Future Trends of 3D Si Sensors

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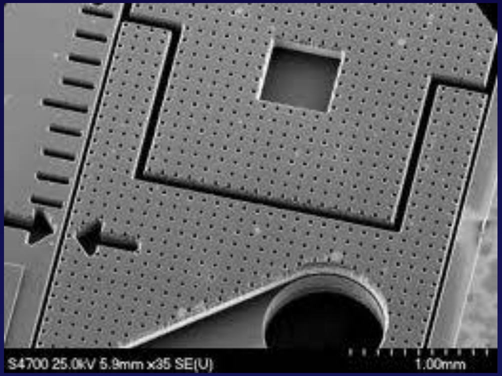
❖Introduction

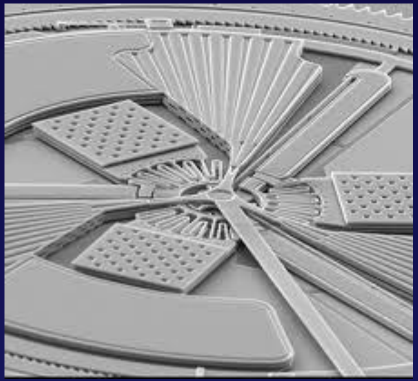
❖Current status of 3D silicon technology

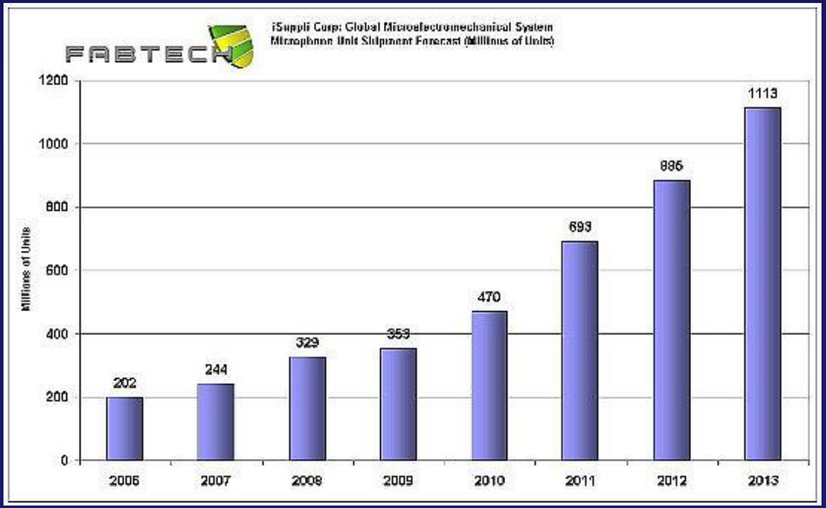
❖Future challenges and technological trends

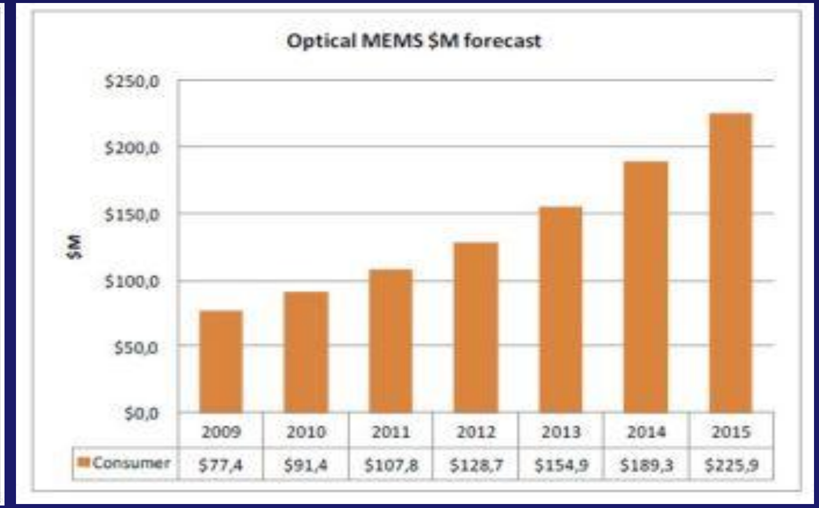
MEMS and 3D sensors

Micro-Electro-Mechanical Systems, or MEMS, is a technology that in its most general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of micro-fabrication, developed in the '70ies was first commercialized in the '80ies

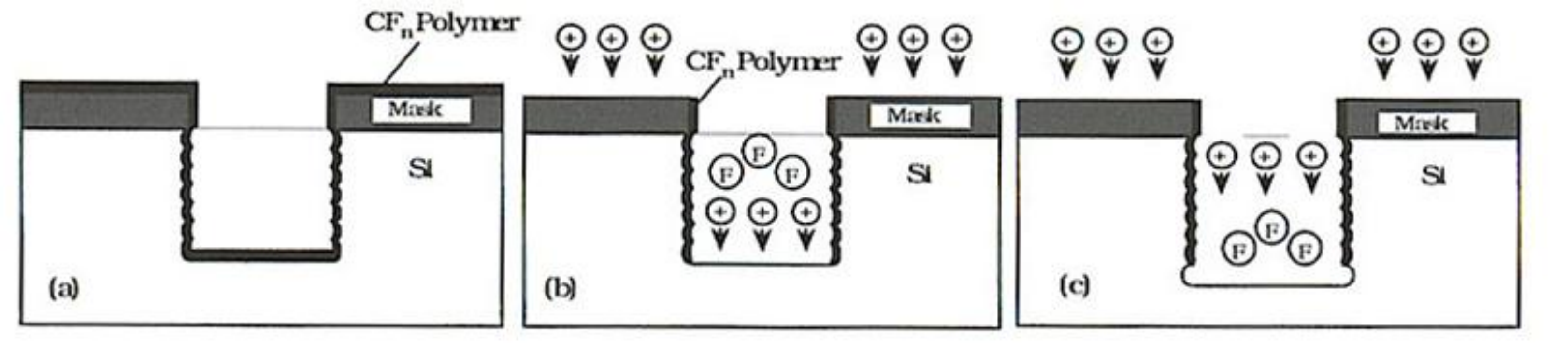






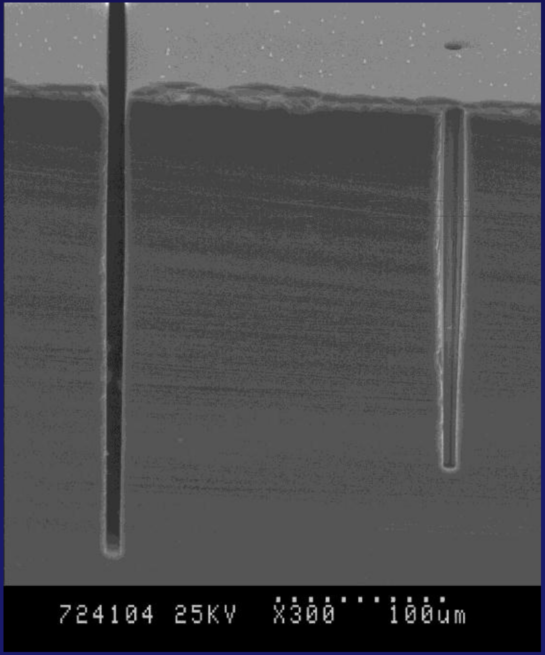


3D sensors and micromachining



BOSCH PROCESS: alternating passivation (C_4F_8) and etch cycles (SF_6):

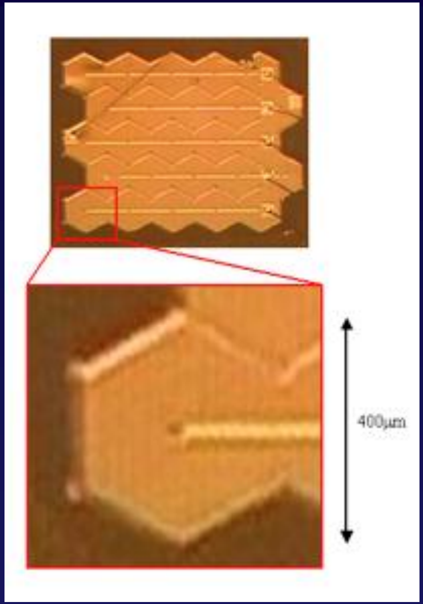
- Within the plasma an electric field is applied perpendicular to the silicon surface.
- The etch cycle consists of fluorine based etchants which react with silicon surface, removing silicon. The etch rates are ~1-5µm/minute.
- To minimize side wall etching, etch cycle is stopped and replaced with a passivation gas which creates a Teflon-like coating homogenously around the cavity. Energetic fluorine ions, accelerated by the e-field, remove the coating from the cavity bottom but NOT the side walls.

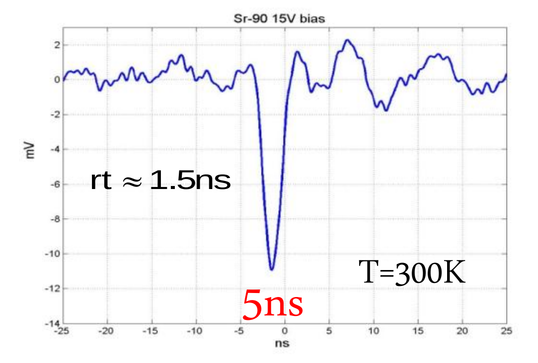


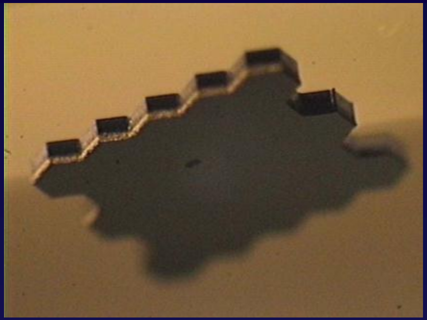
Slide from J. Hasi

Different shapes depending on applications

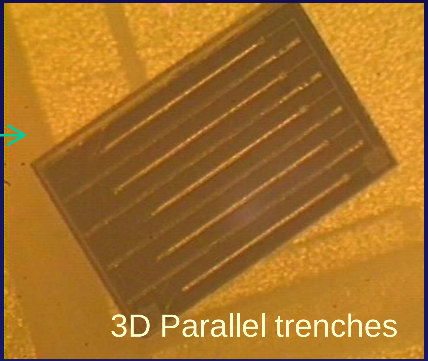
Test with -.130nm fast amplifier designed at CERN by G.(Anelli)



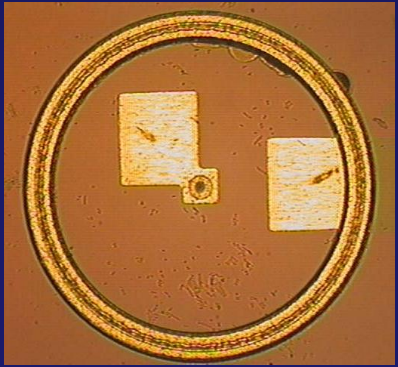


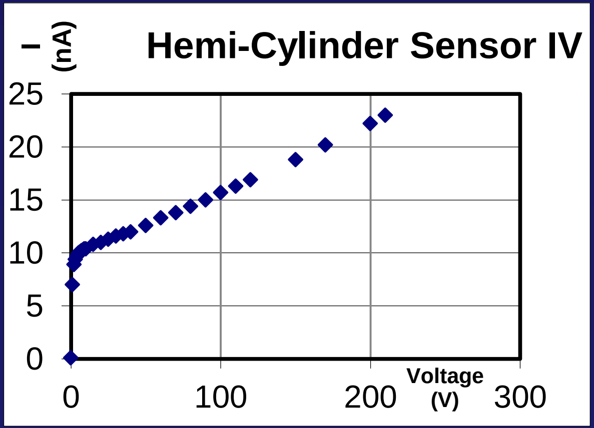


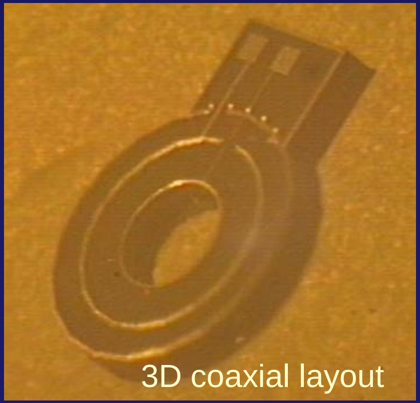
Hexagonal or parallel trench shapes:
Enhanced speed


3D Parallel trenches

This will be used for Micro-dosimetry

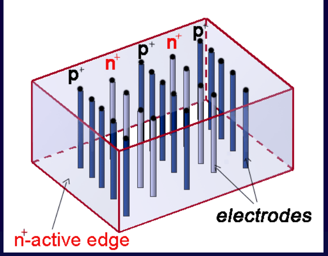


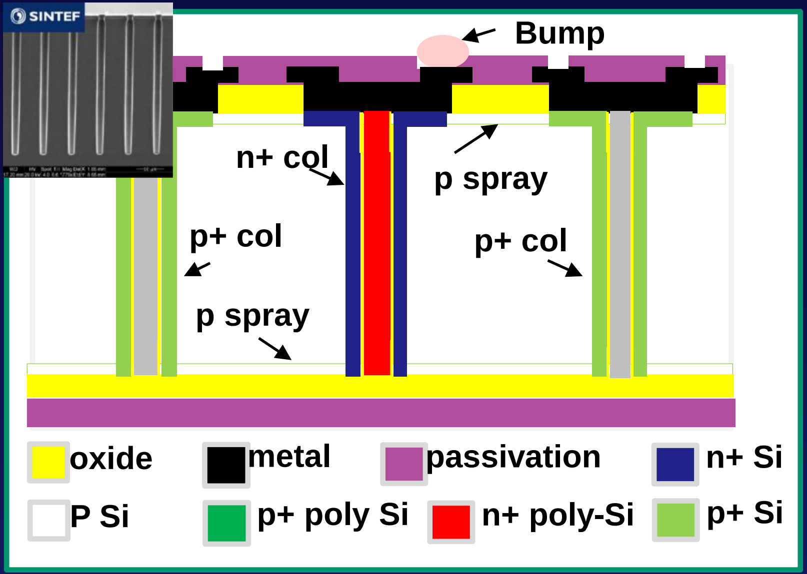



3D coaxial layout

Fabrication J. Hasi and C. Kenney, SLAC/Stanford

Existing 3D designs:





The Stanford Nanofabrication Facility

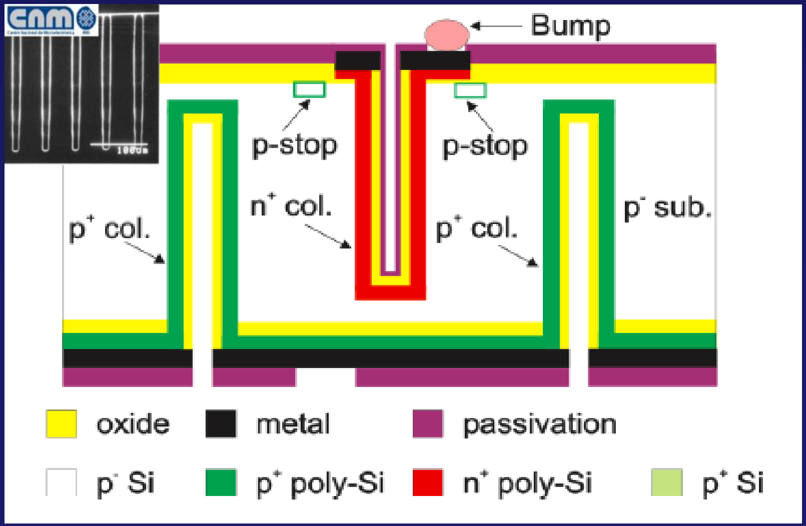
SINTEF

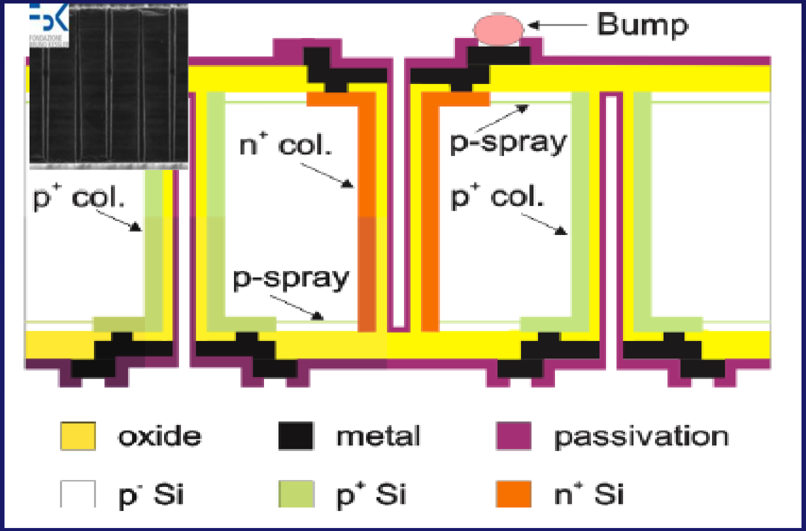
Single side, full 3D with active edges requires a support wafer which is removed later

ITC irst
FONDAZIONE BRUNO KESSLER

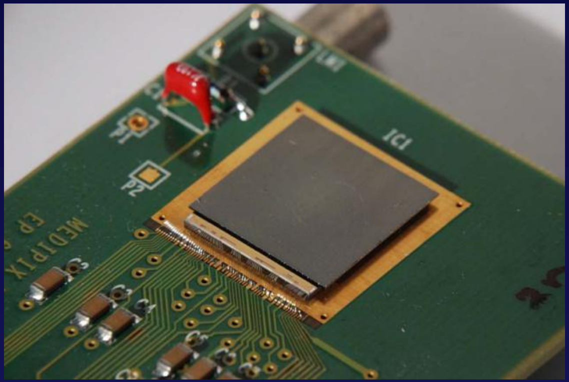
CNM

Double sided full or partially through3D with slim-fences (~200um)





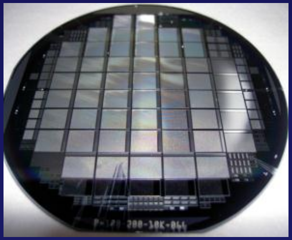
3D sensors bump-bonded with pixel frontends



G. Pellegrini et al.Nucl. Instr. Meth. In Phys. Res. Volume 504, Issues 1–3, 21 May 2003, Pages 149–153

Fabricated at CNM Now also being fabricated at FBK and SINTEF applications is synchrotron light sources and Neutron imaging

Medipix2 and Timepix (see LHCb upgrade talk on Monday)



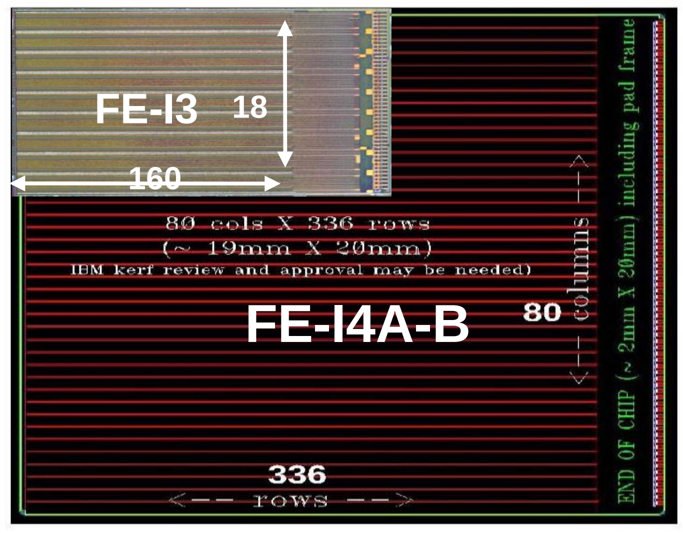
FE-I3 wafer from Stanford also fabricated At SINTEF, CNM, FBK

ATLAS FE-I3
P. Hansson et al. Nucl. Ins. And Meth. In Phts Res. A 628 (2011) 216–220

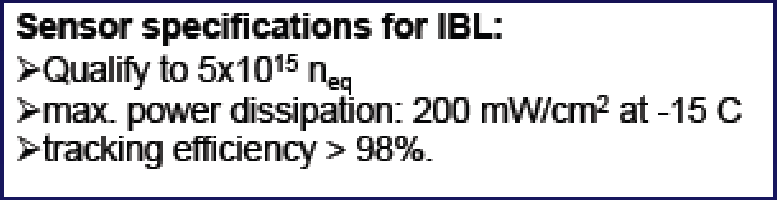
CMS (see poster by M. Obertino et al.)

FE-I4 for the ATLAS IBL

total dimension FE-I4: 20.2x19.0mm2
total pixel number: 26880
Total number of holes/chip : >100.000

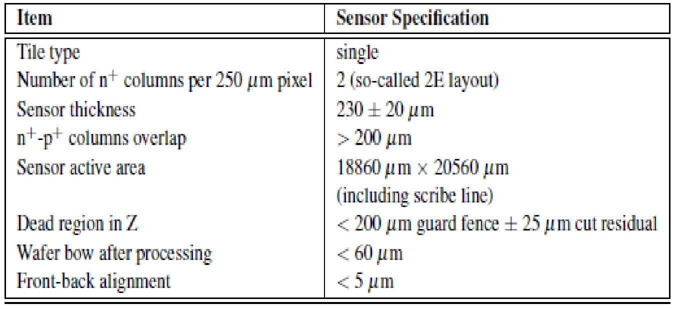


4 runs were completed in February 2012 by CNM and FBK with double side process with 306 good chips, a total of ~ 100 wafers and an yield exceeding 60% fulfilling the following:

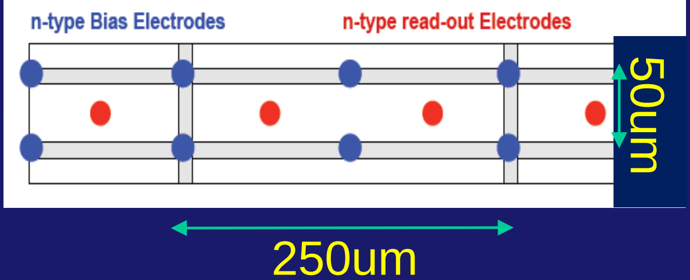


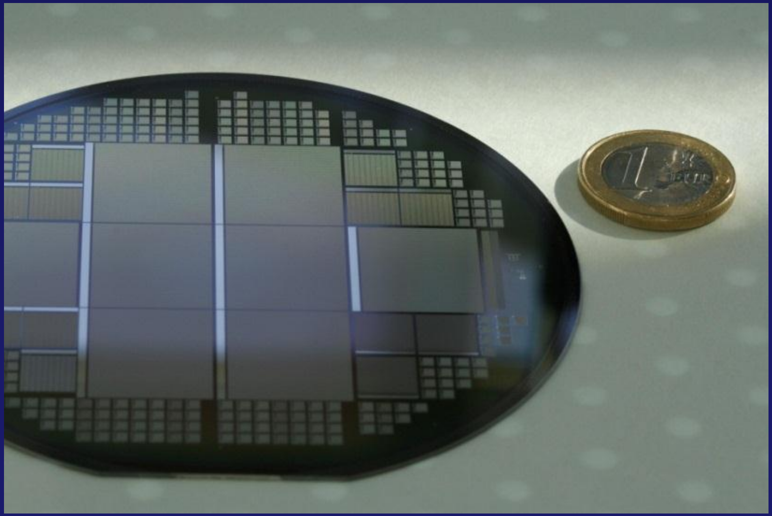
Sensor specifications for IBL:

- Qualify to 5x10^{15} n$_{eq}$
- max. power dissipation: 200 mW/cm^2 at -15 C
- tracking efficiency > 98%.

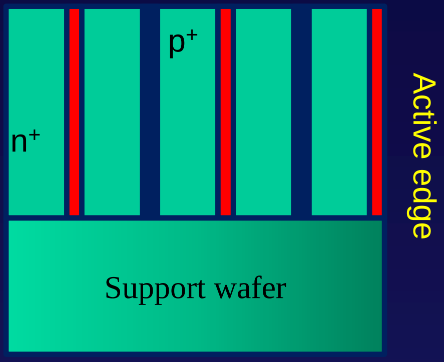


Item	Sensor Specification
Tile type	single
Number of n$^+$ columns per 250 μm pixel	2 (so-called 2E layout)
Sensor thickness	230 ± 20 μm
n$^+$-p$^+$ columns overlap	> 200 μm
Sensor active area	18860 μm × 20560 μm (including scribe line)
Dead region in Z	< 200 μm guard fence ± 25 μm cut residual
Wafer bow after processing	< 60 μm
Front-back alignment	< 5 μm

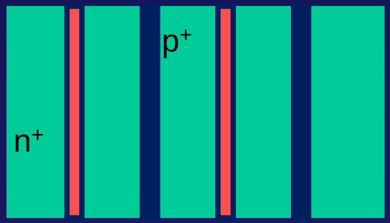




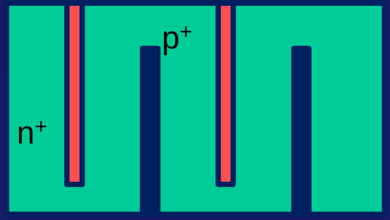
3D sensors signal efficiency compatibility



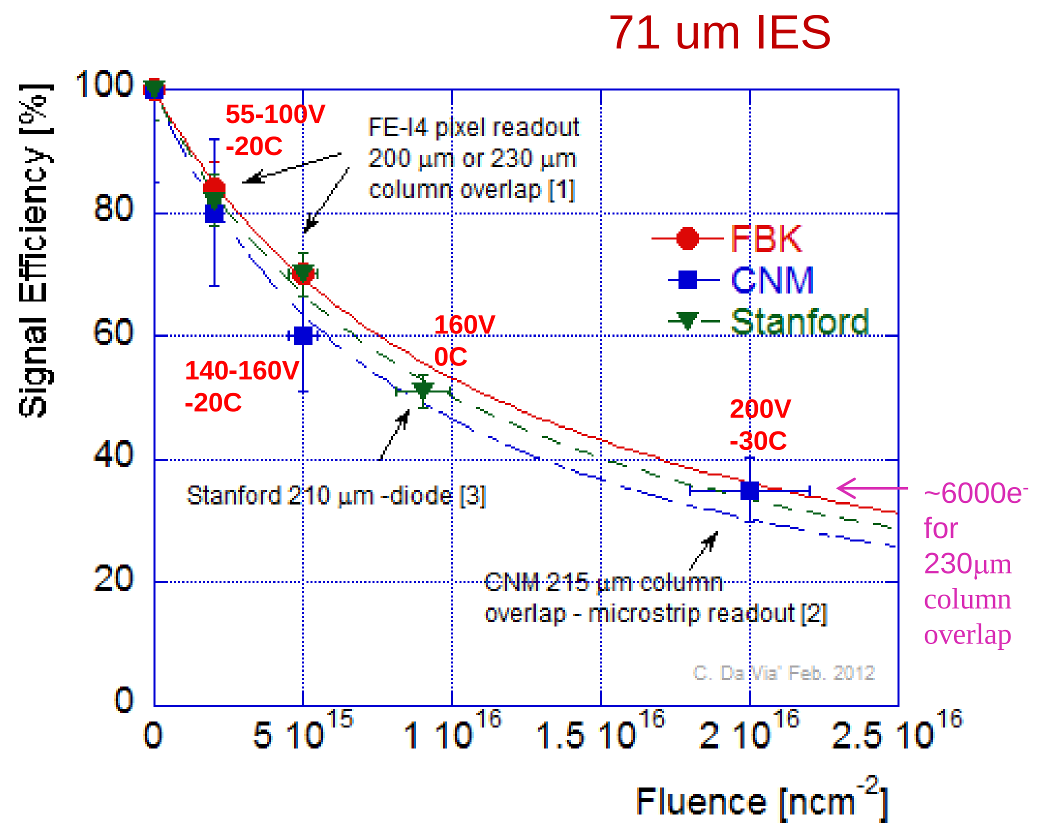
SINTEF/STANFORD



FBK



CNM



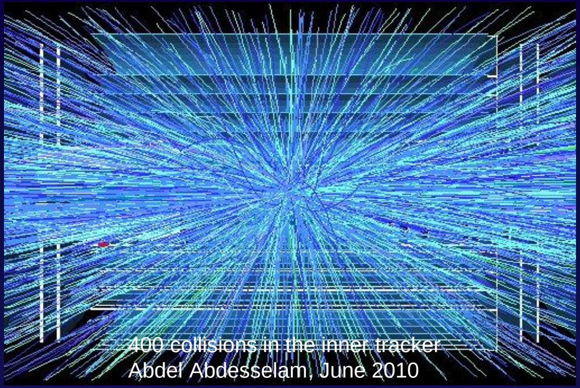
~6000e- for 230µm column overlap

[1] 2011 CNM-FBK IBL Modules. (C. Gemme, A. Micelli, S. Grinstein, lab tests) (test beam coordinated by P. Grenier, J. Wingarted, A. La Rosa) , to be published in JINST.
[2[ ]M. Kohler et al. IEEE Trans. Nucl. Scie. Volume 57, issue 5, 2010
[3] C. Da Via, et al., Nucl.Instrum.Meth.A604:505-511,2009

Precise tracking systems challenges at HL-LHC

Precise vertex determination

Important role in pattern recognition/ track reconstruction 200 pileup events/bc at $5\times10^{34}cm^{-2}s^{-1}$

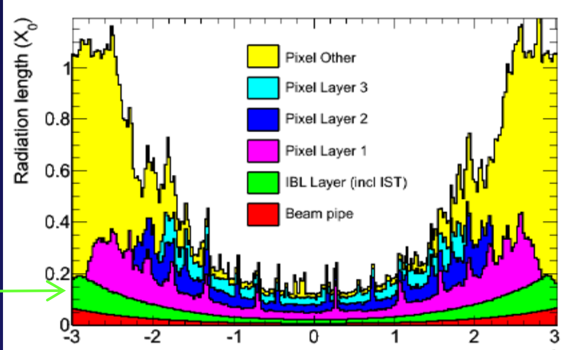

400 collisions in the inner tracker
Abdel Abdesselam, June 2010

Key Issues:

➢Material budget – less multiple scattering, better primary vertex resolution

Thin/small beam-pipe
Ultra-light detectors
Many channels to reduce occupancy
High data rates –

IBL 1.5%X_0

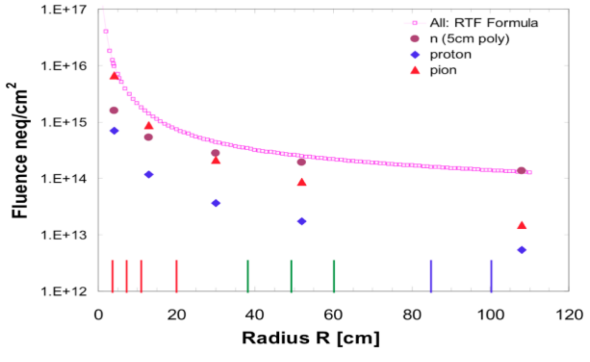


•High-precision detectors very close to IP

➢ **Ultra radiation hard detectors**

Radiation hardness up to
$2X10^{16}$ 1MeV ncm^{-2} at innermost layers at 3000 fb^{-1} ⟶
IBL~$3x10^{15}ncm^{-2}$ ($5X10^{15}$ ncm^{-2} with safety) at 300 fb^{-1}

➢ For forward and diffractive physics experiments: dis-homogenous irradiation

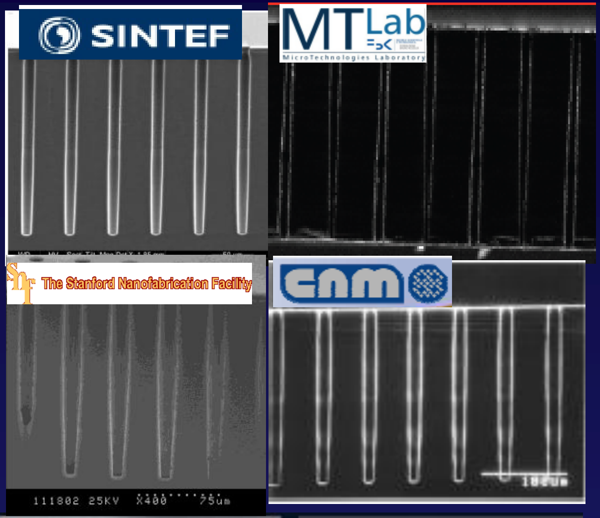


StripsATLAS Radiation Taskforce [ATL-GEN-2005-01]

➢ How can micromachining help coping with the above challenges

- ❖ Further improved aspect ratio to reduce electrode size and inefficiency
- ❖ Aggressive 3D inter-electrode spacing for improved radiation tolerance
- ❖ Control of charge multiplication before and after irradiation to reduce sensor thickness
- ❖ New ideas for active edges without support wafer if thicknesses is greater than 150um
- ❖ Use of micro-channels for reduced mass embedded cooling on FEC wafer
- ❖ Use FEC to apply bias voltage (possible for reduced bias after irradiation)
- ❖ Use alternative bias schemes to cope with dis-homogenous irradiation

1- trends in aspect ratio

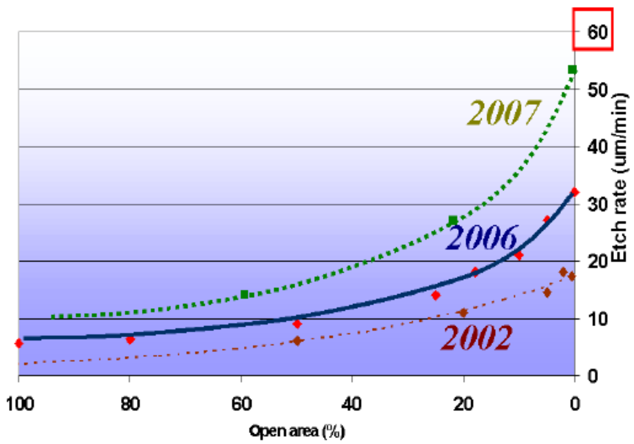


11:1 1997

24:1 2009

Today

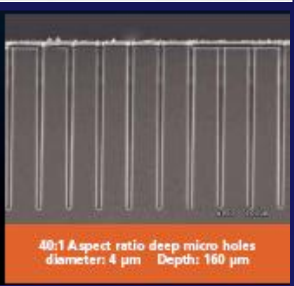
M. Puech. ALCATEL



Etching rate depends on exposed area

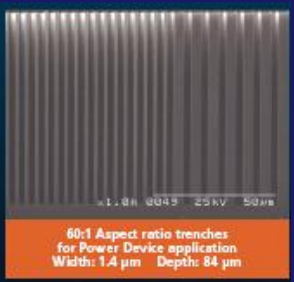
40-60:1


60:1 Aspect ratio 3D Via contacts
Width: 5 µm Depth: 300 µm

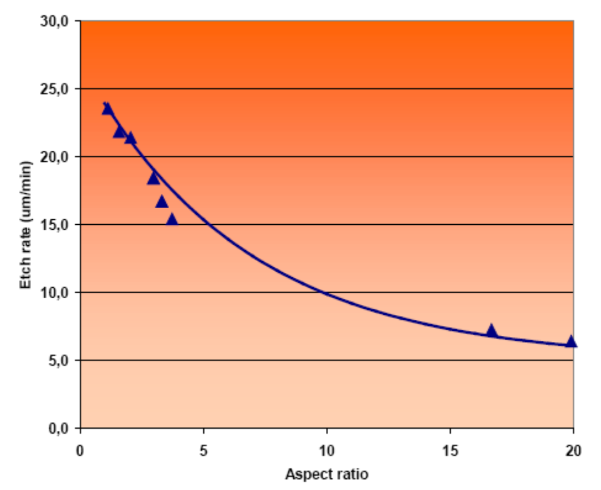

40:1 Aspect ratio deep micro holes
diameter: 4 µm Depth: 160 µm

110:1!!!

110:1 Aspect ratio of
sub micron trenches



60:1 Aspect ratio trenches
for Power Device application
Width: 1.4 µm Depth: 84 µm



etching rate depends on aspect ratio

"SHARP"
SUPER HIGH ASPECT RATIO > 110:1
UNIQUE ALCATEL DRIE PATENTED PROCESS

ALCATEL
Micro Machining Systems

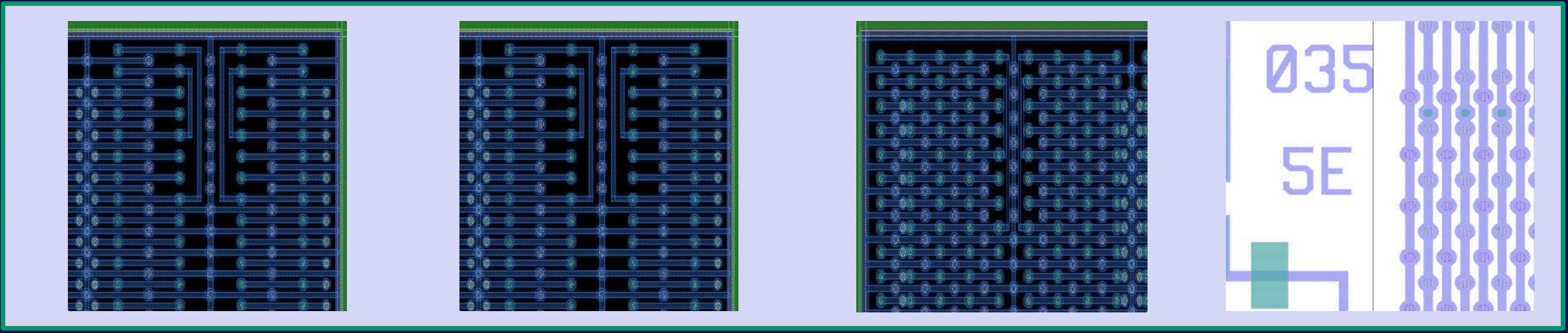
2-Radiation Tolerance of 3D sensors

$\lambda = \tau \times v$

Drift length — Trapping time — Drift Velocity (saturated)

$$S = \frac{\lambda}{L}\left[1 - \exp\left(-\frac{L}{\lambda}\right)\right]$$

L= Inter-Electrode Spacing

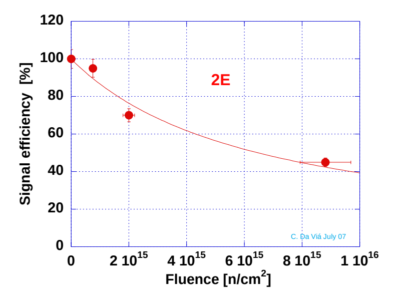


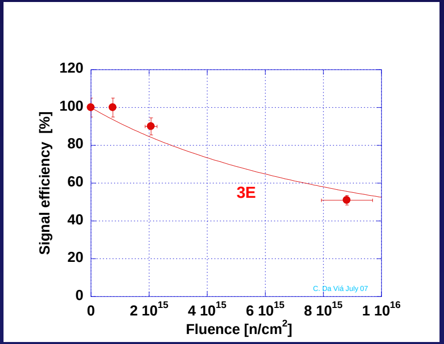
2E = 103um

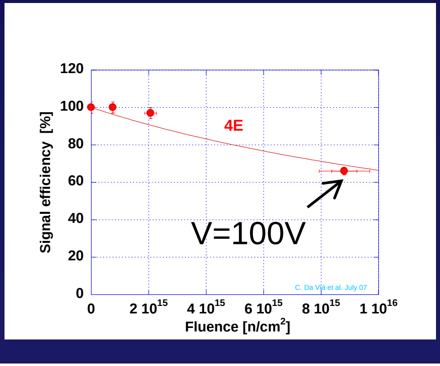
3E= 71um (IBL DESIGN)

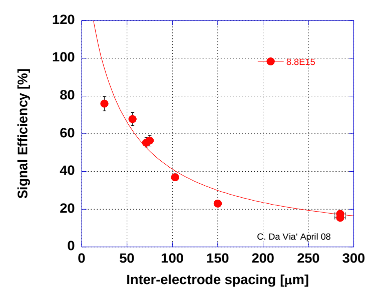
4E= 56um

5E= 47um









At 9x10^{15} ncm $^{-2}$ And biases below 200V

L=IES [um]	105	71	56	47
Signal Efficiency [%]	45	51	66	68
Charge 50um [e-]	1800	2040	2640	2720
Charge 100um [e-]	3200	4080	5280	5440

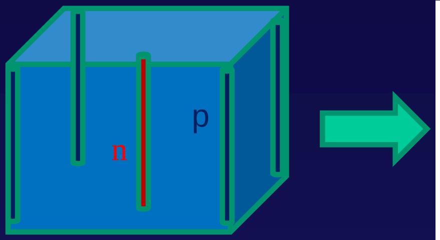
Nucl. Instrum. Meth. A 603 (2009) 319-324

Behaviour expected at reduced cell dimensions

How much signal can we expect?

Expected pixel dimension with 65nm technology

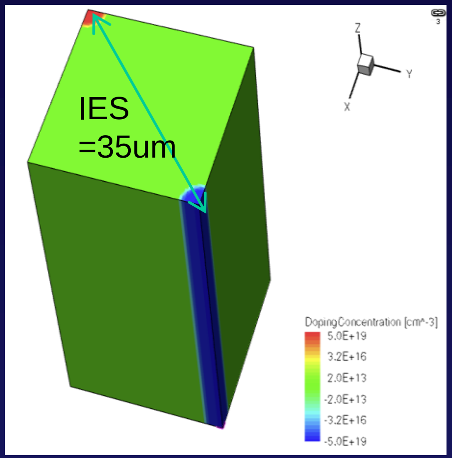
50x50x50um^3



Inter-Electrode Spacing=35um

Simulated structure:

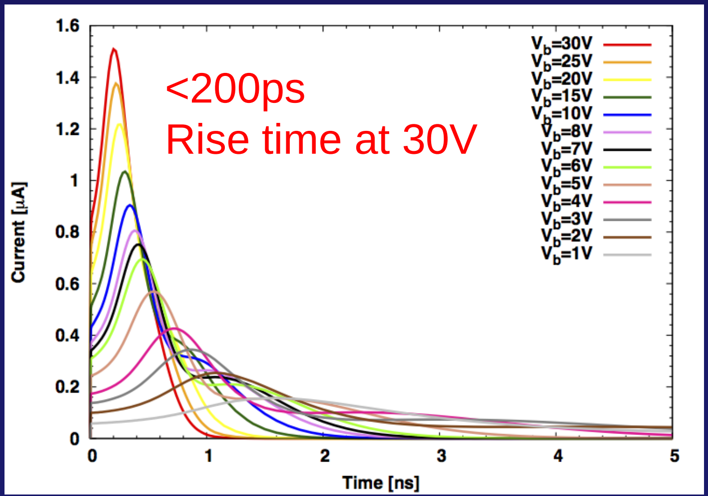
- 25x25x50um
- Electrodes diameter 3um
- MIP in the center

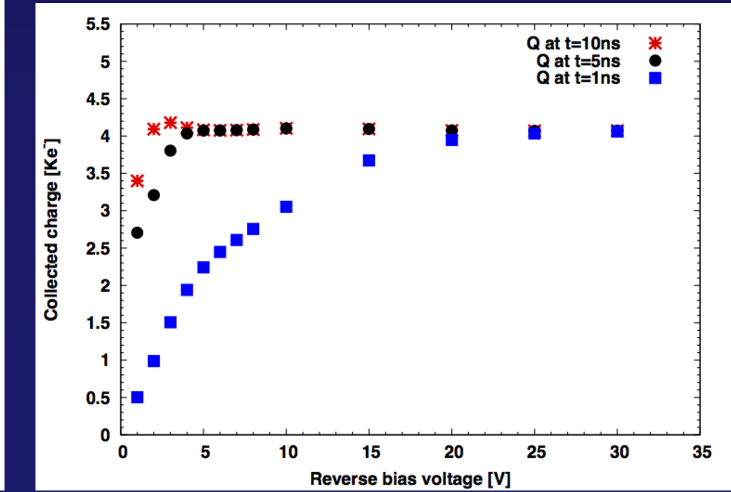


Simulation Marco Povoli, Trento/Manchester

- Expected charge in 50um silicon is equal to 4000 electrons
- Collected charge is reported at different integration times (1,5 and 10 ns)
- At 5 and 10ns integration time full collection is reached well before 5V of bias
- If the proper bias voltage is applied (e.g. 30V) devices can collect full charge in less than 1ns

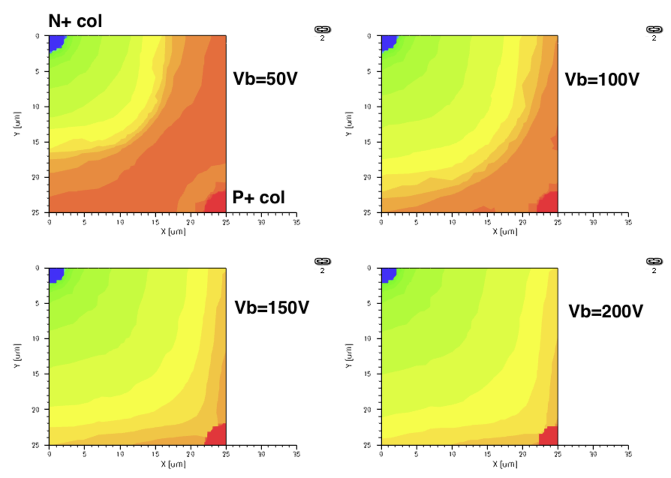
PRE-IRRADIATED RESPONSE


<200ps
Rise time at 30V



50x50x50um3
Simulations after irradiation at 2×10^{16} ncm $^{-2}$

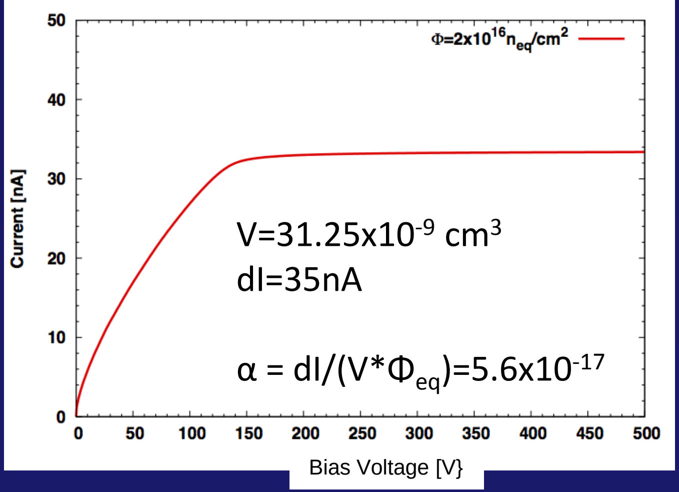
Simulation Marco Povoli, Trento/Manchester



Depletion evolution

Leakage current

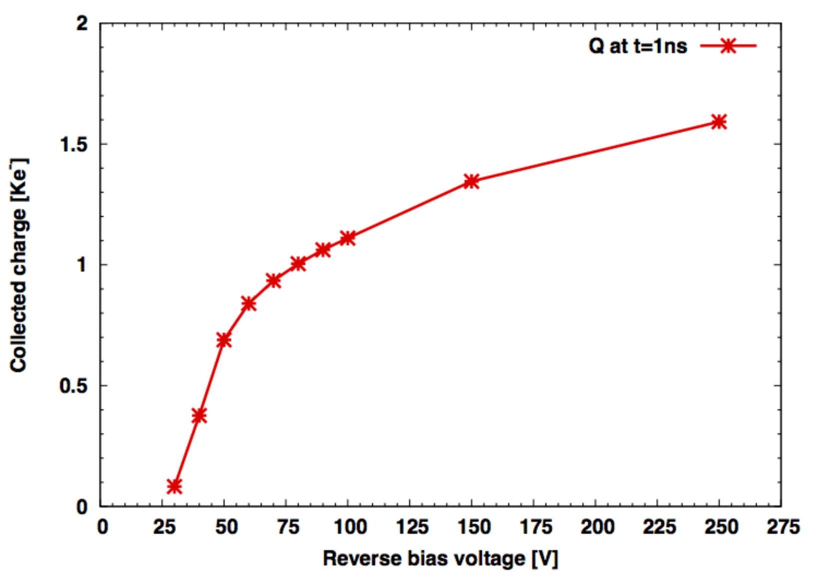
Signal versus bias.



$V=31.25\times10^{-9}$ cm ^{3}

dI=35nA

$\alpha = dI/(V^*\Phi_{eq})=5.6\times10^{-17}$

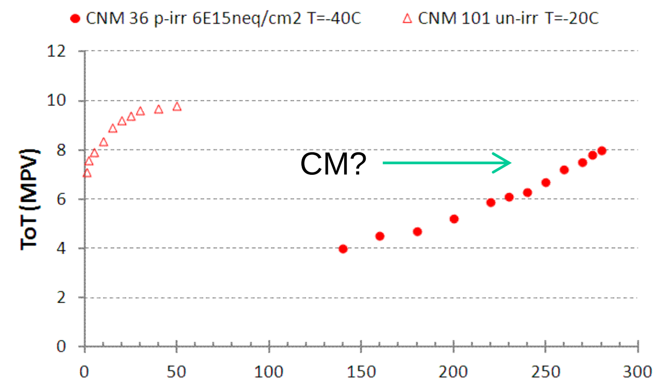


Charge Multiplication by design in 3D sensors

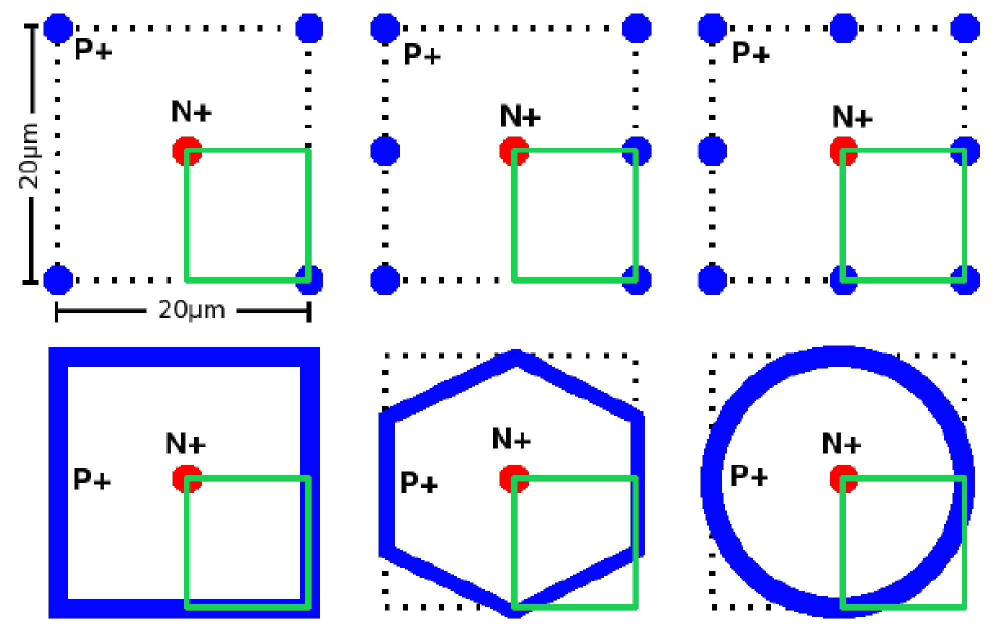
- Charge Multiplication has been observed in 3D sensors after irradiation
- Can we control it by design to compensate the signal loss in thinner sensors before (and after) irradiation?

Yes if IES is small enough (hence E-field is high)

Smaller 3D cells are possible with fine pitch bump bonding or vertical integration



IBL CNM sensors+FE-I4 measurements by S. Grinstein IFAE Barcelona



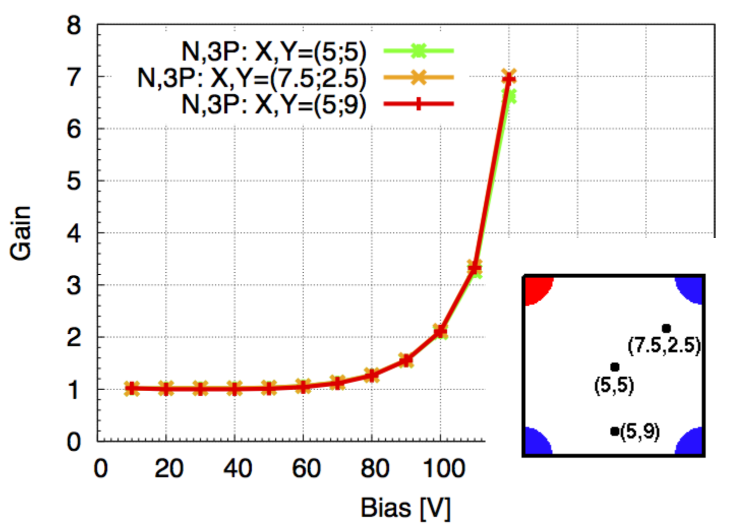
Possible geometries for enhanced e-field before irradiation

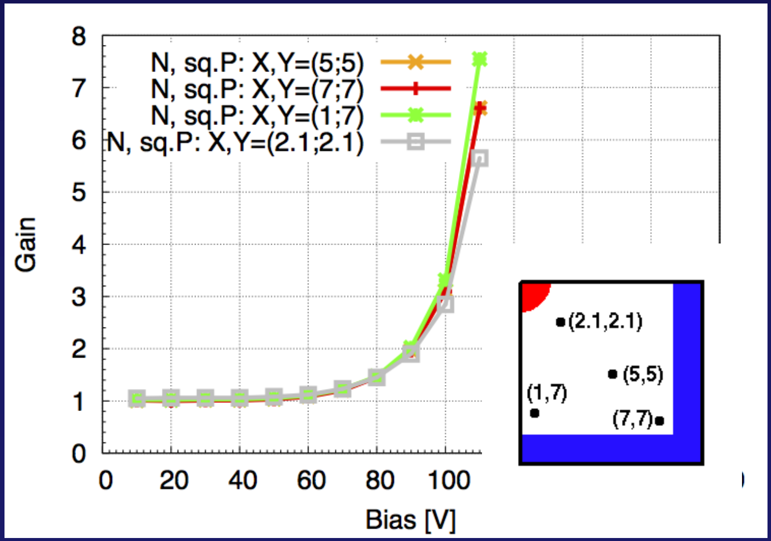
GF. Dalla Betta, C. Da Via, C-H. Lai,
M. Povoli (simulations), S. Watts

🟩 **Simulation domain**
🟥 **N+ electrodes**
🟦 **P+ electrodes**

Charge Multiplication Simulations

- n-side readout for electron multiplication
- MIPs hitting at different positions
- CM possible before irradiation at ~100V
- Gains up to 7-8, good spatial uniformity

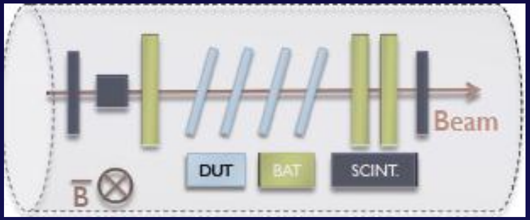




M. Povoli Trento

Full 3D with active edges FE-I3 ATLAS

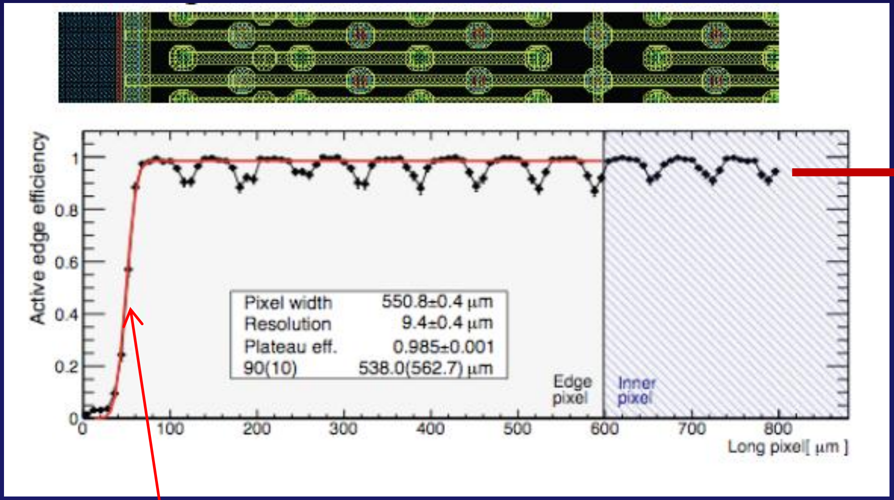
Current design requires the use of a support wafer which should be removed afterwards

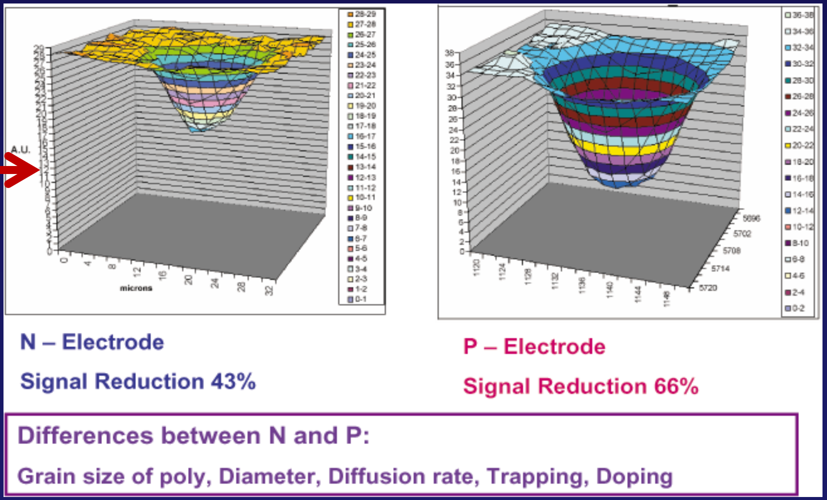


Test beam setup at CERN

120 GeV pions at CERN SpS

2 um, 14 KeV X-Rays beam at ALS (Berkeley)





N – Electrode

Signal Reduction 43%

P – Electrode

Signal Reduction 66%

Differences between N and P:

Grain size of poly, Diameter, Diffusion rate, Trapping, Doping

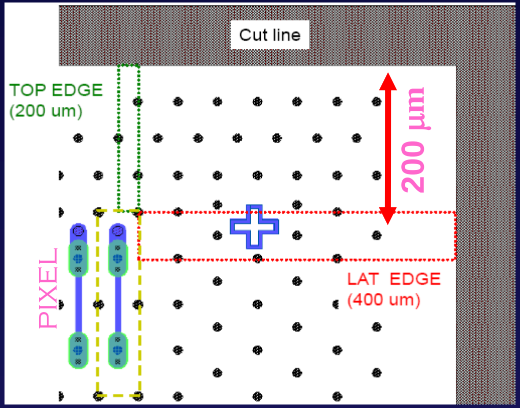
Active Edge = 543-537= 6±9.8 µm

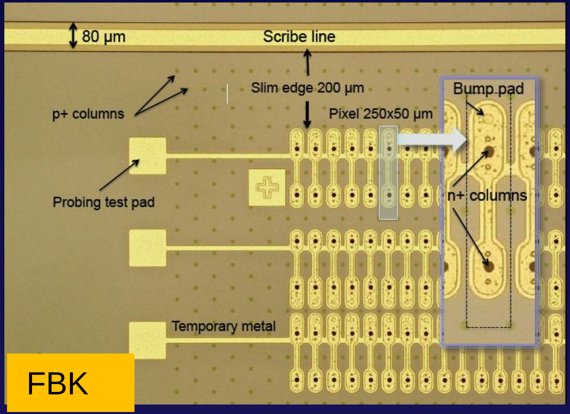
Electrodes response is not zero if filled with poly-silicon

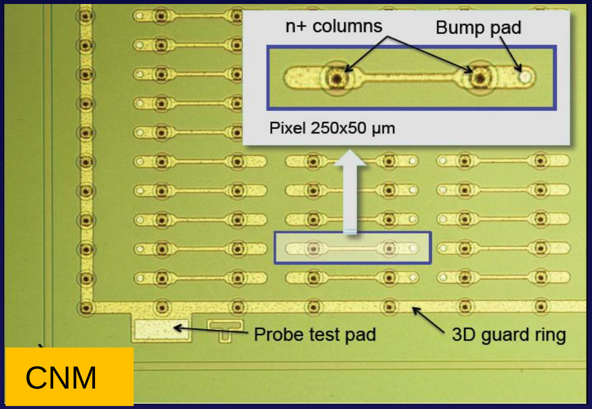
P. Hansson et al. Nuclear Instruments and Methods in Physics Research A 628 (2011) 216–220

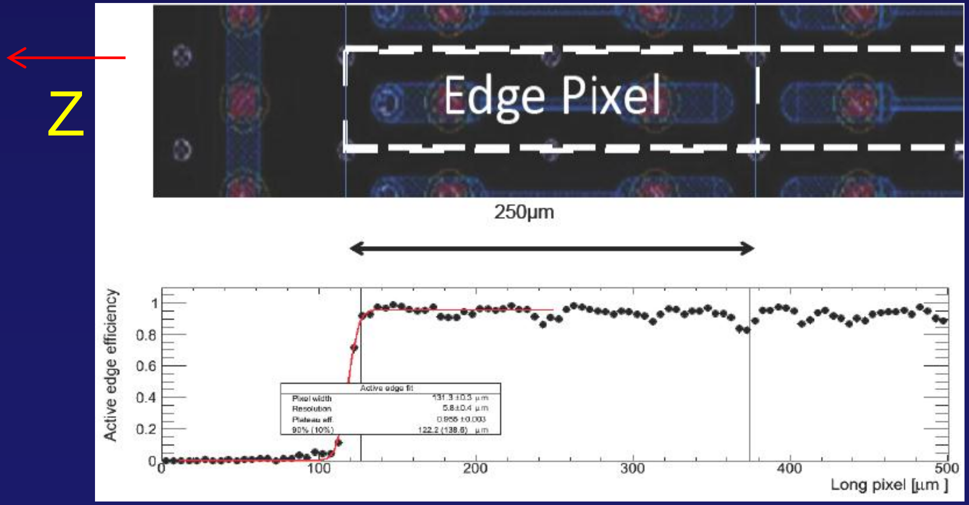
J. Hasi PhD Thesis

To simplify the process the IBL design uses 200 μm guard fences with a total edge region of ~240um









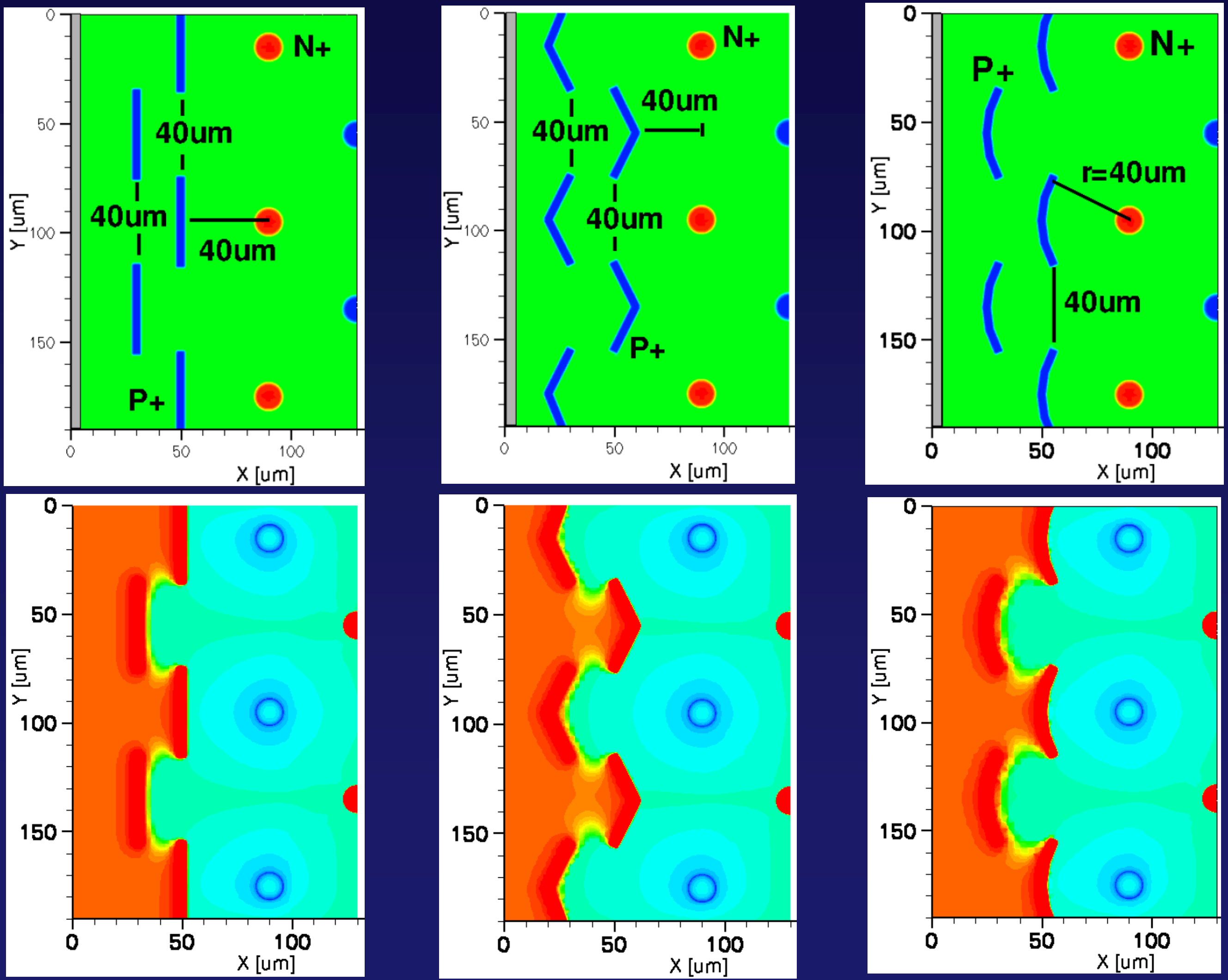
3D-CNM34, irradiated with protons at 5E15neq/cm2: 1D hit efficiency in the long pixel direction for edge pixels. All edge pixels have added together.

Operating conditions :
FE-I4 threshold = 1300e, bias voltage = -140V, magnetic field = 1.6T, tilt angle = 0 degrees.

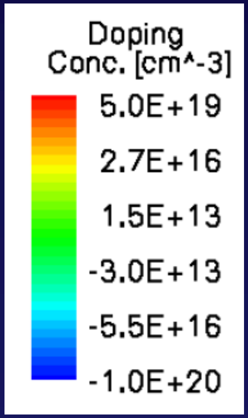
Efficiency at 50% is ~200um um: field penetrates within fences

Improved edge designs with double side processing

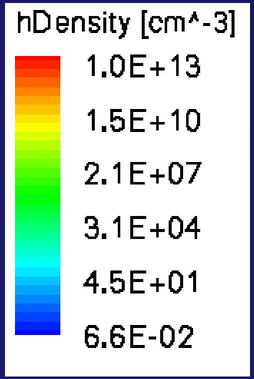
G.F. Dalla Betta et al., IEEE NSS 2011



Narrow trenches in place of columns

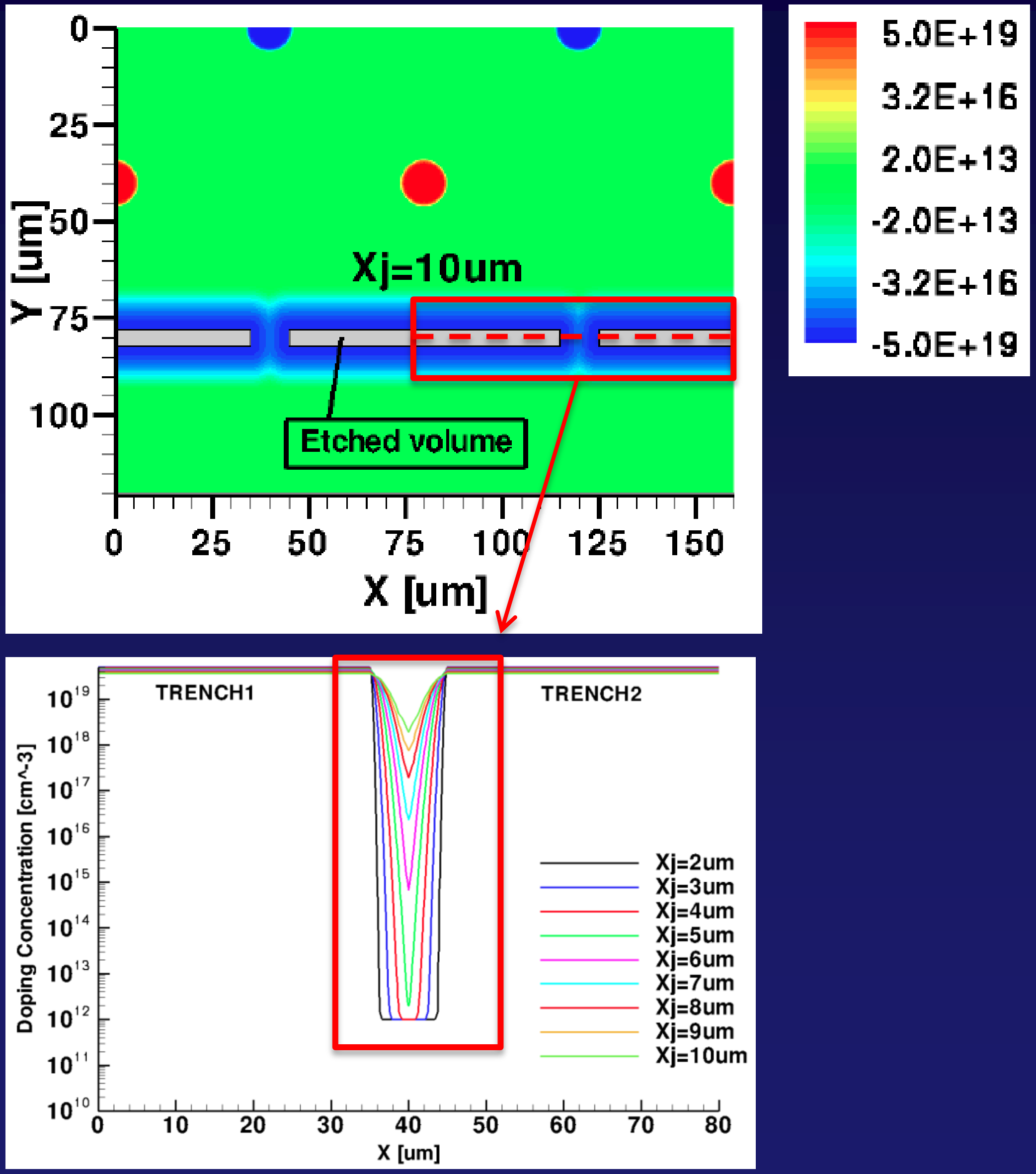


V_{bias}=50V



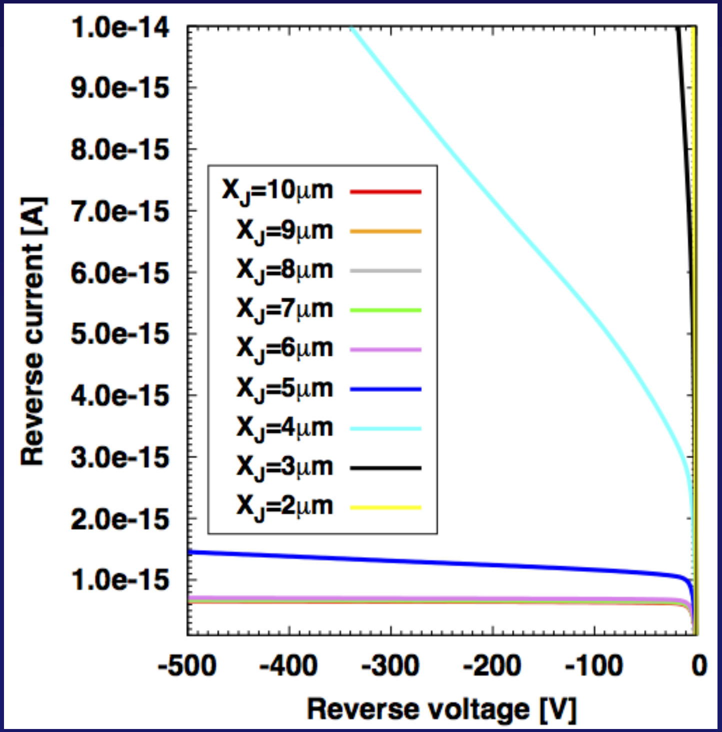
Alternative active edge design in double-side 3D

S. Parker (2012)

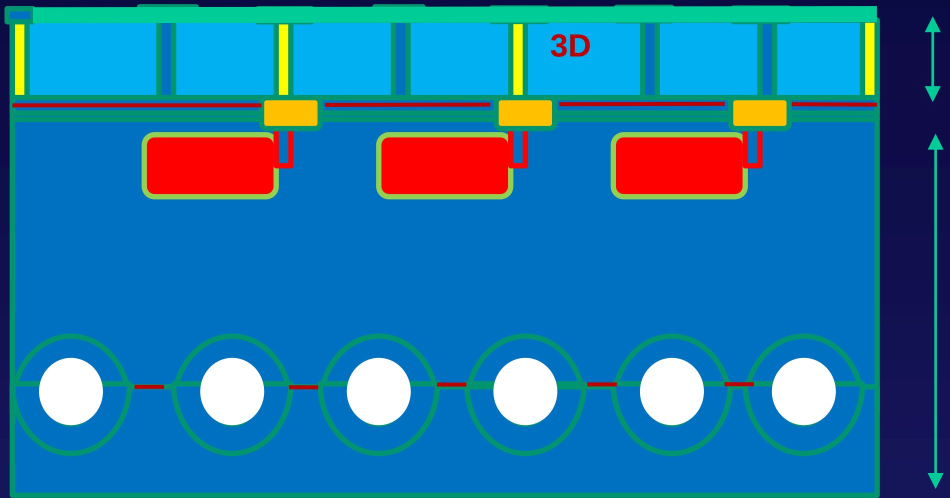


Doping Concentration [cm^{-3}]

A p$^+$ doped wall exploiting diffusion from small trenches …



Low mass 3D system with embedded cooling

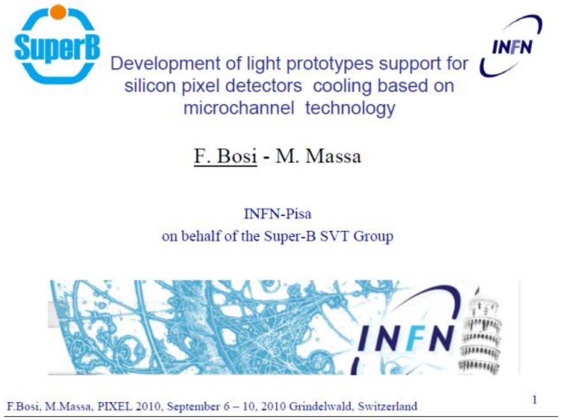


50um
3D epi-silicon

100um
electronics

Embedded
cooling

- Processing vias on thin silicon requires a support wafer
- In 3D Capacitance decrease with thickness
- EPI silicon can be grown up to 150um
- The EPI-Cz interface can stop etching
- The support wafer can be removed after bump bonding (or after UBM using reversible wafer bonding)



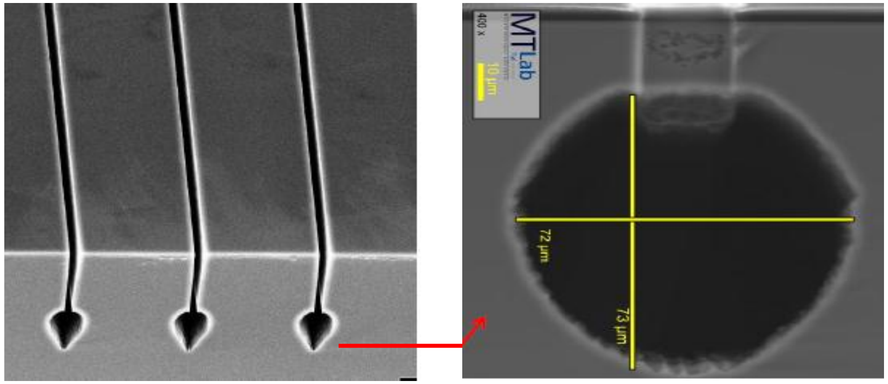
Development of light prototypes support for silicon pixel detectors cooling based on microchannel technology

F. Bosi - M. Massa

INFN-Pisa
on behalf of the Super-B SVT Group

F.Bosi, M.Massa, PIXEL 2010, September 6 – 10, 2010 Grindelwald, Switzerland

1



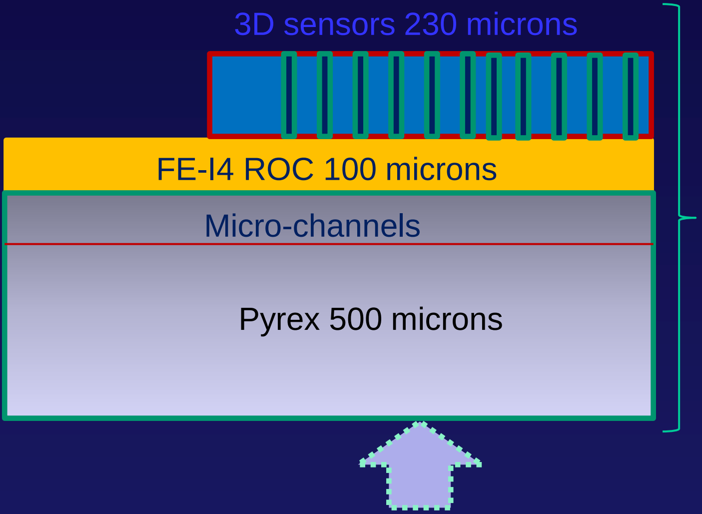
Micro-channels fabricated at FBK in collaboration with the Pisa group

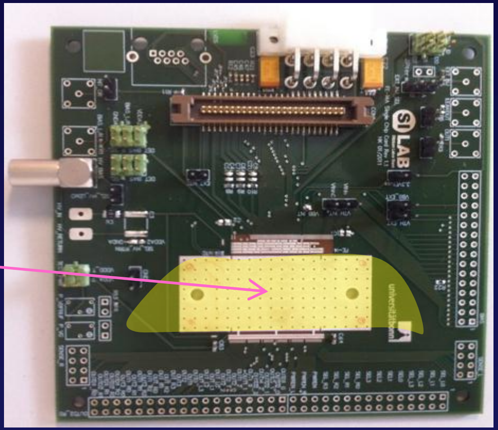
Existing activity and forthcoming 3DATLAS Prototype (ALICE+LHCb)

See presentation from J. Buytaert
Micro-channel cooling for LHCb VELO upgrade

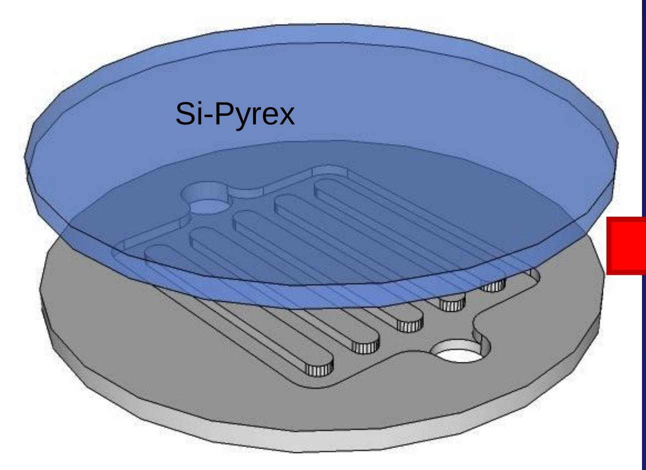
Driving CERN +EPFL group

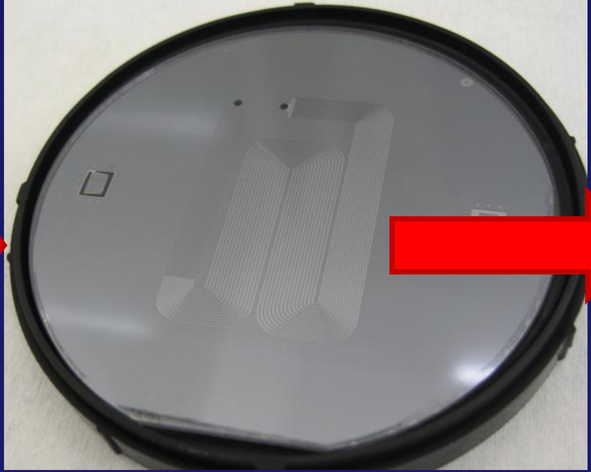
Giulia Romagnoli
Jerome Noel
Paolo Petagna
Alessandro Mapelli
(Jan McGill)
(Alan Honma)

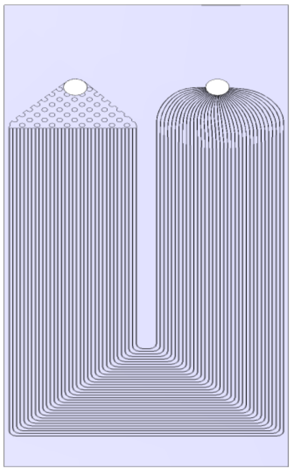




For this test we will use The LHCb VELO snake design





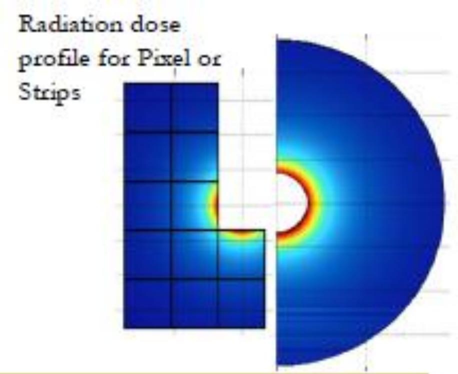


Dis-homogenous irradiation

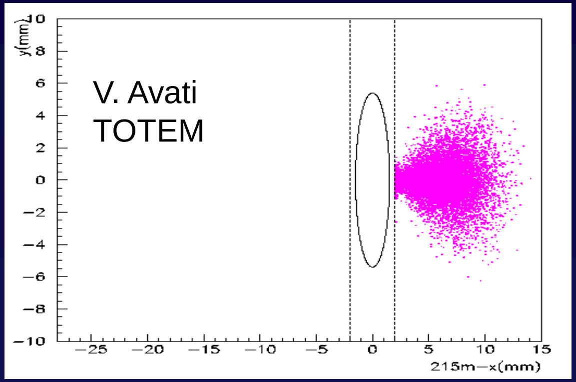
Affects precise tracking and vertex reconstruction close by the beam

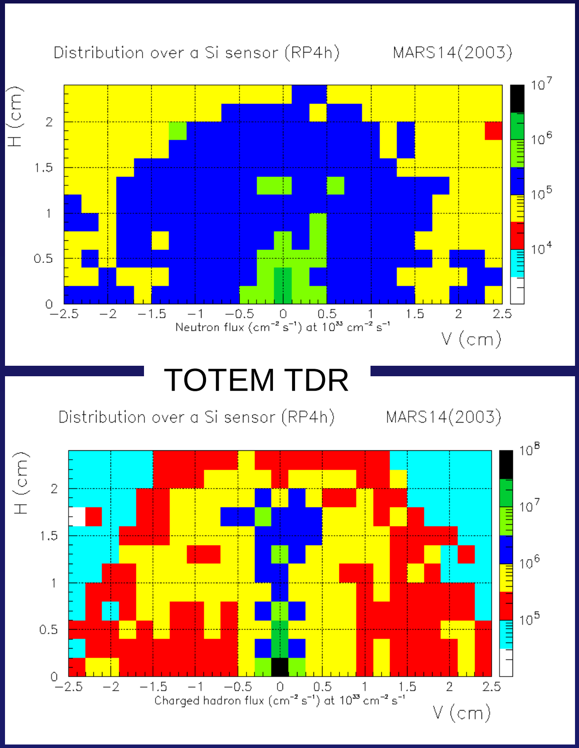
Examples:

- LHCb,
- TOTEM,
- Atlas Forward Physics (AFP)



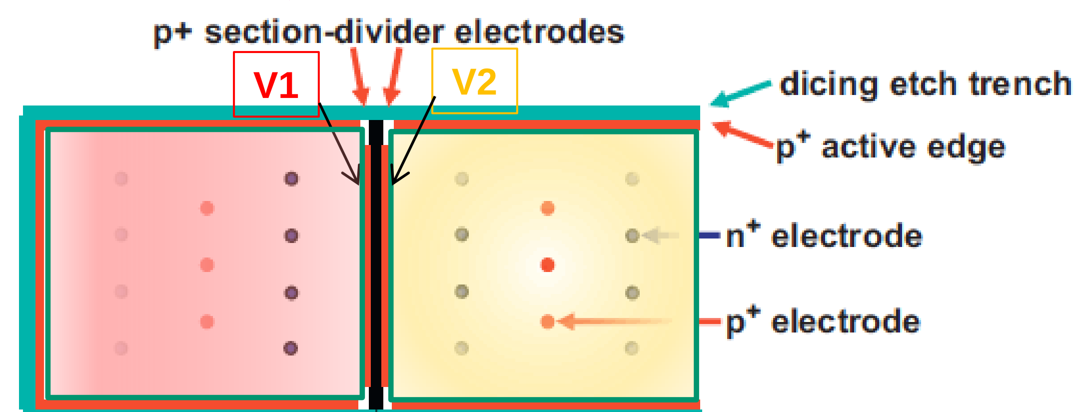
from J. Buytaert
Micro-channel cooling for LHCb VELO upgrade





TOTEM TDR

A possible solution is multiple bias operation
Using section divider active edges.



Prototypes are presently being fabricated at Stanford

S. Parker et. al. NIMA 685(2012), 98

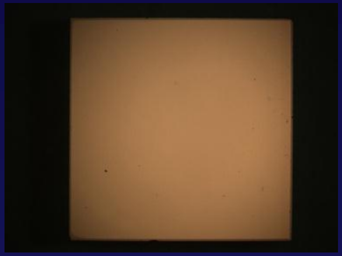
Last but not least: 3D structures on diamond substrate

…the benefits of 3D with no noise

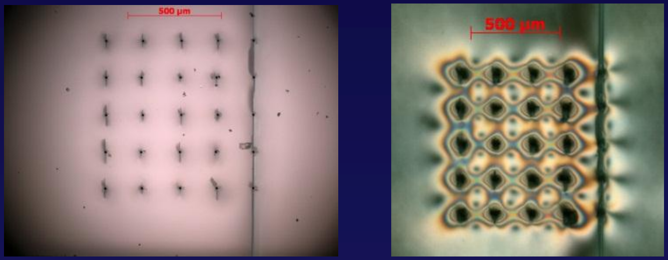
Alexander Oh (Manchester)
Benoit Caylar (CEA Saclay)
Michael Pomorski (CEA Saclay)
Thorsten Wengler (CERN)
Stephen Watts (Manchester)
Iain Haughton (Manchester)
Harris Kagan (Ohio State)
Cinzia Da Via (Manchester)

Samples from DDL
Processing made in Saclay and Manchester

Process flow →



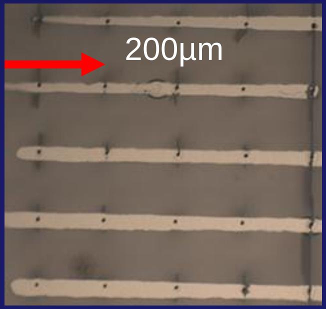
Single crystal diamond

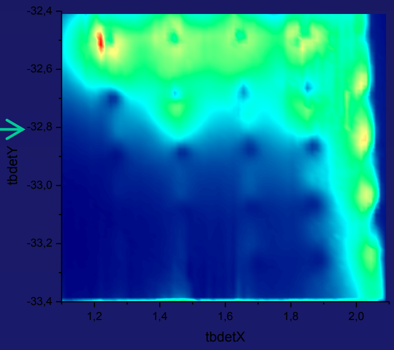


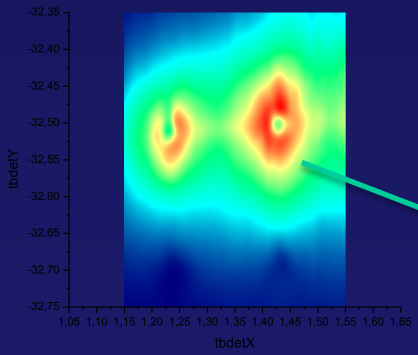
3D electrodes graphitization with an IR high power laser

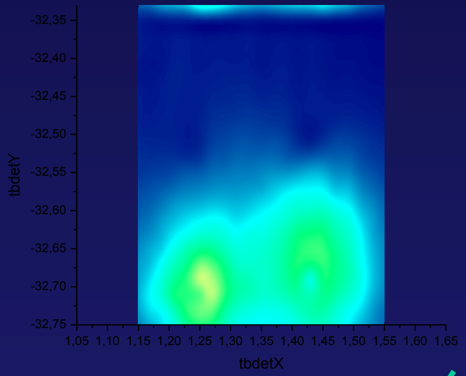
After metallization

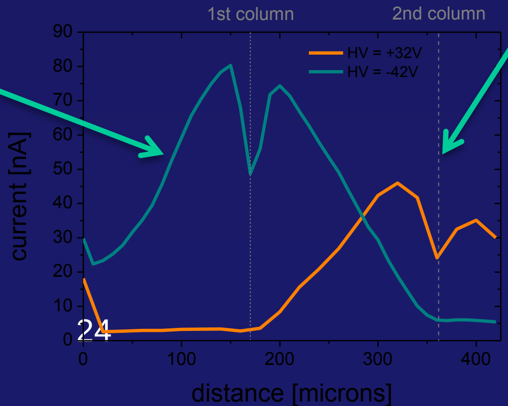
Mapping using at the DIAMOND synchrtron micro-beam
Spot size : 3µm /*/ Beam Energy : 15keV /*/ HV = -40V /*/
Absorber 24











DIAMOND AND RELATED MATERIALS Volume: 20 Issue: 3 Pages: 398-402 DOI: 10.1016/j.diamond.2011.01.042 Published: MAR 2011

ATLAS 3D Silicon Sensors R&D Collaboration

VTT

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18 institutions and 5 processing facilities

**spokesperson*