From Physics to Daily Life

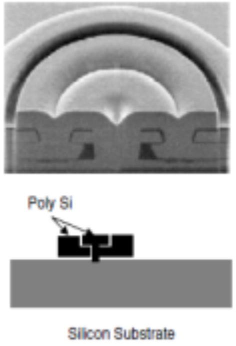
Micro-Fabricated Sensors

Cinzia Da Vià, The University of Manchester, UK

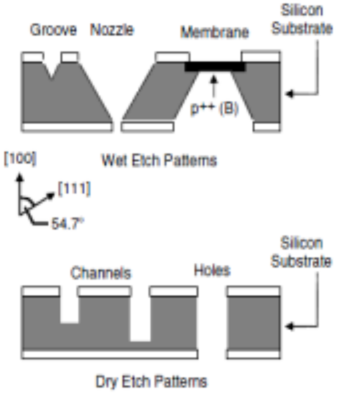
Micro-Fabrication

In Micro-fabrication, used mainly for Micro-Electro Mechanical Systems (MEMS), the process is performed 3 dimensionally within the silicon volume.
Different processing types include:

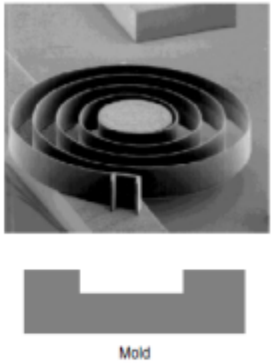
- ❖ Surface: Structures are formed by deposition and etching of sacrificial and structural thin films
- ❖ Bulk, Volume: 3D structures formed by dry or wet etching of silicon substrates
- ❖ LIGA: 3D structures formed by mold fabrication followed by injection molding or electroplating



Surface



Bulk



LIGA

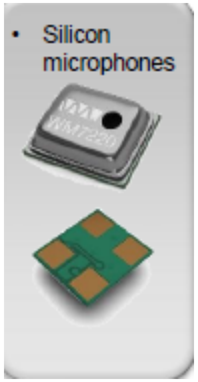
Applications:

- ➢ Everyday life (cars, portable devices..)
- ➢ Medical/Biology
- ➢ Space
- ➢ High Energy Physics
- ➢ …

Industrial applications: sensors and actuators

Sensing Applications

Voice/ sound

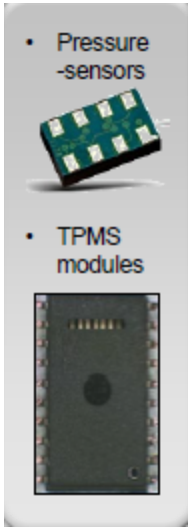


- Silicon microphones

Motion/ position

- Gyroscopes
- Accelerometers
- Magnetometers
- Fusion sensor combos & IMUs

Pressure/ monitoring



- Pressure -sensors
- TPMS modules

TPMS
Tire pressure monitoring system

Actuating Applications

Projecting Receiving light

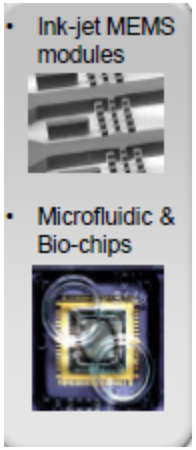
- Micro- mirrors

RF Related functions

- Oscillators / Resonators
- RF-MEMS switches
- FBAR / BAW filters
- SAW filters

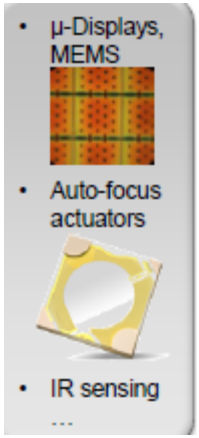
Surface acoustic wave

Managing fluids



- Ink-jet MEMS modules
- Microfluidic & Bio-chips

Emerging MEMS



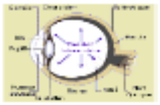
- µ-Displays, MEMS
- Auto-focus actuators
- IR sensing
...

Source: Lami EpoSS 2012

Applications in Bio-Medicine

Pressure Sensing

Ocular pressure

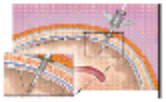


9mmHg <P< 21 mmHg

Blood pressure

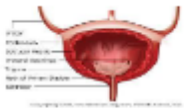
$P_{systolique} < 15$ cmHg.
$P_{diastolique} < 9$cmHg

Intra-brain pressure



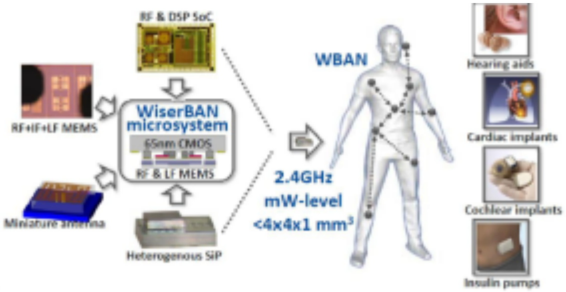
2mmHg <P< 20 mmHg

Bladder pressure

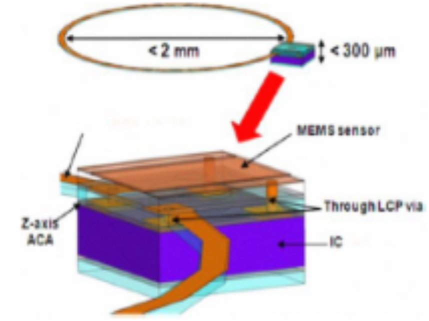


0mmHg <P< 15 mmHg

Implantable Devices

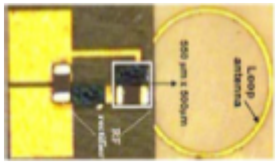


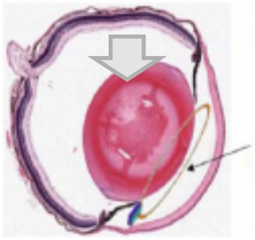
Glaucoma diagnosis



3D IC and MEMS stacking

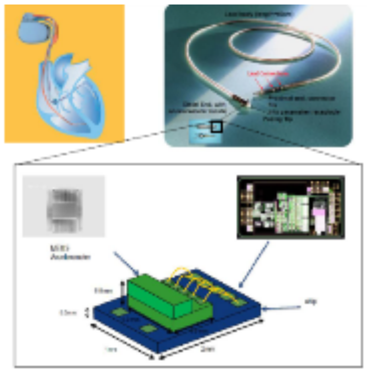
D. Ha et al. IMS 2010

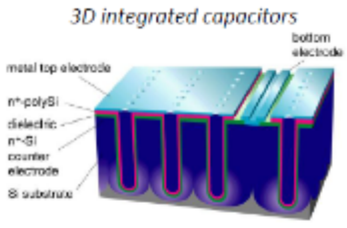




Inserted in a mouse's eye

Acceleration monitoring in pacemakers



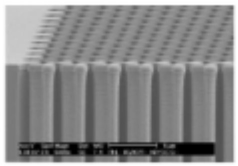


Energy Management
500 nF/mm
Using high k dielectrics

DRIE etched pores

or

DRIE etched pillars

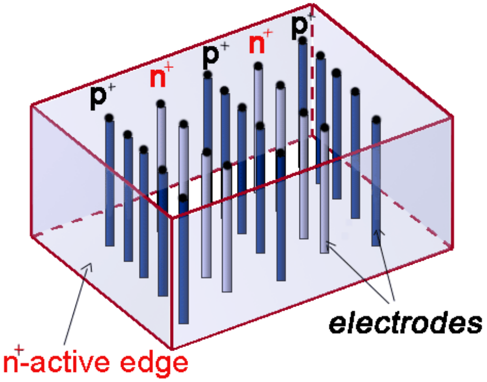


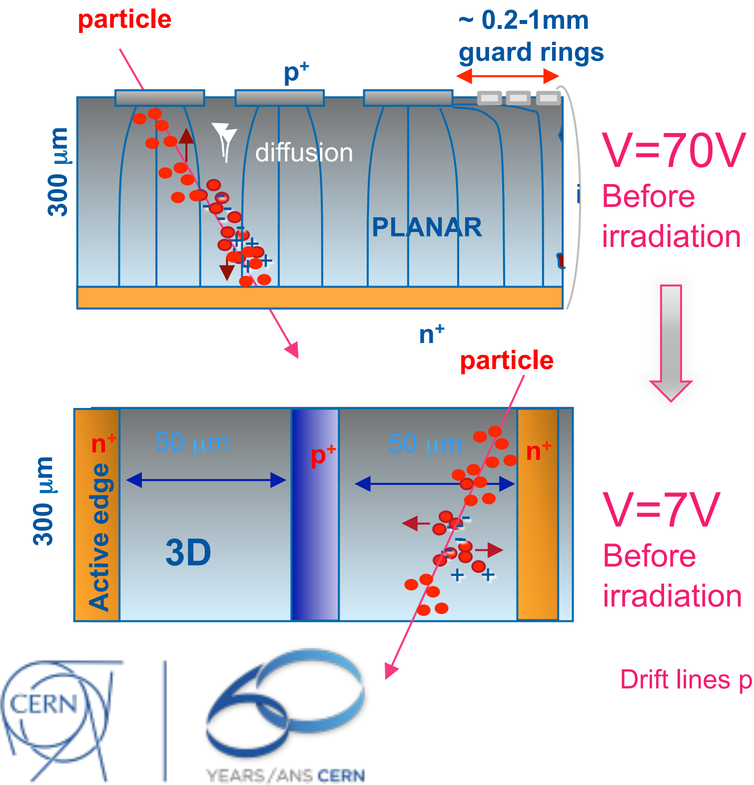
Source: Roozeboom, Lamy et al., NXP, Power SOC 2008

Source A. Rippart INEMI 2011

Applications in HEP*: 3D sensors

*High Energy Physics





Drift lines parallel to the surface

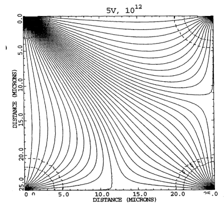
3D silicon detectors were proposed in 1995 by S. Parker, and active edges in 1997 by C. Kenney.

Combine traditional electronics processing and MEMS (Micro Electro Mechanical Systems) technology.

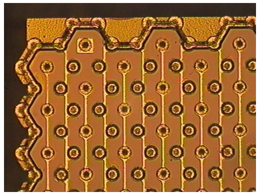
Electrodes are processed inside the detector bulk instead of being implanted on the Wafer's surface.

The edge is an electrode! Dead volume at the Edge < 5 microns!

The electric field is parallel to wafer's surface: and smaller inter-electrode spacing: low bias voltage, low power, reduced charge sharing and high speed – for the same wafer thickness

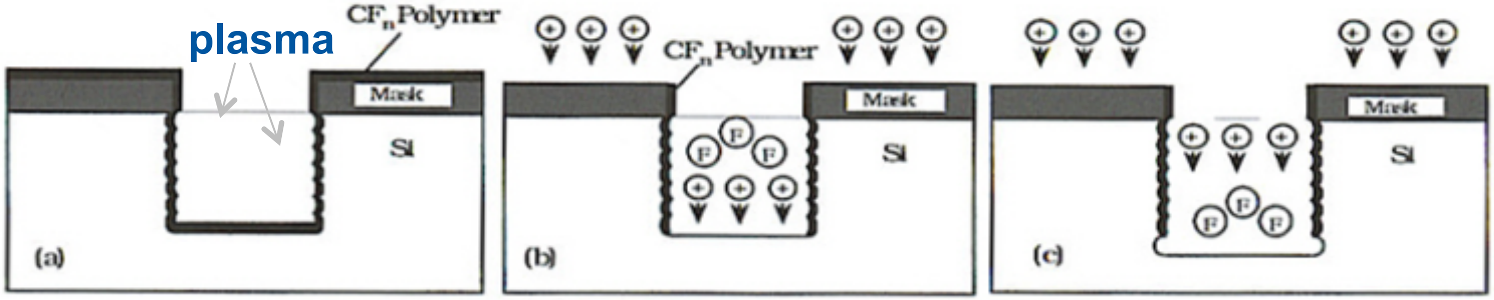


MEDICI simulation of a 3D structure

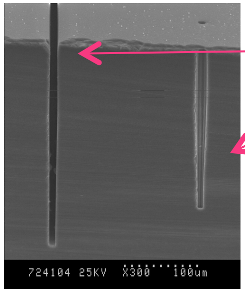


Deep Reactive Ion Etching

Bosch Process

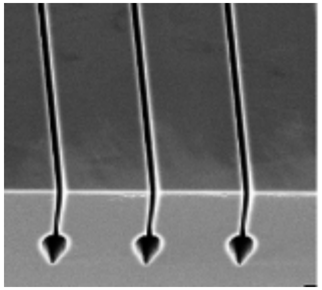


plasma

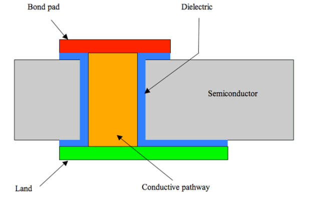


Deep pores and trenches

micro-channels

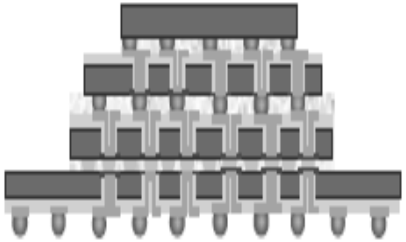


Interconnectivity Using TsV



1. Drawing showing the key features of a through silicon via (TSV). A TSV can be defined as "A structure that provides an electrical pathway through the thickness of a semiconductor (silicon) die between a bond pad on the front face and a land on the rear face. The pathway, bond pads and lands are all electrically isolated from the semiconductor." Drawing not to scale. Source: Tessera.

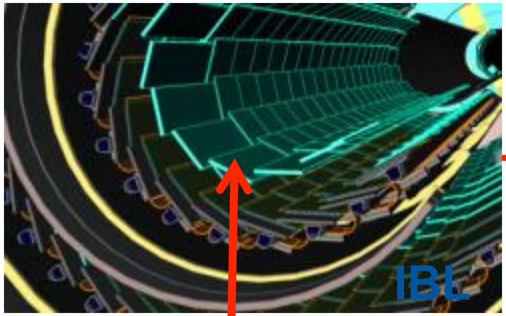
Vertically integrated electronics

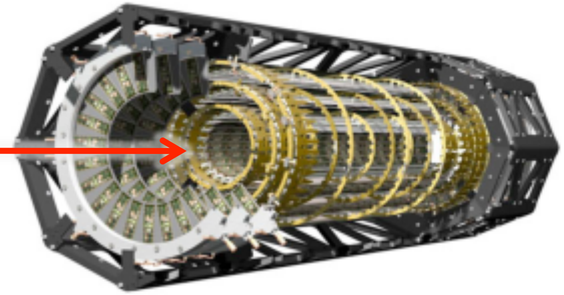


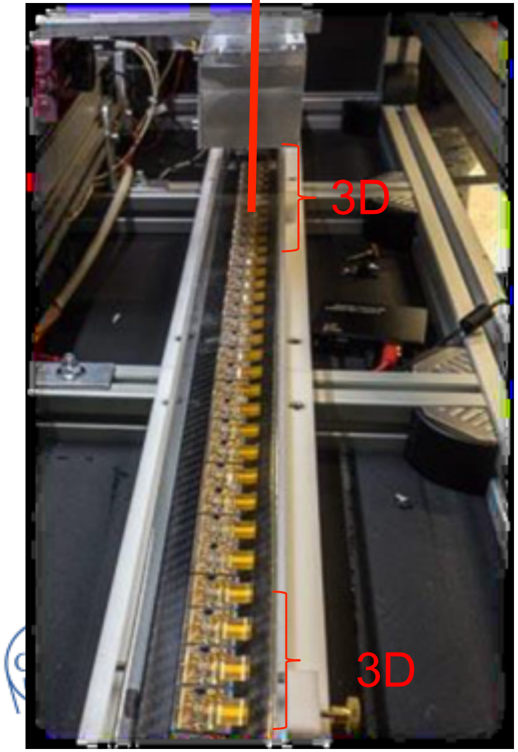
3D sensors are now in the core of ATLAS

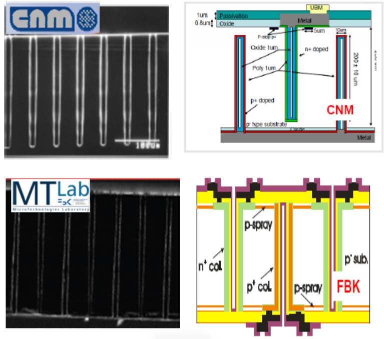
3DATLAS R&D Collaboration

NIMA 694 (2012) 321–330
2012 JINST 7 P11010.

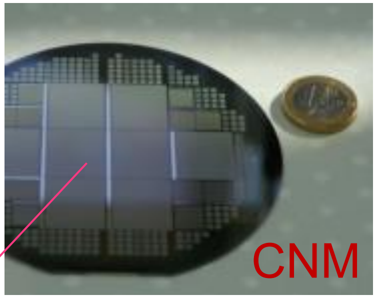




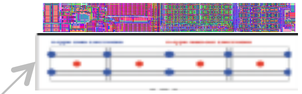




3D sensors just being installed in the first LHC detector upgrade in the ATLAS –Insertable B-Layer (IBL)

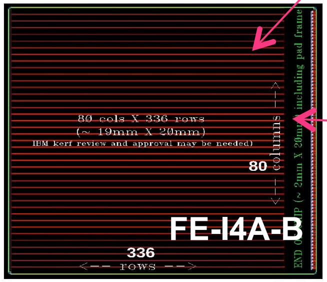


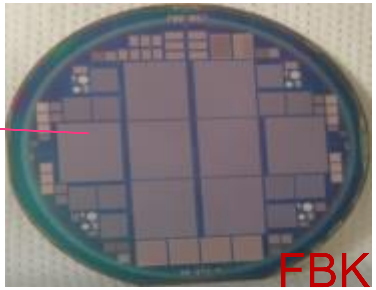
>300 sensors fabricated to cover 25% IBL



250 x 50 um^2

FE-I4 = 2x2cm^2
336 x 80
250x50um^2, 26880 pixels

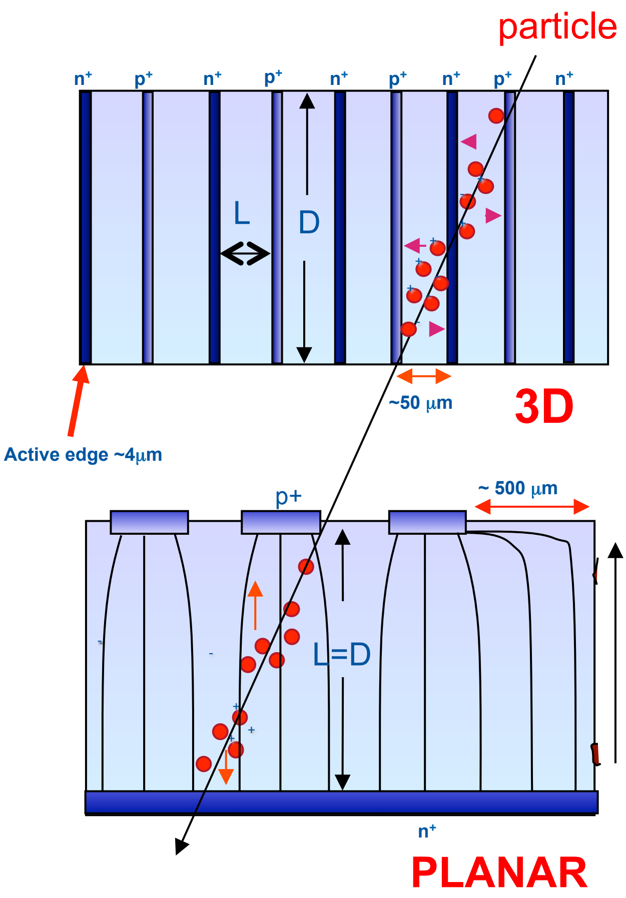




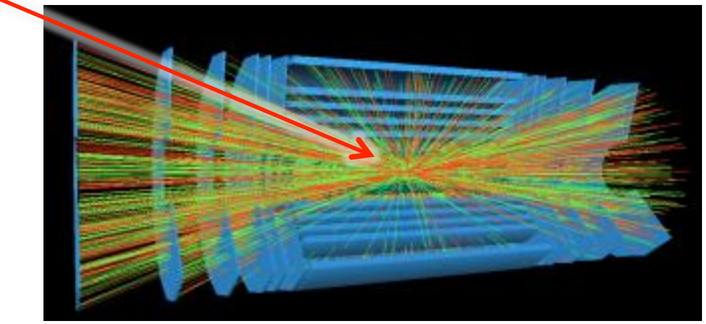
3D sensors and radiation hardness

NIM A 603 (2009) 319–324

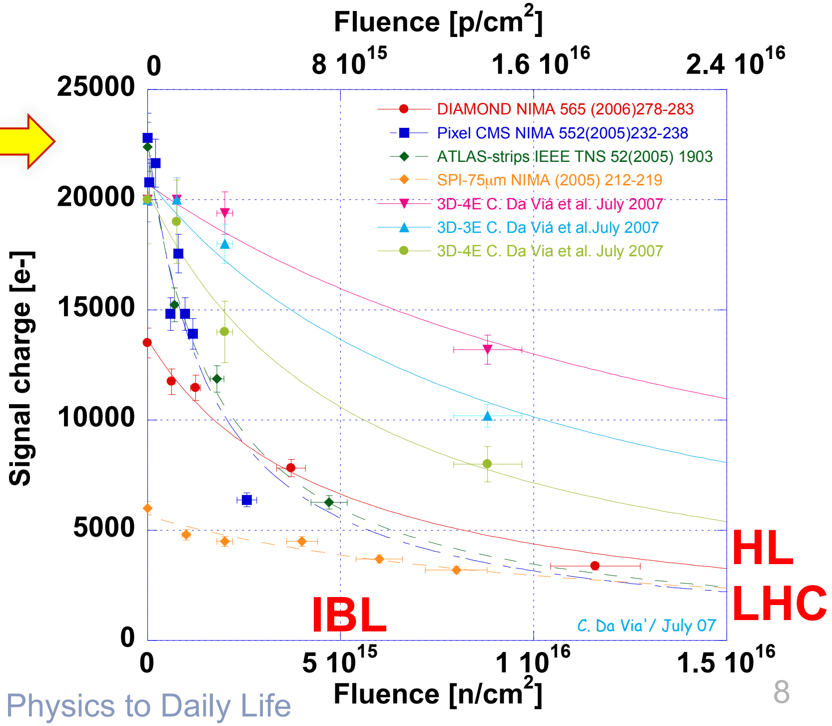
In the LHC experiments Vertex Detectors will be exposed to the highest radiation level



- Shorter drift distance
- Stronger e-field
- Generated signal decoupled from drift distance



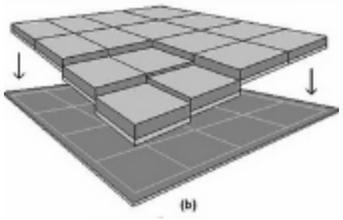
3D 4E (54um)
3D 3E (71um)
3D 2E (105um)
Diamond
Thick Si
Thin Si



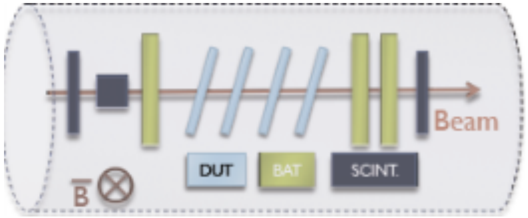
Fluence in 1MeV equivalent neutrons per cm^2

3D sensors with active edges

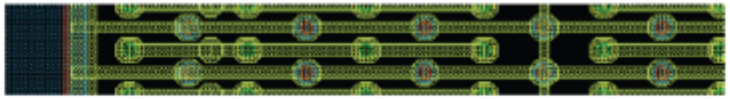
Fully sensitive volumes, large area imagers

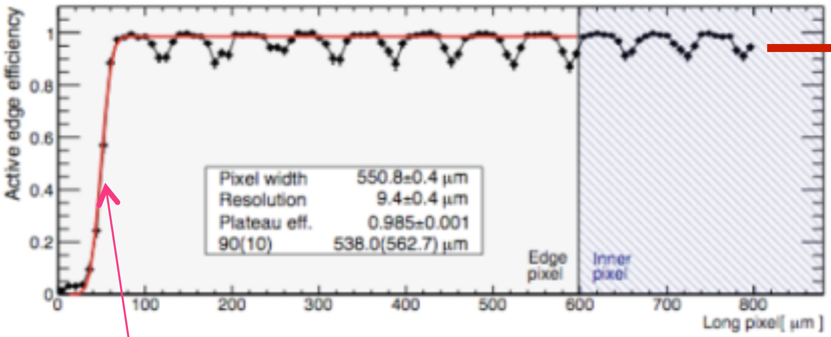


Test beam setup at CERN



120 GeV pions at CERN SpS



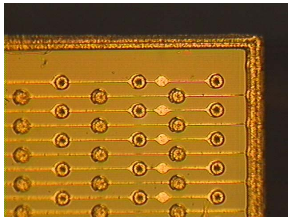


Pixel width	550.8±0.4 µm
Resolution	9.4±0.4 µm
Plateau eff.	0.985±0.001
90(10)	538.0(562.7) µm

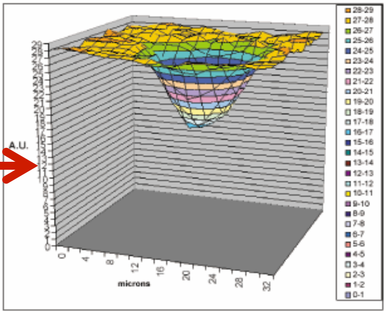
Active Edge = 6±9.8 µm

Test beam with x-ray micro beam At Berkeley USA

2 um, 14 KeV X-rays)

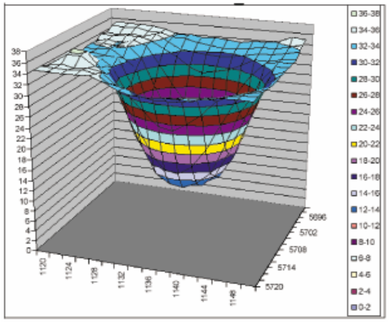


Active edge details



N – Electrode

Signal Reduction 43%



P – Electrode

Signal Reduction 66%

Differences between N and P:

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

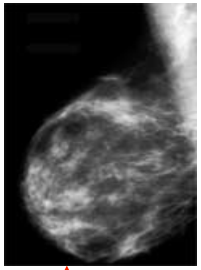
Electrodes response is not zero if filled with poly-silicon

J. Hasi PhD Thesis

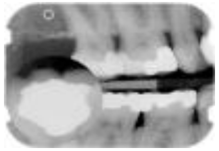
P. Hansson et al. Nuclear Instruments and Methods in Physics Research A 628 (2011) 216–220

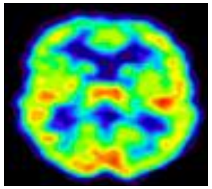
X-ray energies in medicine and biology

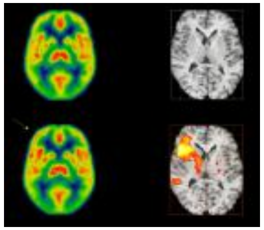
Mammography



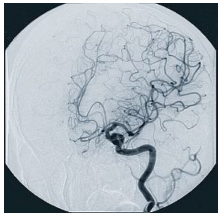
Dental imaging







Angiography

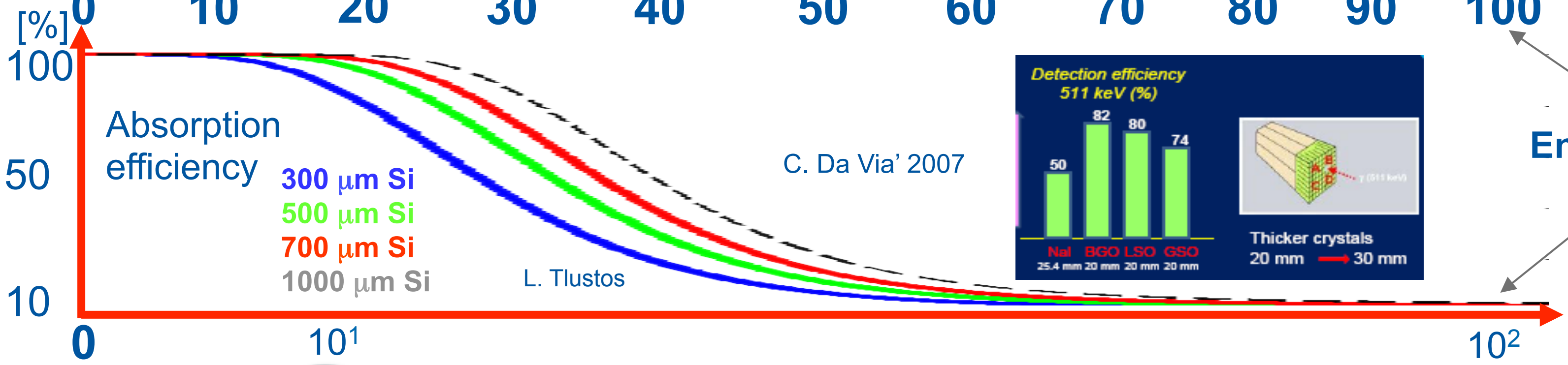


Radiology

Protein crystallography

PET
SPECT

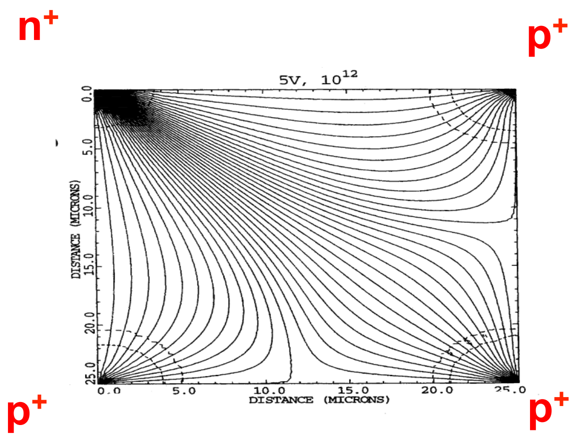
0 10 20 30 40 50 60 70 80 90 100



Energy [keV]

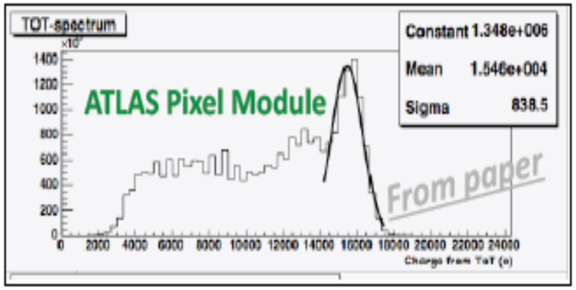
Charge sharing and increased thickness

Medical Imaging, X-ray Spectroscopy

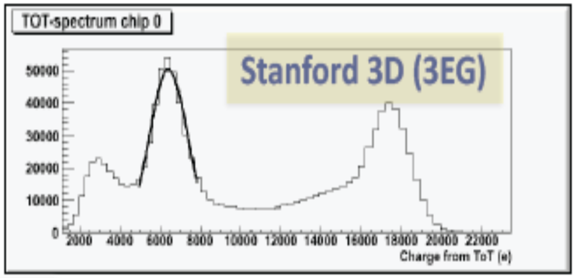


3D Electric field

planar



3D



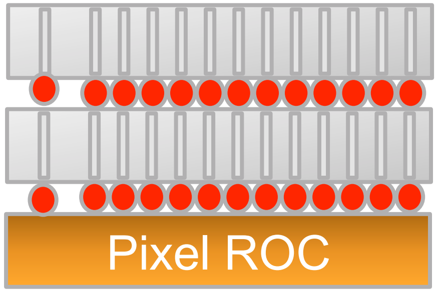
Measurements by A. La Rosa CERN Now UniGeneva (CH)

^{241}Am

Type	Energy	Percentage
Alpha (α)	5.485 MeV	84.5 %
Alpha (α)	5.443 MeV	13.0 %
Beta (β)	52 keV	Unknown
Gamma (γ)	59.5 keV	35.9 %
Gamma (γ)	26.3 keV	2.4 %
Gamma (γ)	13.9 keV	42 %

Reduced charge sharing allows better energy resolution at lower energies

Stacked geometry allows thicker substrates and better detection efficiency at higher X-ray energies with preserved performance



Measurements Performed using the ATLAS FE-I3 Readout chip and the Turb oDaq system (developed in Bonn)

Micro-dosimetry

for Cancer Therapy, Space Radiation Monitoring

3DMiMic Project coordinated by A. Kok et al. SINTEF Norway

Pioneering work from

University of Wollongong

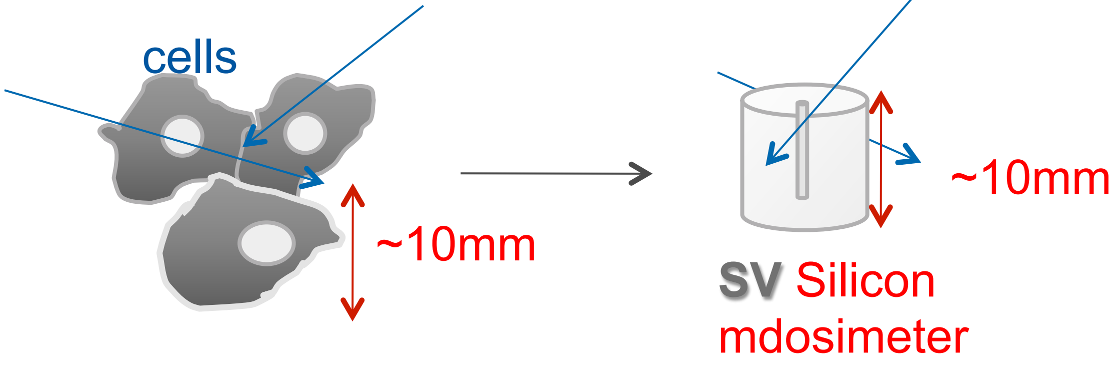
METHOD AND APPARATUS FOR TISSUE EQUIVALENT SOLID STATE MICRODOSIMETRY

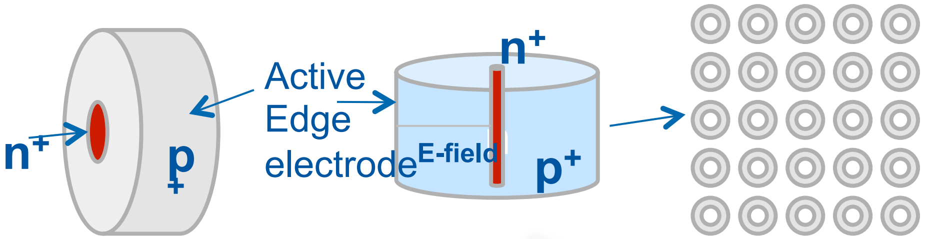
Microdosimetry measures the stochastic energy deposition events at cellular level
Radio-Biological Effectiveness (RBE) depends on linear energy transfer (LET or Lineal Energy) which is different for different radiation type. **Average chord length <l> is** independent on radiation direction

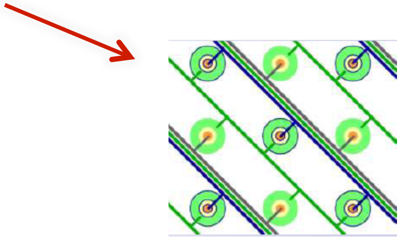
❖**Mixed Field** detection in a small sized array of cell-like elements of well defined Sensitive volume **SV** is required to precisely determine RBE

❖Silicon Dose Equivalent can be determined From the lineal Energy Spectra and the tissue equivalent dose $D_{TE.}$. Quality factors **Q** are determined Experimentally.

$D_{si} = D_{TE}\ S_{Si}/S_{TE}$
Dose equivalent $H = Q\ D_{si}$



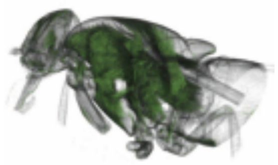




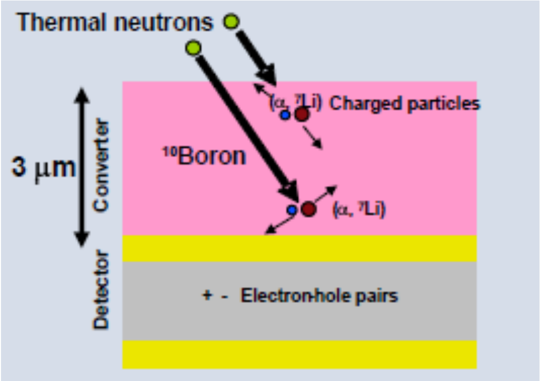
3D sensors with central n^+ electrode surrounded by p^+ trench define cellular size sensitive volume

High Efficiency Neutron Detection

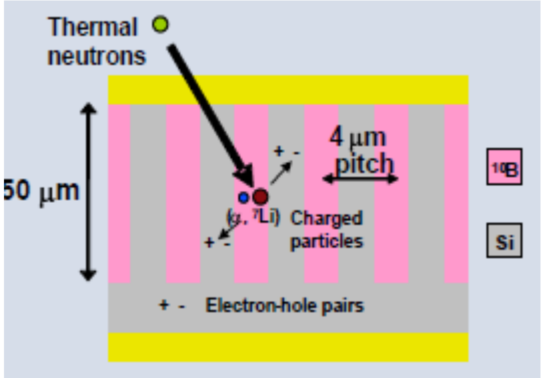
Neutron capture therapy, diffraction



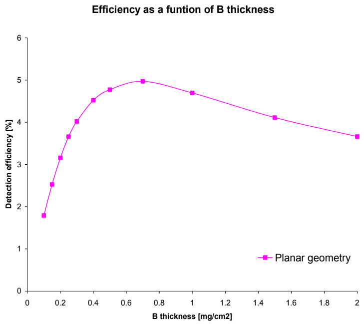
- Silicon is not sensitive to neutrons but is a well established radiation detector
- Need neutron reactive converter materials usually deposited on the surface thin films or different geometries
- With reference to ^{10}B converter:
  - 90% capture in 43 μm
  - Range of reaction products 2-5 μm

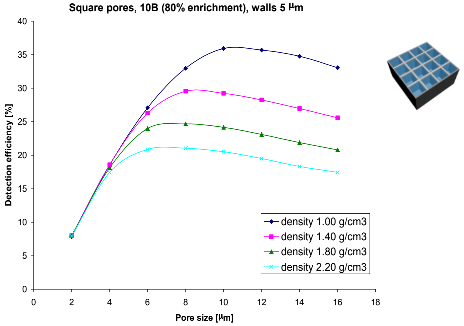


Planar geometry



Micro-fabricated Squares

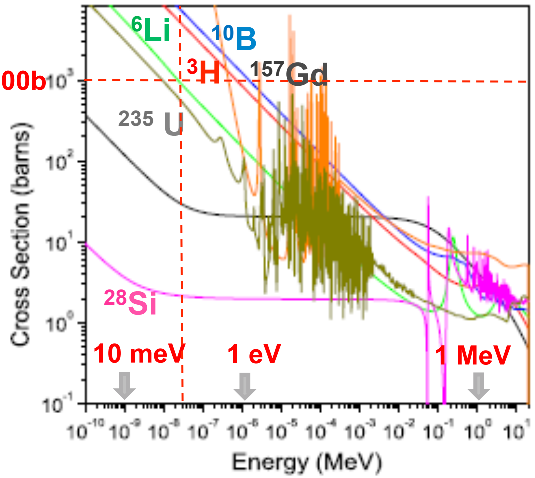




Amorphous ^{10}B, enrichment 80%

Efficiency < 5%

Efficiency up to 36%



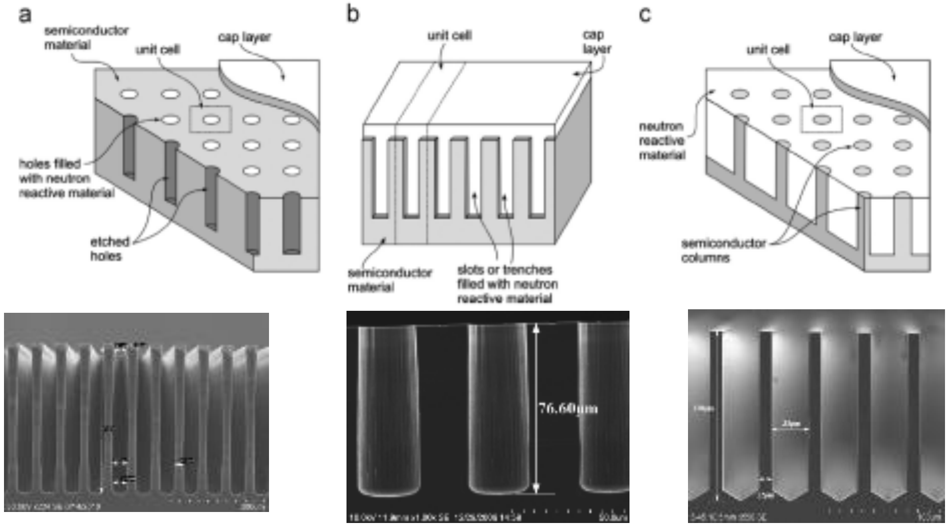
Neutron cross sections of some common n-reactive materials

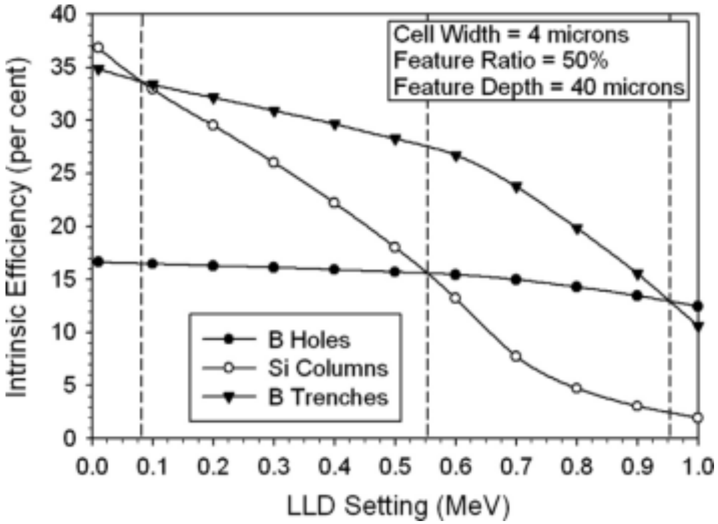
J. Phys.: Condens. Matter 22 (2010) 443201 (32pp)

Uher et al. Nuclear Instruments and Methods in Physics Research A 576 (2007) 32–37

Micro-structured Semiconductor Neutron Detectors (MSND)

D. McGregor et al., J. Crystal Growth 379 (2013) 99





- Extended interaction surface, and higher probability for reaction products to enter the semiconductor
- Different shapes and geometries

Comparison of efficiencies as a function of feature size, as measured by its cell fraction, for hole, trench and column designs with unit cell dimensions of 4 um and feature depths of 40 um. ^{10}B is the back fill material and the LLD was set for 300keV

Maximum efficiencies reported with this method~50%

Conclusions

- Micro Fabricated Sensors developed for High Energy Physics have found applications in other fields like medicine and biology
- Future developments include astronomy, environmental monitoring and space applications