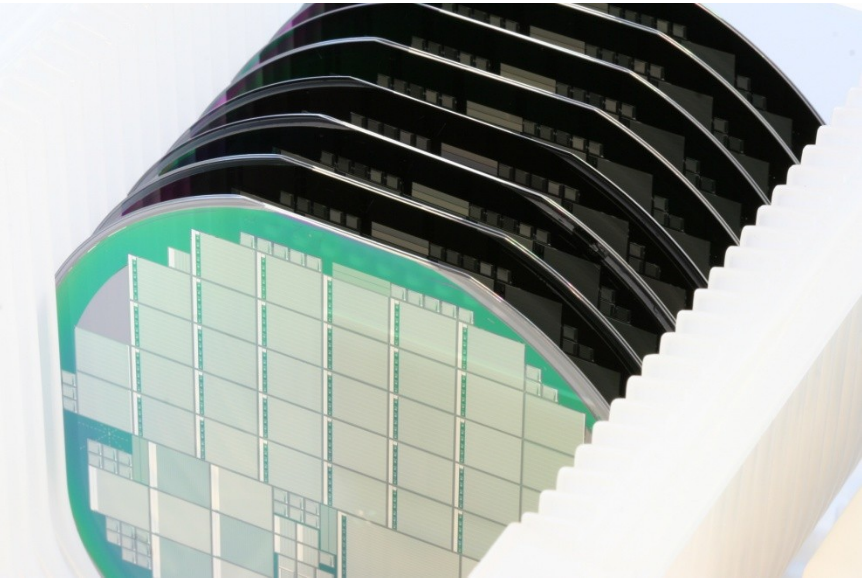
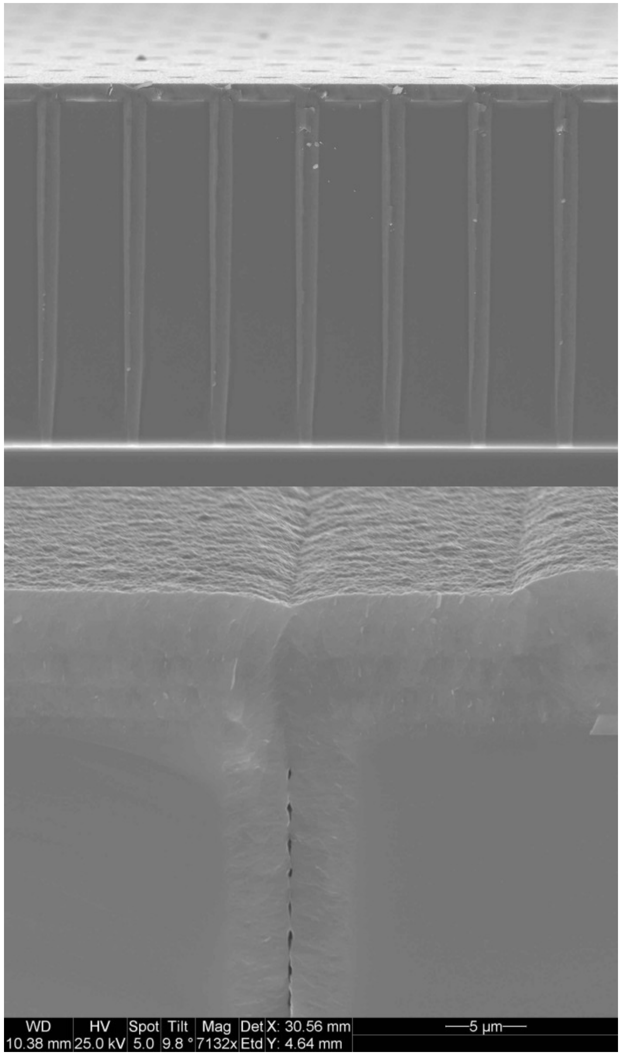
Fabrication of Full 3D Active Edge Sensors





The Stanford Nanofabrication Facility

SINTEF

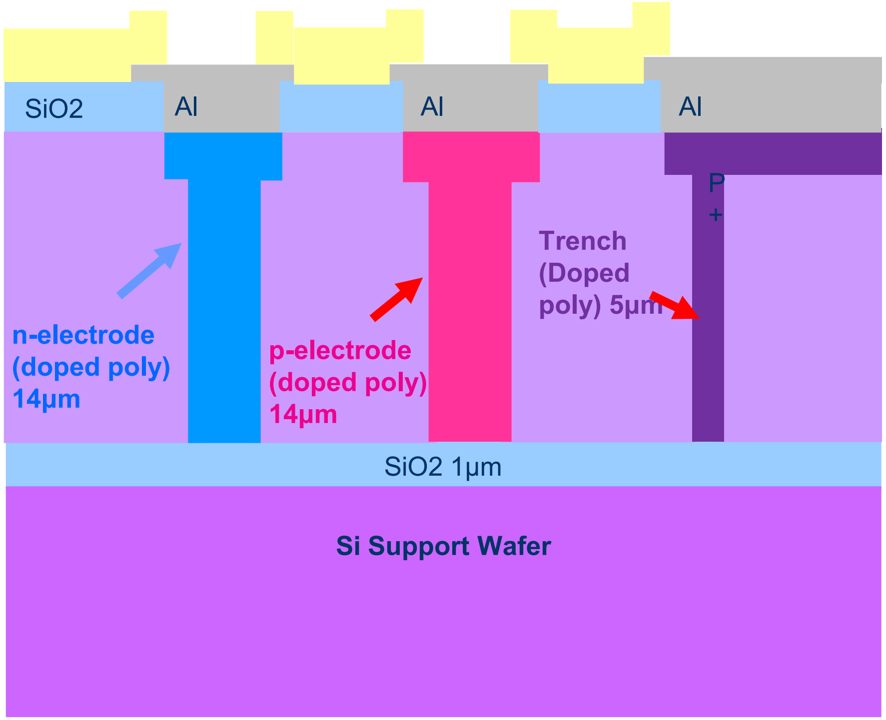
Angela Kok et al

SINTEF - Oslo, Norway

Fabrication of full 3D active edge sensors

- Introduction
- Technology
  - fusion bonding
  - DRIE
  - Polysilicon deposition
- Overall fabrication steps
- Fabrication results in the first two prototype run
  - Processing
  - Yield
  - Test results
- Processing results from current run
- Yield factor issues

Introduction



3D silicon detectors

- by S. Parker in 1995

Combination of traditional **VLSI** processing and **MEMS** (Micro Electro Mechanical Systems) technology

Electrodes are processed inside the detector bulk instead of being implanted on the wafer's surface.

Active edges

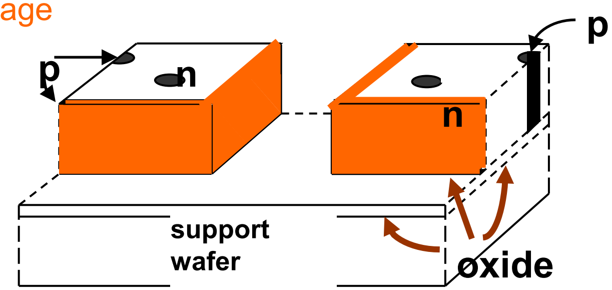
- by C. Kenney in 1997

The edge is an electrode!

Dead volume at the Edge < 2 microns! Essential for

-Large area coverage

-Forward physics

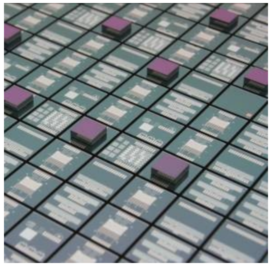


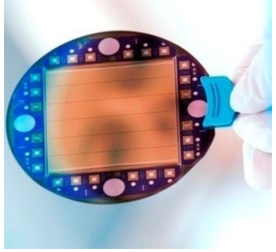
1. NIMA 395 (1997) 328
2. IEEE Trans Nucl Sci 464 (1999) 1224
3. IEEE Trans Nucl Sci 482 (2001) 189
4. IEEE Trans Nucl Sci 485 (2001) 1629
5. IEEE Trans Nucl Sci 48 6 (2001) 2405
6. CERN Courier, Vol 43, Jan 2003, pp 23-26
7. NIM A 509 (2003) 86-91
8. NIM A 524 (2004) 236-244
9. NIM A 549 (2006) 127
10. NIM A 560 (2006) 272
11. IEEE TNS 53 (2006) 1676
12. NIM A 587 (2008) 243-249

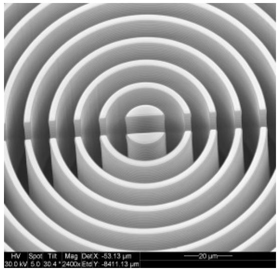
Technology required : Wafer bonding, DRIE and polysilicon deposition

SINTEF MiNaLab (Micro- and Nanotechnology Laboratory)

- Shared facility for the University of Oslo and SINTEF with two separate clean room floors:
  SINTEF: 800 m^2
  University of Oslo: 600 m^2
- SINTEF:
  - **Silicon production line with capacity of 10.000 150 mm wafers**
  - **100 mm and 150 mm wafers**
  - **Microenvironments with class 10**
- The most advanced laboratory in Norway for micro- and nanotechnology, situated on the campus of UiO
- 3D Consortium formed in 2006 primarily with Chris Kenney et al. to transfer 3D to a more production environment

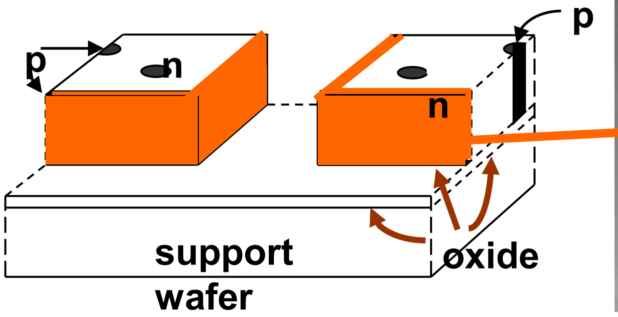




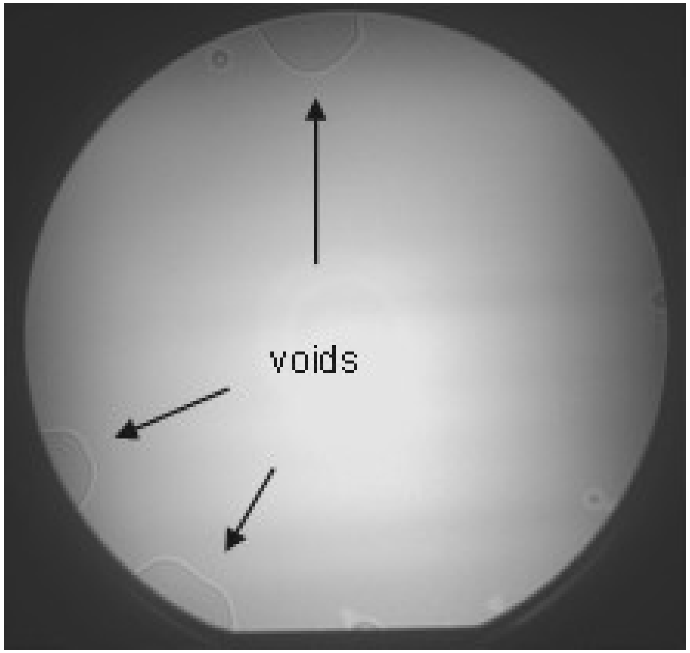


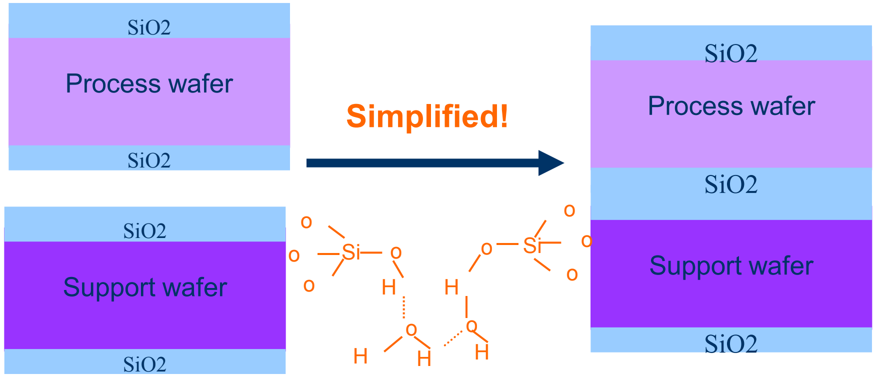
Wafer fusion bonding

- Support wafer essential to fabricate active edge
- Relieve stress and provide support
- Fusion boding
- Oxide to oxide bonding
- High temperature annealing
- Voids affect overall yield



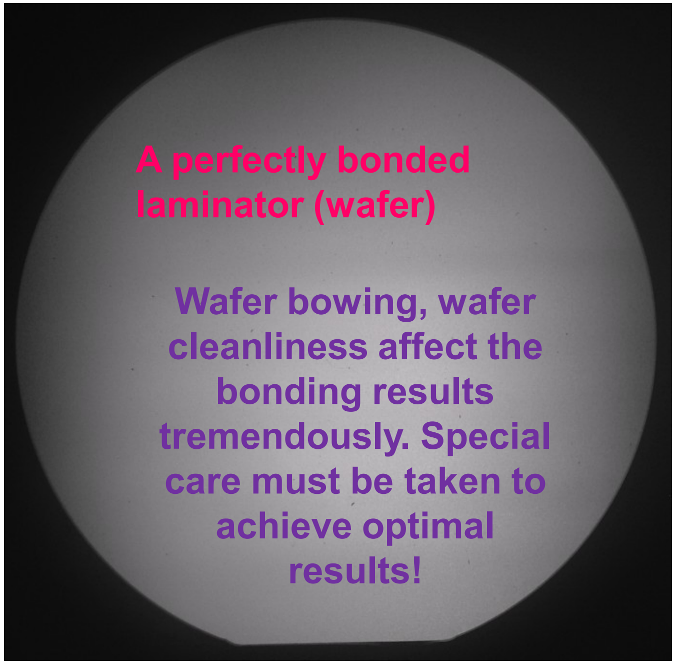
Chips sit on top of a void can fall off – yield issue





Hydrophilic surfaces prepared by a RCA and a piranha rinse

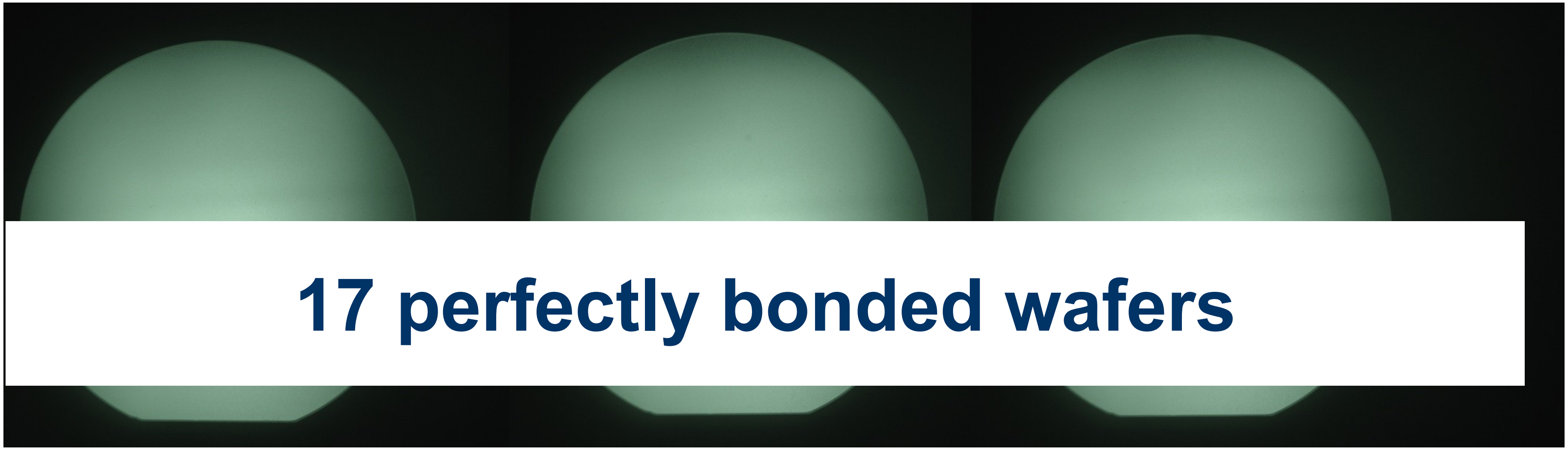
Pre-bonding in a SUSS bonder SB6 at 50°C, follow by high temp annealing



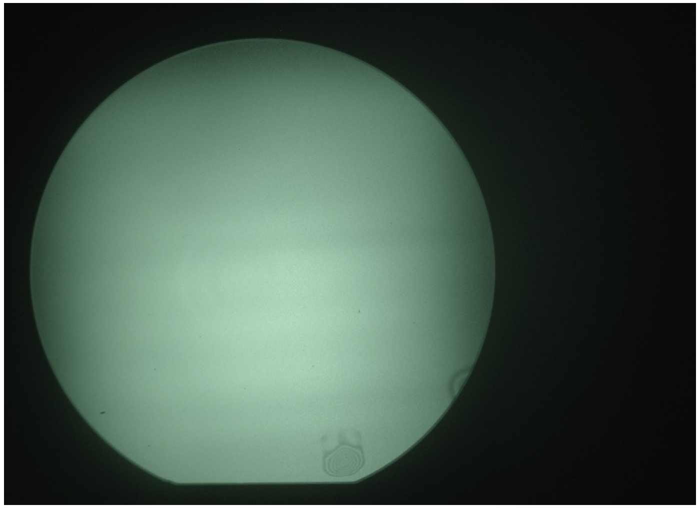
A perfectly bonded laminator (wafer)

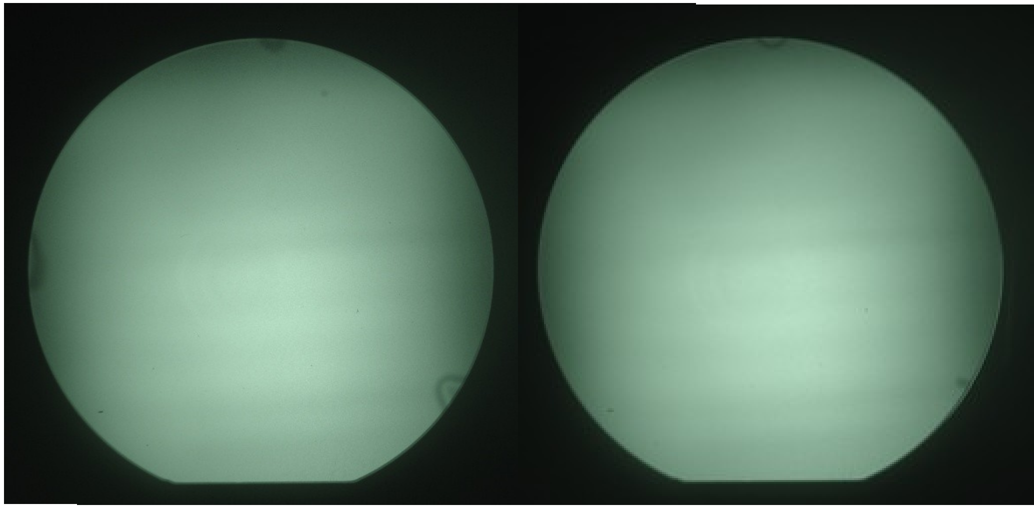
Wafer bowing, wafer cleanliness affect the bonding results tremendously. Special care must be taken to achieve optimal results!

Bonding results from latest batch



17 perfectly bonded wafers

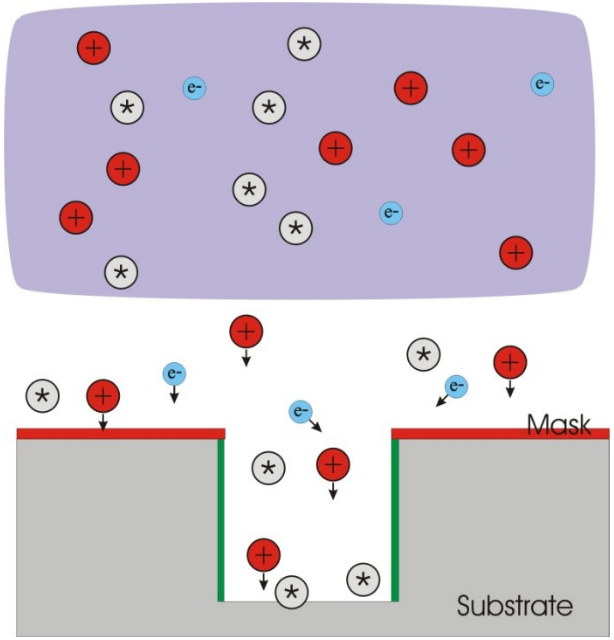


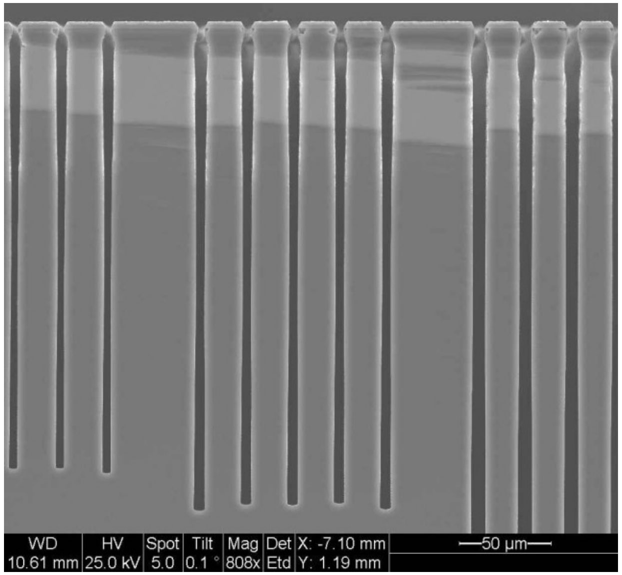


3 wafers with defects/voids

5 wafers with very small defects along the edges

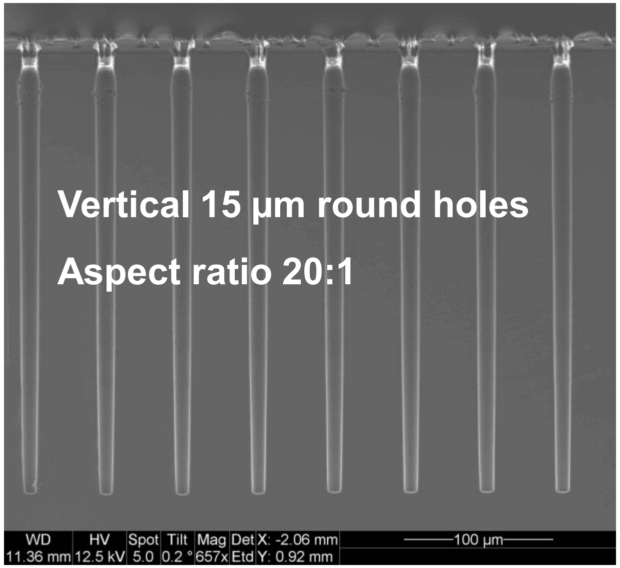
Deep Reactive Ion Etching



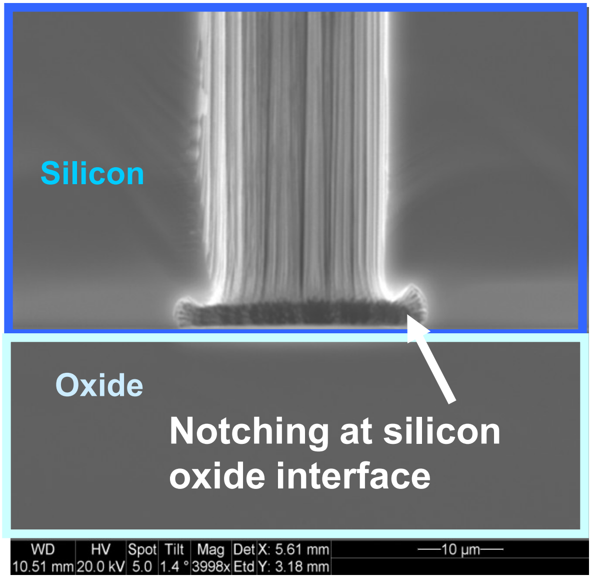


- Alcatel AMS-200
  - Key technology for 3D silicon
  - Vertical sidewalls passivated by polymer(C4F8)
  - Radicals etch exposed substrate (SF6)
  - Aluminium has excellent selectivity
  - Aspect ratio up to 50:1 (depending on size of openings)

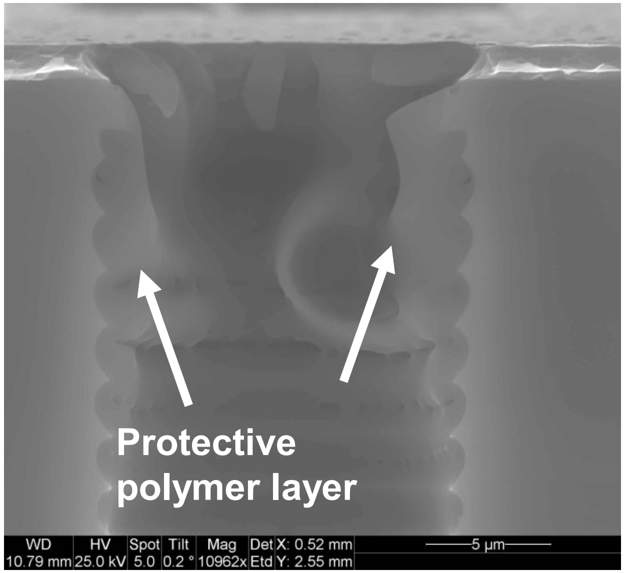
Deep Reactive Ion Etching

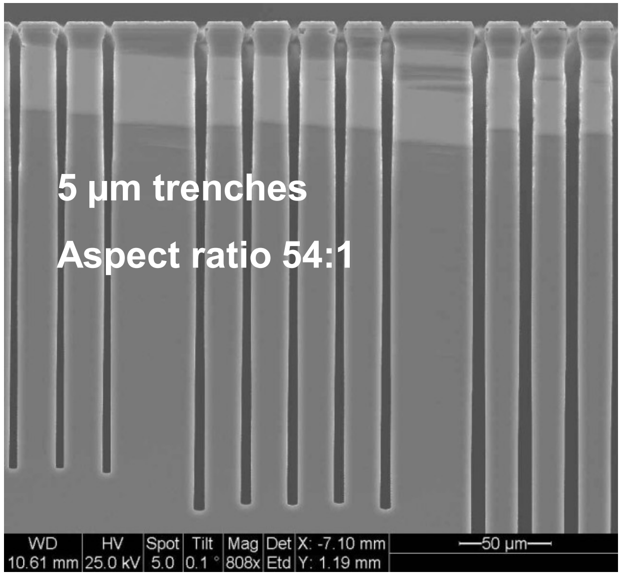

Vertical 15 µm round holes

Aspect ratio 20:1

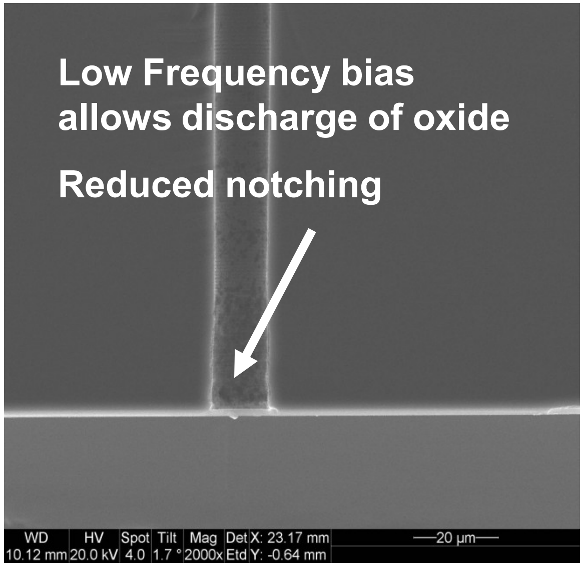


Notching at silicon oxide interface

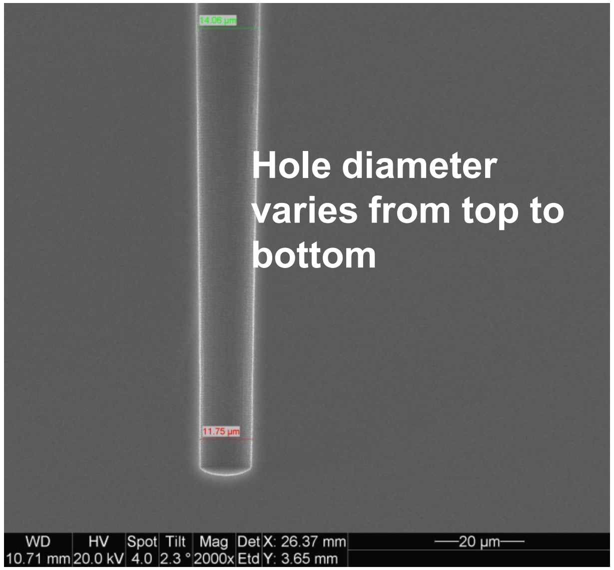

Protective polymer layer


5 µm trenches

Aspect ratio 54:1

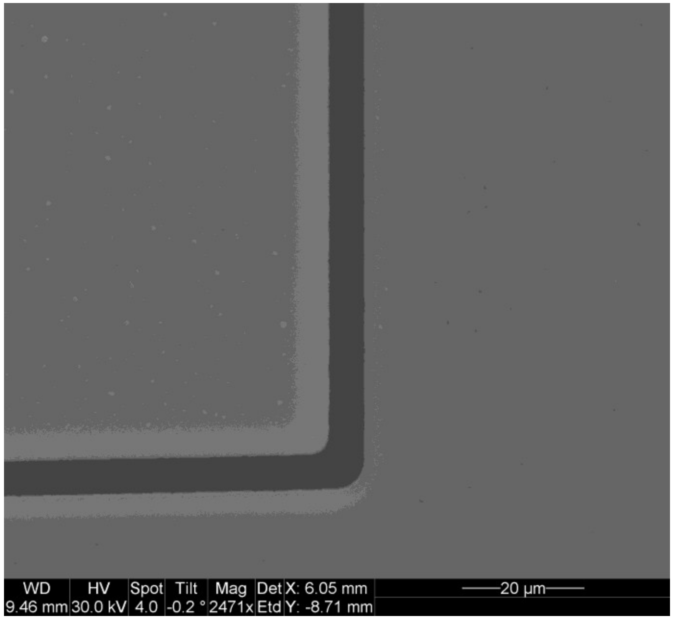

Low Frequency bias allows discharge of oxide

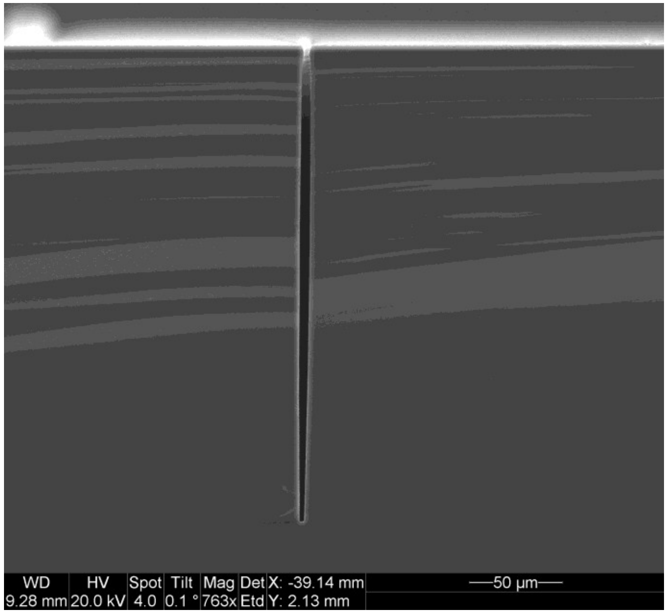
Reduced notching

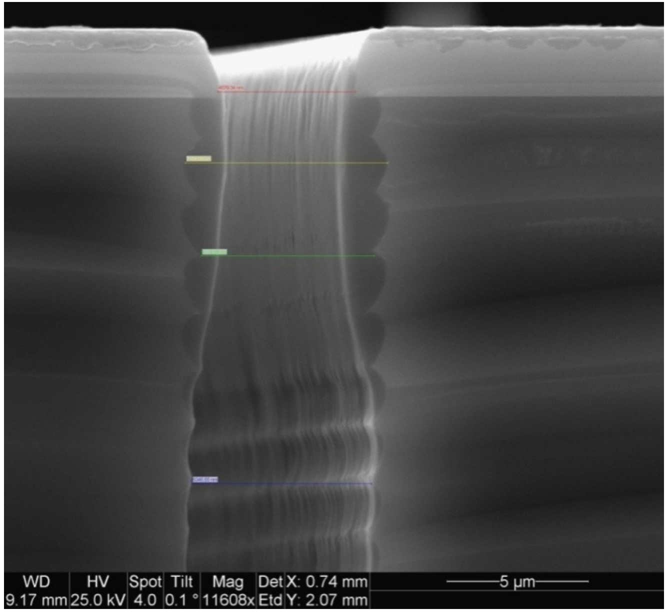

Hole diameter varies from top to bottom

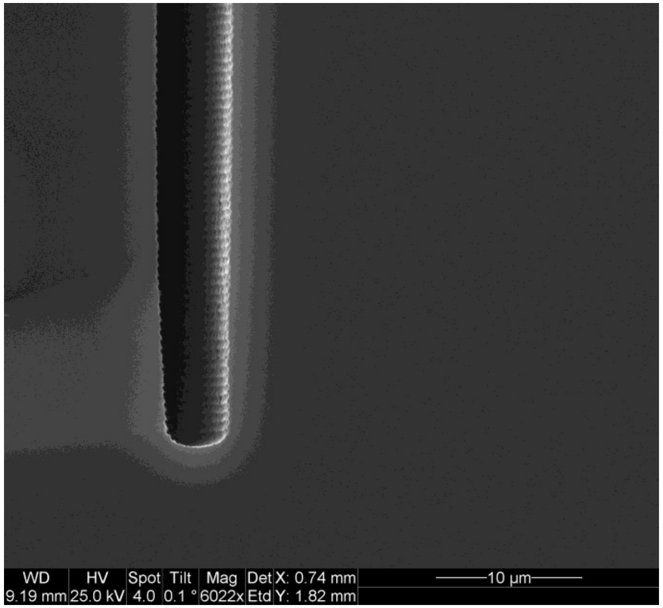
**IEEE Nuclear Science Syposium 2009 N25-164*

DRIE results of active edges/trenches









FILLING AND DOPING THE HOLES

The holes can be filled with doped gas molecules at low pressure and moderate temperatures to form p & n electrodes within the detector.

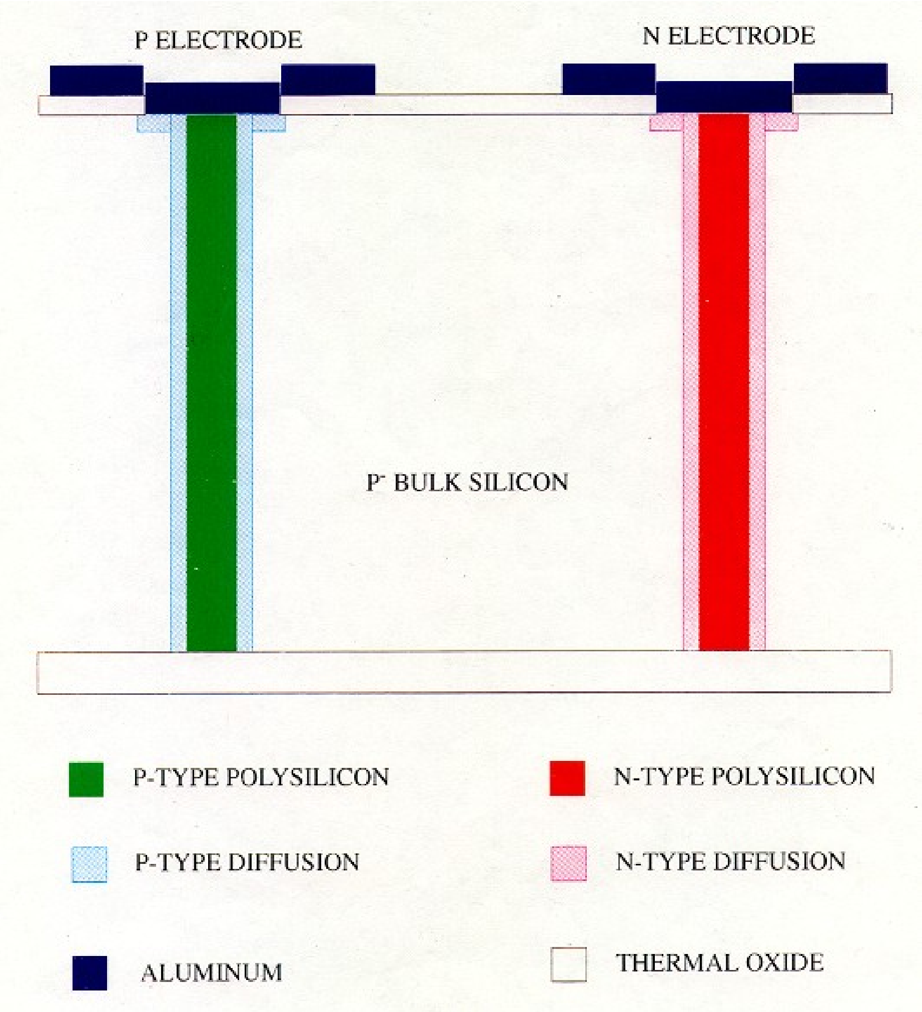
- **POLYCRYSTALLINE SILICON** IS DEPOSITED IN A LOW PRESSURE CHEMICAL VAPOUR DEPOSITION (LPCVD) USING A THERMAL DECOMPOSITION OF SILANE.

$$SiH_4 \xrightarrow{600^\circ C} Si + 2H_2$$

- **DOPED** WITH EITHER BORON OR PHOSPHOROUS TO PRODUCE EITHER N OR P-TYPE ELECTRODES

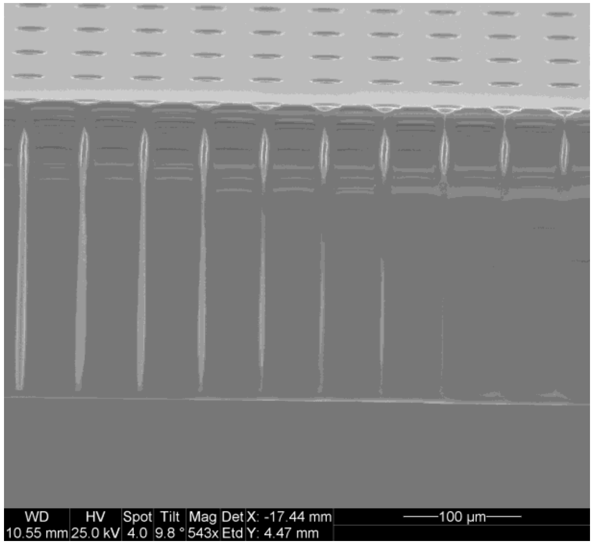
$2P_2O_5$ +5 Si-> 4P + 5 SiO_2
$2B_2O_3$ +3Si -> 4 B +3 SiO_2

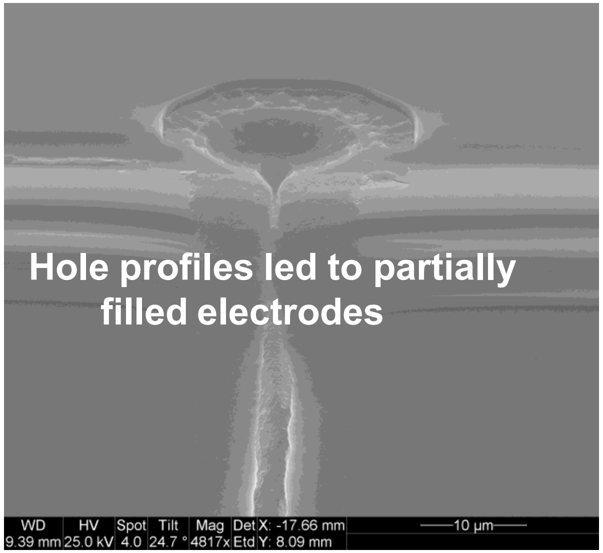
- **ANNEALING** FOLLOWS, IN WHICH THE DOPANTS ARE DIFFUSED INTO THE SURROUNDING SINGLE CRYSTAL SILICON FORMING PN JUNCTIONS

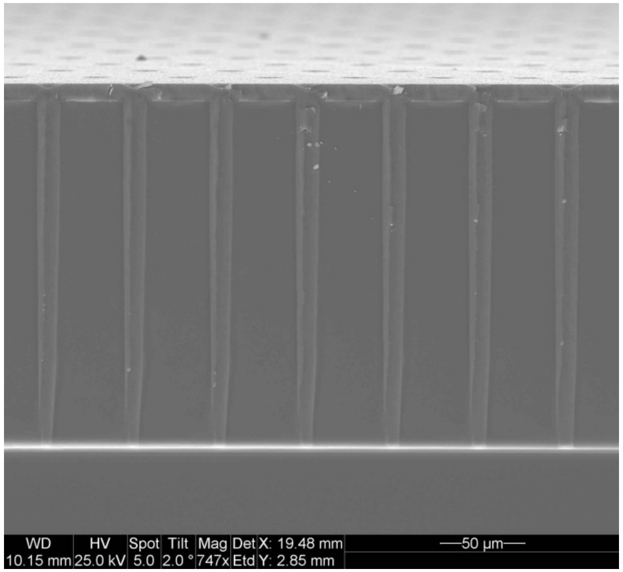


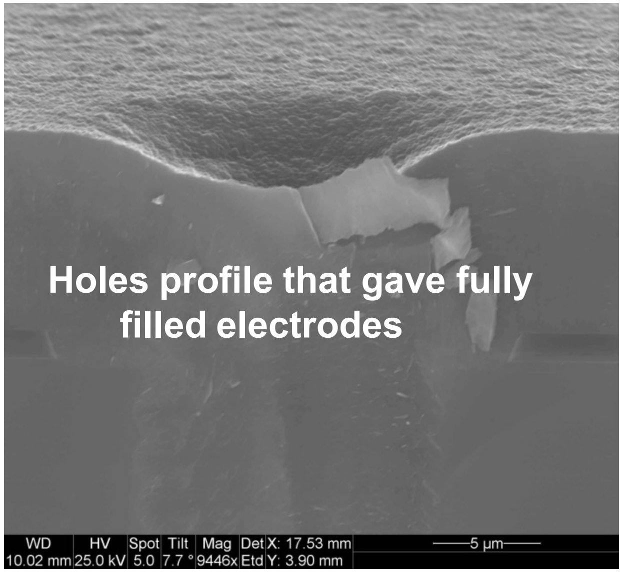
* C. Kenney, J. Hasi (SLAC)

FILLING AND DOPING THE HOLES

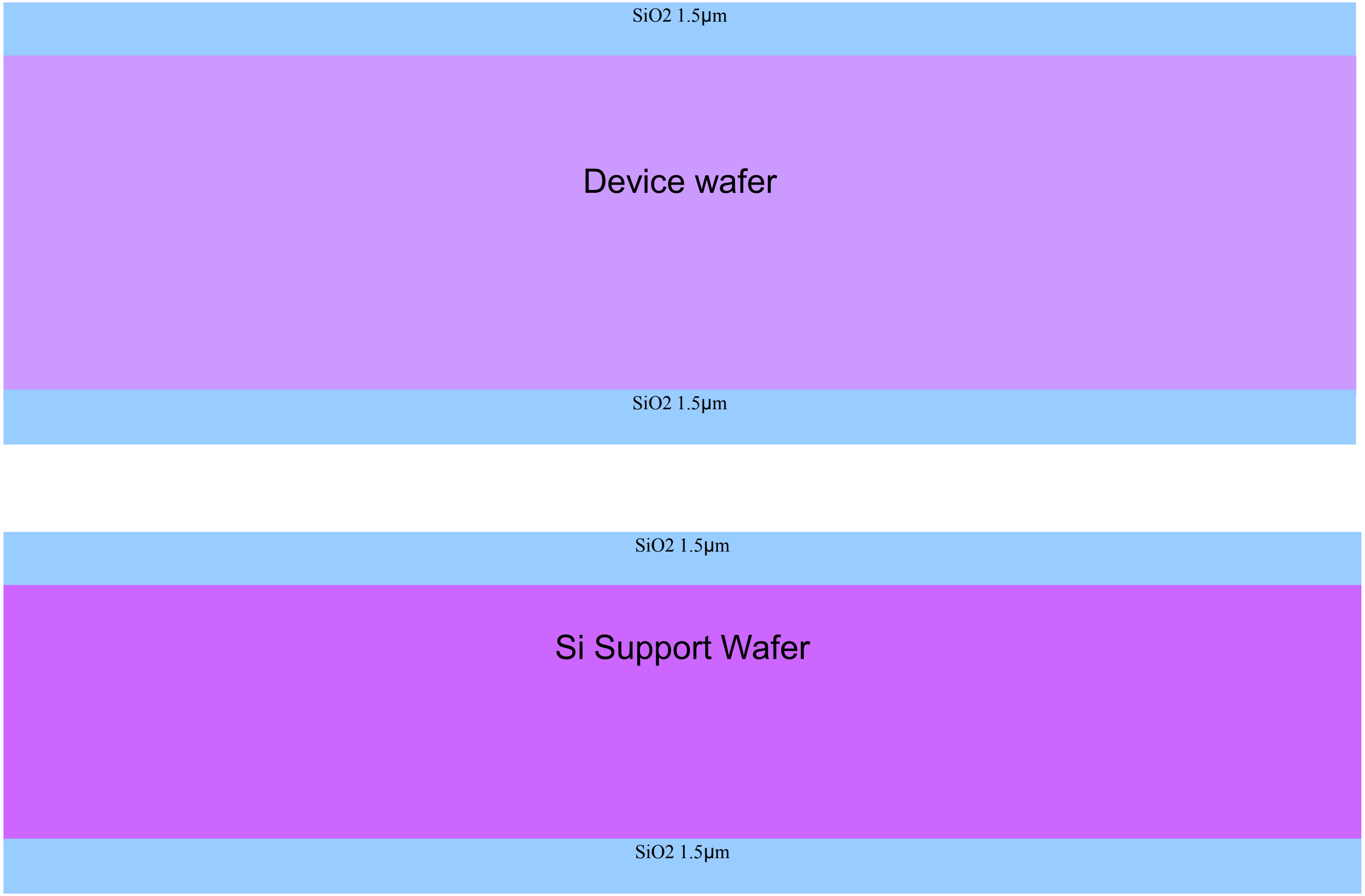



Hole profiles led to partially filled electrodes




Holes profile that gave fully filled electrodes

3D Detector – Fabrication Steps (1)



SiO2 1.5µm

Device wafer

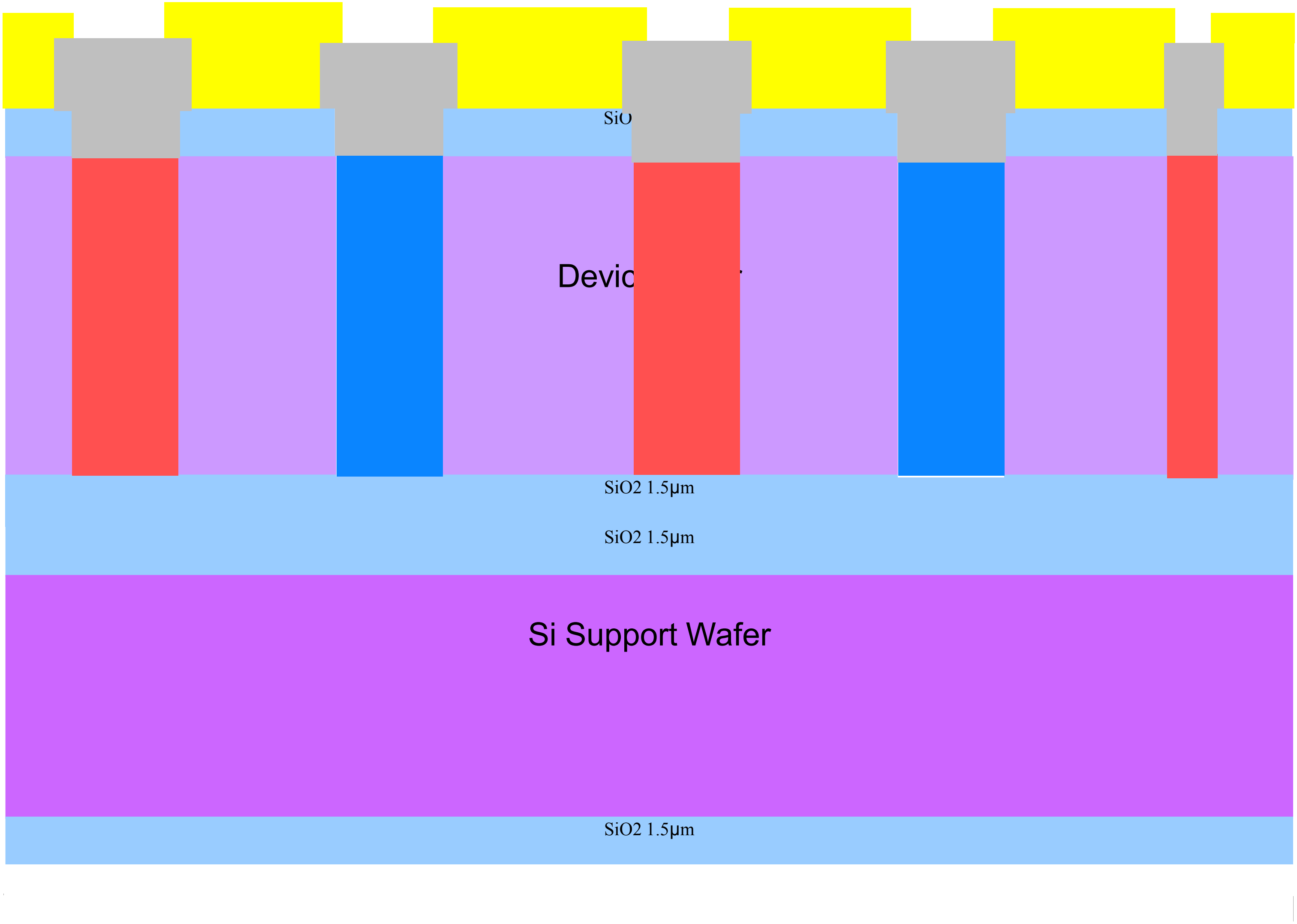
SiO2 1.5µm

SiO2 1.5µm

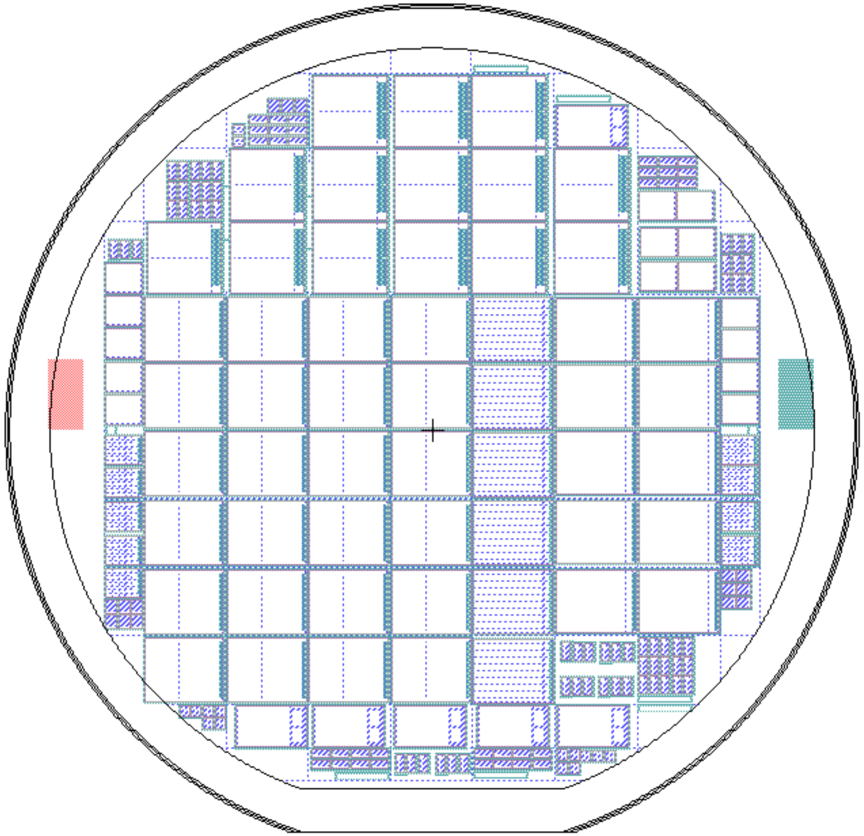
Si Support Wafer

SiO2 1.5µm

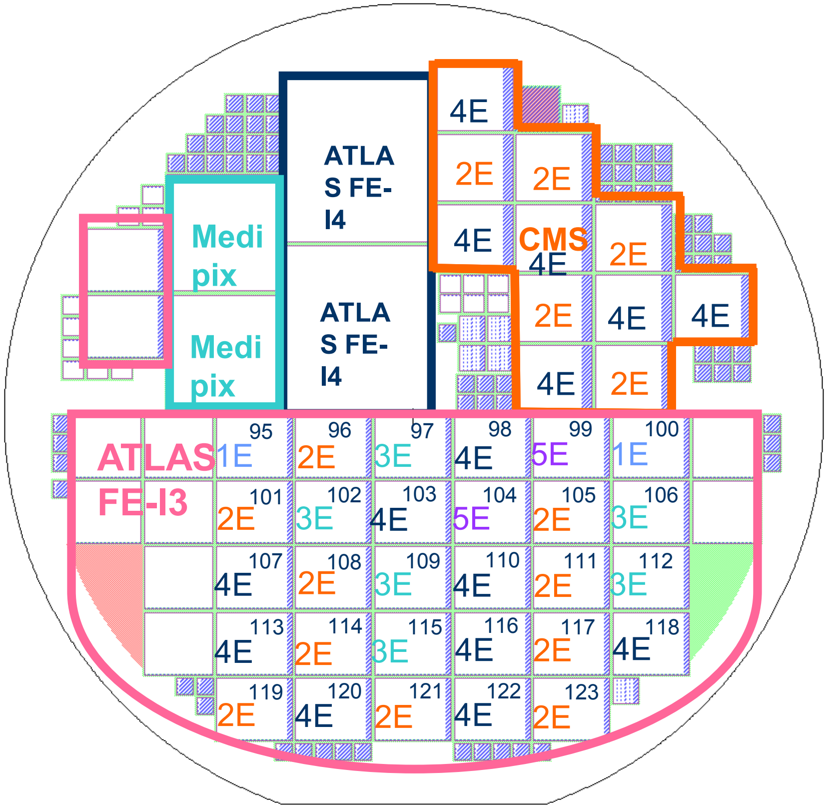
3D Detector – Fabrication Steps



Design layout for the first two prototype runs

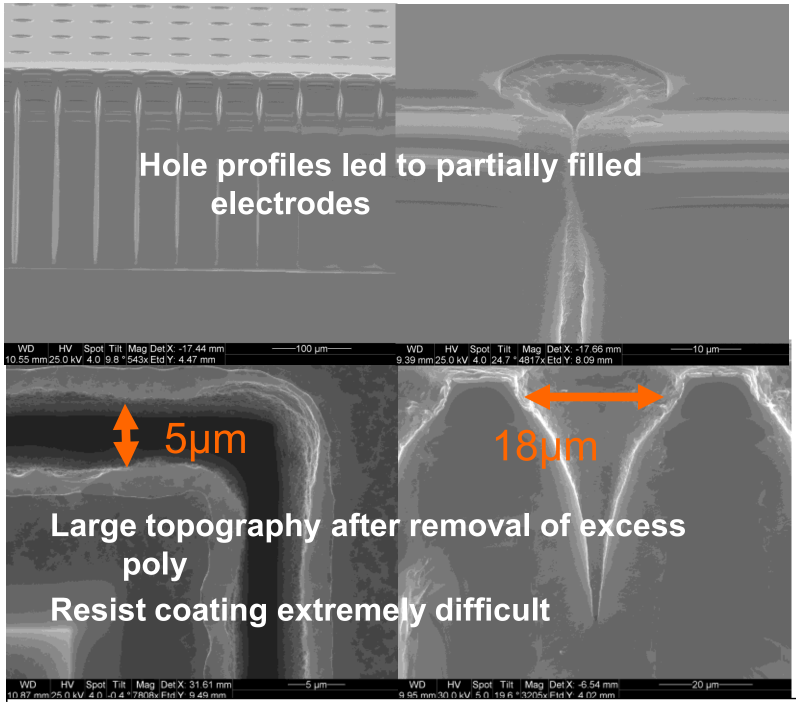


Series A – only small FE-I3



Series B –FE-I3, FE-I4, CMS

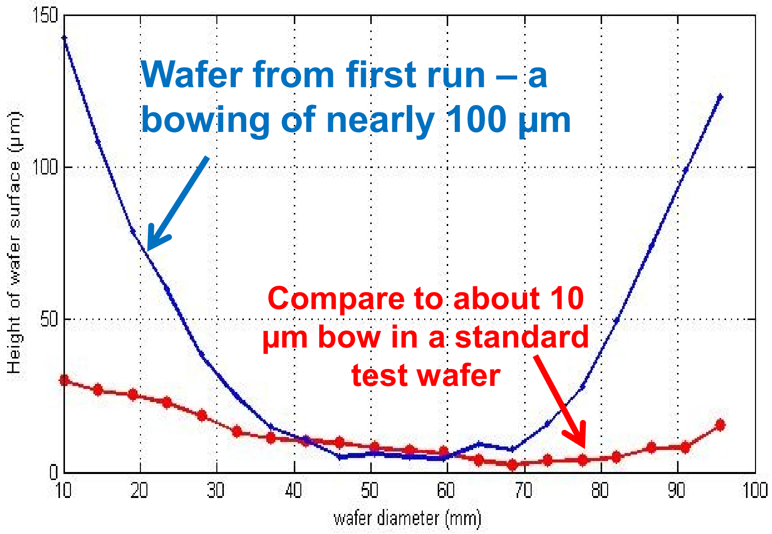
Issues in the first SINTEF fabrication



Hole profiles led to partially filled electrodes

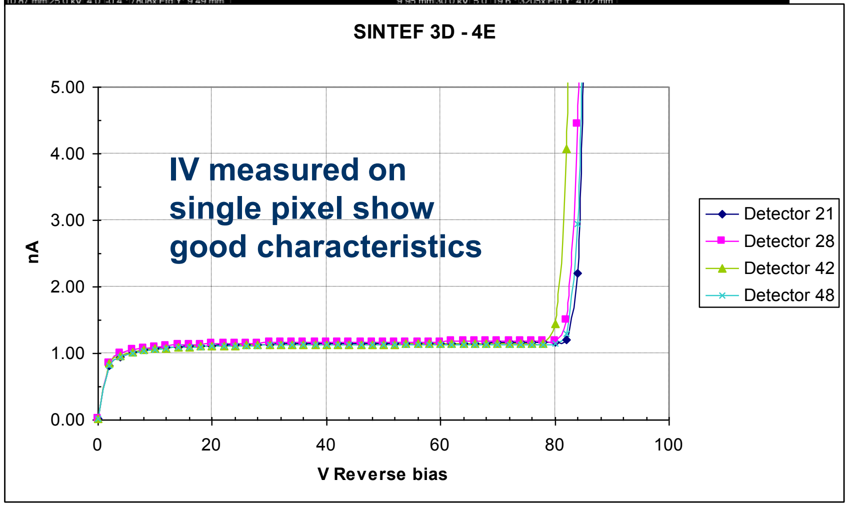
Large topography after removal of excess poly

Resist coating extremely difficult

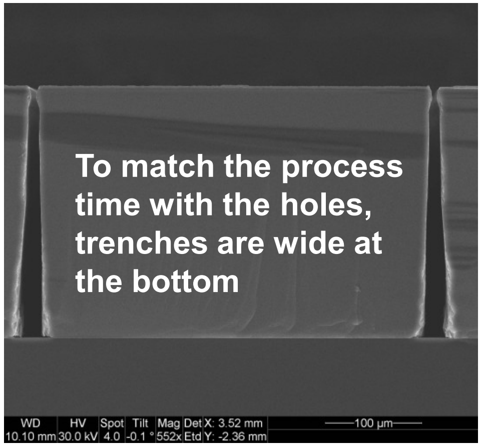


Wafer from first run – a bowing of nearly 100 µm

Compare to about 10 µm bow in a standard test wafer



IV measured on single pixel show good characteristics



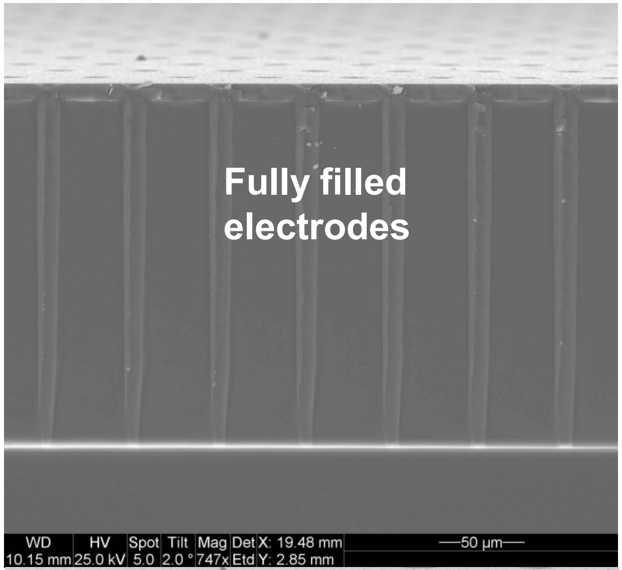
To match the process time with the holes, trenches are wide at the bottom

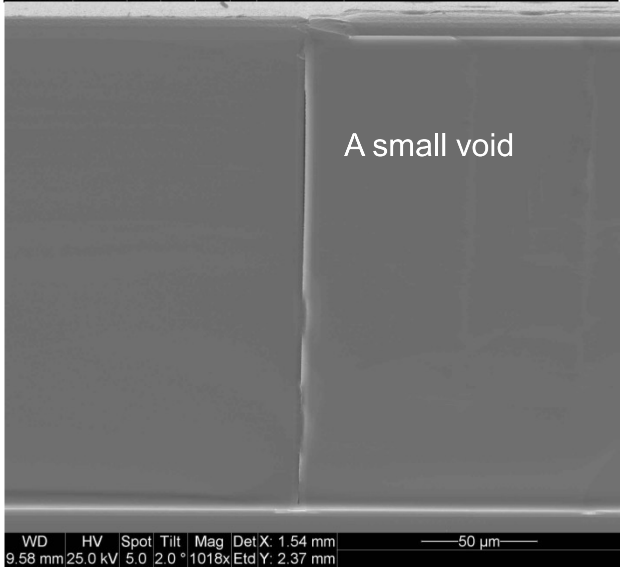
- Wafer breakage
- Difficult lithography
- Unfilled electrodes
- Wide trenches
- Extremely low yield

Improvements in second run

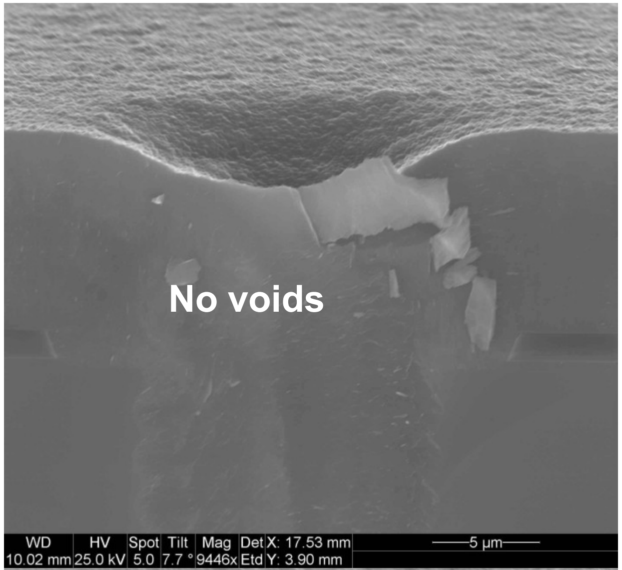
- By changing the hole profiles
- HOLES are fully filled
- Surfaces are reasonably flat
- Better yield in lithography

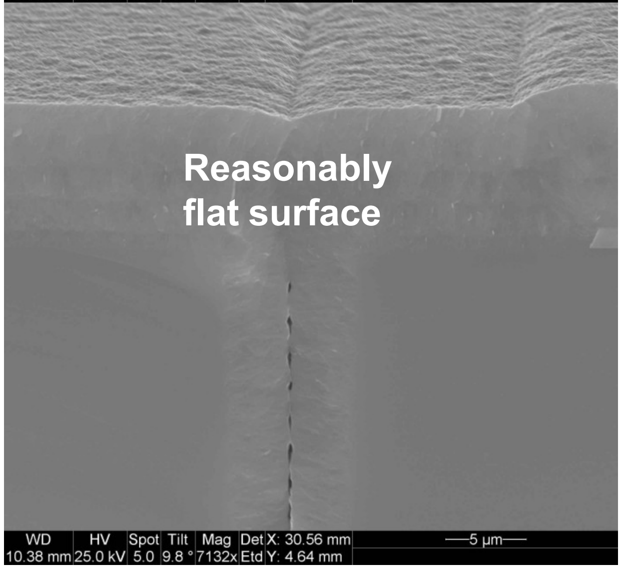
After polyfilling


Fully filled electrodes


A small void

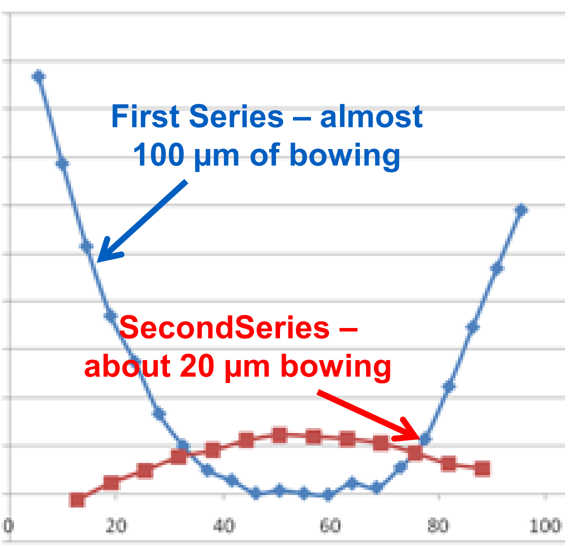
After polyfilling


No voids


Reasonably flat surface

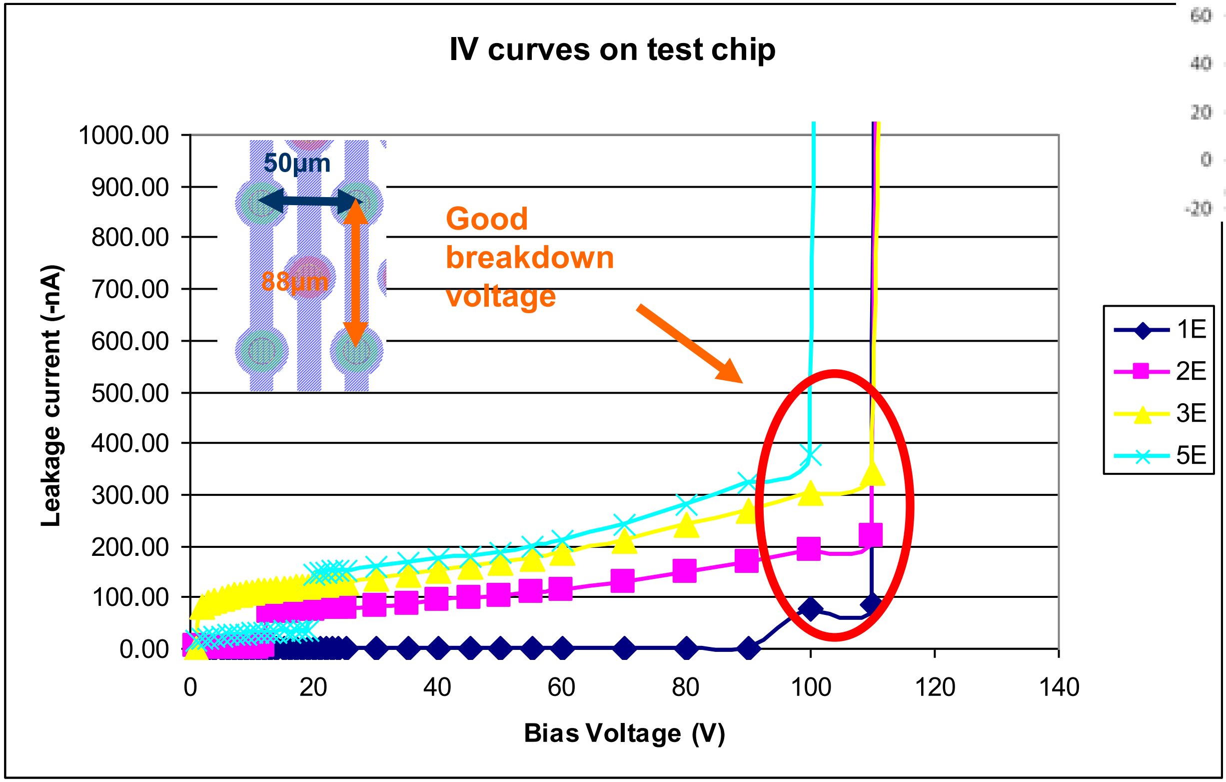
Improvements in second run

- Bowing reduce to less than 20 µm
- Wafer yield increased to 90%



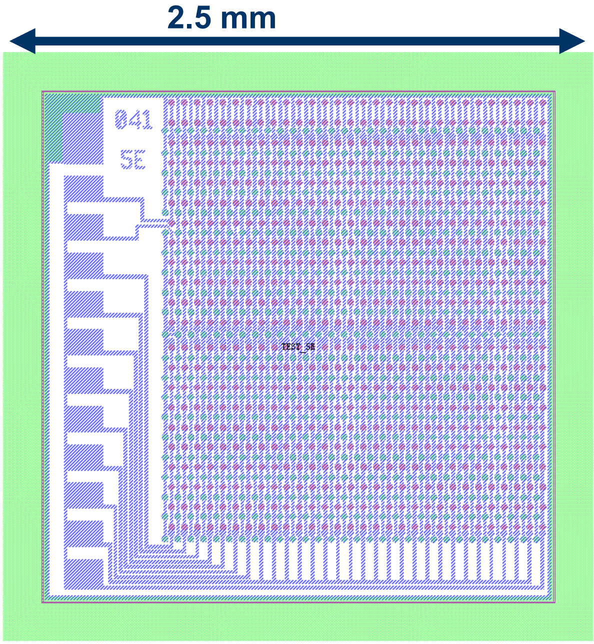
First Series – almost 100 µm of bowing

SecondSeries – about 20 µm bowing



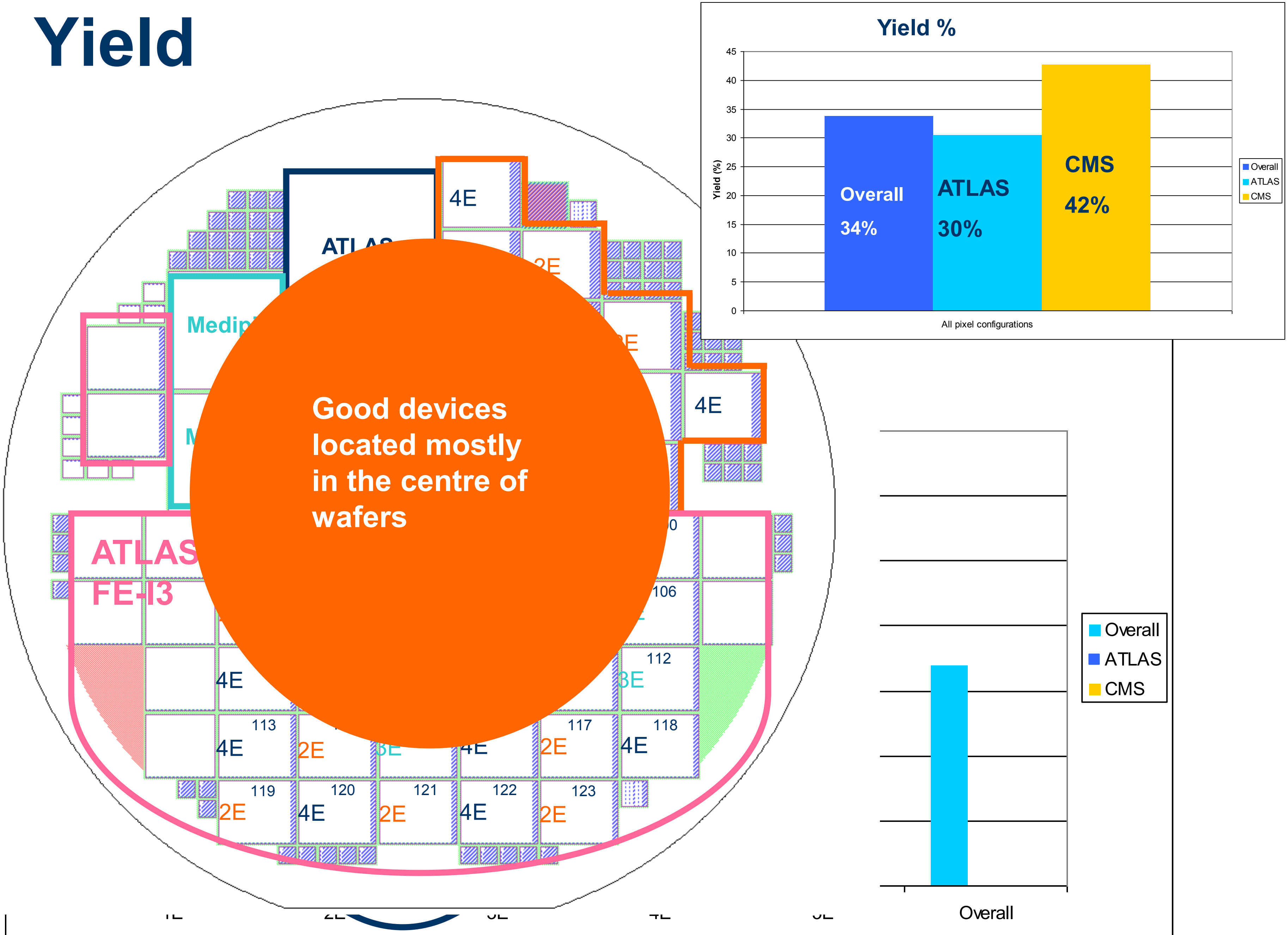
IV curves on test chip

Good breakdown voltage



2.5 mm

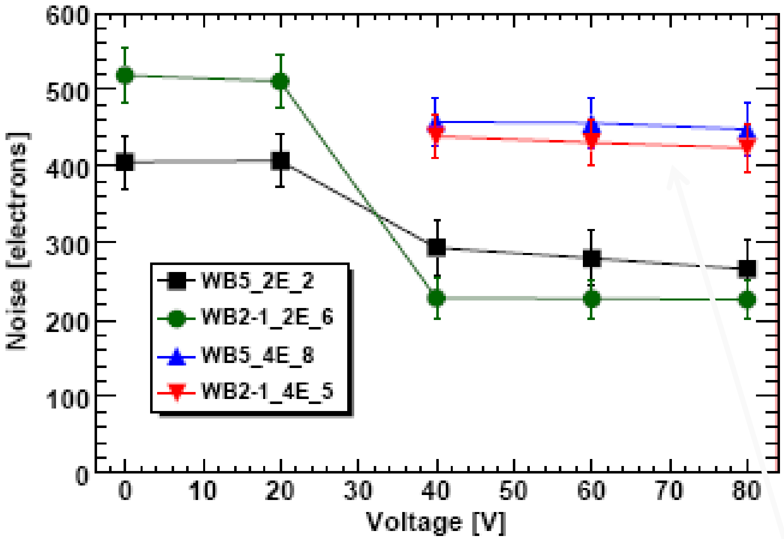
Yield

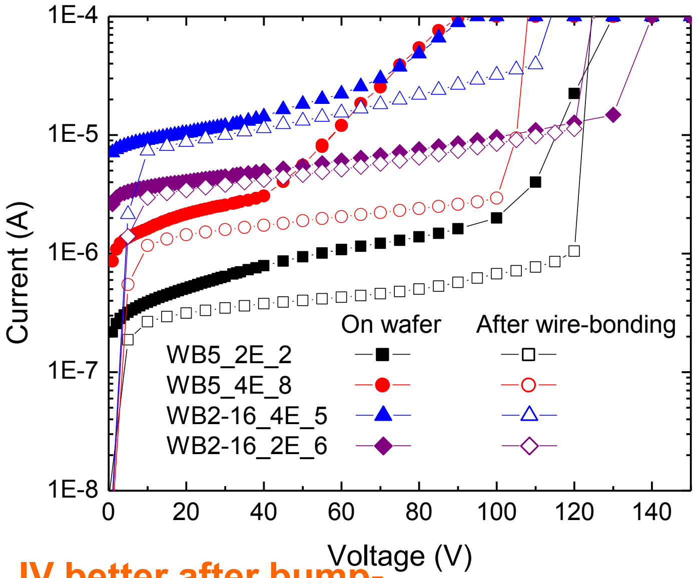


Good devices located mostly in the centre of wafers

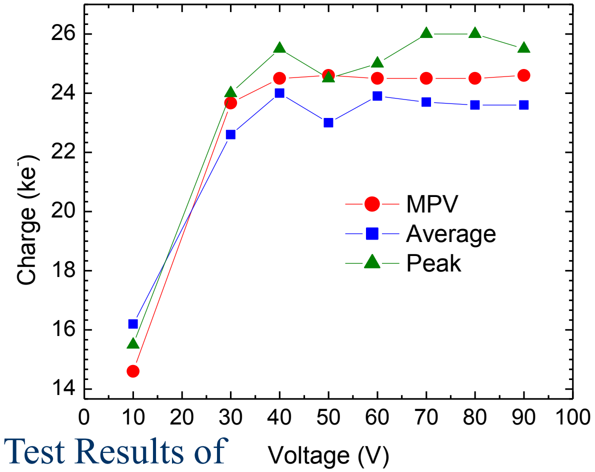
CMS Sensors

- See Ozhan Koybasi's talk





IV better after bump-bonding, MOS effect of test metal



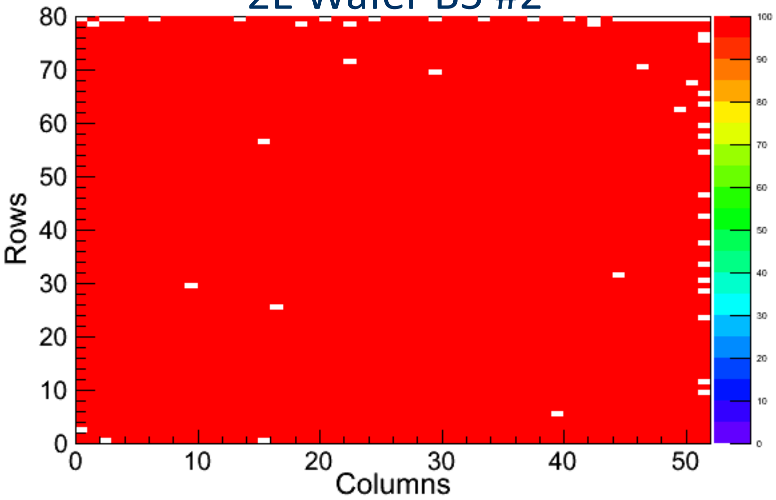
Noise for 4E sensors is high due to higher capacitance – can be improved by further calibration of ROC

Measured efficiency as predicted for 285 µm thick siliscon sensor – no unusual behaviour

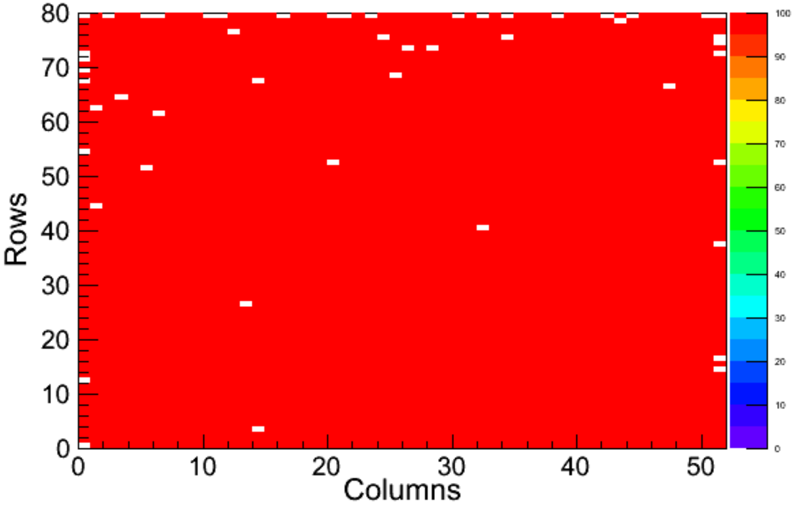
Electrical Characterization and Preliminary Beam Test Results of 3D Silicon CMS Pixel Sensors

Ozhan Koybasi, *Student Member, IEEE,* Enver Alagoz, Alex Krzywda, Kirk Arndt, Gino Bolla, Daniela Bortoletto, Thor-Erik Hansen, Trond Andreas Hansen, Geir Uri Jensen, Angela Kok, Simon Kwan, Nicolas Lietaer, Ryan Rivera, Ian Shipsey, Lorenzo Uplegger, and Cinzia Da Via

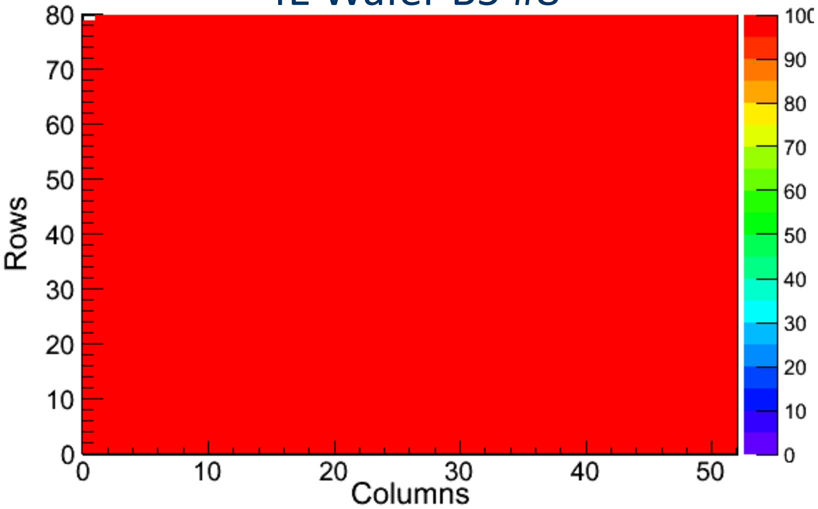
Test – bump bonding tests for CMS devices



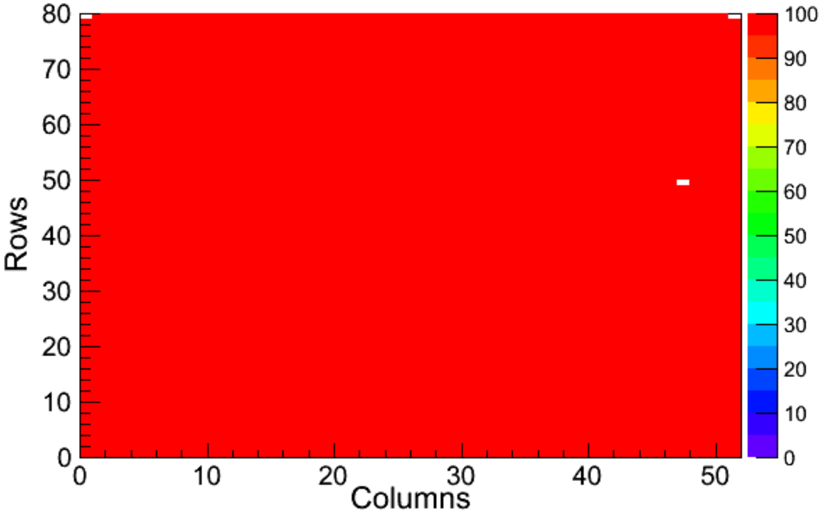
2E Wafer B5 #2



2E Wafer B2-16 #6



4E Wafer B5 #8



4E Wafer B2-16 #5

E.Alagoz[1], O.Koybasi[1], K.Arndt[1], D.Bortoletto[1], I.Shipsey[1], G.Bolla[1], R.Riviera[2], M.Turqueti[2], L.Uplegger[2] and S.W.L.Kwan[2]

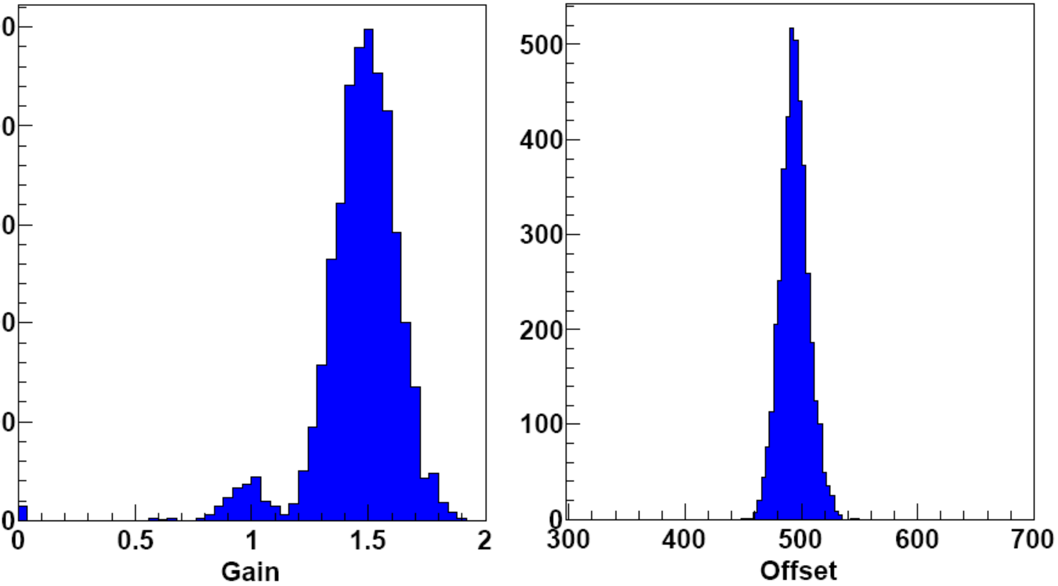
[1]Purdue University, [3]Fermilab

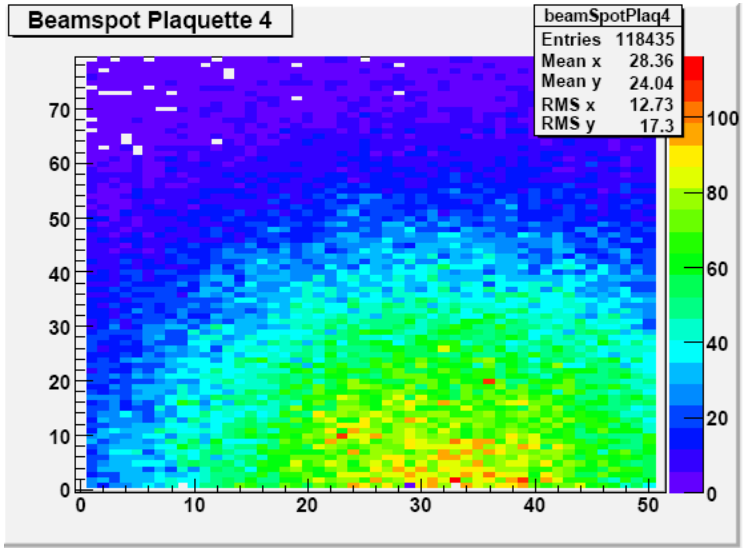
FNAL with 120 GeV protons (CMS 2E)

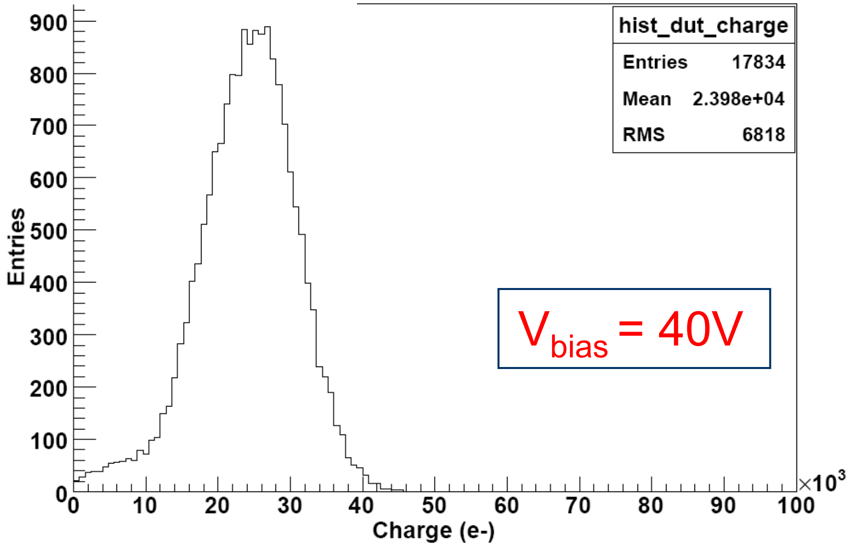
- ADC to electron conversion:
  Vcal* [DAC] = ADC x gain - offset
  Charge (e-) = Vcal x 65.5 – 410

  * 1 Vcal [DAC] = 65.5 electrons

- T ≈ 11 °C on carbon fiber (estimated to be 6 °C higher on the sensor)



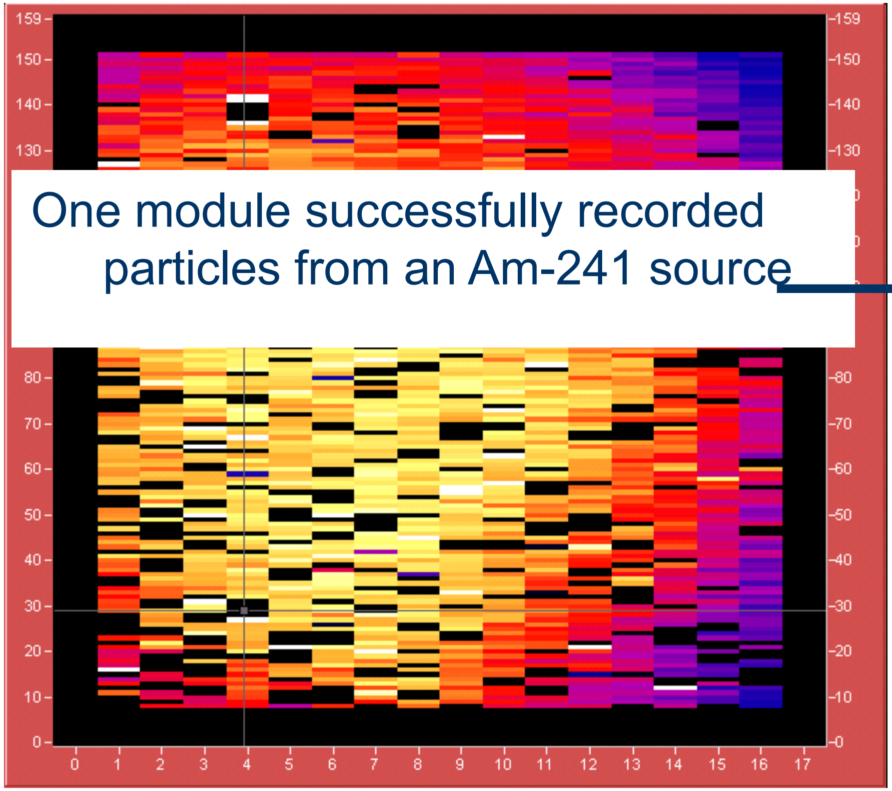




$V_{bias} = 40V$

ATLAS sensors

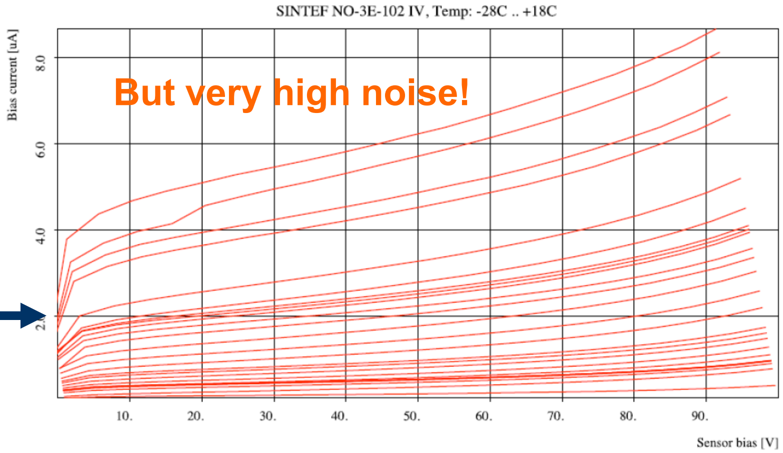
- **Noise was too high for a good convergence**
- **All modules suffered from irreversible breakdown after some hours of operation**



One module successfully recorded particles from an Am-241 source

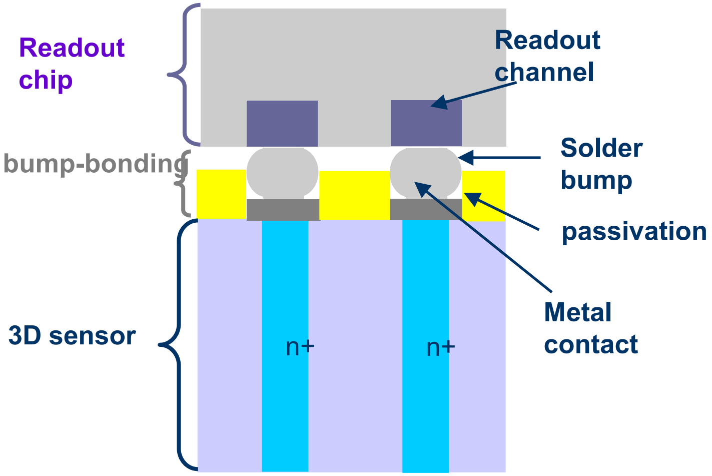
Each square corresponds to the number of hits per pixel

***data taken by E. Bolle, H.Gjersdal and O. Rohne at the University of Oslo**

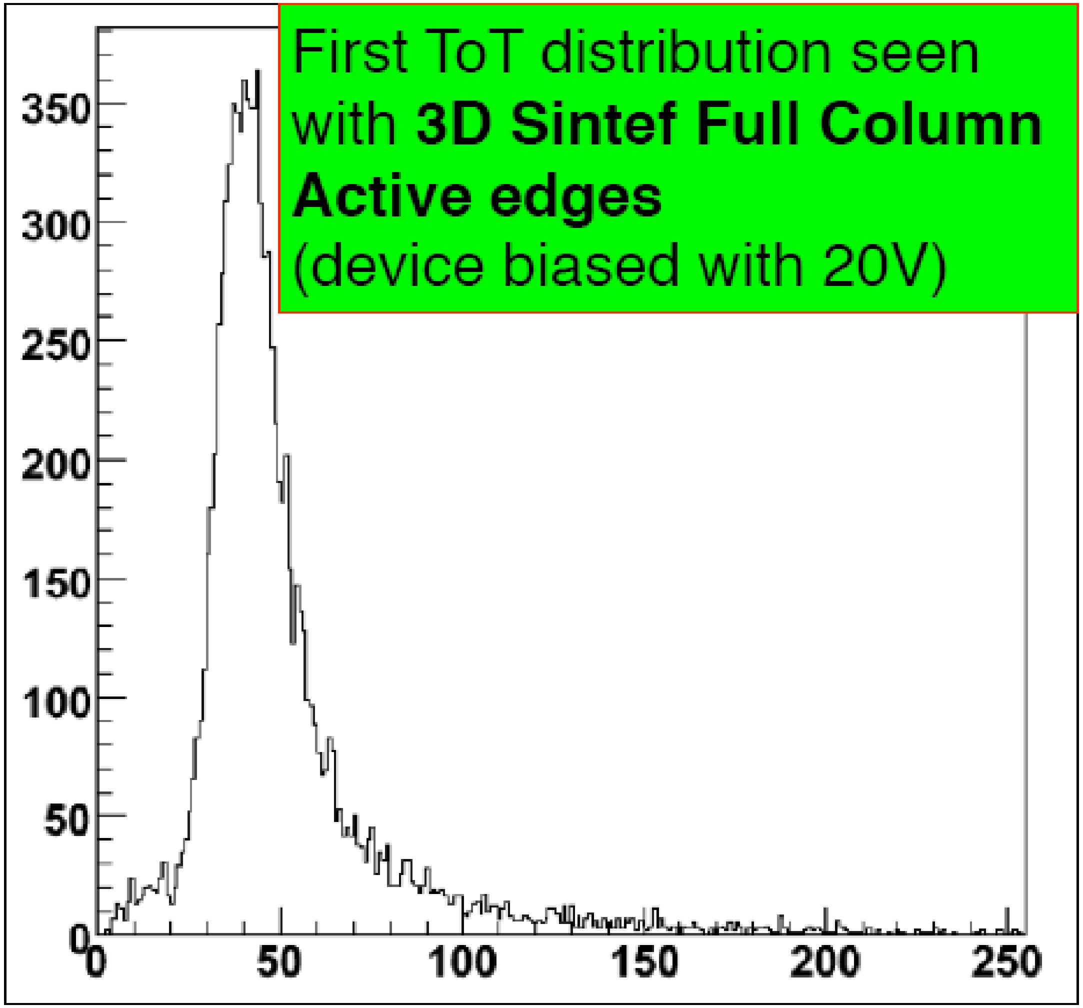


But very high noise!

Post test beam IV curves at different temperatures :O. Rohne and H. Giersdal



ATLAS FE-I3 sensors

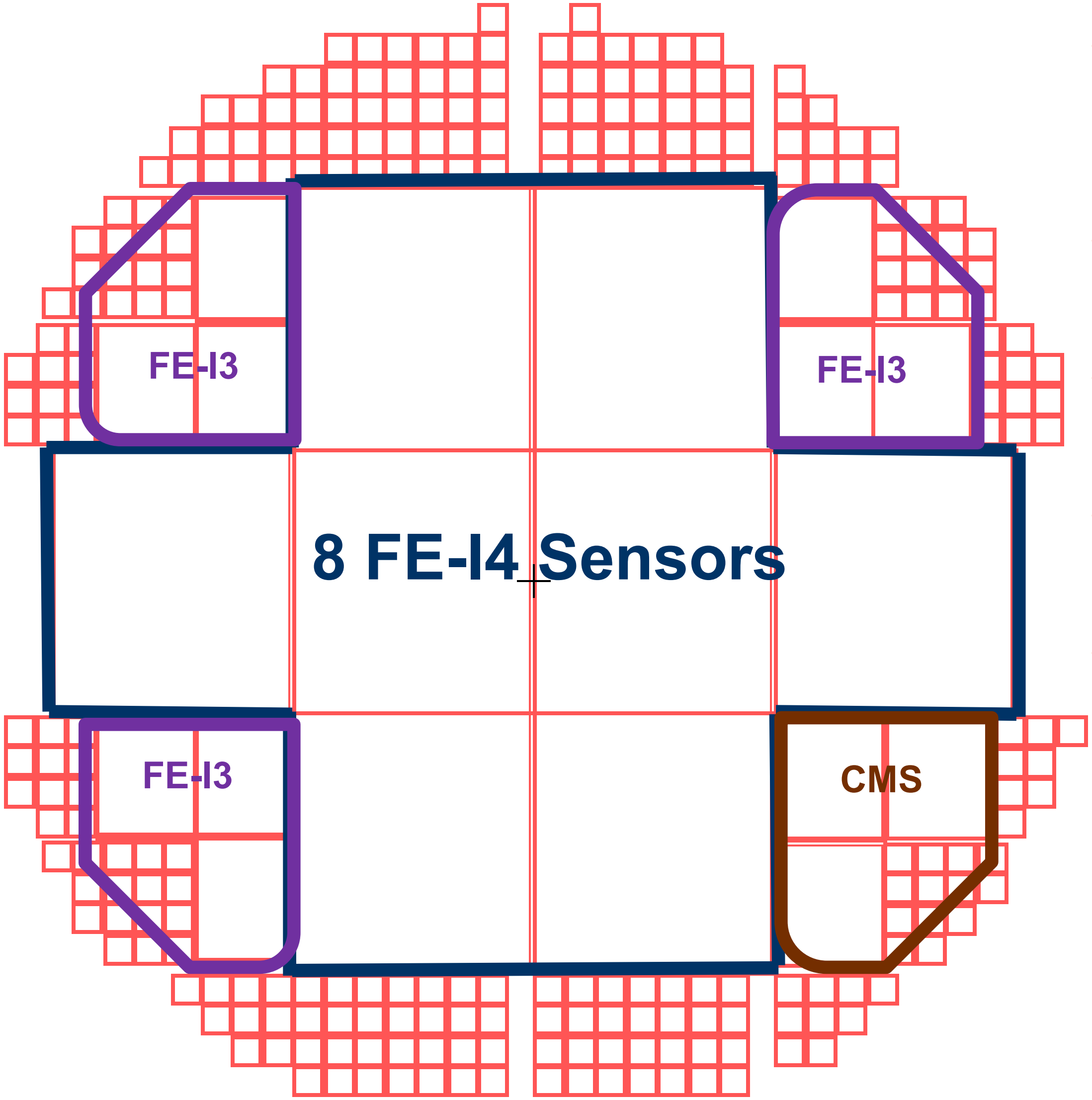


First ToT distribution seen with **3D Sintef Full Column Active edges** (device biased with 20V)

Results taken by Alessandro La Rosa and Philippe Grenier

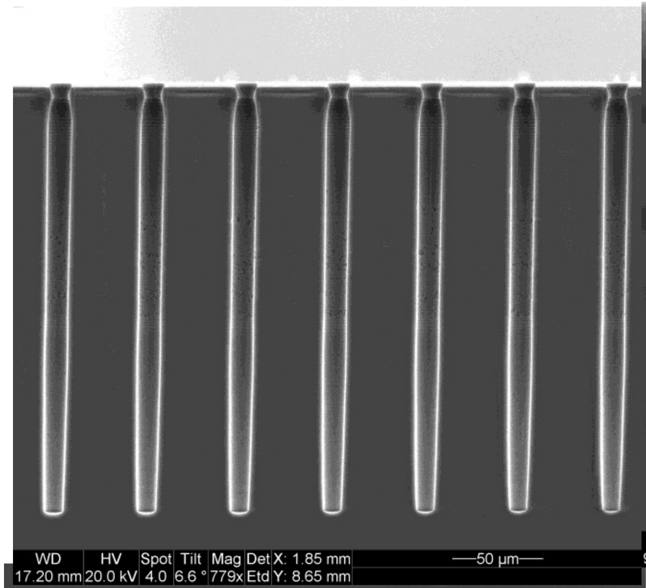
- After identifying some mismatch in sensor and electronic design
- Problem solved
- Latest result from DESY testbeam shows good performances

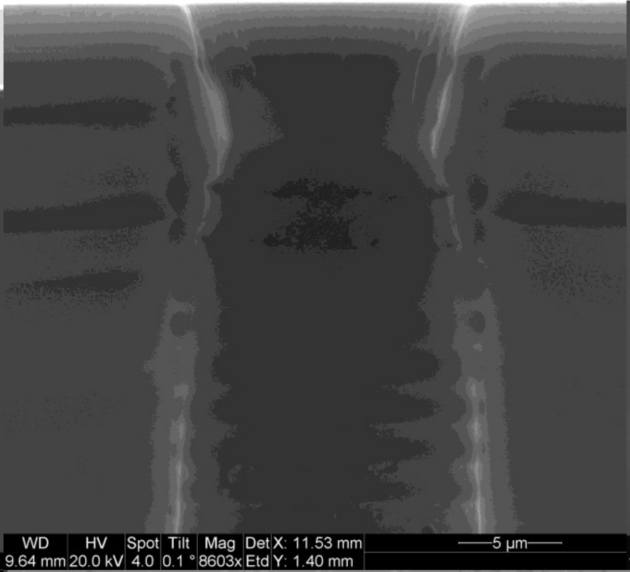
Recent batch common floor plan

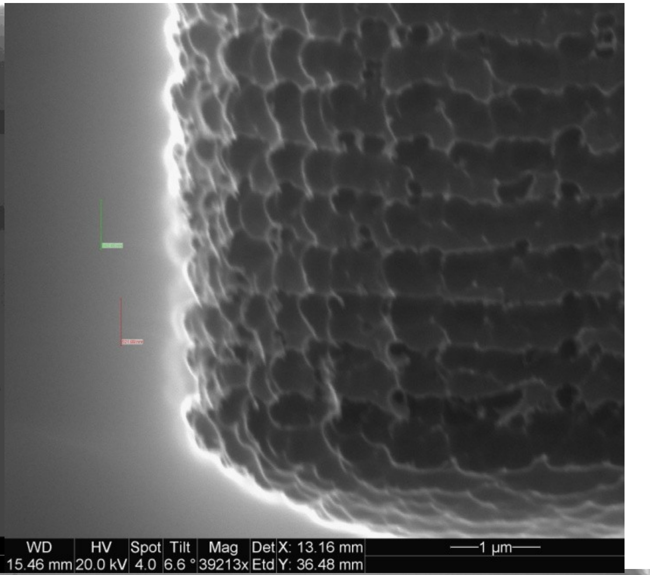


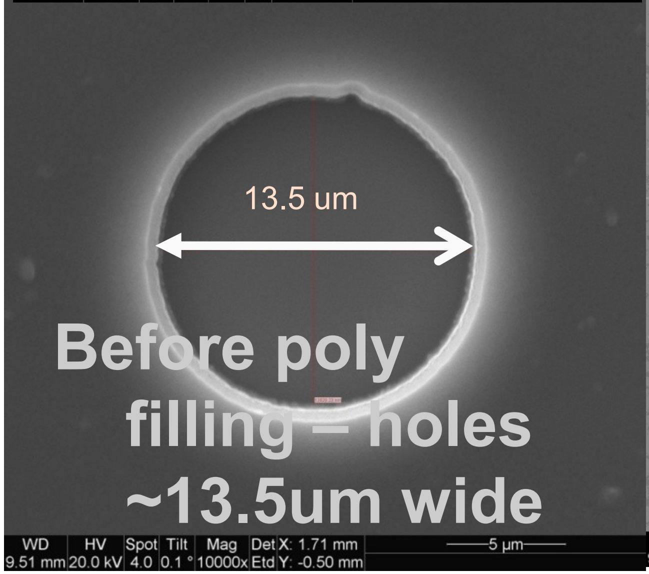
- Latest design, common floor plan for ATLAS
- 8 FE-I4 sensors
- 9 FE-I3 sensors
- 3 CMS sensors
- Process modifications:
  - N-doping by phosphine
  - P-doping by diborane
  - Addition implant to give a better surface fr the contact and p-n junction

DRIE and polyfilling results – 3rd series

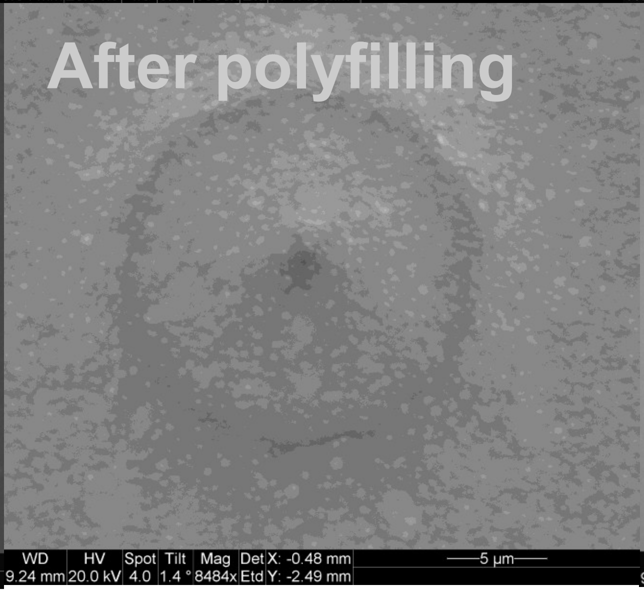




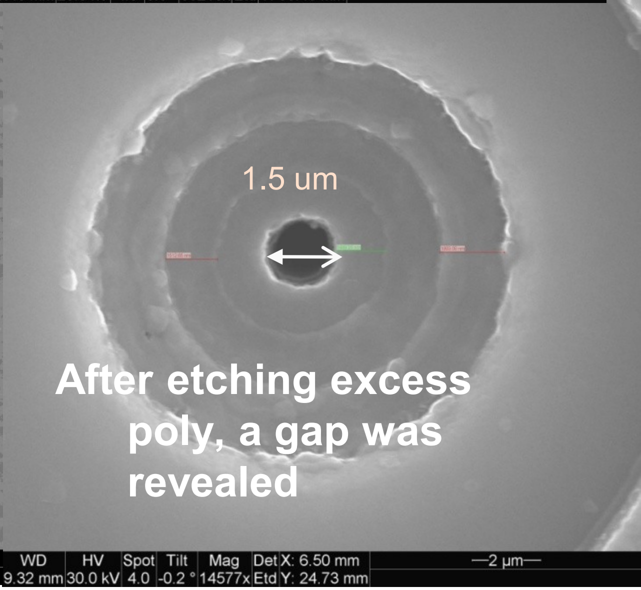




Before poly filling – holes ~13.5um wide

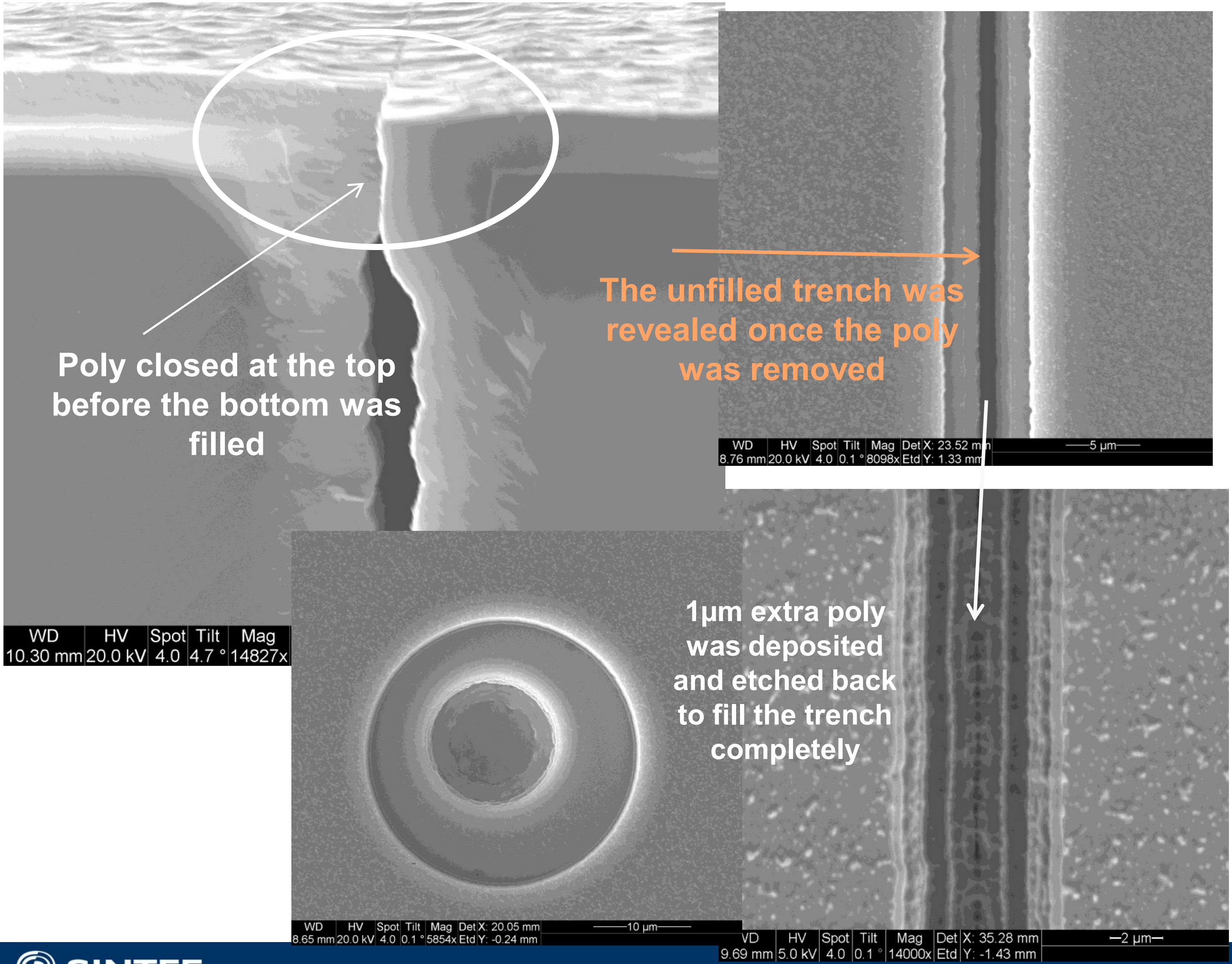


After polyfilling



After etching excess poly, a gap was revealed

DRIE and polyfilling results – 3rd series

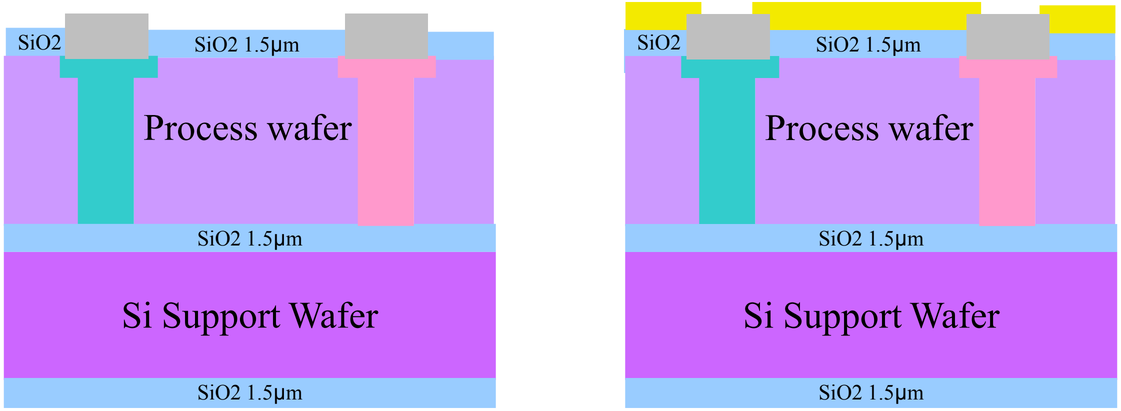


Poly closed at the top before the bottom was filled

The unfilled trench was revealed once the poly was removed

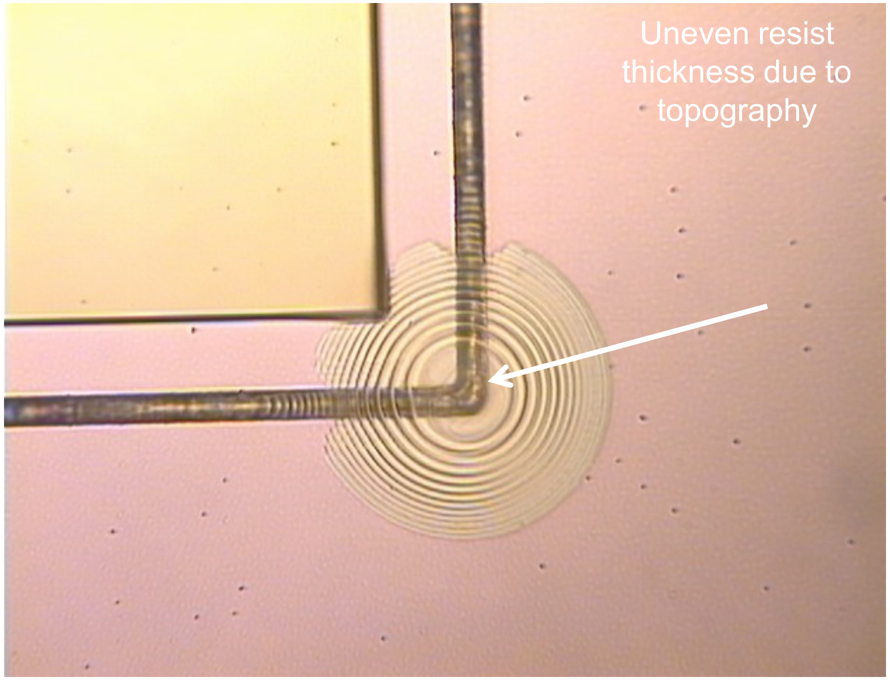
1µm extra poly was deposited and etched back to fill the trench completely

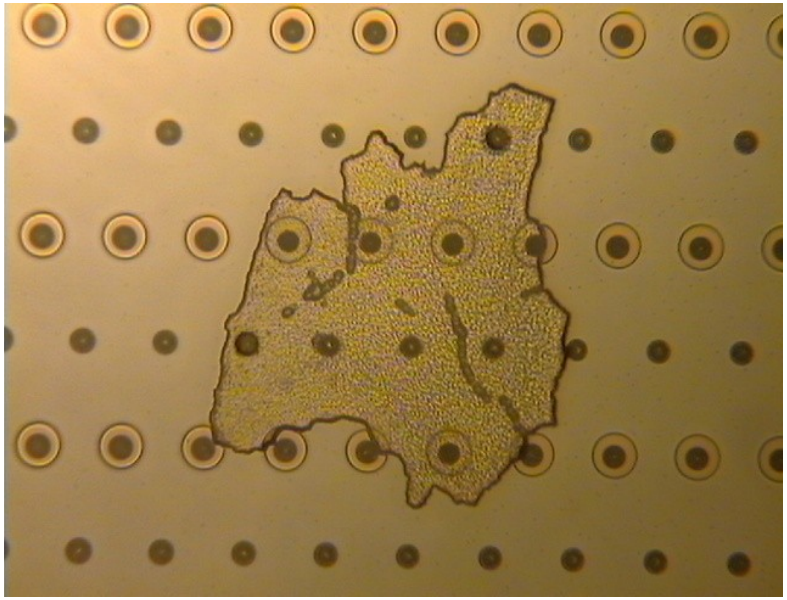
Status of current batch

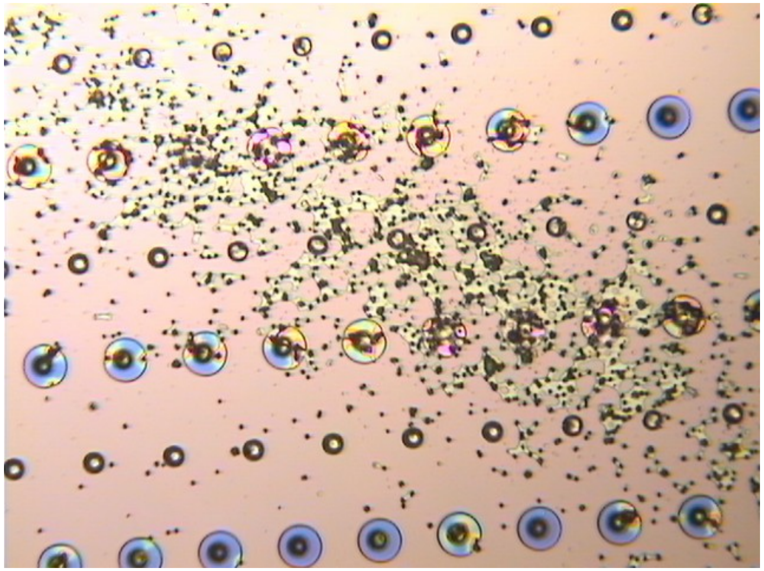


- Test metallisation
- Measurements
- Final metallisation
- Passivation
- Ready for bump-bonding and module assembly by the end of March

Further Yield Factor Observed

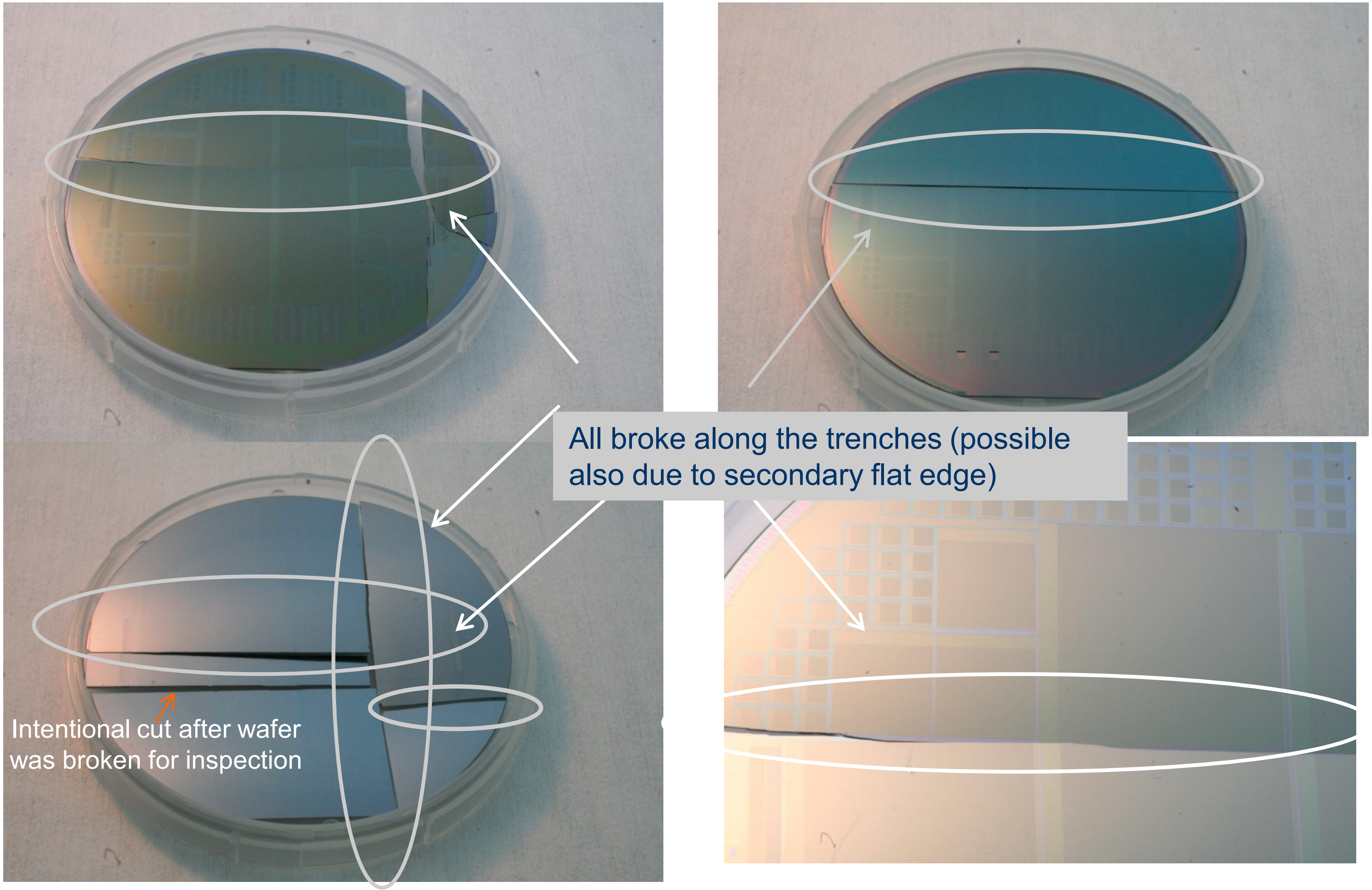

Uneven resist thickness due to topography





- **Poly residue**
  - **Risks of short circuits**
  - **But overetch would destroy electrodes**
- **Topography makes litho difficult**
- **Chemical mechanical polishing could help**

Yield factor when processing larger FE-I4 sensors



All broke along the trenches (possible also due to secondary flat edge)

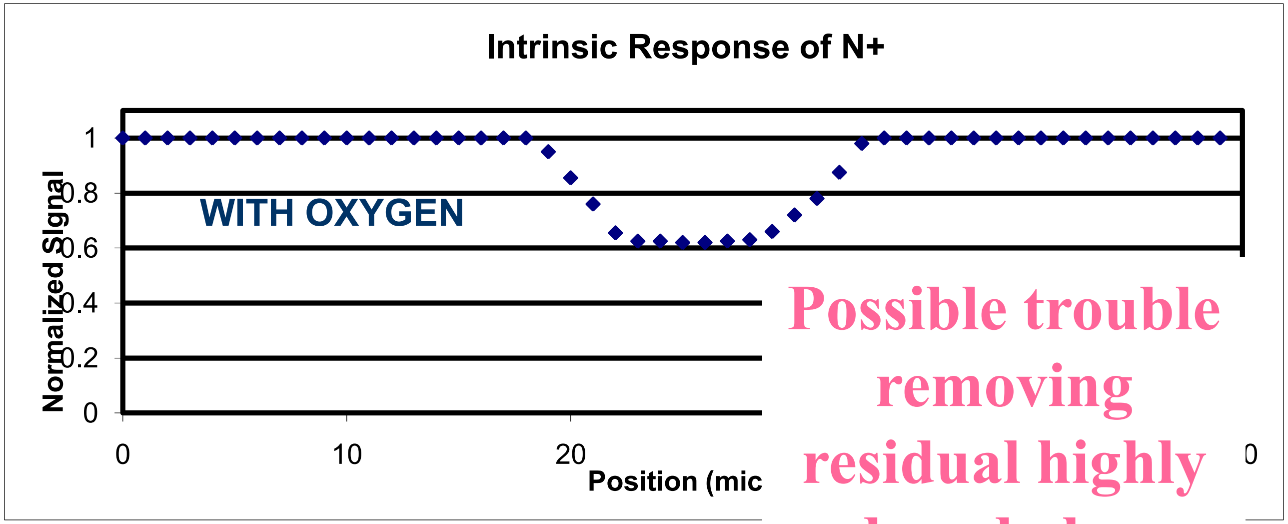
Intentional cut after wafer was broken for inspection

X-RAY STUDIES OF ELECTRODE RESPONSE

Data showing the response of electrodes using to a 2 um wide X-ray beam

N+ electrode efficiency about 60%

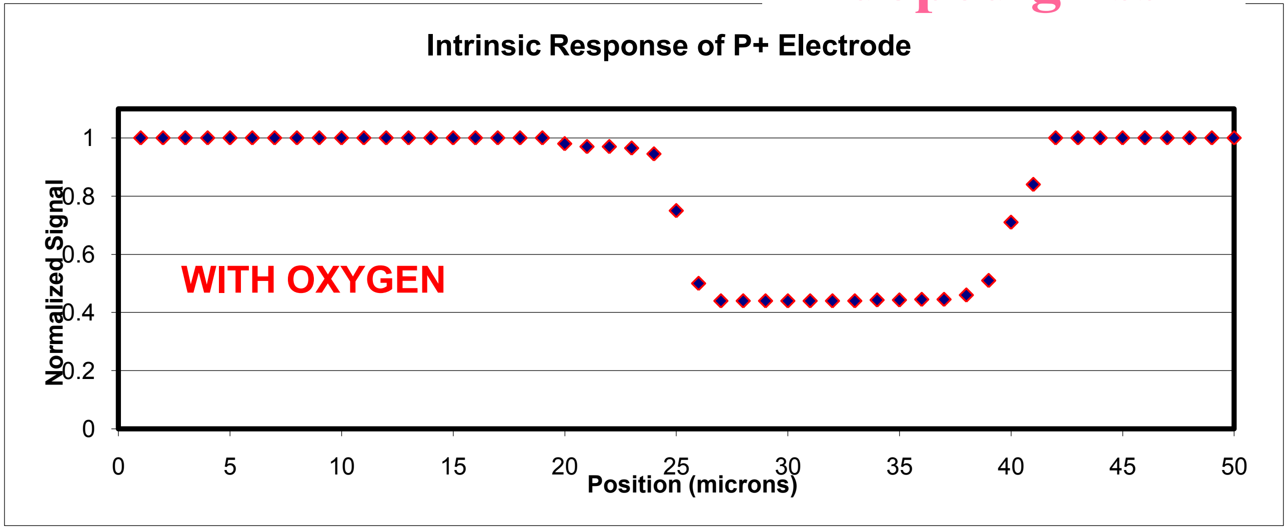
POCL3



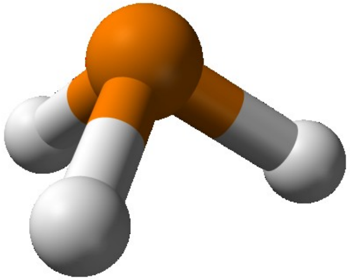
Possible trouble removing residual highly doped glass

P+ electrode efficiency about 42%

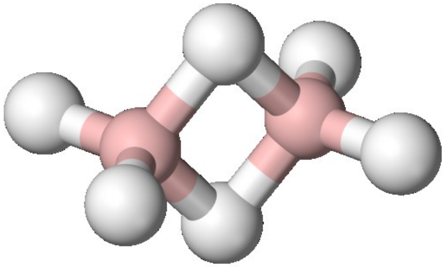
BBr3 + O2



*** C. Kenney, J. Hasi (SLAC)**



Oxygen-Free Doping



Goal = Improve signal collection within the poly

Oxygen trapping

Replace POCL3 with PH3

Replace BBr3/O2 with B2H6

Tried diborane doping on SINTEF second run wafers

Both phosphine and diborane were used in the 3rd run!

Summary

- 2 prototype runs have been completed
- Great improvement in wafer yield in second run
- Both wafer level and test beam results are promising
- Yield is yet to be improved
- Large FE-I4 sensors in the 3rd run are near completion
- Several yield factor stil need to be considered
  - More uniform poly removal – eg. CMP
  - Resistcoating over the topography
  - Wafer bonding
- Electrode efficiency will be further investigated by oxygen free doping
- Further test such as support wafer removal need to be investigated for compatibility with detector system