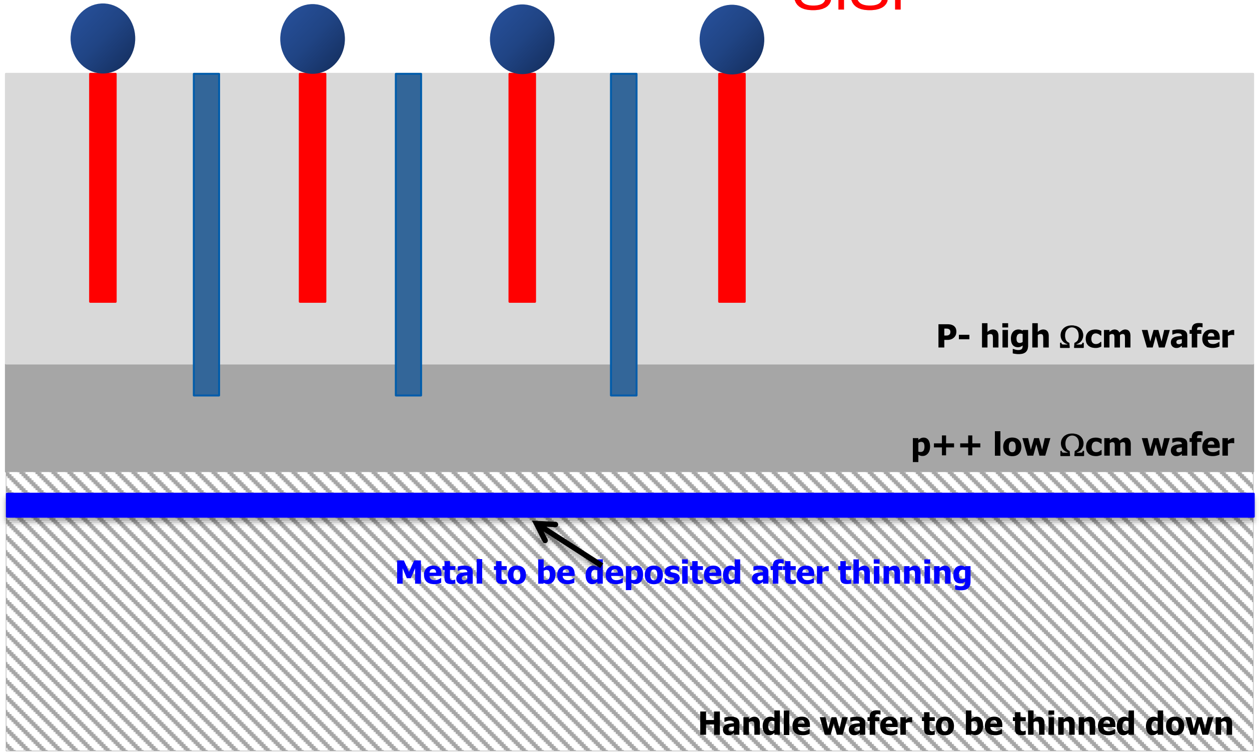
RD53b 50x50 & 25x100 design

CMS
Pre-production:

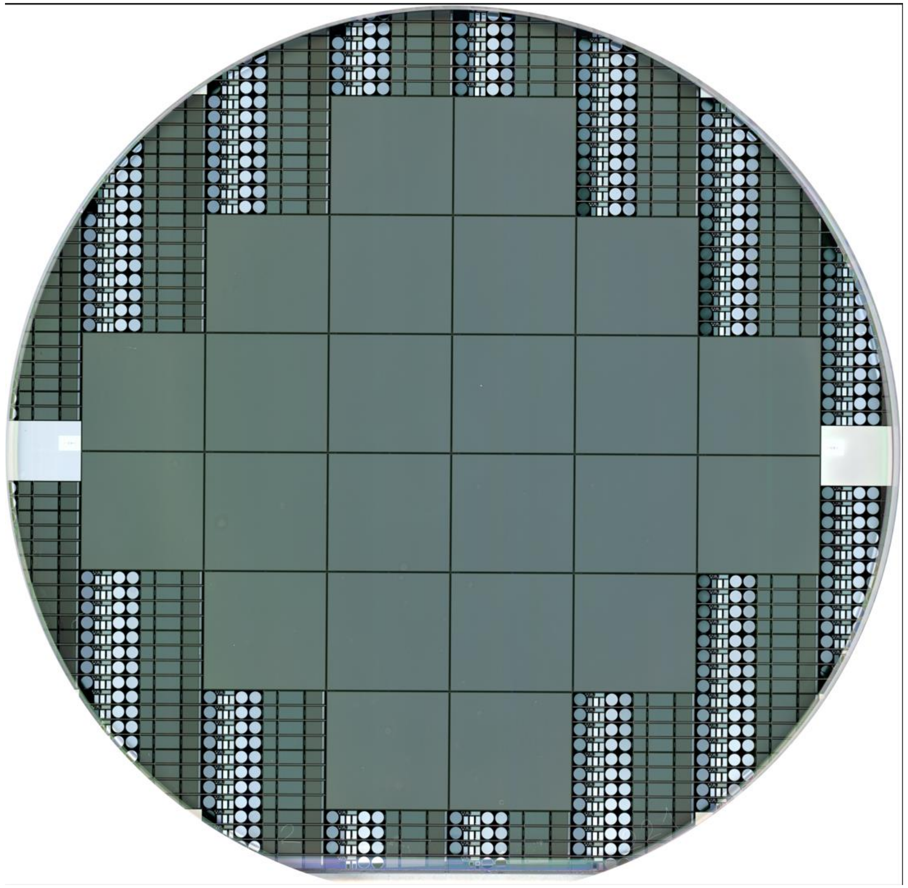
CROC 25X100 design

- 6 inches wafers
- Si-Si wafers:
  - 150 µm of active wafers (FZ p-type, ρ= 5000-10000 Ωcm)
  - 500 µm of support wafers (CZ)
- p-spray isolation
- 5 µm diameter holes
- p-poly filling and Npoly partial filling
- Temporary metal

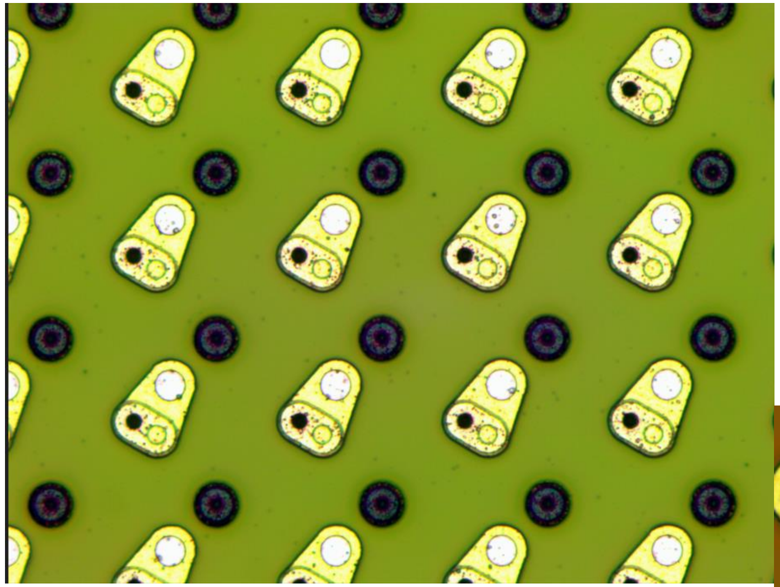
SiSi



Production for ATLAS

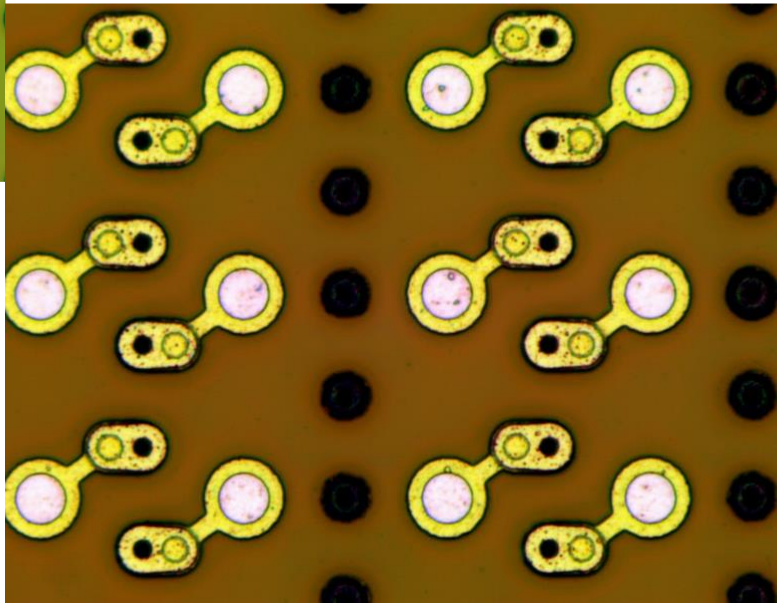


Wafer layout 24 sensors
20.4 x 19.5 mm^2

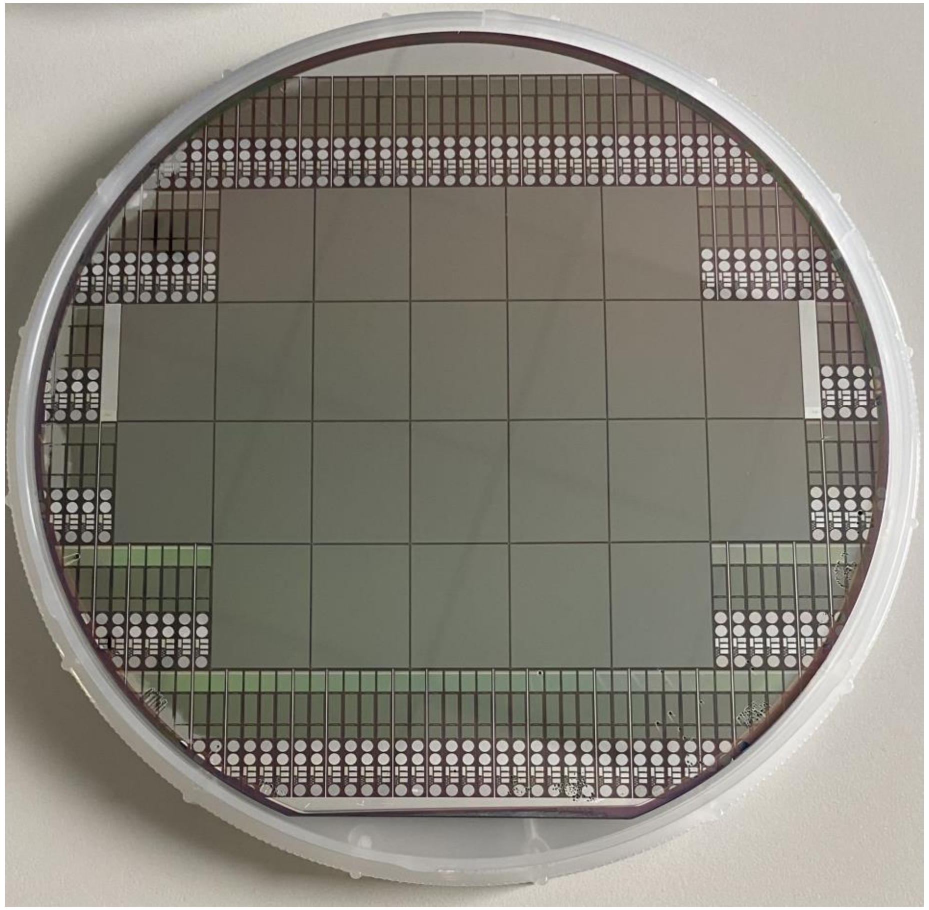


RD53 b design 50 x 50 µm^2

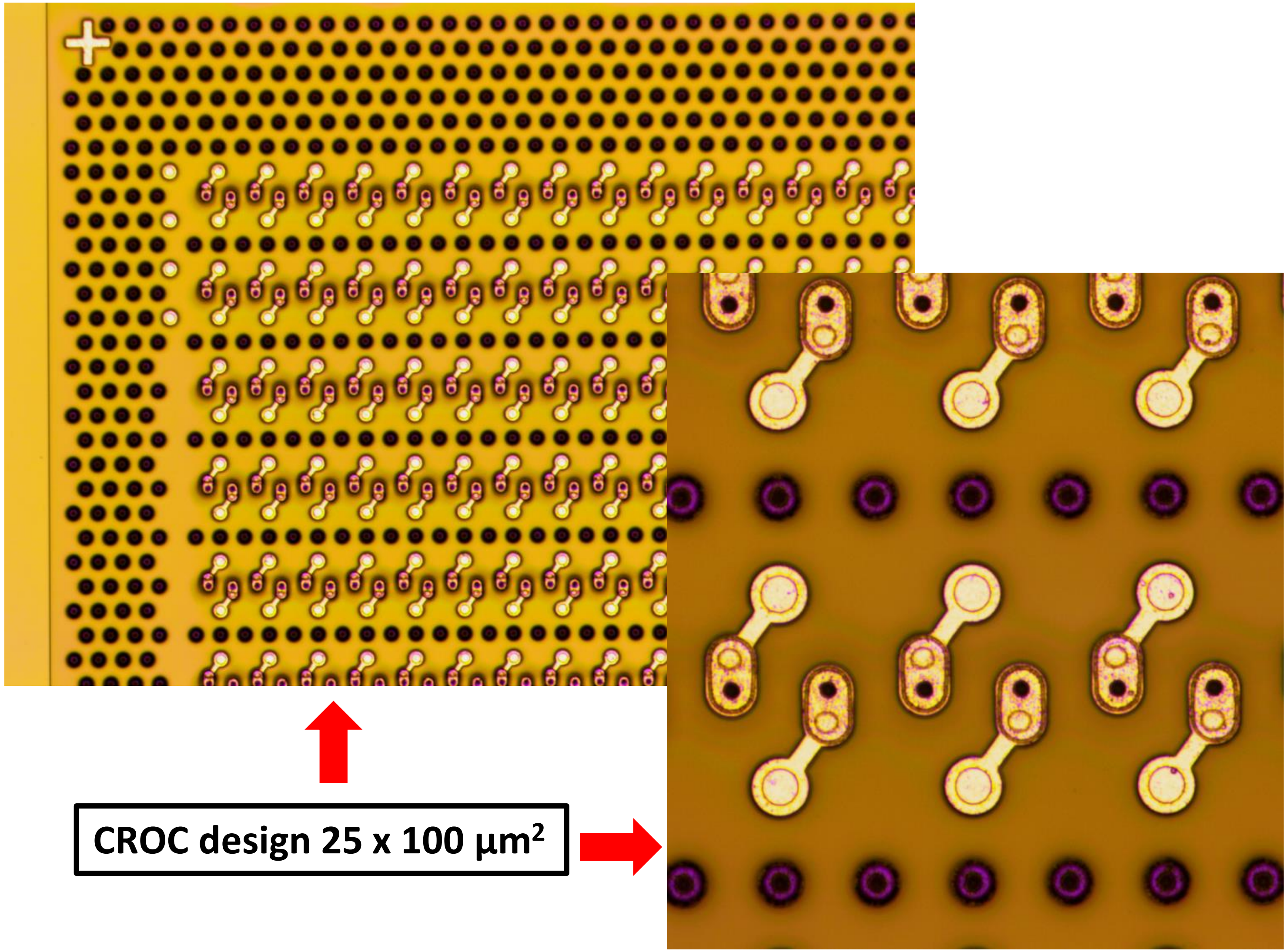
RD53 b design 25 x 100 µm^2



Production for CMS



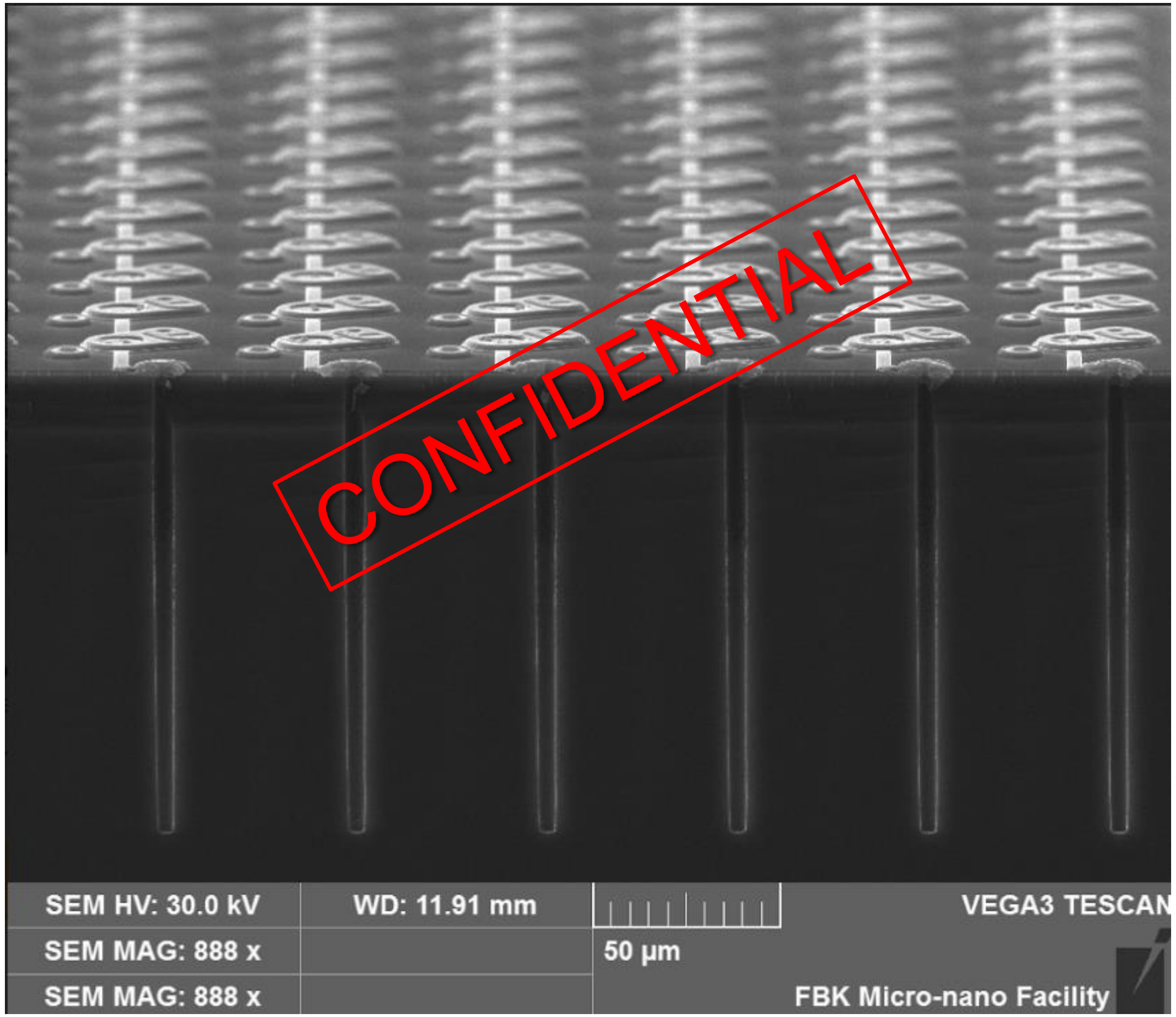
Wafer layout 24 sensors
17.2 x 22.0 mm^2



CROC design 25 x 100 µm^2

SEM images

Cross-section of a test wafer “simil-3D ATLAS” (50x50 Design)



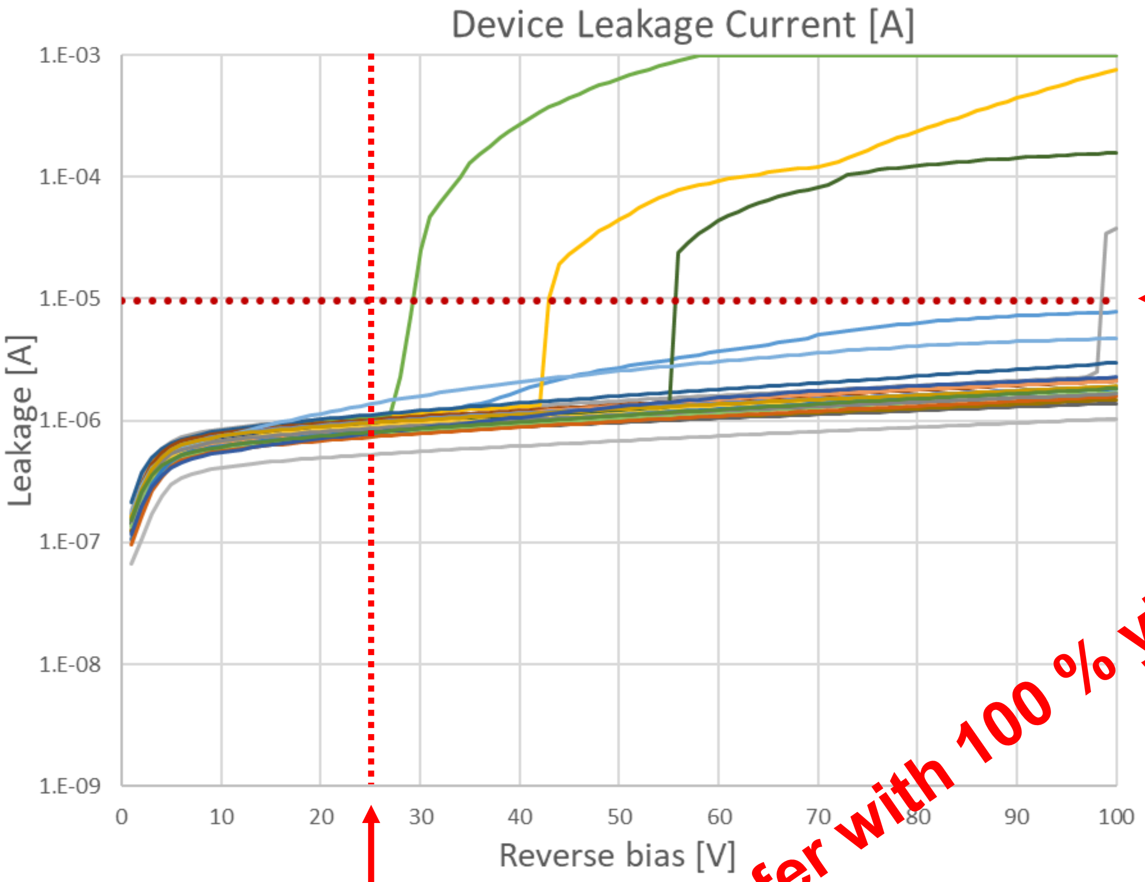
Recent results in 3D production

Wafer w4 from 3D ATLAS RD53b 25x100 production

DEVICE LEAKAGE CURRENT [A] @ Vrev = 25V			
Dev ID	Leakage [A]	VBD [V]	GOOD?
A_3,6	9.83E-07	120.0	Y
B_4,6	9.11E-07	120.0	Y
C_2,5	1.10E-06	98.0	Y
D_3,5	1.09E-06	42.1	Y
E_4,5	9.67E-07	120.0	Y
F_5,5	1.06E-06	27.5	Y
G_1,4	1.12E-06	120.0	Y
H_2,4	1.02E-06	120.0	Y
I_3,4	7.75E-07	104.0	Y
J_4,4	8.09E-07	120.0	Y
K_5,4	9.36E-07	120.0	Y
L_6,4	8.75E-07	55.0	Y
M_1,3	1.38E-06	120.0	Y
N_2,3	8.79E-07	120.0	Y
O_3,3	5.27E-07	120.0	Y
P_4,3	8.95E-07	120.0	Y
Q_5,3	9.77E-07	120.0	Y
R_6,3	7.81E-07	120.0	Y
S_2,2	8.17E-07	120.0	Y
T_3,2	7.34E-07	120.0	Y
U_4,2	8.62E-07	120.0	Y
V_5,2	9.58E-07	120.0	Y
W_3,1	7.89E-07	120.0	Y
X_4,1	8.06E-07	120.0	Y

Product Requirements

PR1	Leakage <	9.6E-06	[A]
PR2	Vbd >	25.0	[V]



Maximum Accepted Leakage Current

Minimum Accepted VBD

Wafer with 100 % yield!!

Yield trend over the years, batch by batch

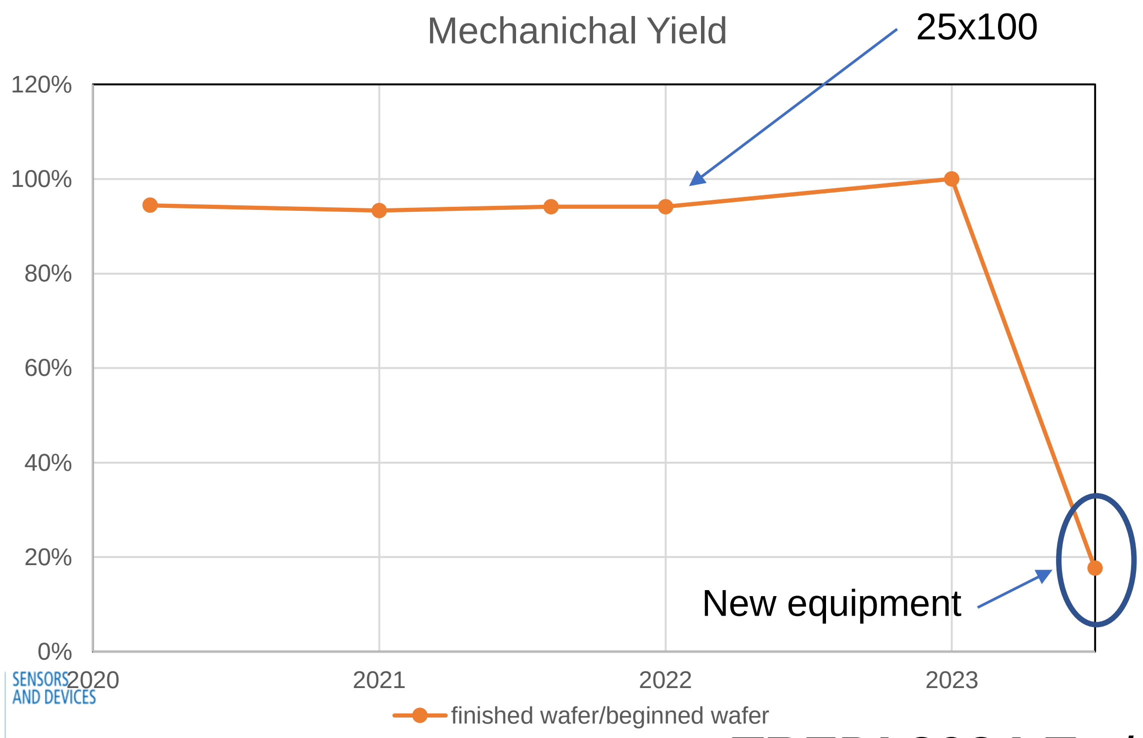
Si 3D for ATLAS production @ FBK

Process Mechanical Yield = finished wafers/ beginned wafers

Device Yield on batch = good devices/all devices of completed wafers

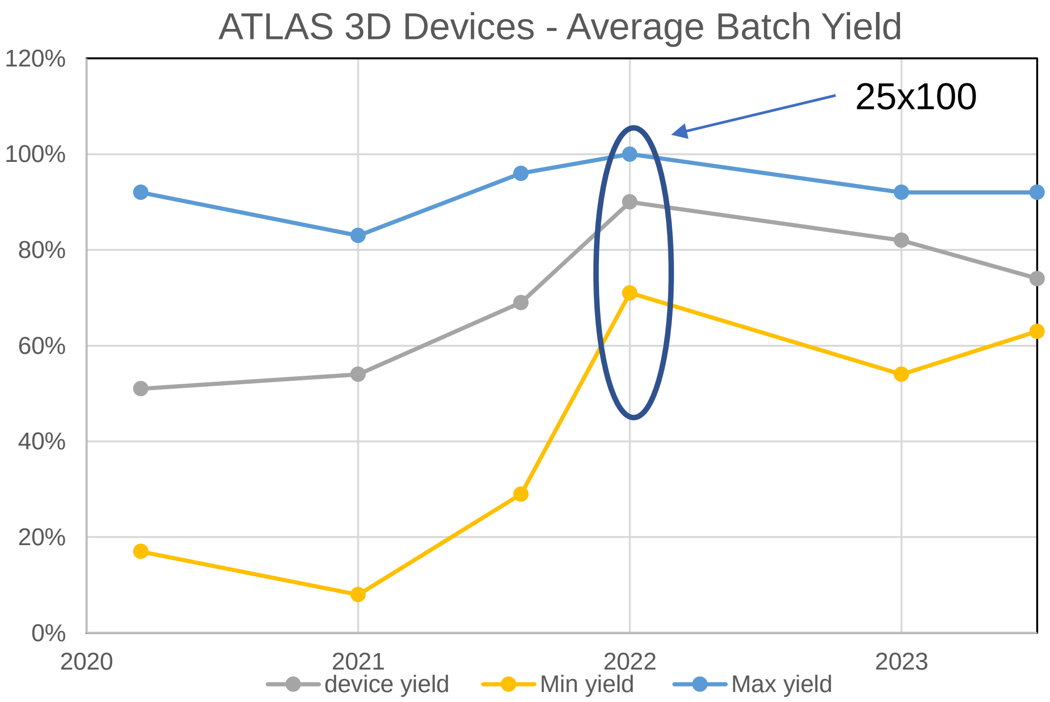
Max Yield: the Yield of best wafer of batch

Min Yield: the Yield of worst wafer of batch


Mechanichal Yield

25x100

New equipment


ATLAS 3D Devices - Average Batch Yield

25x100

Yield trend over the years, batch by batch

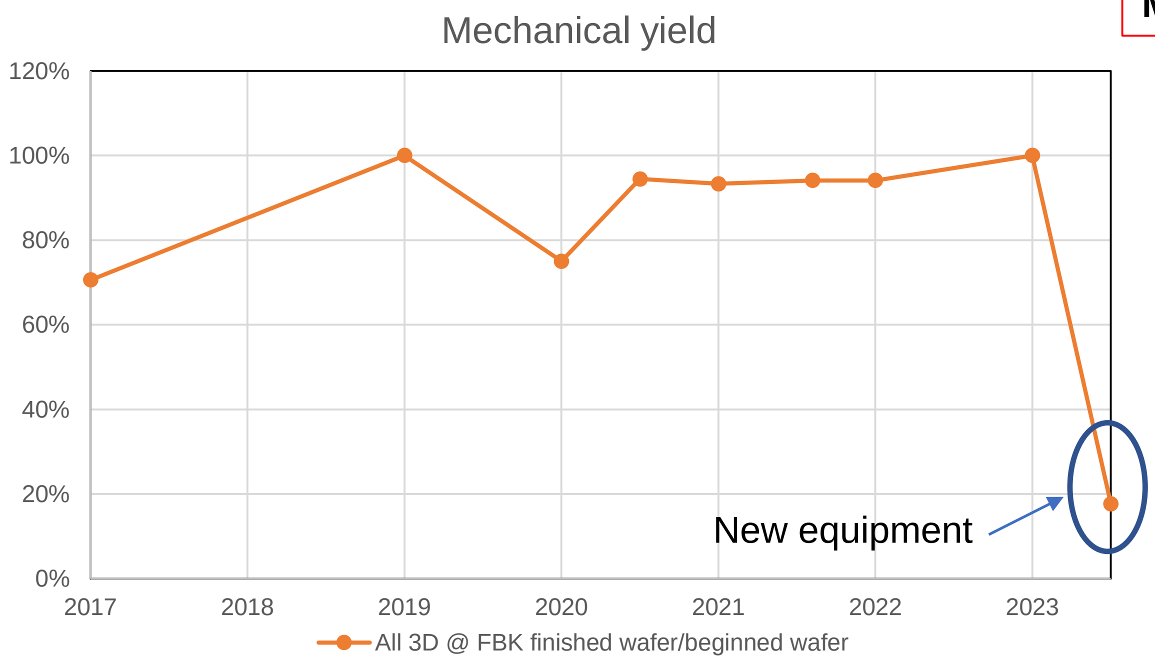
Si-3D @ FBK from 2017

Process Mechanical Yield = finished wafers/ beginned wafers

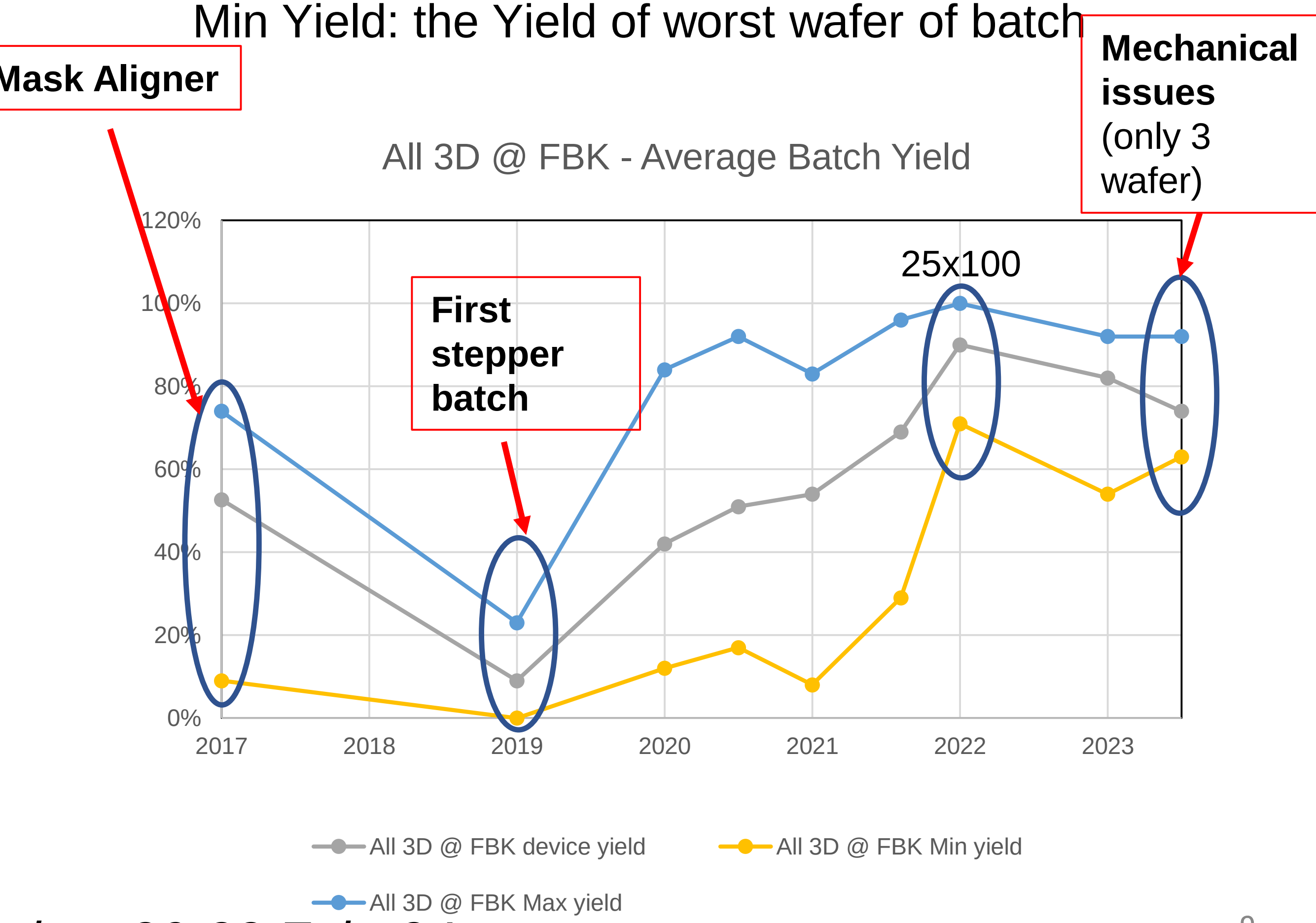
Device Yield on batch = good devices/ completed wafers

Max Yield: the Yield of best wafer of batch

Min Yield: the Yield of worst wafer of batch



New equipment



Mask Aligner

First stepper batch

25x100

Mechanical issues (only 3 wafer)

- **MA good yield but "not uniform"**
- **Processes more reliable over time**

Process improvement over the years

- ✓ Lithography: From Mask Aligner to STEPPER: Improved uniform on wafer and also on batch
- ✓ Optimization of Lithography for hole Etching:
  - ➢ Photoresist coating
  - ➢ Exposition and developing
  - ➢ Baking
- ✓ DRIE holes process improvement
- ✓ Accurate Trenches drying before all depositions
- ✓ Temporary metal removal improvement
- ✓ Renewal of Equipment (lithography, and Dielectrics Etching)
- ✓ Experience: focus on defects, critical points and causes and study of ways to avoid or reduce them

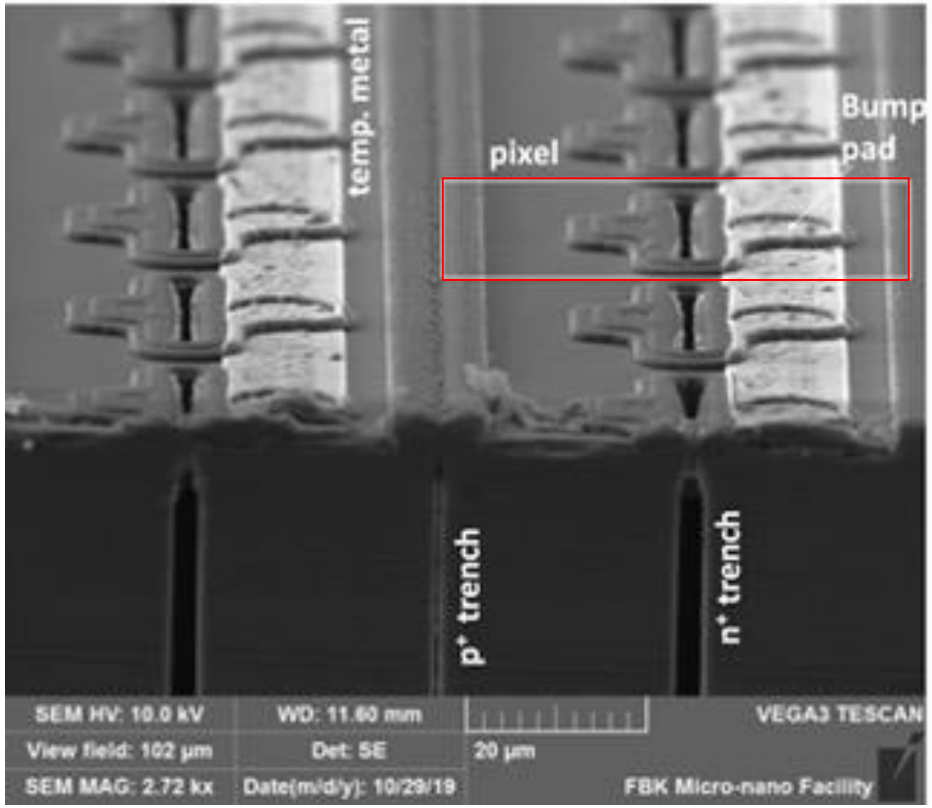
Si 3D Trenches @ FBK
R&D Process (development and device fabrication)

From **Timespot** experience…

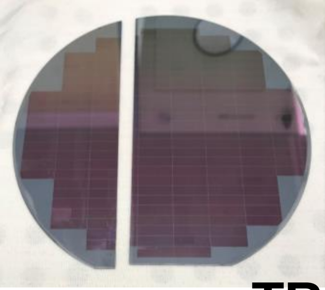
- ✓ Excellent timing performance with 10 ps timing with highly irradiated 3D trench silicon pixel sensors!
- ✓ Modest Process Yield:

Year	**Mechanical yield**	**device yield**	Min yield	Max yield	notes
2018	**50%**	**25%**	6%	71%	on test structures; **0 on devices!!!**
2020	**75%**	**63%**	0%	80%	on 2.3x1.7 mm^2

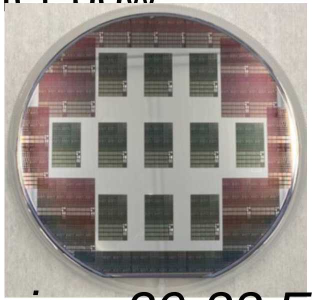
  - ➢ due to important Lithographic issues
  - ➢ reduced number of device in order to control wafer bow



65% broken wafers and >150 um of bow max during the tests with high density

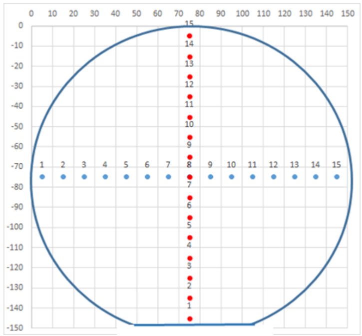


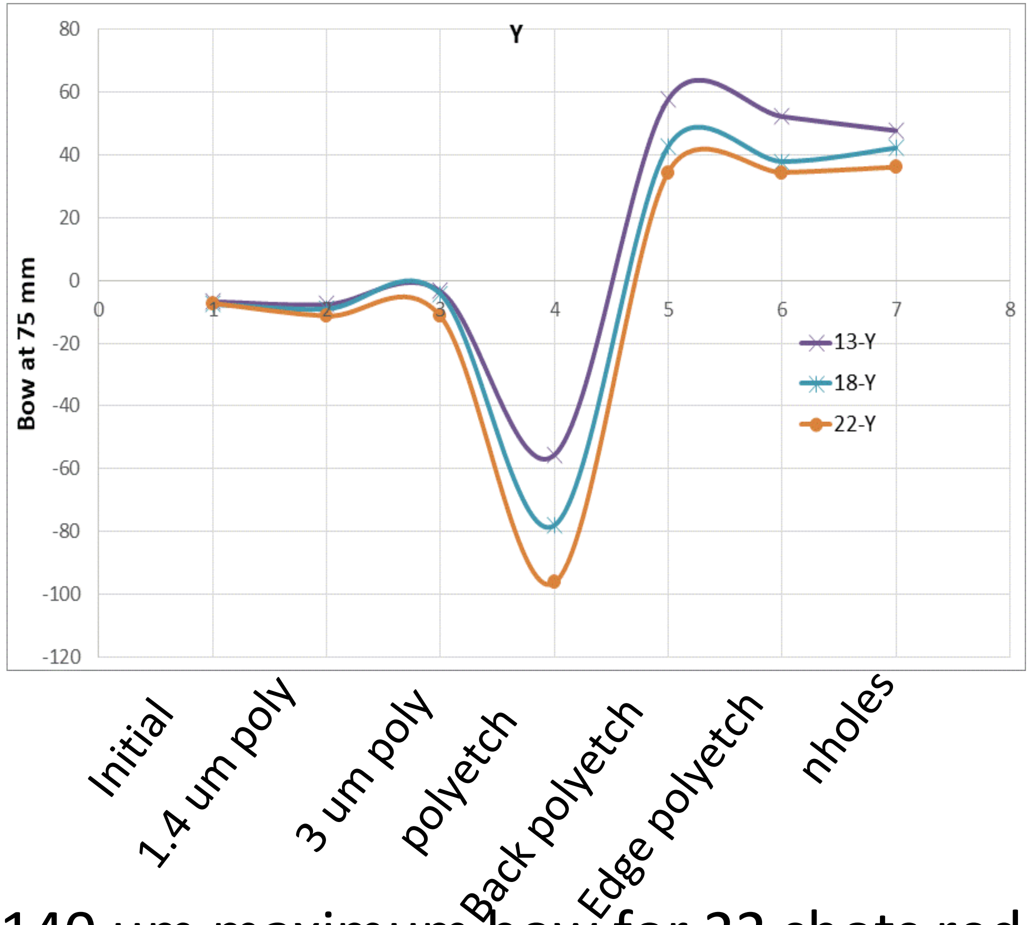
Reduced number of shots

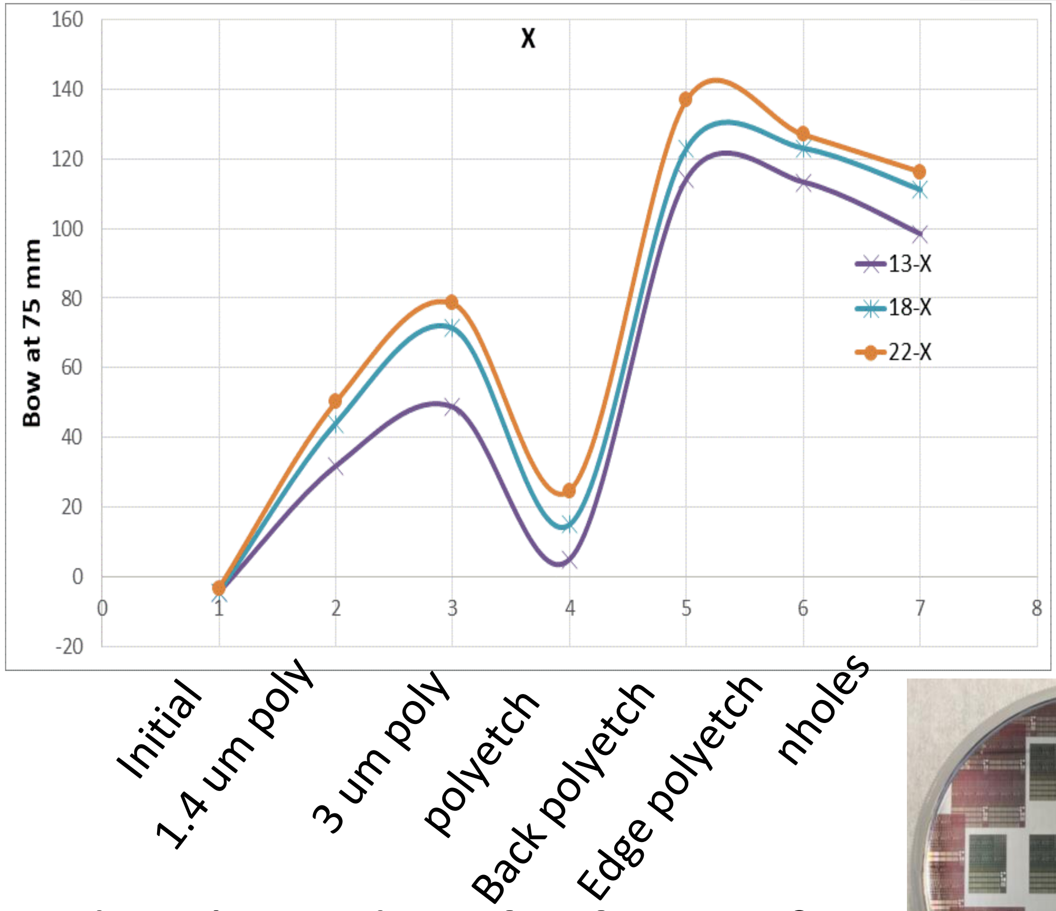


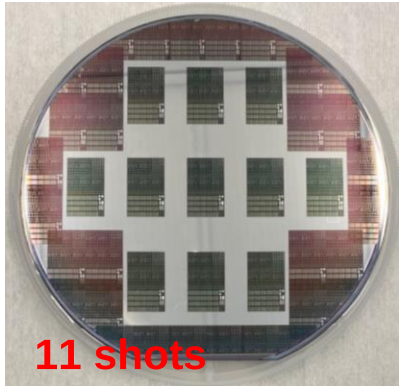
BOW vs Layout density – test for increase layout density (and good devices!) using Timespot reticle

Bow obtained from 15 points along 2 diameters (y and x) of the wafer by DCM3D Sensofar-Tech Leica Profilometer








11 shots

140 µm maximum bow for 22 shots reduced at the end, **no broken wafers**

➡ **Try to increase the number of shots on wafer**

Si 3D Trenches Process for AIDA

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA no 101004761

✓ **Adaptation of the design to the process :**
- width & length of trenches optimization
- enlargement of the npoly area and removal of the contacts from the trench)

✓ **Optimization of process:**
- Accurate Trenches drying before all depositions
- Study of Trenches filling
- Temporary metal removal improvement
- Renewal of Equipment (lithography, and Dielectrics Etching)

Split table of batch

- Lot Status: step 244/294. At the metal deposition
- Estimated finishing date: Mid/End March 2024

Wafer	Layout Split	ppoly filling	Extra poly
1	18 DIE	BPSG (2.3um)	
2	18 DIE	BPSG (2.3um)	
3	18 DIE	BPSG (2.3um)	
4	18 DIE	BPSG (2.3um)	
5	18 DIE	p-Poly 2000 nm	500
6	18 DIE	p-Poly 2000 nm	500
7	18 DIE	p-Poly 2000 nm	500
8	18 DIE	p-Poly 2000 nm	1000
9	18 DIE	p-Poly 2000 nm	1000
10	18 DIE	p-Poly 2000 nm	1000
11	18 DIE	p-Poly 2000 nm	1000
12	18 DIE	p-Poly 2000 nm	500
13	18 DIE	p-Poly 2000 nm	500
14	18 DIE	p-Poly 2000 nm	500
15	29 DIE	BPSG (2.3um)	
~~16~~	~~29 DIE~~	~~p-Poly 2000 nm~~	~~1000~~
17	29 DIE	p-Poly 2000 nm	1000
18	29 DIE	BPSG (2.3um)	

18 wafers

Wafer Layout

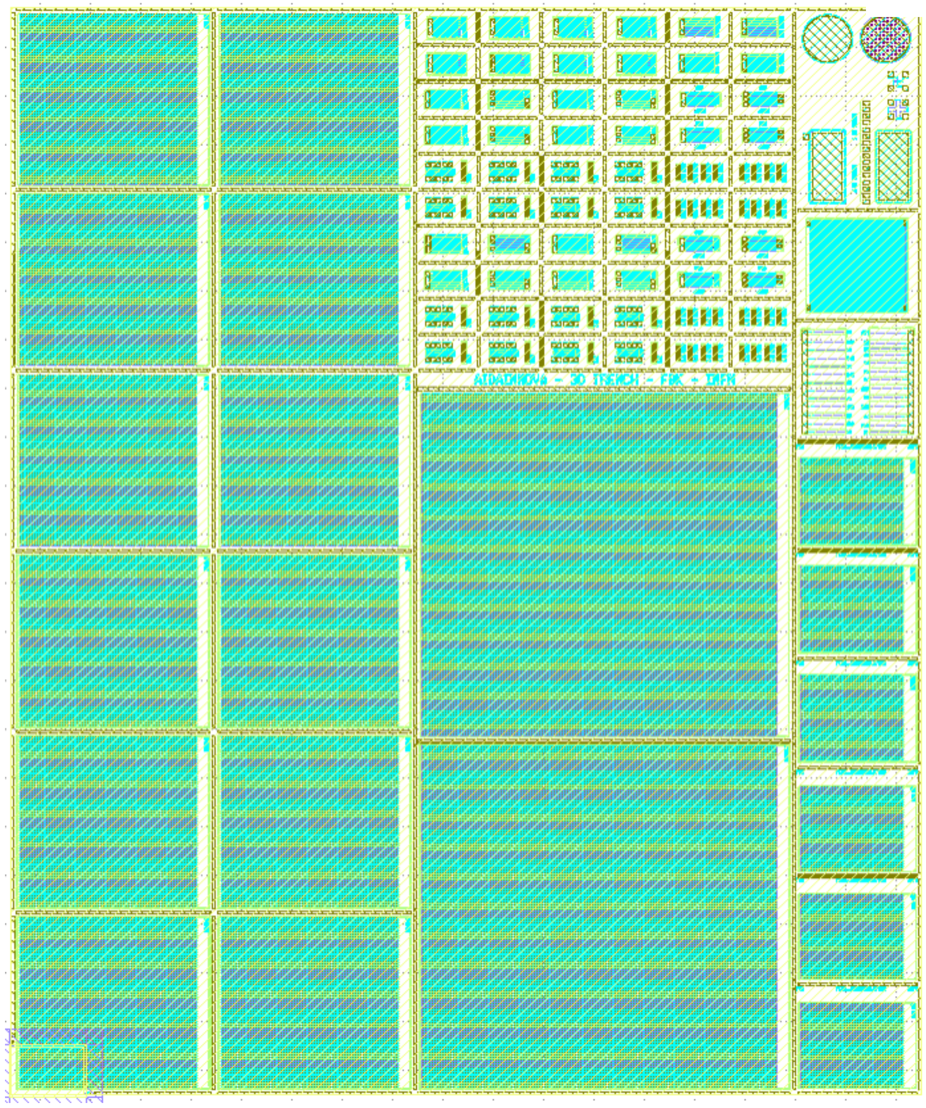
- 14 wafers with18 DIE
- 4 wafers with 29 DIE

Process Split

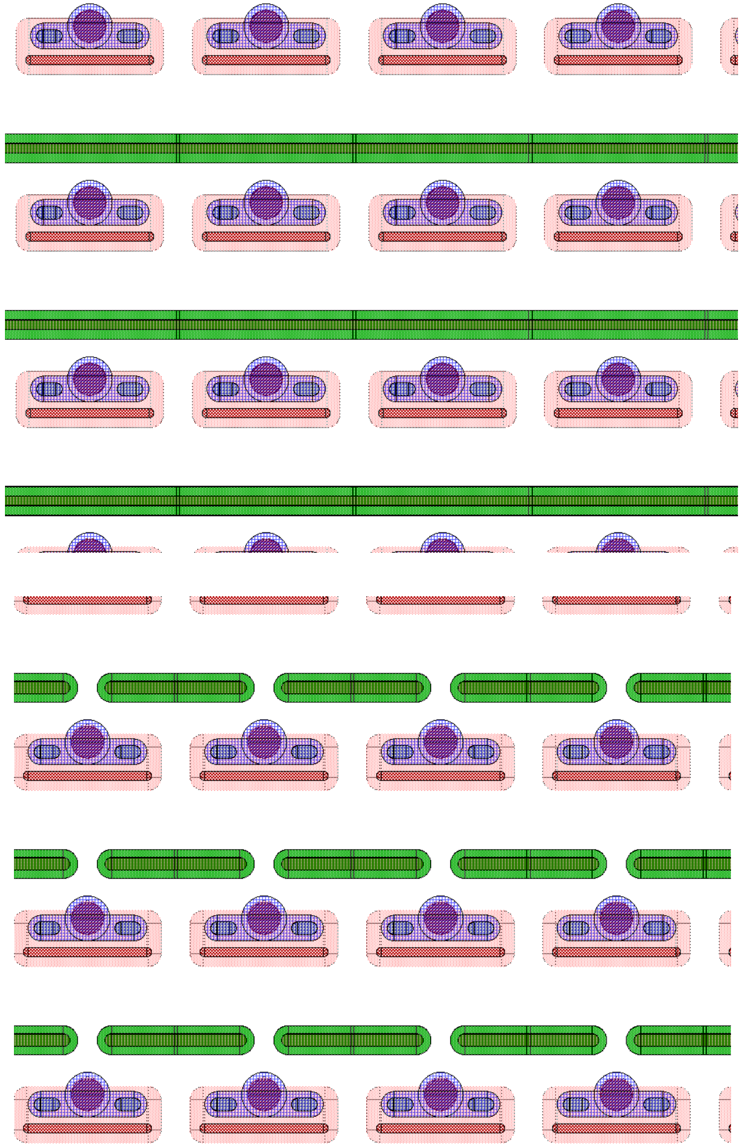
- 12 poly filling
- 6 BPSG filling

W16 broke: too high warp?

Layout (evolution of TimeSPOT)



- Pitch 55 µm
- Gap 9 µm
- 128 ch, 64 ch, 32 c
- Area of larger devices:
- 7.3 x 7.5 mm^2

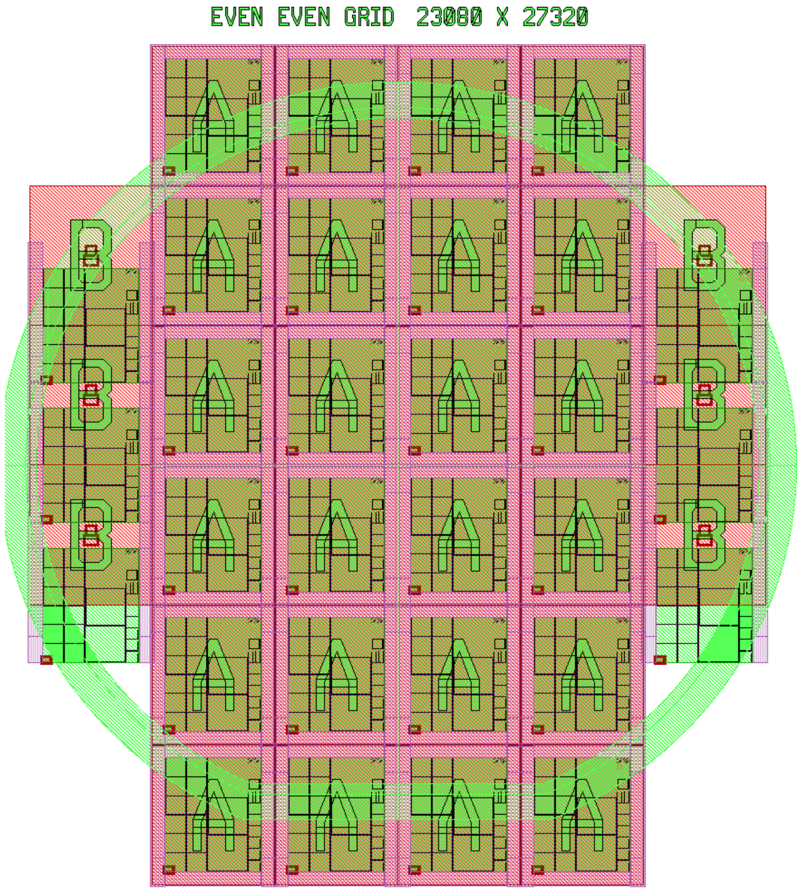


3 um wide
long continuous
p-trenches

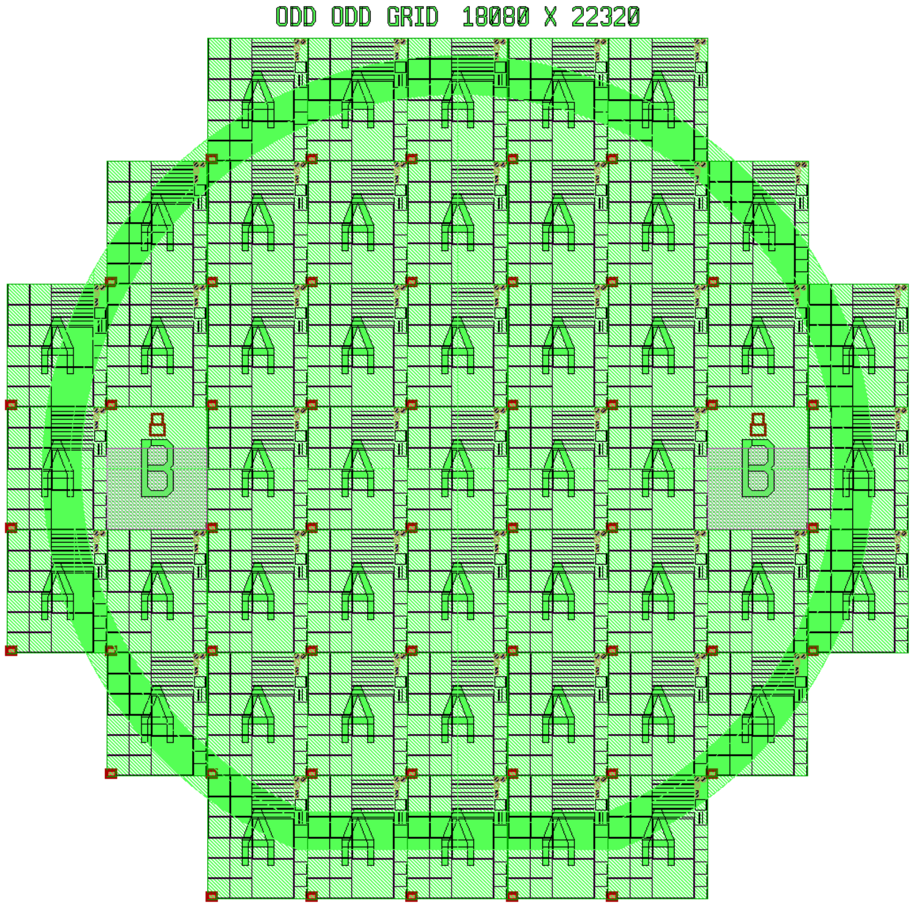
4 um wide
segmented
p-trenches

Wafer Layout

18 DIE



29 DIE



p-holes: two geometries

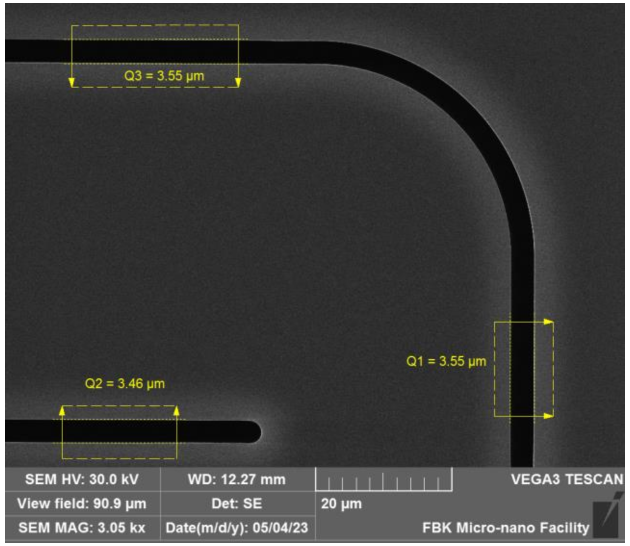
Short and narrow trenches to improve subsequent lithography process

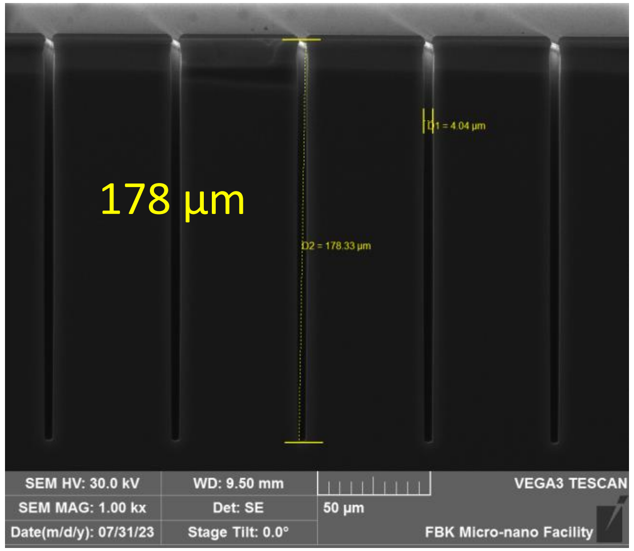
3D AIDA

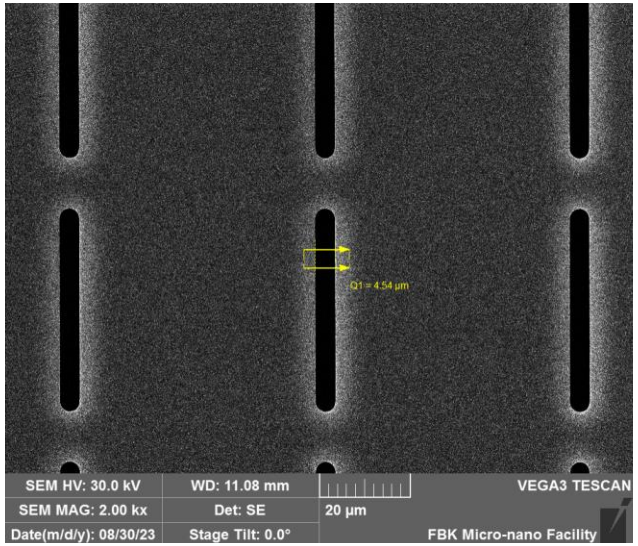
Long trenches:
3µm x ∞

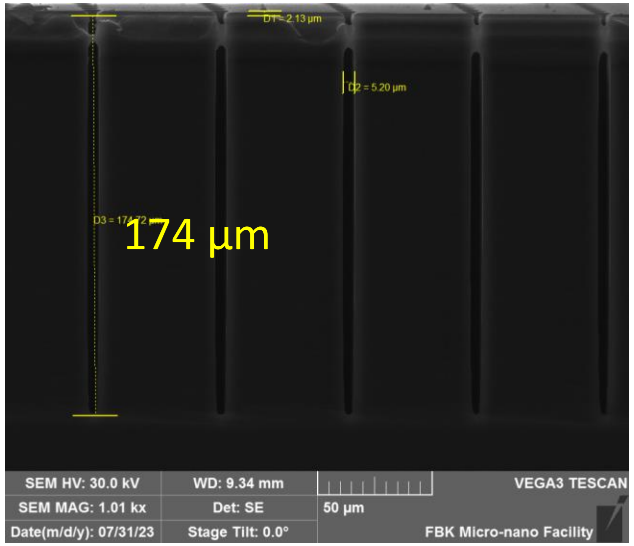
TimeSPOT process:
trenches
4µm x ∞

Short trenches:
4 µm x 40 µm



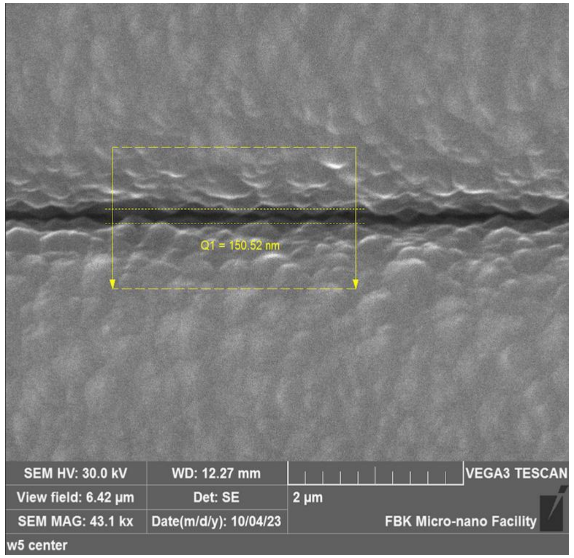




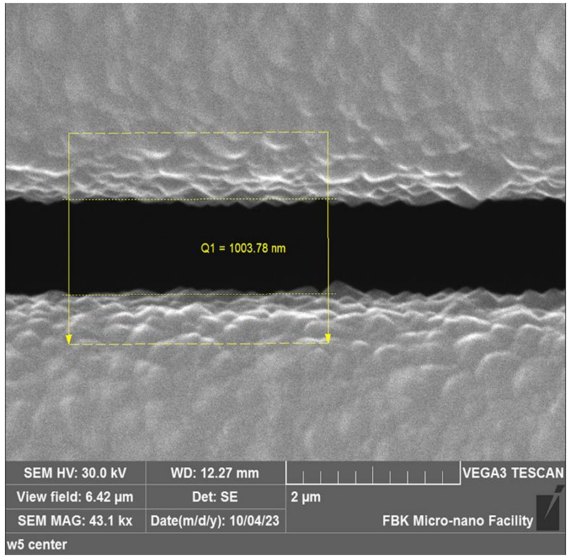


p-holes filling with poly silicon

Long wide trenches and thick poly cap induce lithography issues



Long 3um trench

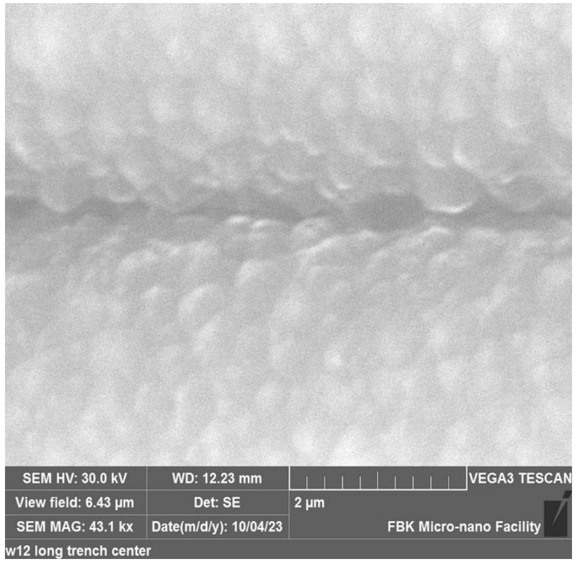


Short 4um trench

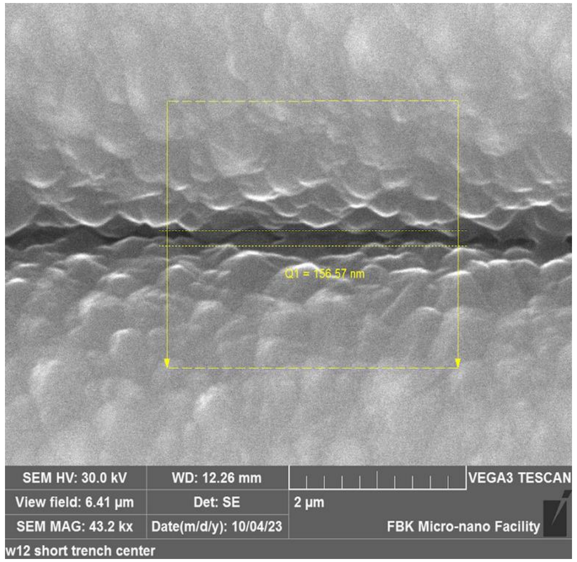
Poly-Si 2 µm

- Long 3um trenches: almost completely closed.
- Short 4um trenches: open. Remaining opening width of **1um**.

Added other 1 µm of poly-Si and all trenches have been closed



Long 3um trench



Short 4um trench

Poly-Si 2.5 µm

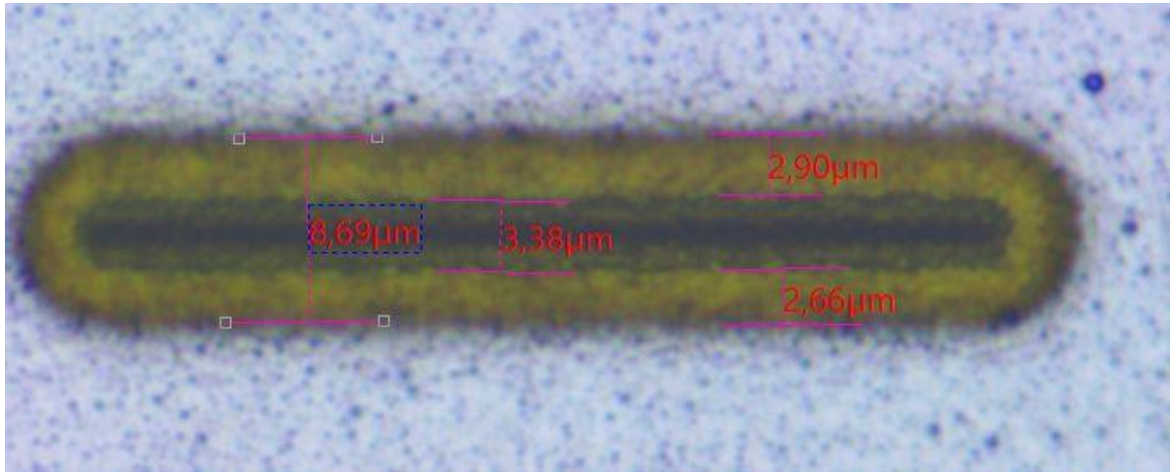
- Long 3um trenches: closed.
- Short 4um trenches: almost completely closed.

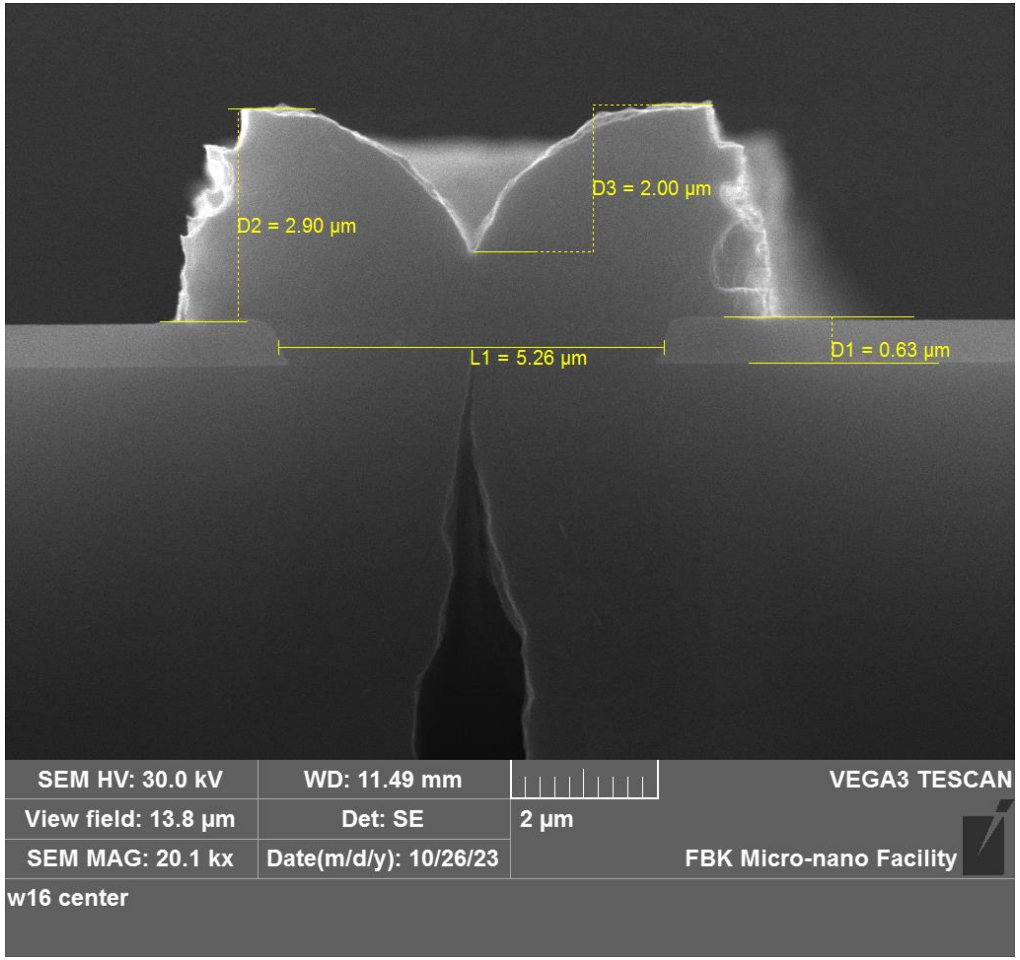
We kept them as they were at the first deposition

Poly Trench filling and definition
Cross section

W16 (broken) layout 29 DIE with:

3 µm thickness on 4 µm trenches





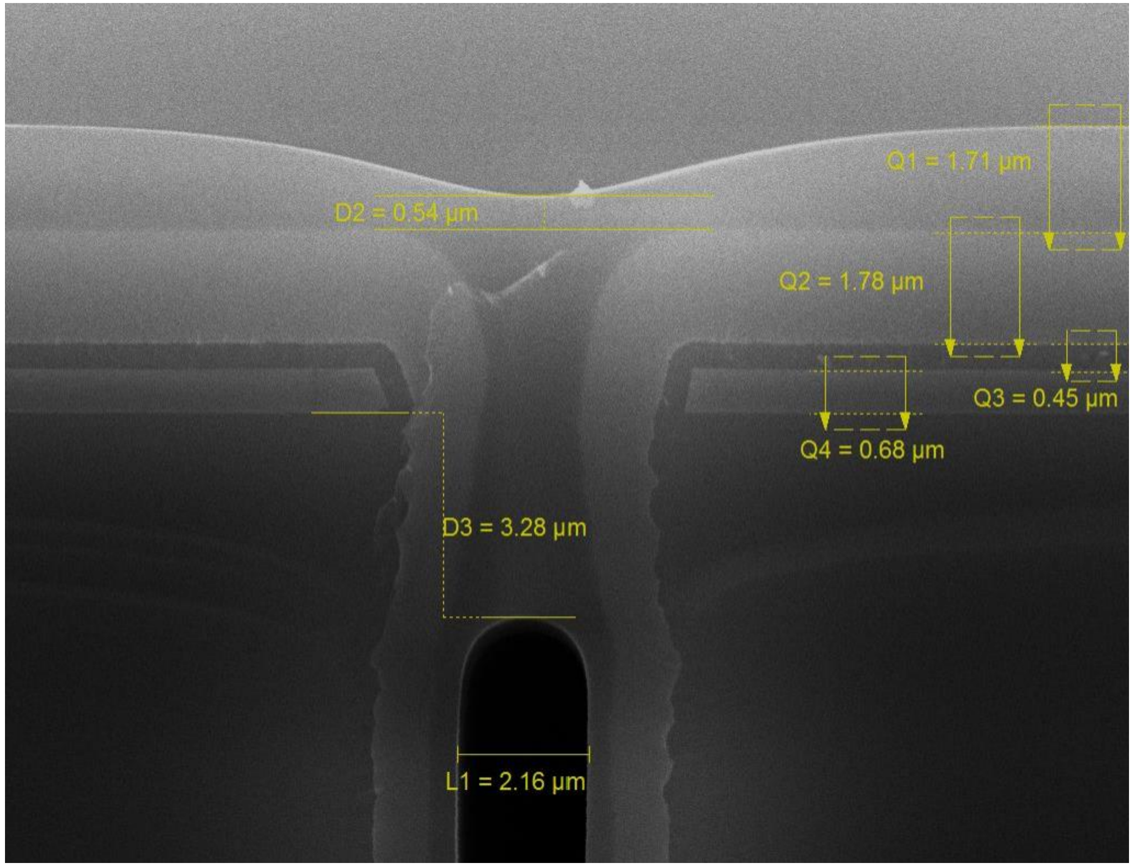
BPSG Trench filling
Cross section

Test wafer with:

2.3 µm thickness on 4 µm trenches

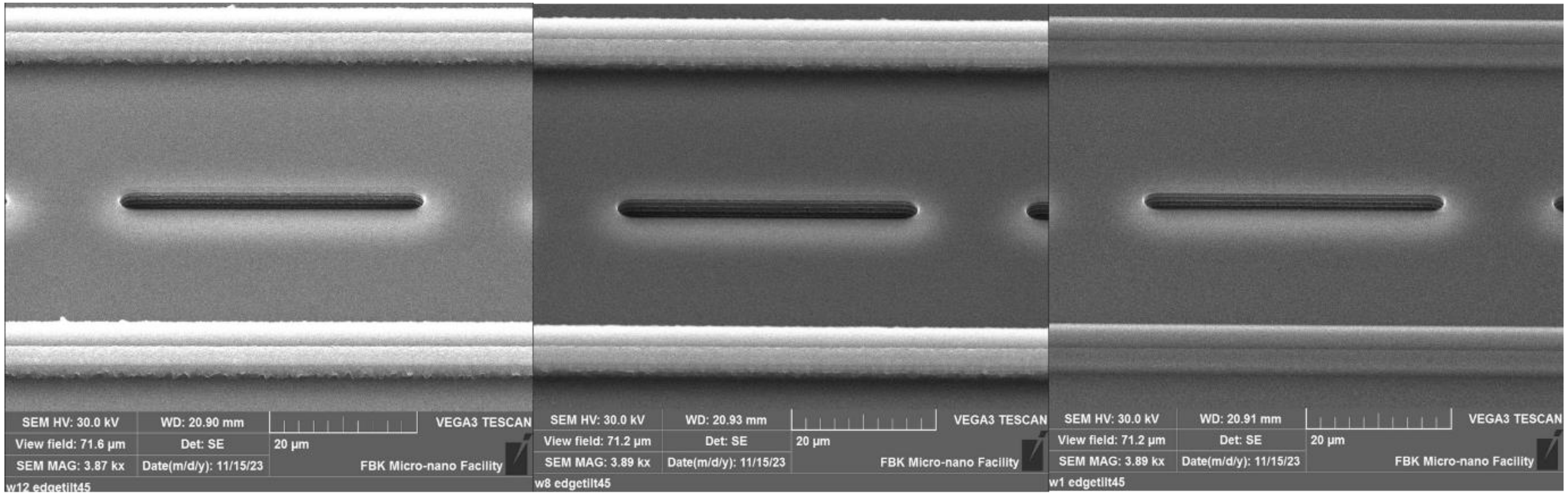
⬇

“poly cap” is less thick and smoother with the trench better closed

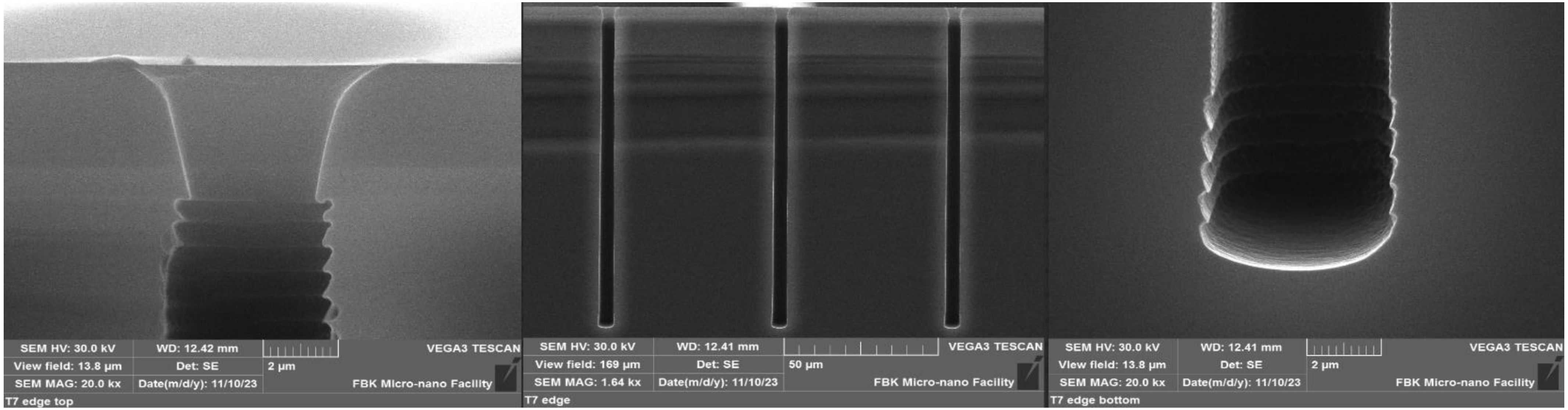


BPSG filling

N-holes after DRIE



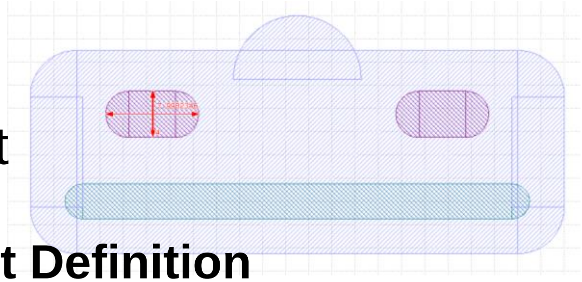
SEM tilt45: w12 Poly3000nm vs w8 Poly2500nm vs w1 BPSG (2300nm)



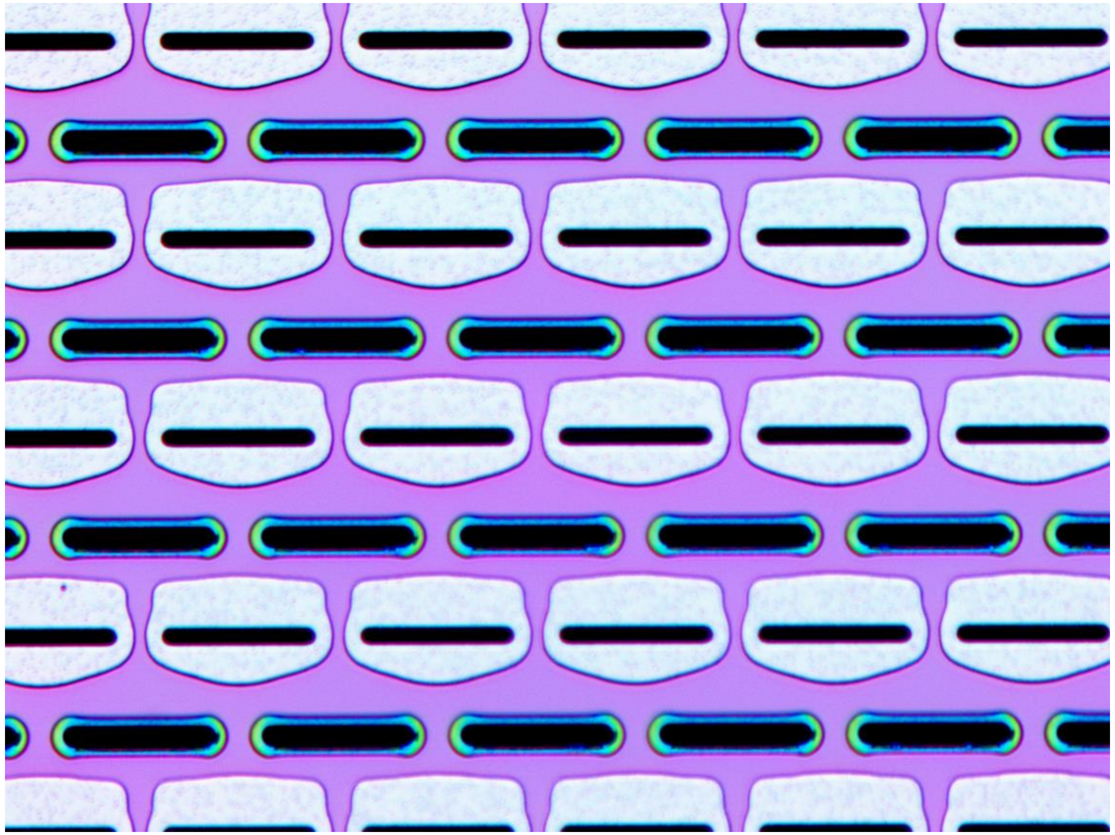
T7 - SEM inspection Nhole DRIE etch

N-Poly Litho Optimization & Contact lithography

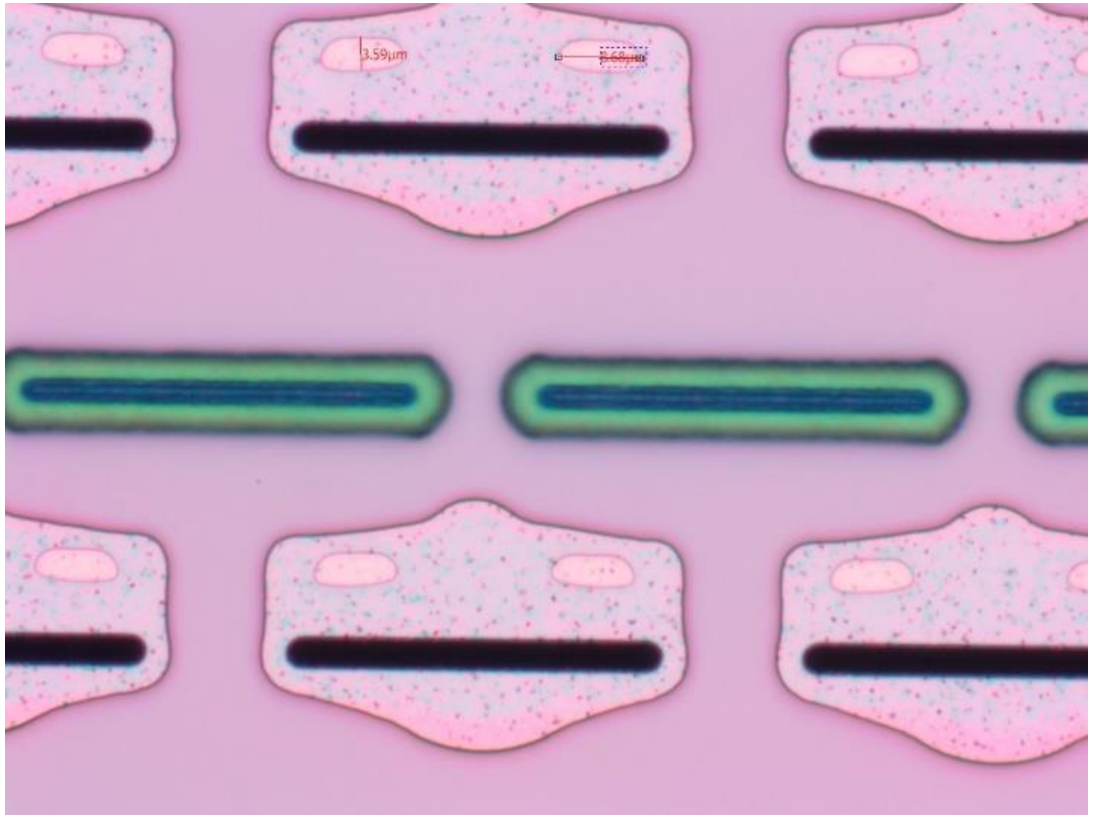
Designed pixel layout



Poly Definition



Contact Definition



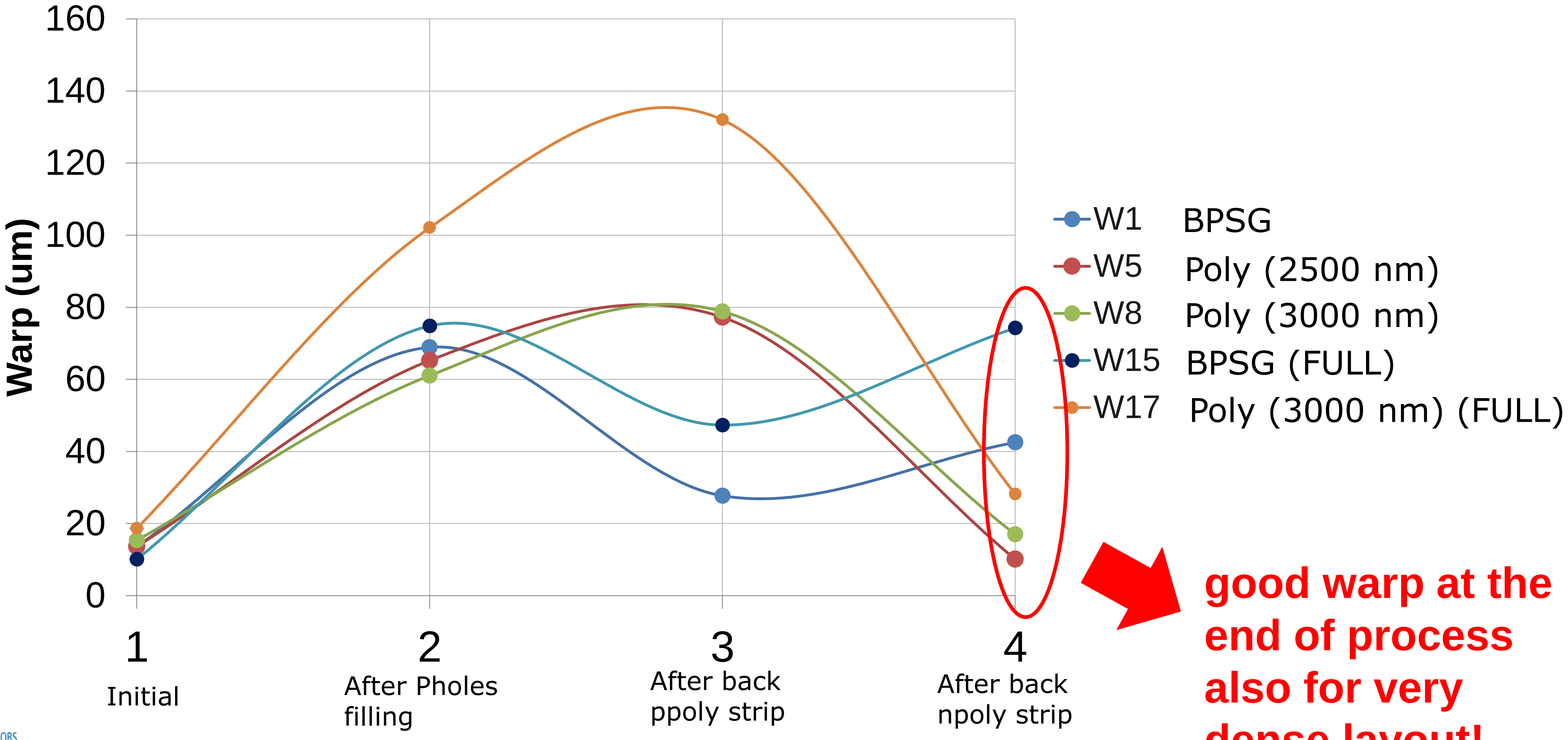
We had to accept a slight deformation, obtaining really nice frog!

Contact from 4x8 to 3.5x8.7

Ok for device!!

Warp 3D_AIDA231

(measured with MicroProf® FRT GmbH system, on a matrix of 76x73 points)



good warp at the end of process also for very dense layout!

Waiting for finish process…

We hope in a general improvement of process due to:

✓ Improvement for Trenches Etching and filling in reducing bow

✓ Improvement for Lithography processes (recipes and new equipments)

✓ Improvements for the lithographic results and for the measured bow thanks to new trenches design

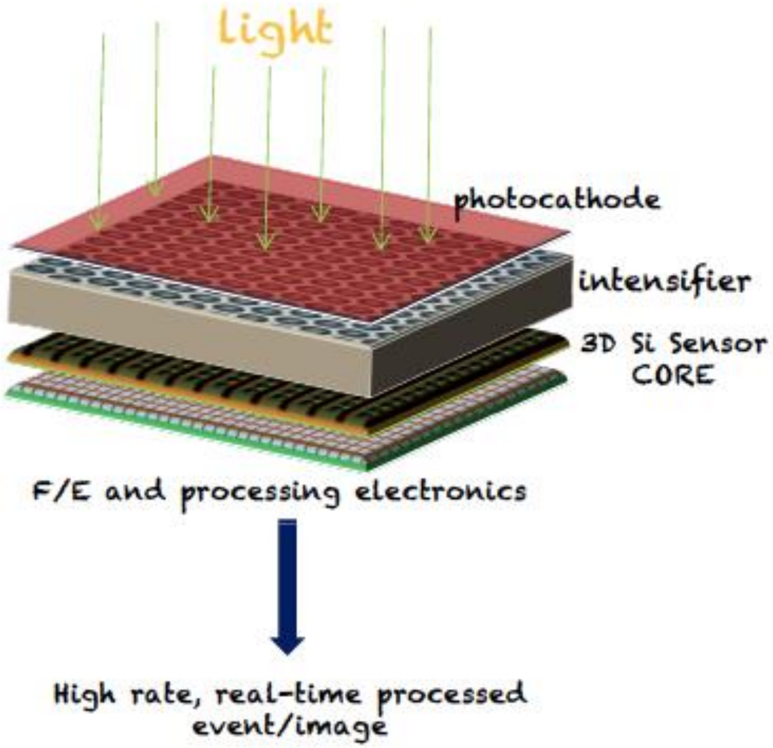
OPTIME
One–ps–Timing-using-MEMS technology

OPTIME

INFN project

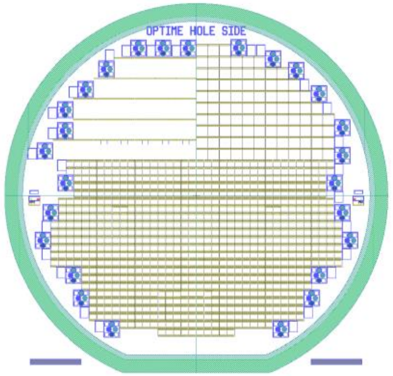
Cagliari, Torino, TIFPA (& FBK)

- The OPTIME project aims to fabricate a visible-light-sensitive device capable of a time resolution of ~1ps in single-photon detection and a concurrent space resolution below 10 µm
- The same detection mechanism can be easily extended to a wider spectrum of radiation (UV to IR, X–rays and even neutrons) by a suitable choice of a so-called converter stage
- The core of the OPTIME device is based on **3D silicon sensors** suitably designed with an optimized geometry of the sensitive volume and with the addition of a relatively low-gain multiplication stage

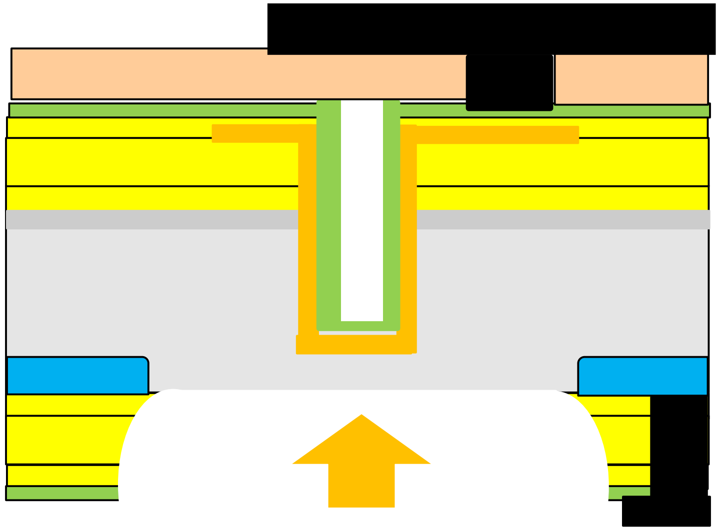


A. Lai INFN Cagliari

Main process features



- Double side process, with a Hole side and a Thin Entrance window side
- Mask Aligner lithographies
- Very deep holes
- Hole Depth splitting: 25 and 15 µm to bottom side
- Splitting on TEW on back side: implanted and not implanted



Thin Entrance window

Splitting

- 12 Wafer FZ p-type, 275 µm thick
- Holes diameter: 13 µm

Wfs (#)	**Simat label**	**TEW**	**Nominal Distance to bottom**
1	012	**implanted**	**25**
2	081		
3	082		
4	020	**implanted**	**15**
5	021		
6	008		
7	084	**not implanted**	**25**
8	073		
9	060		
10	010	**not implanted**	**15**
~~**11**~~	~~011~~		
12	005		

W11 removed for a process issue

- 2 types of TEW
- 2 different depths

Process optimization

- Thin wafers 275 um: bow control during the process
- Very deep holes:
  - ✓ enlargement of holes to allowing reach a suitable DRIE depth
  - ✓ Hole lithography optimization
  - ✓ Etching recipes
- Partial poly filling:
  - ✓ N-Poly Litho Optimization
  - ✓ Contact Litho Optimization

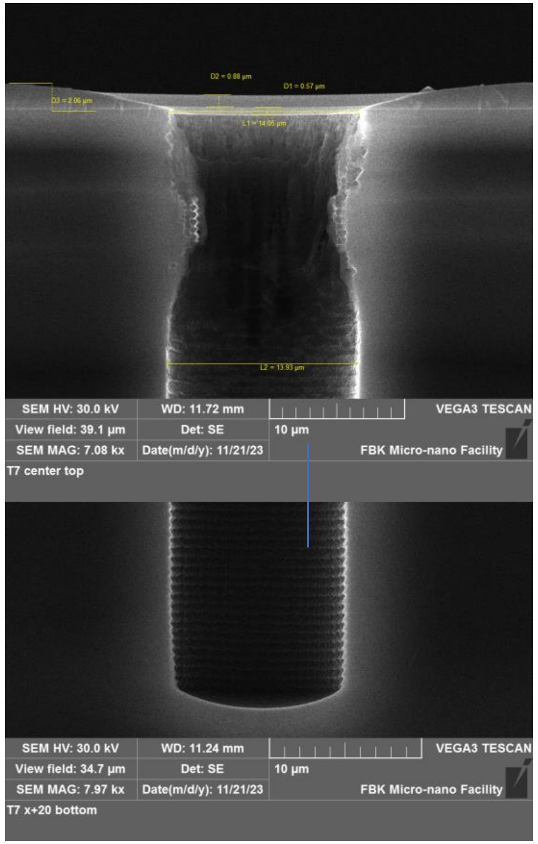
Hole etching

On 3 test wafers:

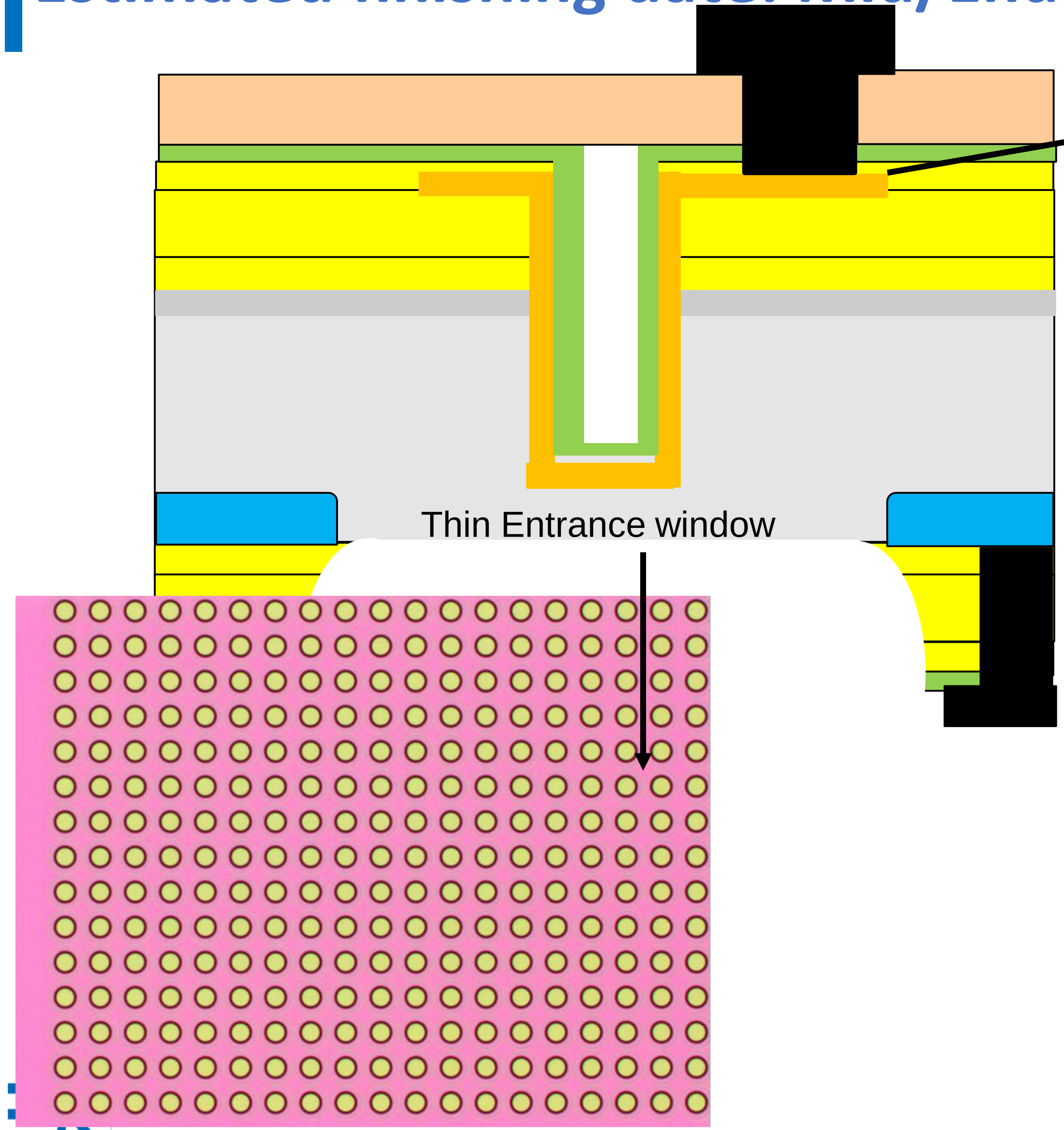
- $\Delta\langle D\rangle_{wafer} \simeq 2\ \mu m$
- $(D_{max}-D_{min})_{wafer} \simeq 6\ \mu m$
- $\Delta\langle D\rangle_{3\ wafer} \simeq 6\ \mu m$

The depths are suitably uniform, but there is a few holes with lower depth

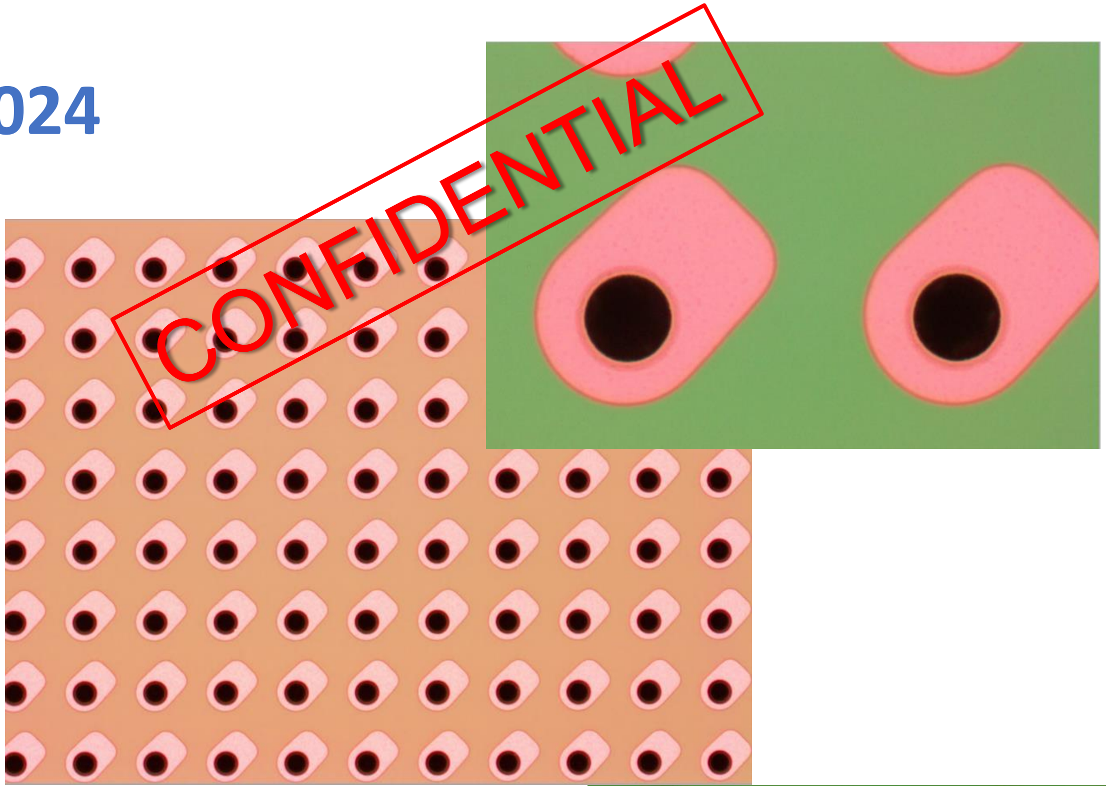
Cross section of W11



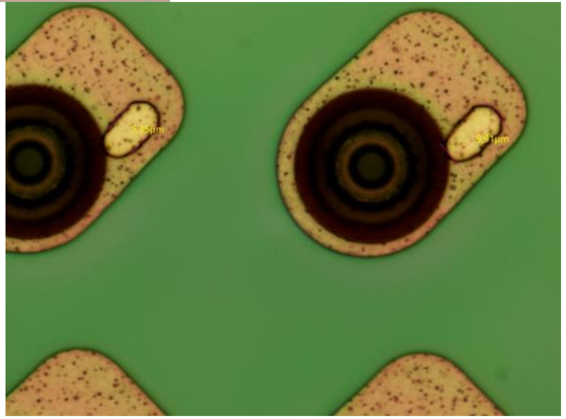
Process Status: 125/205
Estimated finishing date: Mid/End April 2024



Hole with
poly-Si
defined
around



Contacts
Lithography in
progress,
metal and
passivation
are still
missing from
the images



Conclusions

- 3D Detectors for both ATLAS and CMS experiments are in production
  - Excellent results have been obtained from a constant study of critical issues and finding new solutions
  - Evident Increase in yield over the years
- Continuing development of 3D sensors based on trenches
- 3D Optime batch: an example of continuous research at FBK into new projects and applications for 3D sensors

Thanks for your attention!!!

FONDAZIONE BRUNO KESSLER

FUTURE BUILT ON KNOWLEDGE

AIDA innova

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OPTIME

INFN project

Cagliari, Torino, TIFPA (& FBK)

Bow and warp

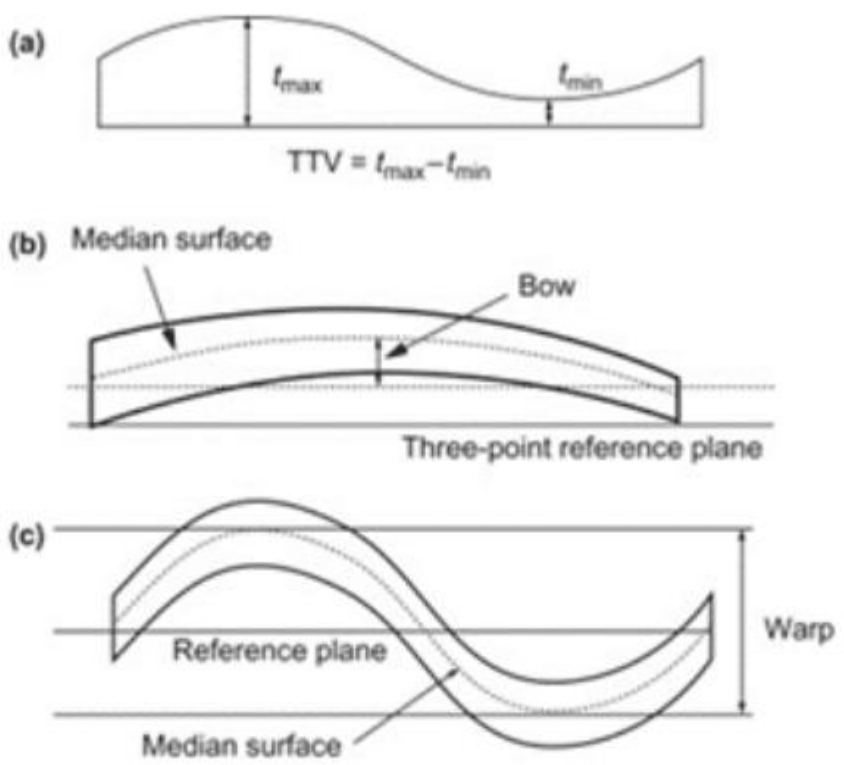

Fig 1 Representation of Wafer TTV, Bow and Warp