3D Silicon Sensors

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CPAD 2016, Caltech

3D Sensor Introduction

3D sensor was first proposed in 1994 by S. Parker, C. Kenney, J. Segal

- NIM A 395 (1997) 328

Interest from HEP experiments lead to a massive R&D and industrialization effort

- Stanford Nanofabrication Facility, SINTEF, FBK, CNM are the fabricators

Until eventually 3D Sensors were installed in ATLAS IBL detector

- First use of 3D sensors in a HEP experiment

Other Installations

- ATLAS AFP, CMS TOTEM

R&D continued after the IBL project,

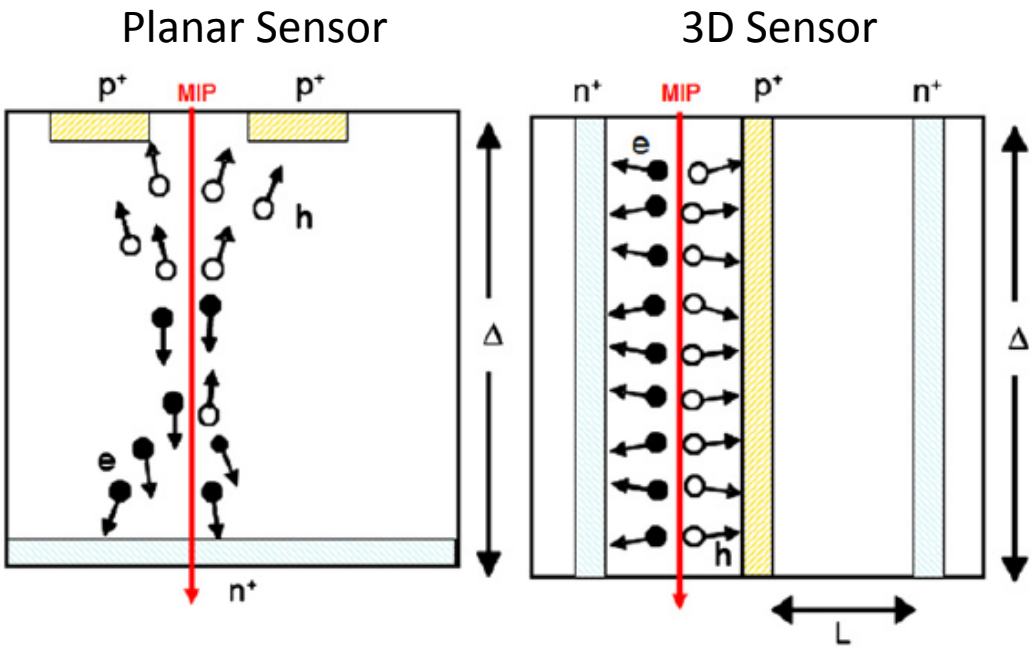
- Example further development by UNM/UTN/FBK collaboration

Leading to the HL-LHC Phase II Upgrades

- New Very Demanding Requirements

3D Sensor Design

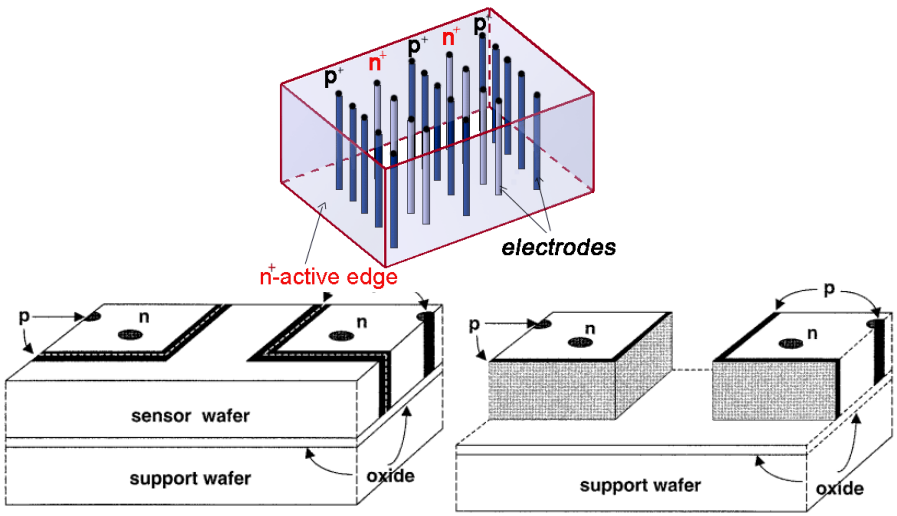
- 3D sensor
  - Electrode distance decoupled from the sensitive detector thickness
  - More Radiation Hard
  - Lower Depletion Voltage
    -> less power dissipation, cooling
  - Shorter drift distance
    -> faster charge collection
    -> less charge trapping
  - Allows for Active or Slim edges
- 3D sensor challenges
  - Complex production process
    -> long production time
    -> lower yield
    -> higher cost
  - Higher Capacitance
    -> higher noise



Layout cross-sections emphasizing the decoupling of the active thickness (Δ) and collection distance (L) in 3D sensors
NIM A 694 (2012) 321

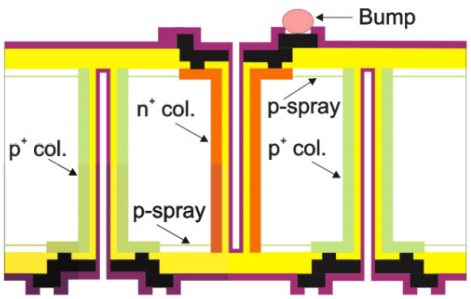
3D Sensor R&D Technologies

SNF (Stanford) / SINTEF (Oslo)

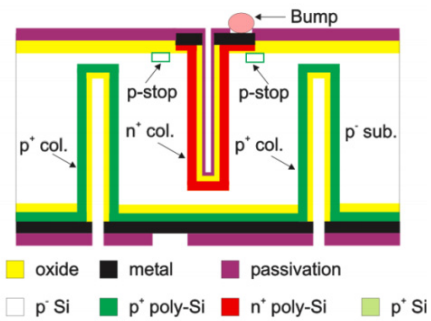


C. Kenney et al., IEEE TNS 48 (2001) 2405

FBK (Trento)



CNM (Barcelona)



A. Zoboli et al., IEEE TNS 55(5) (2008) 2775 G. Giacomini, et al., IEEE TNS 60(3) (2013) 2357

Single-sided process ('Full 3D')

Both column types (n,p) etched from top

Needs support wafer -> removal needed

Bias to be applied to top side

-> Overhanging bias tab, top side biasing

Allows active edges

-> only few μm of inactive material

Double-Sided Process

n columns etched from top, p from the back

FBK: passing through columns, p-spray

CNM: non passing through columns, p-stop

No support wafer needed

No bias tab, bias applied to back side

-> reduced processing complexity

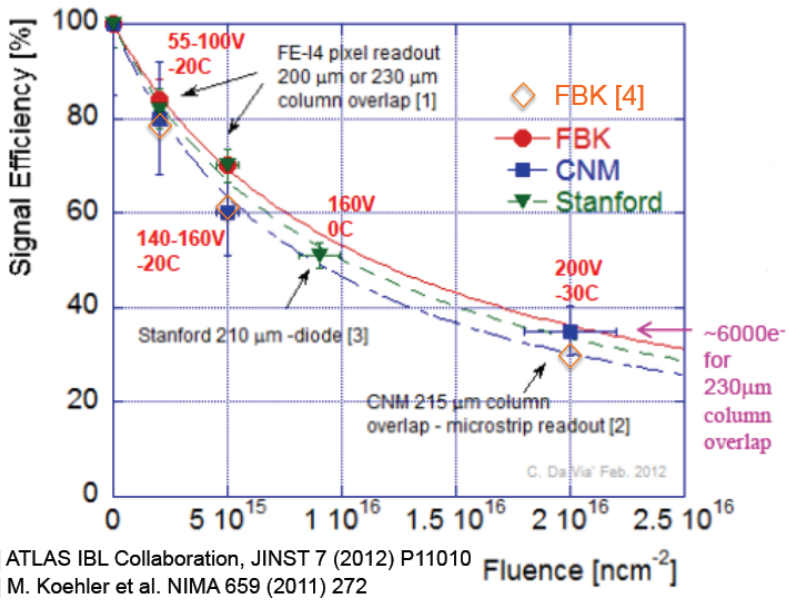
Allows Slim Edges

FBK: p+ guard fence -> ~ 100 μm inactive

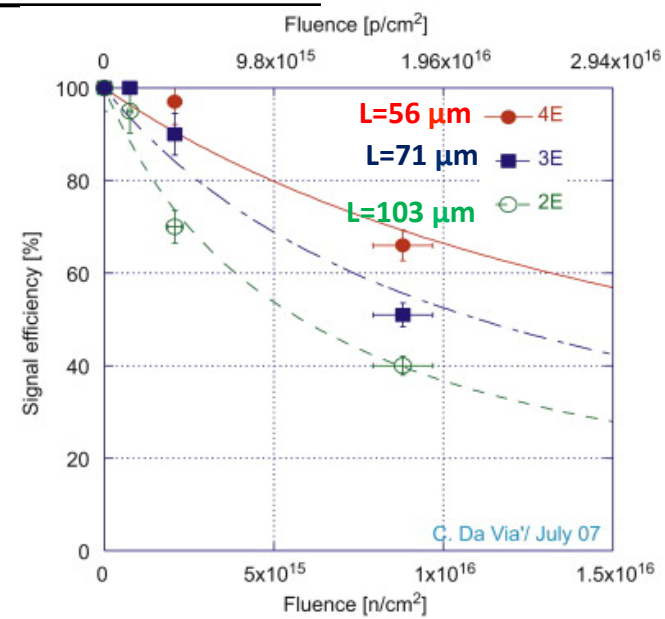
CNM: p+ fence + guard rings -> ~ 200 μm

3D Sensor R&D Performance

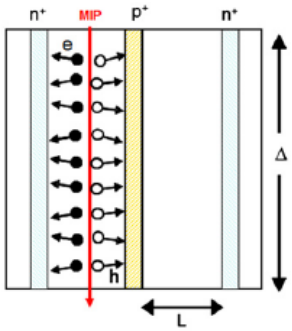
Some of the main results of the R&D:



[1] ATLAS IBL Collaboration, JINST 7 (2012) P11010
[2] M. Koehler et al. NIMA 659 (2011) 272
[3] C. Da Via, et al., NIMA 604 (2009) 505
[4] G.-F. Dalla Betta, et al., HSTD9 (2013)



C. Da Via et al., NIM A 604 (2009) 505



- Signal efficiency of 60 – 70% was achieved at 5×10^{15} neq/cm^2 Vbias = 160V, for both single & double-sided sensors
- Signal efficiency ~ 30% at 2×10^{16} neq/cm^2 with Vbias = 200V

- Signal efficiency improves with decreasing electrode distance L

3D Sensor R&D Performance

Double-sided 3D sensors, without a support wafer offered:

– reduced process complexity,

– faster production times

Bias can be applied to the sensor back-side:

– assembly within pixel detector systems is much easier

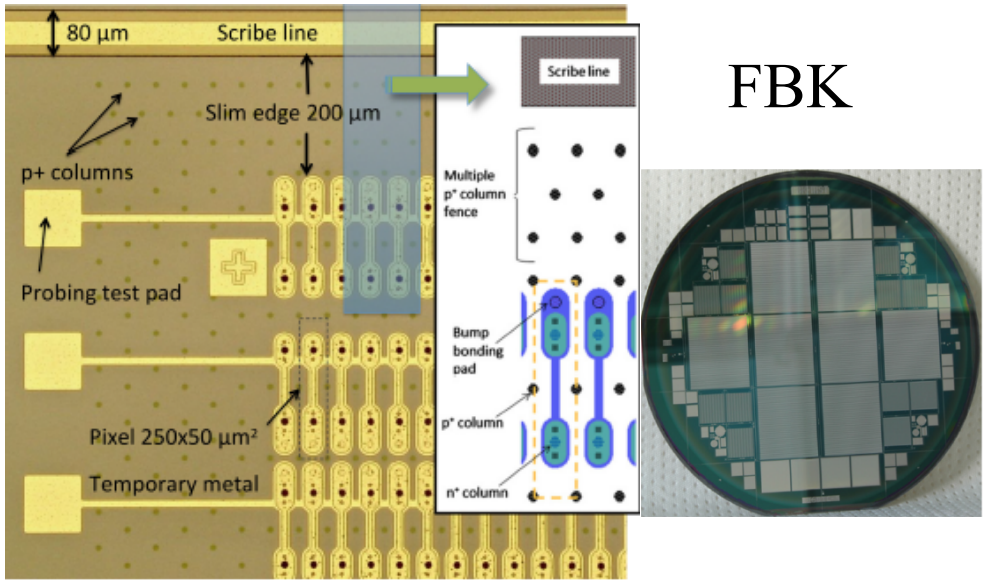
front-side layout is simpler

Although active edges are not feasible,

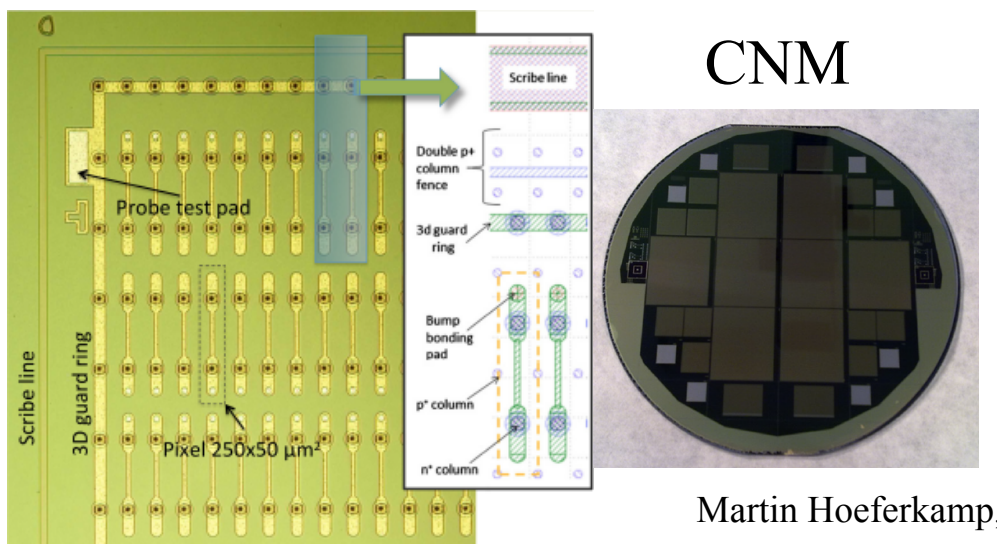
very compact slim edges are (<200 μm)

ATLAS IBL 3D Sensor Production

NIM A 694 (2012) 321, G. Darbo, JINST 10 (2015) C05001



FBK



CNM

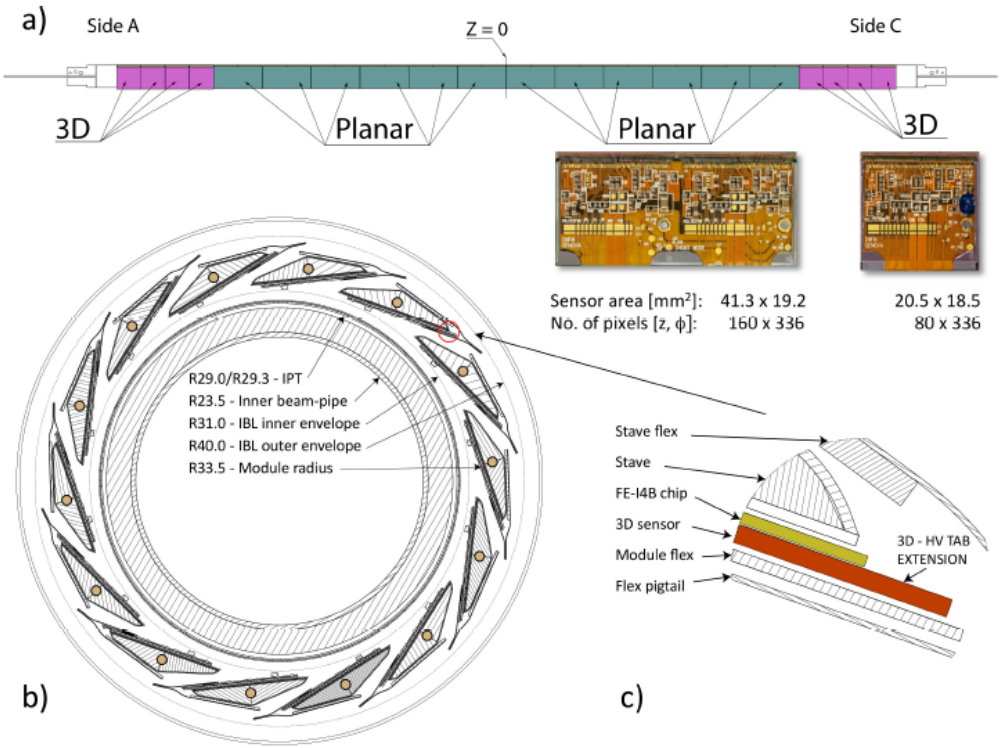
IBL 3D sensor decision 2011

- FE-I4 geometry: 80x336 pixels of 250x50 µm^2
- 2 n+ junction columns/pixel (2E) surrounded by 6 p+ ohmic columns, 230 µm p-substrate L=67 µm
- Slim edge of 200 µm along columns

Technology

- FBK:
  - Passing-through columns
  - P+ guard fence
  - Sensor QA selection from IV on temporary metal
- CNM:
  - Columns ~ 20 µm shorter than the thickness
  - P+ guard fence + 3D guard ring
  - Sensor selection from IV on guard ring

ATLAS IBL Detector



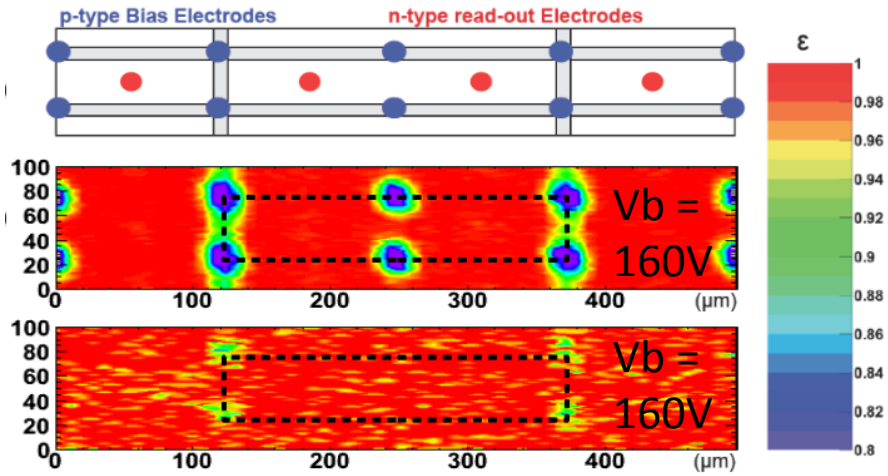
a) Stave layout with the organization of planar and 3D sensor modules
b) Layout of the IBL detector with the 14 staves around the IBL positioning tube (IPT)
c) One stave side where a 3D sensor module is visible

- ATLAS Pixel Detector first upgrade during long shutdown 1 (2013-2015): new pixel layer at 3.3 cm
- FEI4: largest pixel front-end chip
- Designed for radiation levels of 5×10^{15} neq/cm^2, 250 Mrad
- Sensor technology decision
  - 75% planar sensors, n-in-n 200 μm thick (CIS)
  - 25% 3D sensors, double-sided 230 μm thick (FBK +CNM)

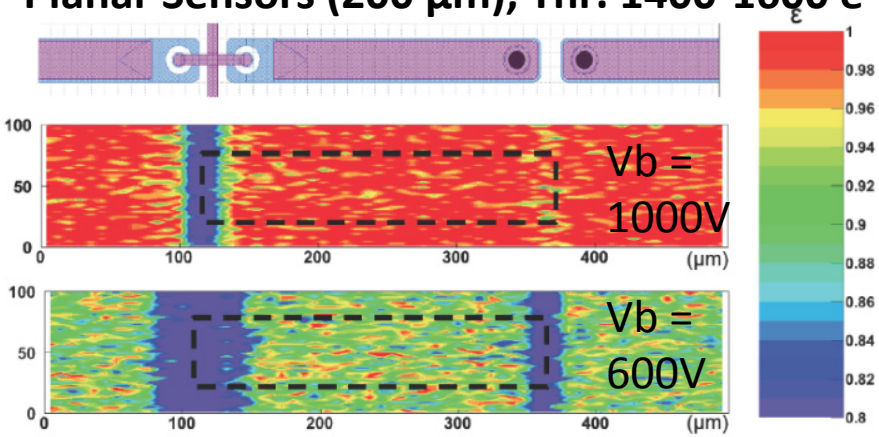
G. Darbo, JINST 10 (2015) C05001

IBL 3D Sensors: Radiation Hardness

3D Sensors (230 µm), Thr. 1500 e



Planar Sensors (200 µm), Thr. 1400-1600 e



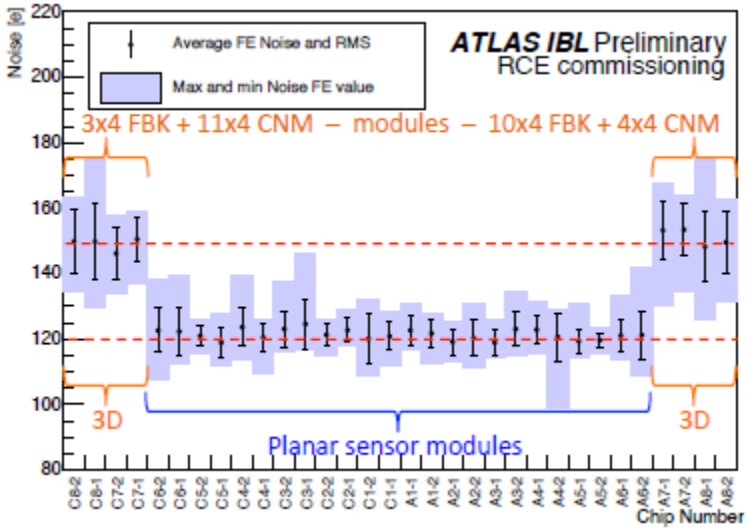
ATLAS IBL Coll., JINST 7 (2012) P11010

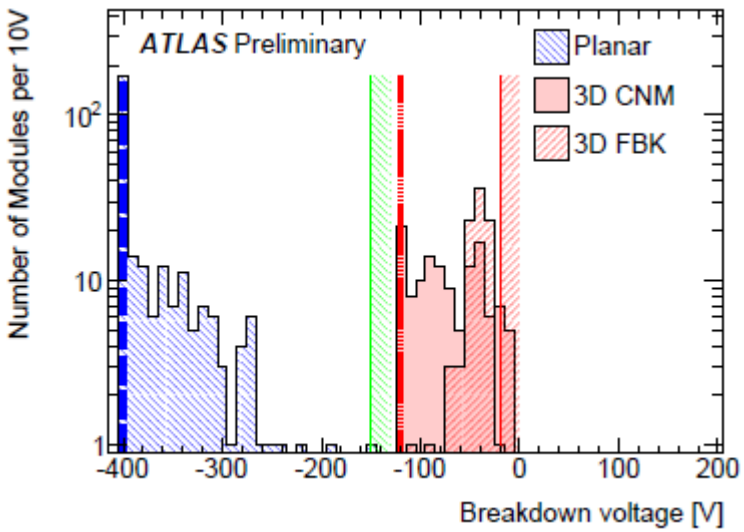
- Radiation hardness tests at 5×10^{15} neq/cm^2
- 3D Sensors
  - Fully efficient at Vbias = 160V, 15° inclined
  - Power dissipation ~15mW/cm^2 at T=-15C
- Planar Sensors
  - Require Vbias = 1000V for similar efficiency
  - Power dissipation ~90 mW/cm^2 at T=-15C

Advantage of 3D at high radiation fluence: lower operating voltages and lower power for similar signals to planar

IBL 3D Sensors: Noise, Breakdown Voltage

G. Darbo, JINST 10 (2015) C05001





- Planar modules have an average noise that is 30 e^- lower than 3D, due to the lower capacitance of planar pixel sensors of 110 fF vs to 169 fF for 3D sensors

- Breakdown voltage (Vbd) for CNM sensors is higher before irradiation than for FBK sensors, and slightly higher after IBL lifetime dose $5x10^{15}$ neq/cm^2

Advantage of Planar sensors:
lower capacitance and lower noise
higher breakdown voltage

IBL 3D Sensors Experience

- In general 3D sensor technology is quite complicated:

– Critical process steps like DRIE (Deep Reactive Ion Etching) for etching the columns can induce major bulk damage

– Process defects are difficult to spot if they are deep in the bulk

– Even a single defect can spoil an entire sensor

– Need for accurate I-V testing on wafer

- Without a support wafer, double-sided wafers are more fragile:

– mechanical yield is an issue

– great care to be taken, especially in wafer edge protection

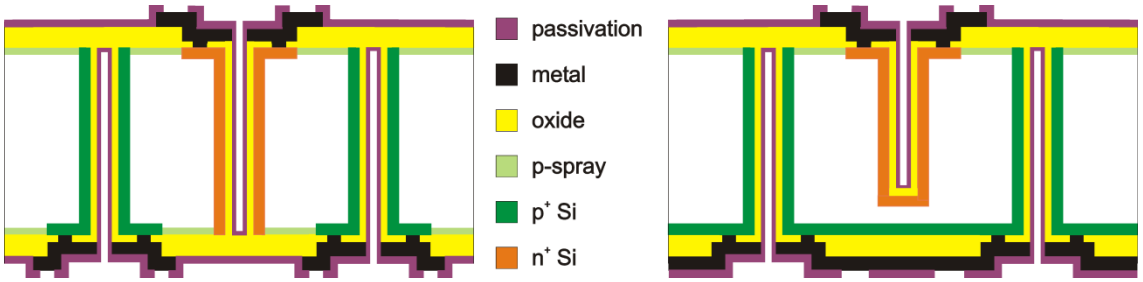
Wafer bowing can be pronounced:

– impacts on alignment quality and bump bonding feasibility

– can affect electrical characteristics and yield

FBK 3D Sensors Breakdown Voltage Study

- Since 2012 Univ. of New Mexico has been collaborating with Univ. of Trento and FBK in an experimental study of 3D sensors with layout and process modifications aimed at breakdown voltage (Vbd) improvement.
- This study included a total of 122 samples from two production batches differing in geometries and fabrication details, and several irradiation campaigns with different radiation types.



2016 JINST 11 P09006

Layout cross sections of the 3D sensors under study: (left) devices from the ATLAS10 batch of the IBL production, with passing-through junction (n) electrodes; (right) devices from DTC5 R&D batch, with partially-through junction electrodes. In both cases the ohmic (p) electrodes are passing-through

FBK 3D Sensors Breakdown Voltage Study

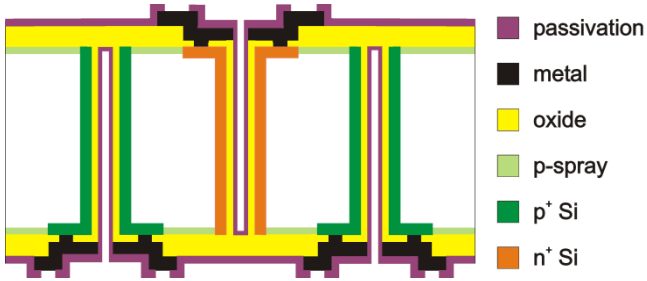
Motivations for the study:

- The Vbd of 3D sensors is lower than for planar sensors due to process & design constraints
- Before irradiation not a problem because Vbd is >> full depletion voltage (Vfd)
- After irradiation both Vbd and Vfd increase but to a different extent depending on the structures, irradiation scenarios and annealing conditions
  - The increase in Vfd depends on the bulk radiation damage, can be predicted analytically (Hamburg Model)
  - The increase in Vbd depends on both bulk & surface damage, very hard to predict
  - TCAD simulations are accurate for non-irradiated sensors, but much less accurate for irradiated sensors due to lack of models incorporating both bulk & surface damage (these are under development by several groups)
- For FBK IBL devices irradiated to high fluences, the margin between the operational voltage and the Vbd (for the required 97% eff) was quite narrow
- For FBK IBL devices irradiated with protons to 2x10^16 neq/cm^2, the Vbd was less than the Vfd
- For HL-LHC upgrades improvement of the 3D sensor Vbd is necessary

FBK 3D Sensors Breakdown Voltage Study

Devices used in the study:

ATLAS10



DTC5

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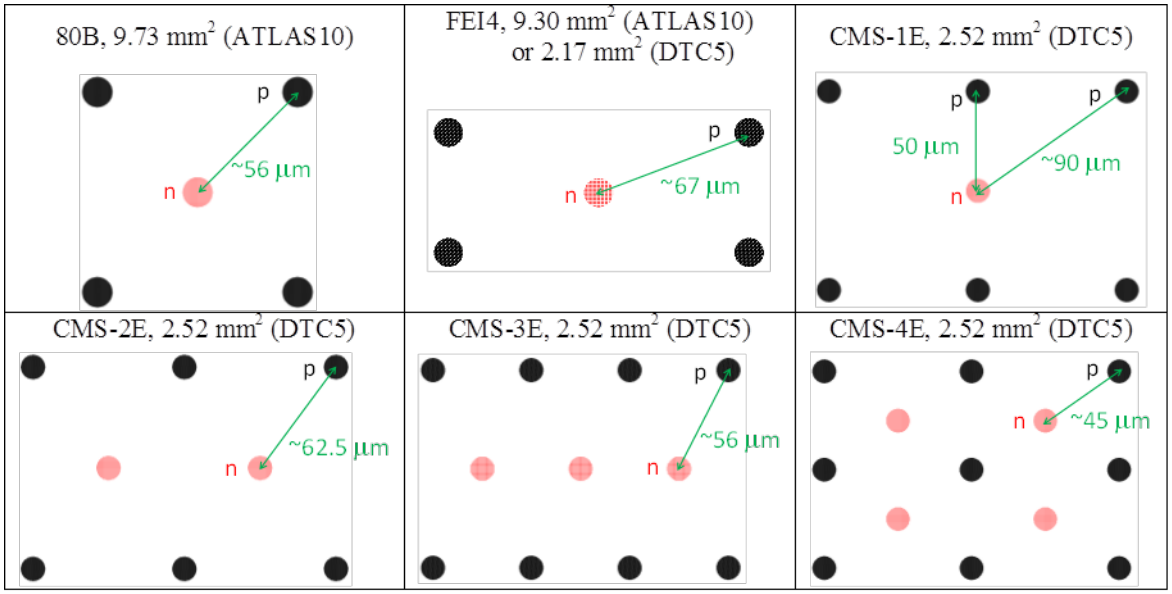

The device geometries with sketches of the column configuration showing the inter-electrode spacing

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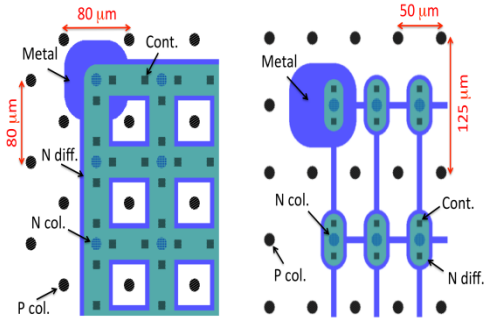


Layout of the corner regions of the 3D diodes examined, with indication of the main features

FBK 3D Sensors Breakdown Voltage Study

Irradiations:

Samples / Irradiation	ATLAS10		DTC5		2016 JINST 11 P09006	
	80B	FEI4	FEI4	CMS	Fluence (neq/cm^2)	TID (Mrad)
X-ray@Legnaro	7 (UTN)	6 (UTN)	4 (UTN)	-		1,2
γ-ray@Sandia	-	-	5 (UNM)	-		100
Neutrons@JSI	12 (UTN)	9 (UTN)	4 (UTN)	-	5x10^15	5.5
Neutrons@Sandia	-	-	14 (UNM)	-	1x10^16	6
25 MeV protons@KIT	-	-	4 (UTN)	-	1x10^16	1500
800 MeV protons@LANSCE	6 (UNM) +6 (UTN)	4 (UNM) +5 (UTN)	14 (UNM) +12 (UTN)	10 (UTN)	5.5x10^15	232

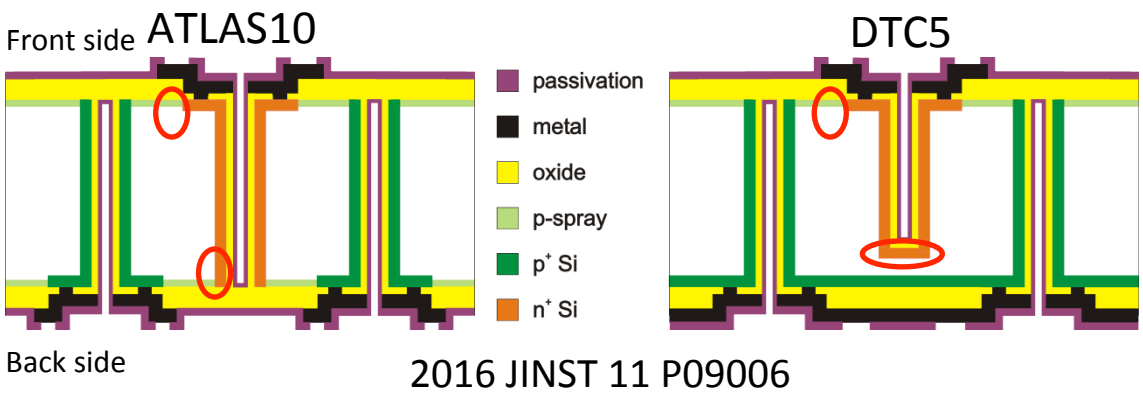
All 122 samples indicating where they were irradiated and measured, fluences

Tests:

- Some devices were tested at the Univ. of New Mexico (UNM) and others at the Univ. of Trento (UTN)
- The focus was mainly on high-field effects on the breakdown voltage (Vbr) behavior although other parameters such as leakage current and depletion voltage were measured.

FBK 3D Sensors Breakdown Voltage Study

Results:



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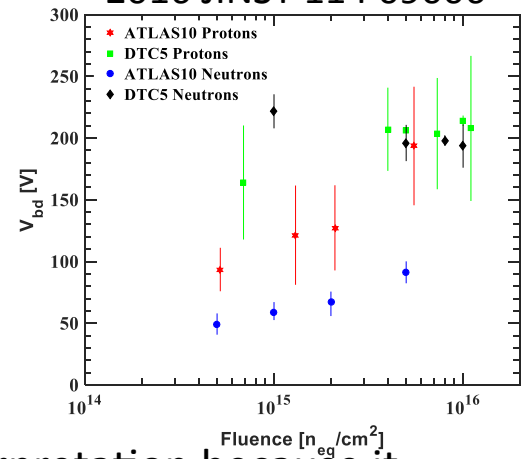

The Vbd behavior does not lend itself to a straightforward interpretation because it strongly depends on sensor geometry and the irradiation scenario.

- The ATLAS10 devices have lower Vbd than the DTC5 devices
- X-ray and Gamma irradiations show the increase of oxide charge and interface state densities with TID lowers the electric field peaks on both the front and back sides thus improving the Vbd
- In ATLAS10 devices Vbd mainly due to damage on the back side, at the junction of the n+ column and the p-spray
- For neutron irradiation Vbd decrease is more pronounced at the lowest fluence because of lower TID than for proton irradiation
- In DTC5 devices Vbd occurs at the front side or at the junction column tips (~250V)

FBK 3D Sensors Breakdown Voltage Study

Conclusions:

- Both ATLAS10 and DTC5 sensors are suitable for proton fluences of the order of $5x10^{15}$ neq/cm^2, but not for fluences of the order of $1x10^{16}$ neq/cm^2
- But devices with partially-through n-columns result in much higher Vbd than those with passing-through n-columns
- Vbd prevents them from operation at optimal bias voltage (> Vfd) unless the inter-electrode spacing is reduced
- 3D sensors at the HL-LHC involve radiation fluences up to $2x10^{16}$ neq/cm^2 and small-pitch pixels (e.g., 50x50 μm^2 with L= ~35μm or 25x100 μm^2 with L= ~28μm)
- This will significantly reduce the depletion voltage and make future 3D sensors more robust against charge trapping, but it could also cause higher electric fields and Vbd reduction

FBK 3D Sensors Breakdown Voltage Study

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Investigation of leakage current and breakdown voltage in irradiated double-sided 3D silicon sensors

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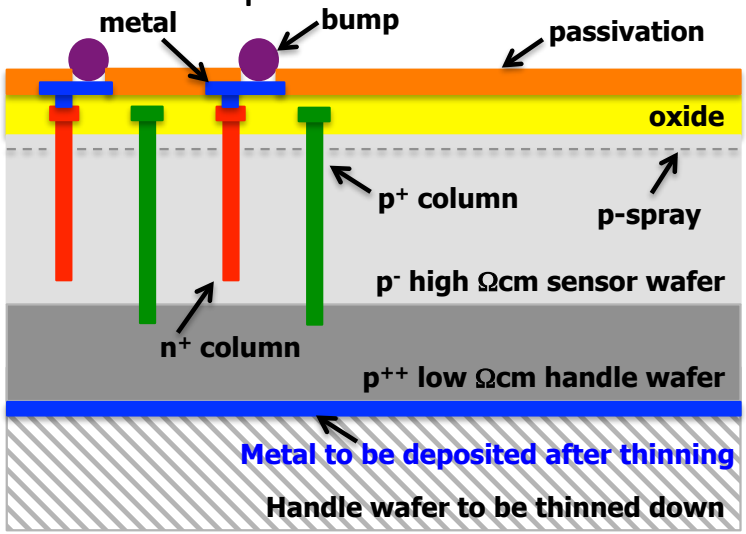
3D Sensors for the HL-LHC

- Increased luminosity requires
  - higher hit-rate capability
  - increased granularity
  - higher radiation tolerance
  - Lower mass detectors
- Next generation FE chip (RD53 65 nm)
  - 50x50 μm^2 and 25x100 μm^2 pixels
  - $C_{DET} \leq 100fF$
  - Ileak ≤ 10 nA/pixel
  - Threshold: ~1000 electrons
- **Implications for 3D sensors**
  - thinner sensors
  - narrower electrodes
  - reduced electrode spacing
  - very slim (or active) edges

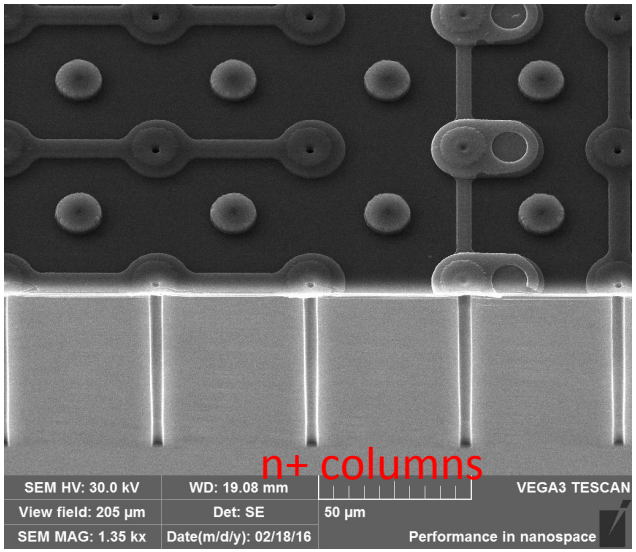
FBK: Single-Sided 3D Sensor Design

February 2016, 10 wafers, p-type, SiSi Direct Wafer Bonded, 100 and 130 um active thickness

Double-sided process not favored for thin sensors, especially on 6” wafers



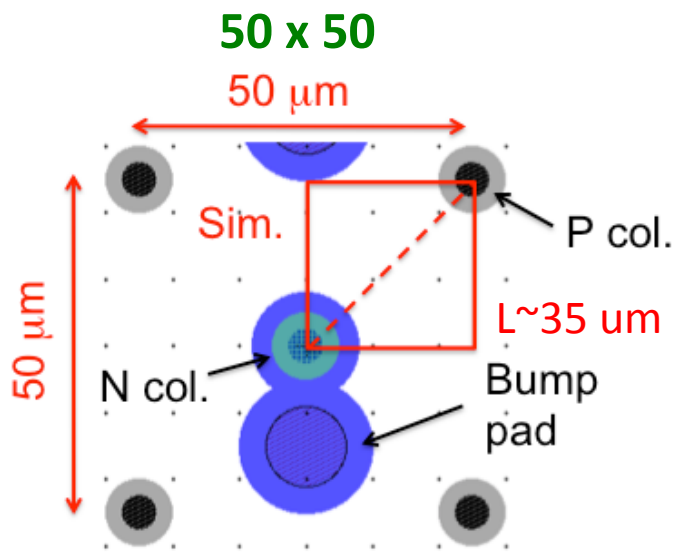
G.-F. Dalla Betta (UTN)



G.-F. Dalla Betta (UTN)

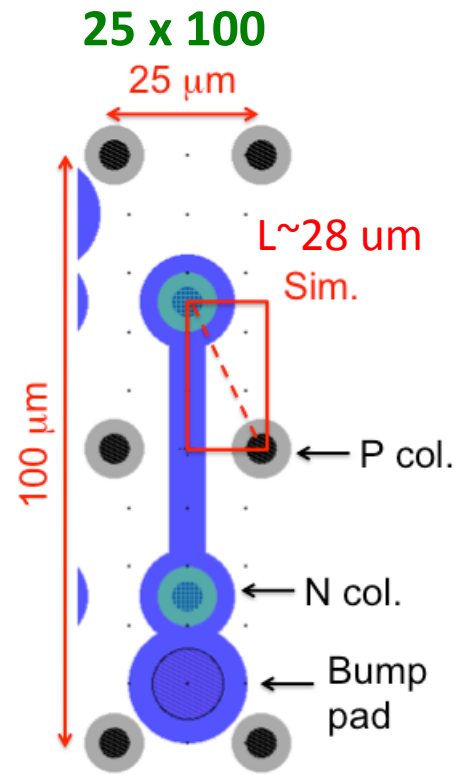
- Thin sensors on support wafer: SiSi Direct Wafer Bonded substrates
- Ohmic p columns/trenches depth > active layer depth (for bias)
- Junction n columns depth < active layer depth (for high V_{bd})
- Reduction of hole diameters to ~5 um
- Holes (at least partially) filled with poly-Si

FBK: New Small-Pitch 3D Pixels



G.-F. Dalla Betta (UTN)

All designs require a column diameter of 5 μm

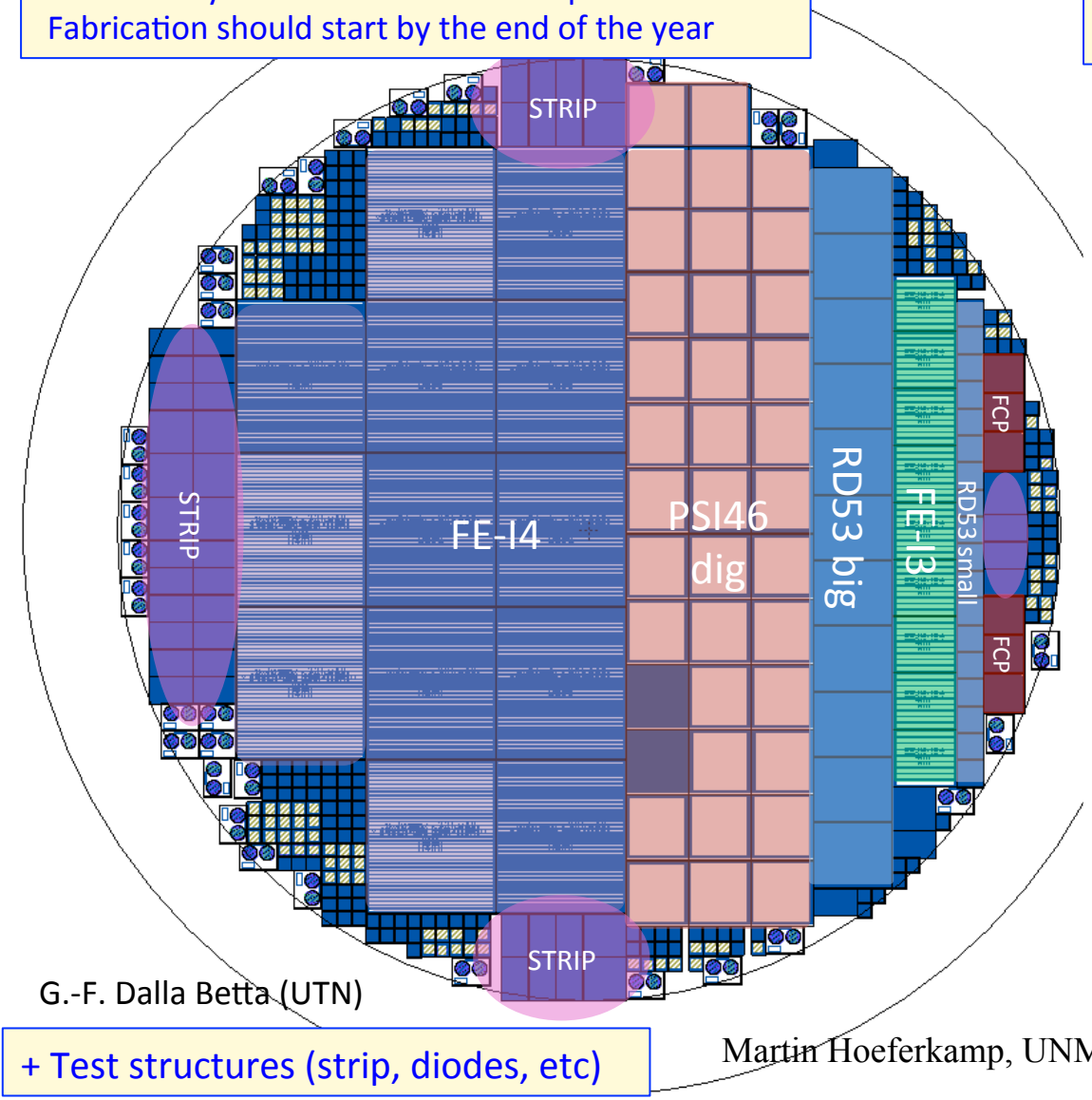


G.-F. Dalla Betta (UTN)

- 50x50 design safe, 25x100 is more difficult … too little clearances due to relatively large bump pad size
- Alternative designs, featuring bonding pads on top of the columns are planned for

FBK: 3D Pixel Wafer Layout

Final: mostly oriented to RD53A compatible sensors.
Fabrication should start by the end of the year



G.-F. Dalla Betta (UTN)

+ Test structures (strip, diodes, etc)

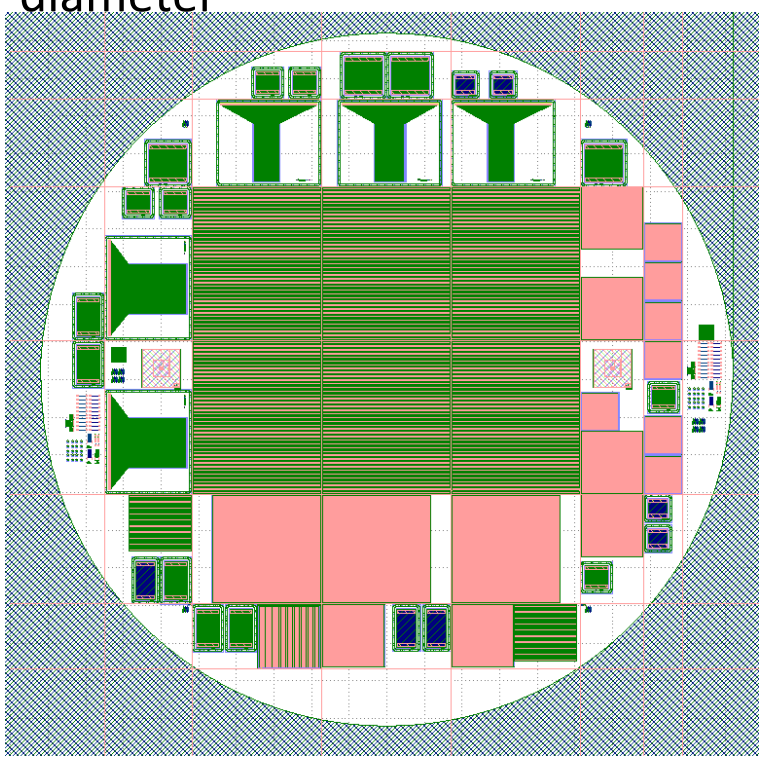
Many different pixel geometries and pitch variations:

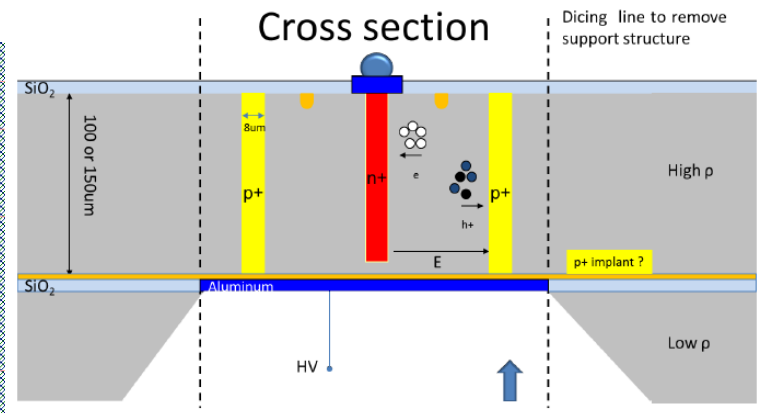
- FE-I4
  - 50 x 250 (2E) std
  - 50 x 50 (1E)
  - 25 x 100 (1E and 2E)
  - 25 x 500 (1E)
- FE-I3
  - 50 x 50 (1E)
  - 25 x 100 (1E and 2E)
- PSI46dig
  - 100 x 150 (2E and 3E) std
  - 50 x 50 (1E and 2E)
  - 50 x 100, 100 x 100 (2E + 4E)
  - 50 x 100, 100 X 150 (2E + 6E)
  - 25 x 100 (1E and 2E)
- FCP
  - 30 x 100 (1E)
- RD53 (small and big)
  - 50 x 50 (1E)
  - 25 x 100 (1E)
  - 25 x 100 (2E)

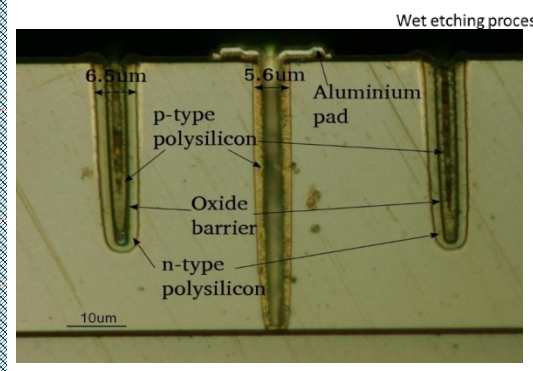
CNM: 3D Sensors

Joint Multi-Project Pixel Wafer run for ATLAS, CMS, LHCb (G. Pellegrini, 27th RD50 Workshop, CERN, 2-4 Dec. 2015)

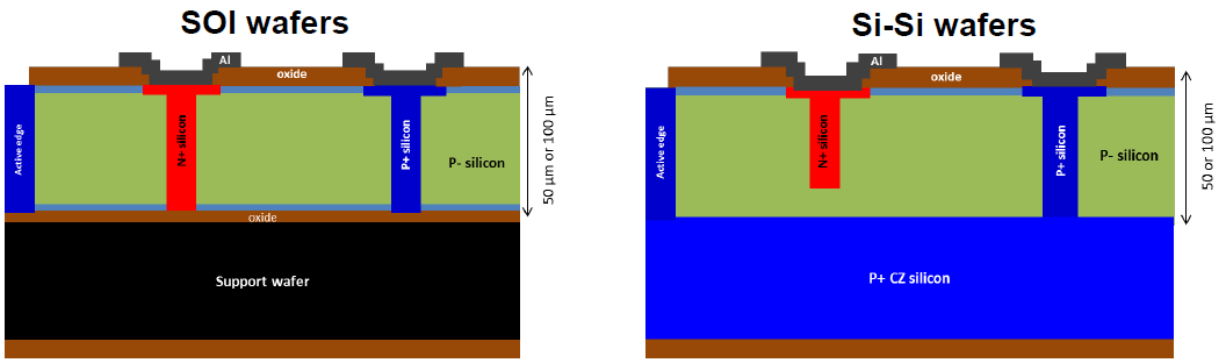
- Reduced thickness 100−150μm(small leakage current).
- First prototype of new generation 3D pixels finished (January 2016)
- 50μm thick detectors with SOI support wafer (350μm), 5μm hole diameter







SINTEF, Stanford Nanofabrication Lab: 3D Sensors



- SINTEF: Run 4 wafers under processing (expected by March 2017)

- SOI and Si-Si wafers with 100 µm and 50 µm thick sensors

- 2 column types: fully passing (SOI) and partially passing (Si-Si) n-type columns

- High aspect ratio holes (4-5 µm hole diameter, up to 100 µm depth) Active edge sensors

- SNL: One small-pitch 3D sensor batch also under fabrication with similar design characteristics

Summary

- Development of 3D pixel sensors for the ATLAS IBL provided valuable experience and lessons learned.
- A new generation of 3D sensor designs and fabrication runs geared towards meeting the HL-LHC requirements is under way
- Extensive characterization and rad-hardness studies in progress