3D sensors and Micro Fabricated Systems

Cinzia Da Vià, The University of Manchester, UK

Outline

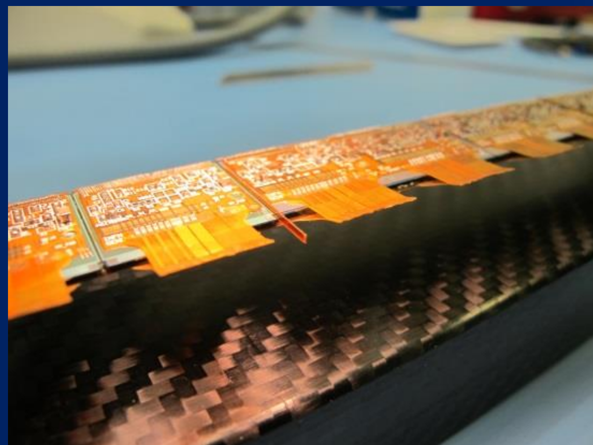
- 3D sensors
- Micro-Fabrication
- Applications in Bio-Medicine and Space, Else
- Wow can HEP profit from "More than Moore" ?

3D for the ATLAS IBL by the 3DATLAS R&D Collaboration
25% of the total IBL modules

NIMA 694 (2012) 321–330

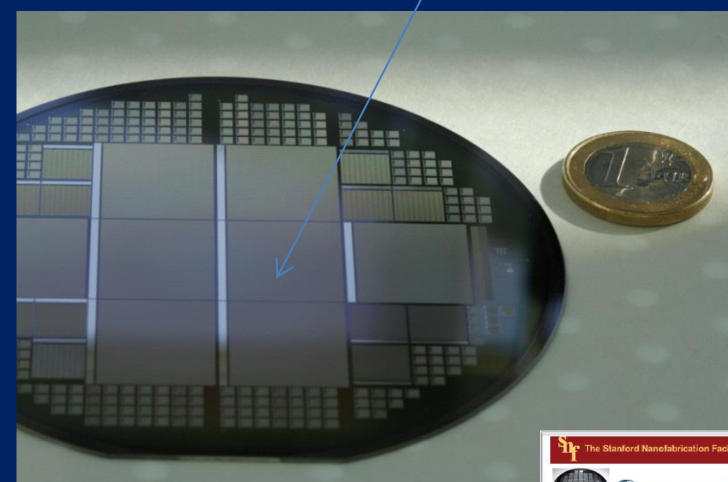
total pixel number: 26880

Total number of columns per chip : >100.000

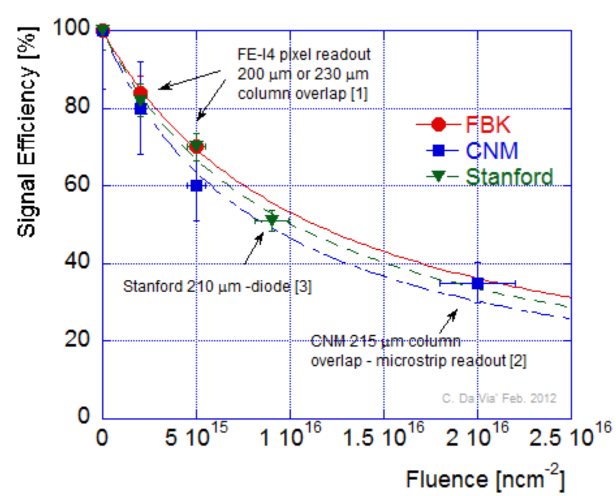


4+1 runs were completed in February and October 2012 by CNM (Barcelona, Spain) and FBK (Trento, Italy) with double side process with >350 good chips, more than 100 wafers and an yield exceeding 60% fulfilling the following:

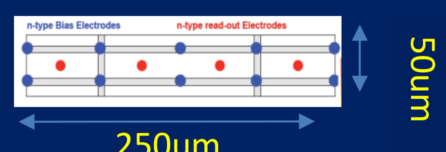
Sensor specifications for IBL:
- Qualify to $5x10^{15}$ n_{eq}
- max. power dissipation: 200 mW/cm^2 at -15 C
- tracking efficiency > 98%.



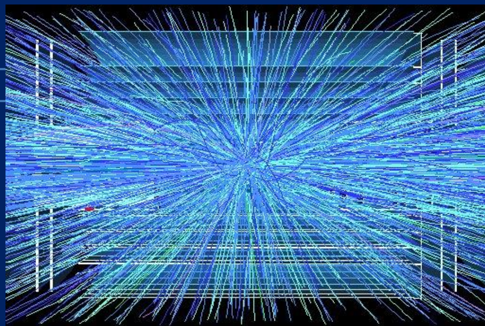
V_{bias} is less than 300V at all fluences



IES=71um

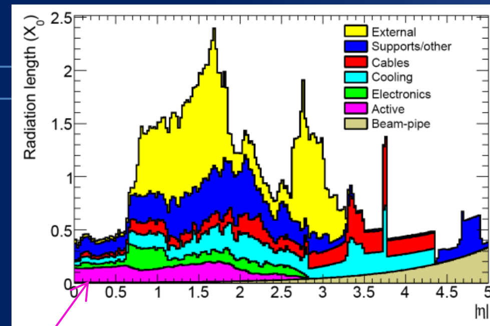


The HL-LHC ATLAS Vertex detectors challenges:



Precision reconstruction

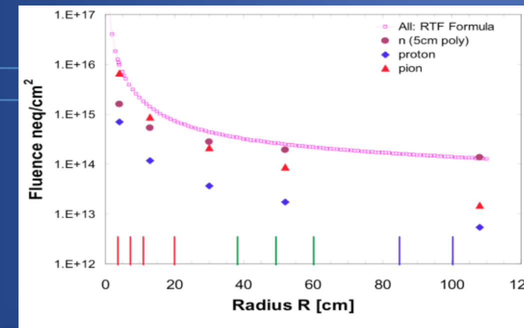
Needs the signal over threshold



Material budget

is not the sensor

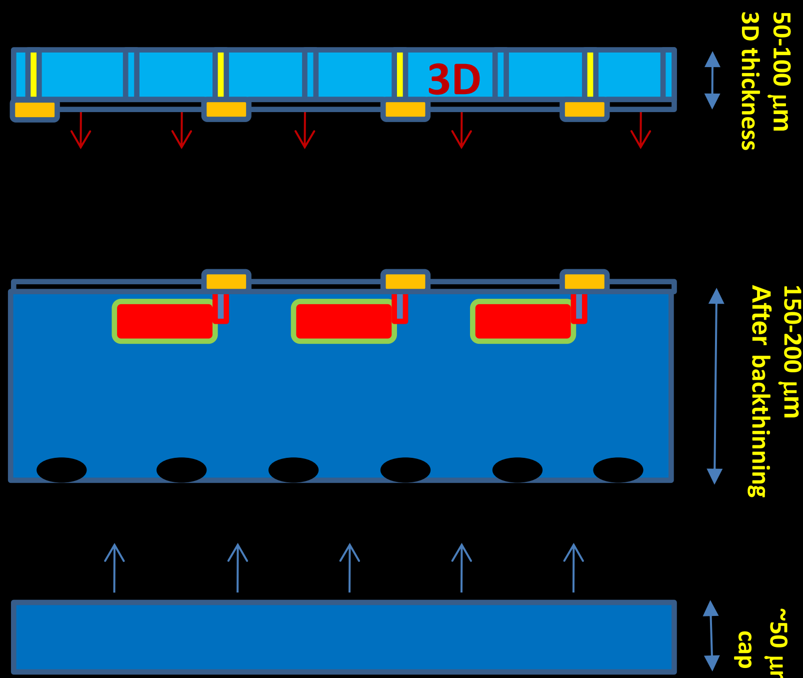
IBL 1.5%X_0



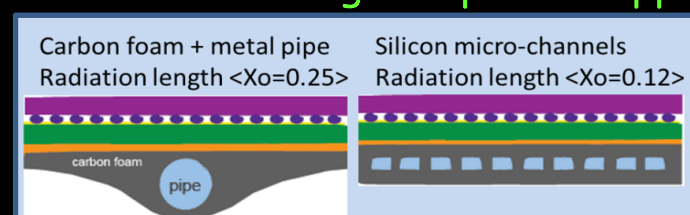
Radiation tolerance

and power budget

Micro-Fabrication offers possible solution:



- Thin (or thick) 3D silicon sensor modules with active edges
- Interconnected with micro-bump bonds and through chip bias supply



- Embedded micro-cooling

3D layout: Thin Versus Thick at 2×10^{16} ncm^{-2}

Thin (50-100 um):

Aggressive

- Needs support wafer (and to remove it)
- Lower capacitance
- Smaller electrodes (full sensitivity)
- Smaller generated signal (requires charge multiplication to reliably work)

Thick (150-200um)

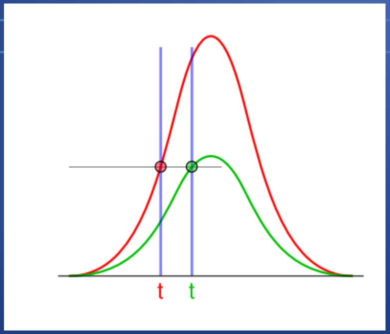
Conservative

- Double side processing
- Alternative active edges (to qualify)
- Higher capacitance for aggressive IES
- Bigger electrodes (possible dead regions)
- Bigger generated signals (in case charge multiplication not reliable)

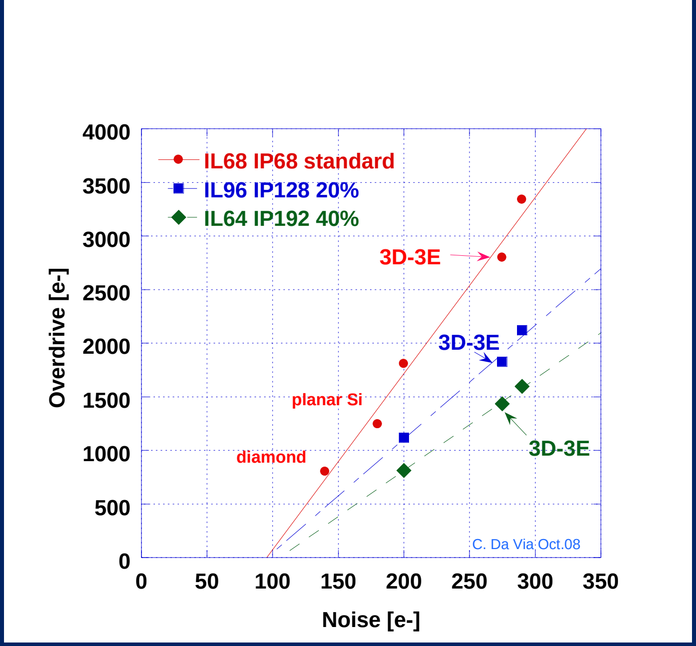
But what is the minimum signal after irradiation to be over threshold? (required min signal= (threshold +overdrive) x2) Assume to use 4E 3D Layout with 56um IES note IBL used 3E = 71um

Required signal. Threshold and overdrive measurements using FE-I3

- No data available with FE-I4 and 3D yet
- Overdrive is different at different FE power consumptions (more power less overdrive)
- Time walk and overdrive depend on C
- In time threshold = bare threshold + overdrive
- Required signal = in time threshold x 2



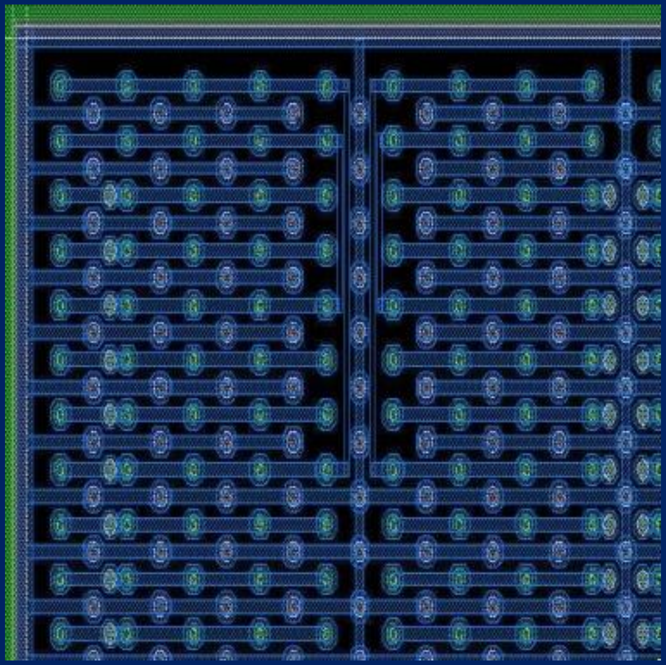
Threshold triggered system
Difference between t and t gives the time walk
New bunch crossing every 25ns
Need to cross threshold within 20ns to be accepted
How much overdrive is needed to cross threshold within 20ns?

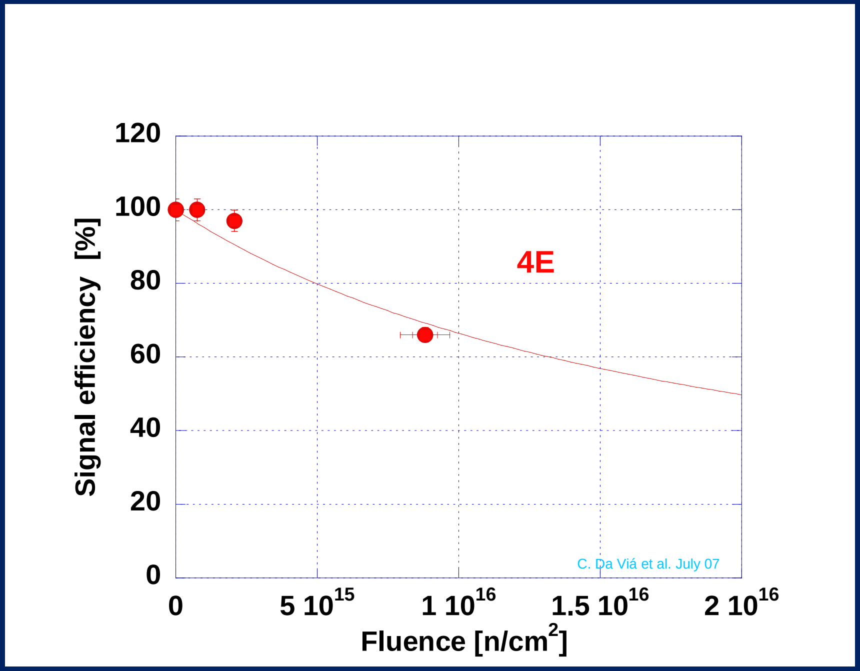


Sensor	Bare Threshold [e-]	OverdriveI P68 IL68 [e-] Nominal P	Overdrive IP128 IL96 [e-] +20% P	Overdrive IP192 IL64 [e-] +40%P
Si planar	2500	1250		
3D-2E	2500	1800	1120	820
3D-3E	**3200**	**2800**	1830	1440
3D-4E	**3200**	**3340**	2130	1600
Diamond	1500	800		

3D 4E after $2x10^{16}$

- 56 μm inter electrode spacing
- At $2x10^{16}$ expected signal is 50% from original one at 100V!
- 200μm x 75 = 15 000/2 = 7500e





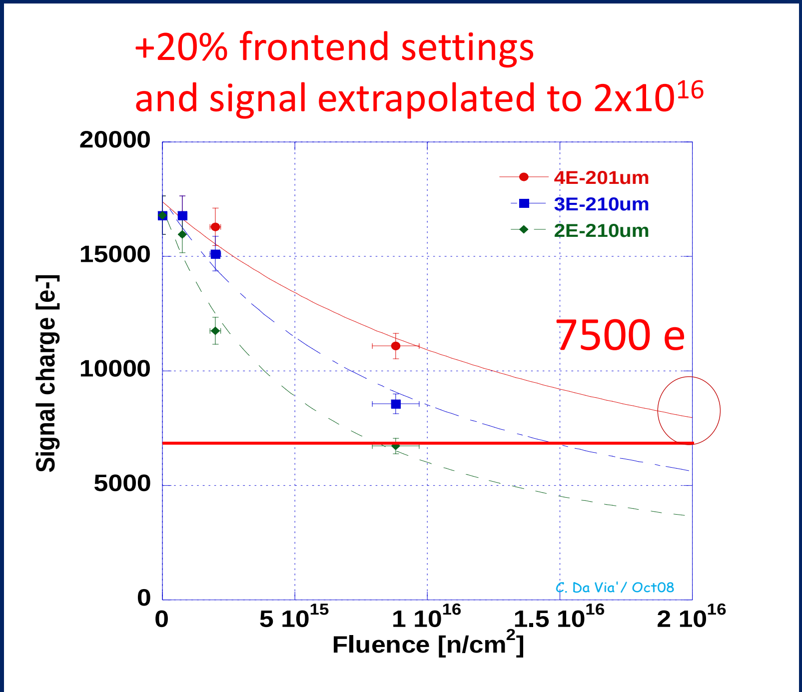
IL68 IP68 Analogue current=91mA., VDDA = 1.6V and VDD = 2.0V
IL96 IP128 Analogue current=126mA (+38%) VDDA = 1.6V VDD= 2.0V
IL64 IP192 Analogue current =158mA (+76%) VDDA = 1.6V VDD= 2.0V

Required Signal after $2x10^{16}$

- Use FE-I4 bare threshold (1300e)
- Use measured overdrive for 4E with FE-I3 + 20% (2130 e) to compensate for 65nm speed (extra power taken into account in total budget)

Required signal = [Bare Threshold + Overdrive] x 2 = 6860 e^-

✓ Available signal = ~7920 e (50um) or ~7500e (200um)



FE-I3

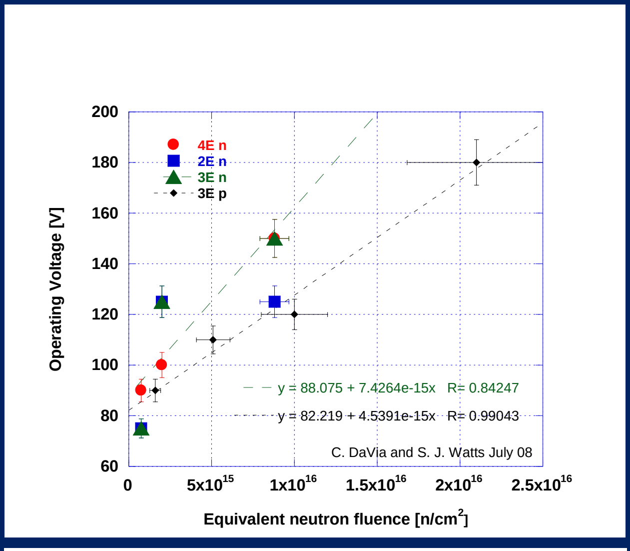
Sensor	Bare Threshold [e-]	Overdrive IP128 IL96 [e-]	In time Threshold [e-]	Required signal [e-]
Si planar	2500			
3D-2E	2500	1120	3620	7240
3D-3E	3200	1830	5030	10060
3D-4E	3200	2130	5330	10660
diamond	1500			

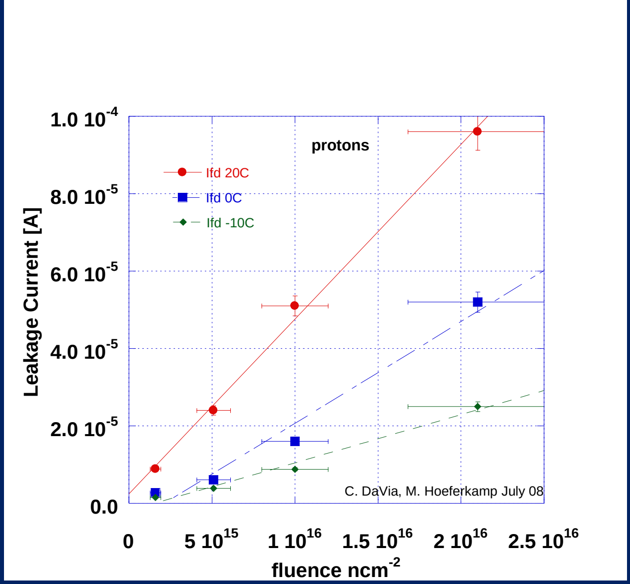
FE-I4 (extrapolation at same FE-I3 overdrive)

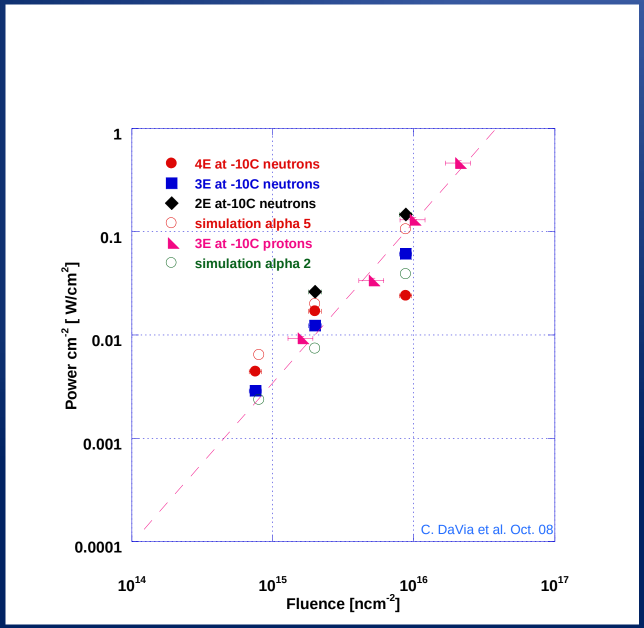
Sensor	Bare Threshold [e-]	Overdrive [e-]	In time threshold [e-]	Required signal [e-]
3D-4E	1300	2130	3430	**6860**

Bare 3D Power dissipation Up to $2x10^{16}ncm^2$

Processing: J. Hasi Manchesteri, C. Kenney, MBC
Measurements: M.Hoeferkamp UNMT. Slavicek Prague
Analysis and simulation C.DaVia, S.Watts, Manchester







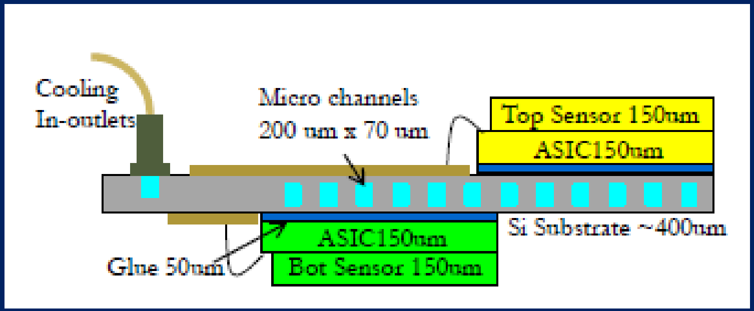
Power/cm² at -10°C

At $1.0x10^{15}$ ncm^{-2} ~ 3 $mWcm^{-2}$
At $5.0x10^{15}$ ncm^{-2} ~ 33 $mWcm^{-2}$
At $1.0x10^{16}ncm^{-2}$ ~ 120 $mWcm^{-2}$

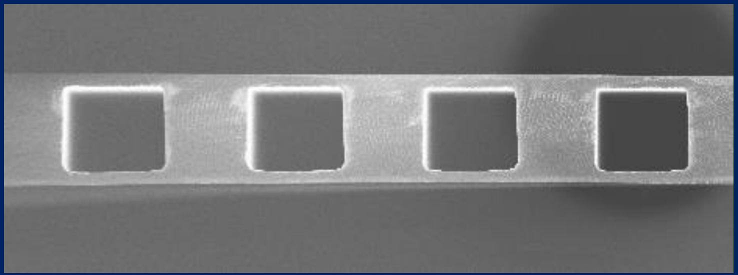
At $2.1x10^{16}$ ncm^{-2} ~ $443mWcm^{-2}$

Micro-channel cooling

Pioneering work for HEP within CERN PH-DT



LHCb system layout. J. Buytaert, Pixel2012



csem

- Cooling device based on the ATLAS design
- Pressure tests >100bar

❖ Explored since a while in microprocessor industry

Cooling channel is integrated in the substrate:

❖ Can customize the routing of channels to run exactly under the heat sources.

Many parallel channels:

❖ large liquid-to-substrate heat exchange surface.

Low mass :

❖ No extra 'bulky' thermal interface required between cooling channel and substrate.

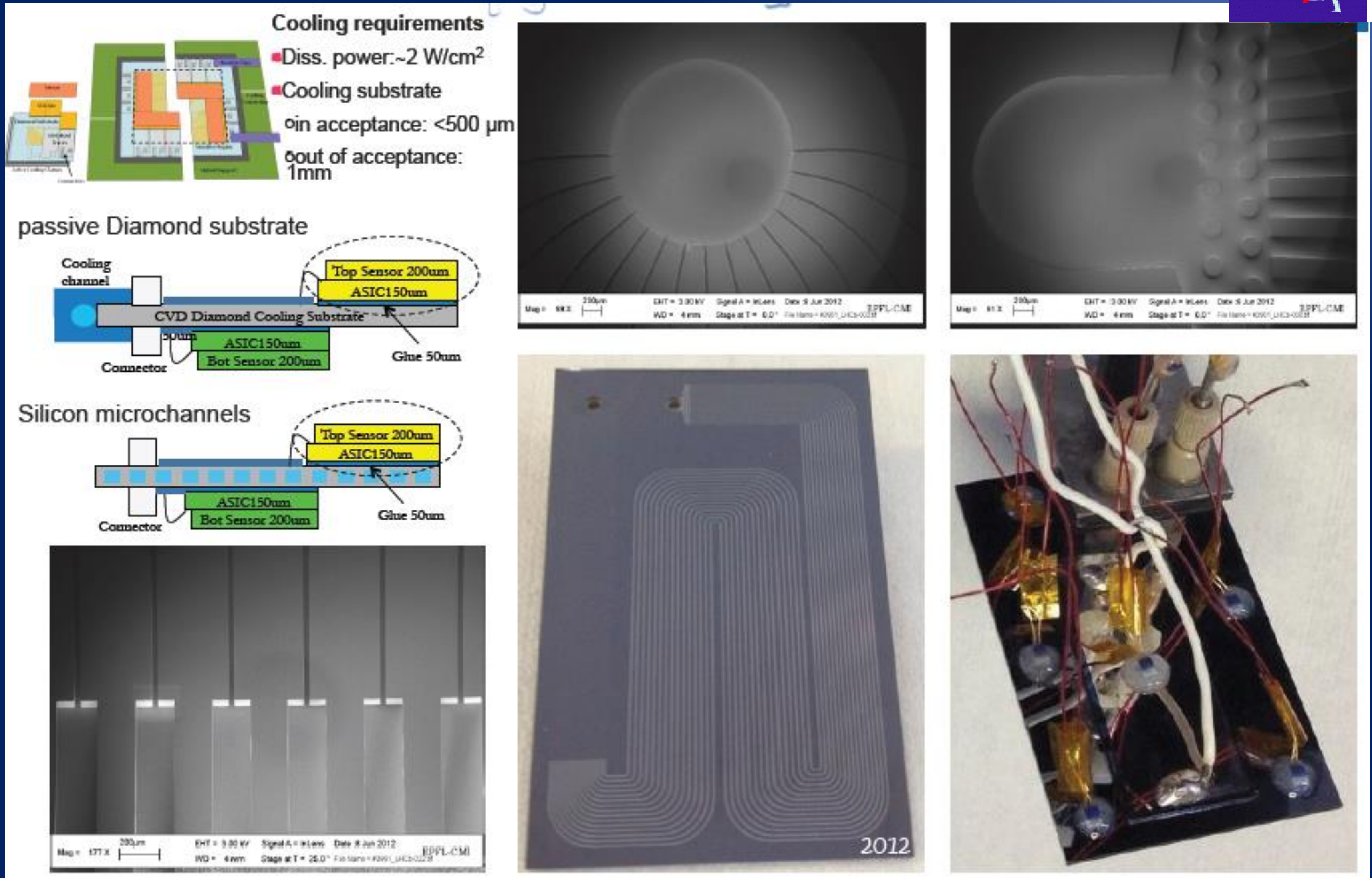
No heat flows in the substrate plane:

❖ Small thermal gradients across the module.

All material is silicon :

❖ No mechanical stress due to CTE mismatch.

LHCb VELO Upgrade using CO2 Cooling

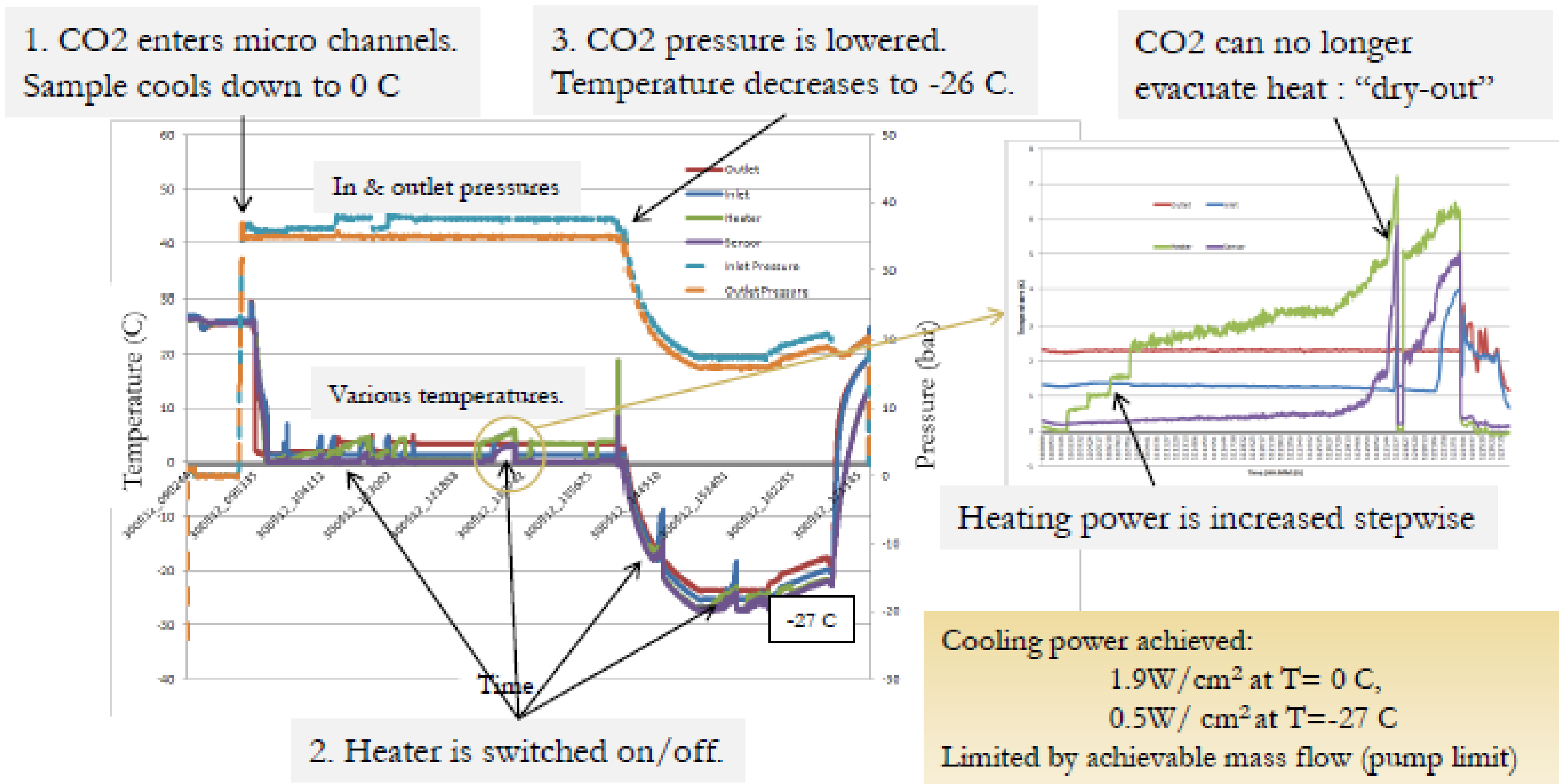


Courtesy A. Mapelli

Cooling Power Test

Test sample equipped
With cooling tubes, heater
And Pt100 probes

Still with old NanoPorts
(Upchurch Scientific, UK)
Guarantedd up to 103bars
But bonded to surface with adhesive
Polymer rings not guaranteed for radiation
hardness and thermal cycling



Cooling power achieved:
1.9W/cm^2 at T= 0 C,
0.5W/ cm^2 at T=-27 C
Limited by achievable mass flow (pump limit)
Expect much higher with improved pump !

Courtesy of Jan Buytaert LHCb

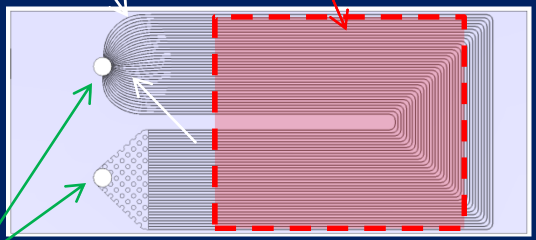
New 3D + ATLAS Prototype

Giulia Romagnoli
Jerome Noel
Paolo Petagna
Alessandro Mapelli

1st design:

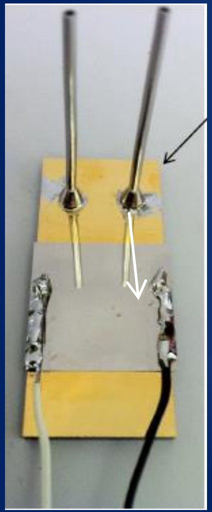
35 micro-channels
50 x 50 µm separated by 200 µm wide walls

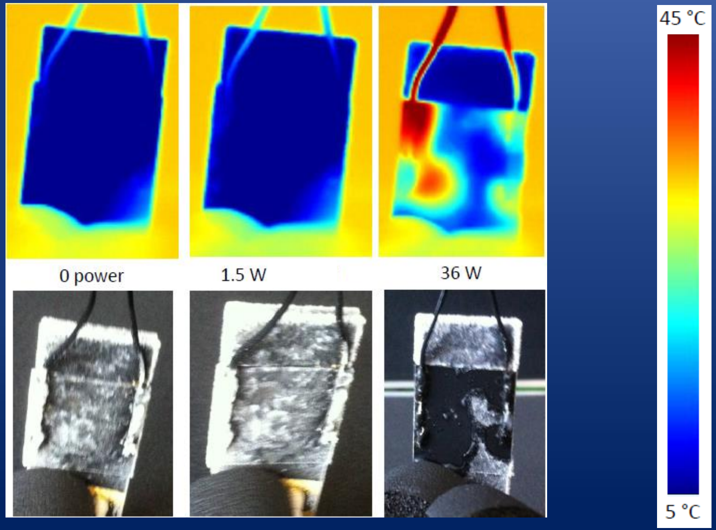
Restrictions
(10 µm wide x 50 µm deep, 7 mm long)
to bring CO_2 in critical conditions at the channels entrance

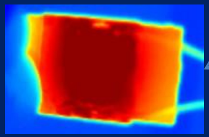


2 holes for fluidic inlet and outlet
(1.6 mm diameter)

Pillars in the outlet
to maximize the bonded surface



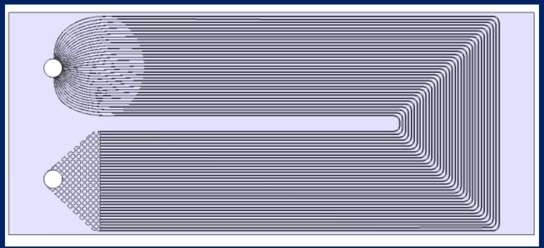


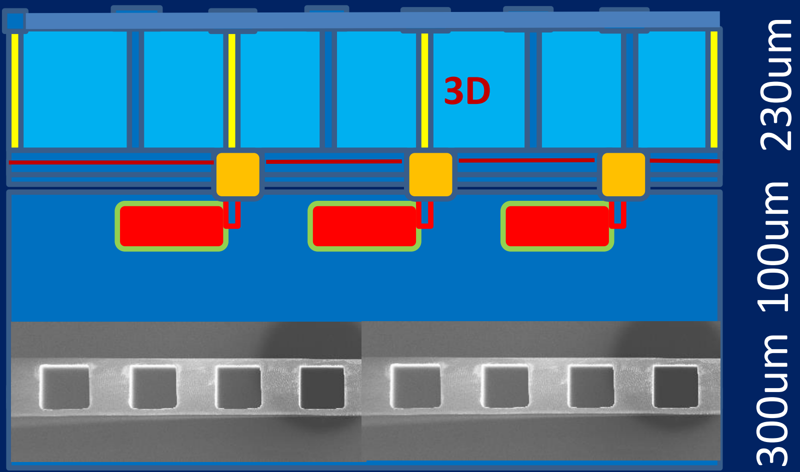


No cooling!!!

2nd design:

Increased the depth of channels and restrictions to 190um!
- Increased the pitch between the pillars to increase the device strength (and so the maximum sustainable pressure)





Manufactured at CSEM
Measurements Giulia Romagnoli

Cooling where it needs at $2x10^{16}$ n/cm^2

❖P3D+=Power density 3D sensors: Use existing data =
442mW/cm^2 with ~200V bias voltage and 200um thickness

❖FE- 65nm TARGET FOR FE-65 IS 400mW/cm2

❖ PTOT= Power density module = [(P3D+PROC)]

= 442 + 400 = **850mW/cm2**

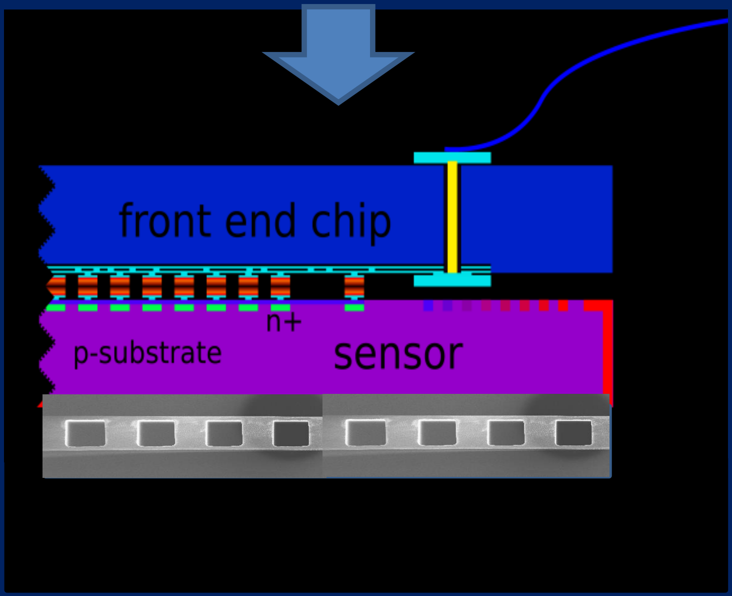
For planar sensors the radiation induced Leakage current is the same but the bias voltage is ~ 5 times larger so a rough estimate for the power dissipation for the module is

~ **2.5 W/cm2**

This figure is similar to the VELO detector

Ongoing Development FBK, CSEM, CERN PhDT with the program of

Cooling channel could be embedded on the sensor side to be effective!

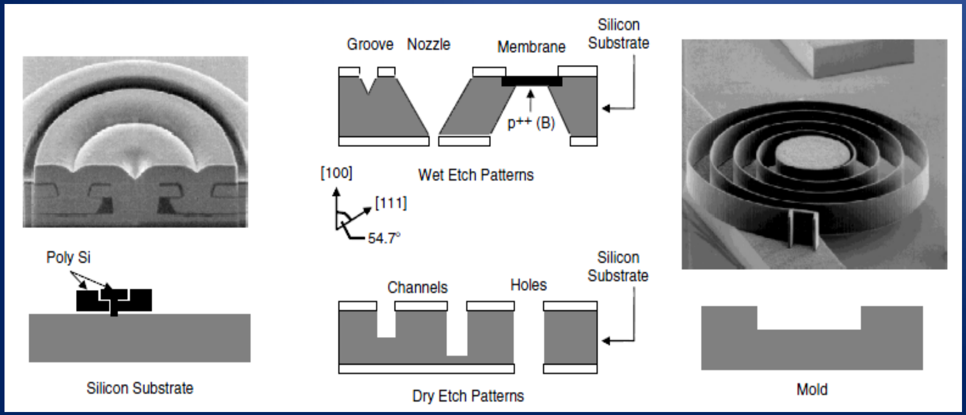


Micro-Fabrication?

In Micro-fabrication, used mainly for Micro-Electro Mechanical Systems (MEMS), the process is performed 3 dimensionally within the silicon volume

- ❖ 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

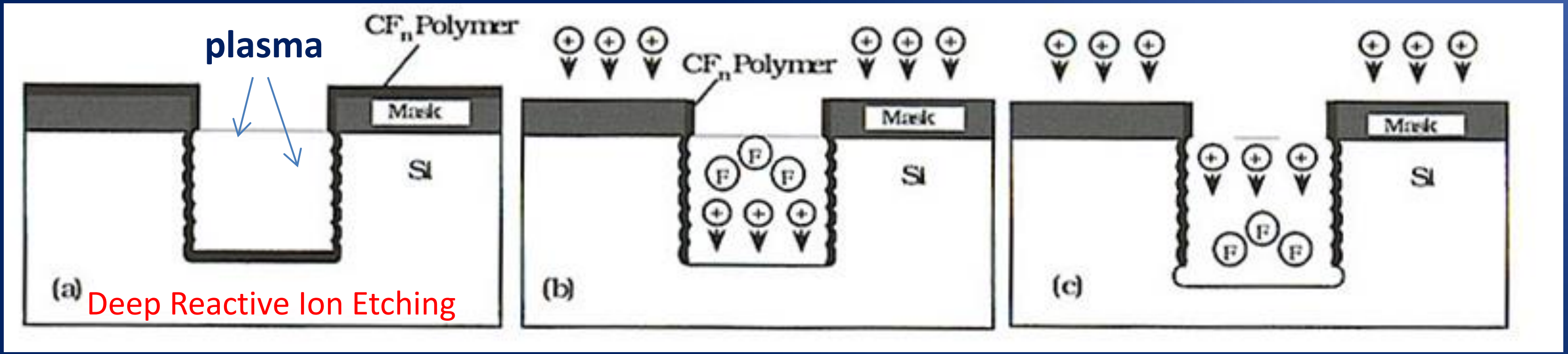
surface bulk Liga



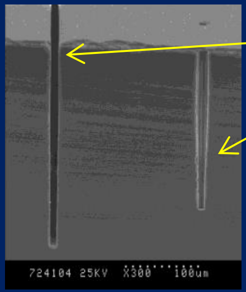
Applications:

- ➢ Everyday life (cars, portable devices..)
- ➢ Medical/Biology
- ➢ Space
- ➢ HEP
- ➢ … others..

"Bulk": Deep Reactive Ion Etching

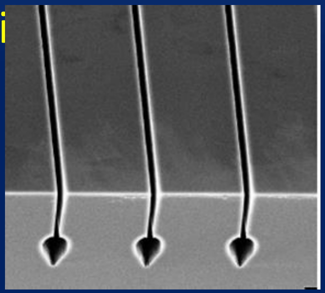


Bosh Process

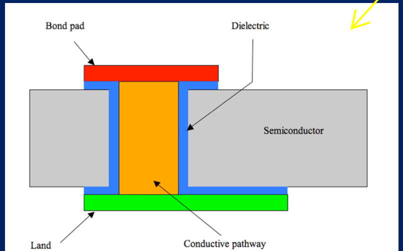


For 3D sensors electrode definiti[on] and active edges

For cooling micro-channels



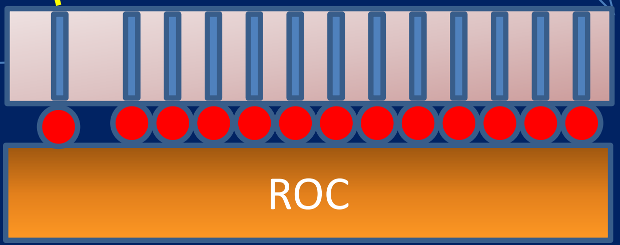
Interconnectivity
Using TsV



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.

Extra holes
On 3D sensor side
To carry signal out

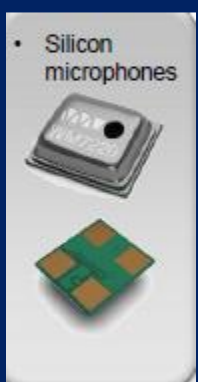
1- conformal metal
2-doped poly



Industry: MEMS Sensors and actuators

Sensing Applications

Voice/ sound



Motion/ position

Pressure/ monitoring

TPMS
Tire pressure m onitoring system

Actuating Applications

Projecting Receiving light

RF Related functions

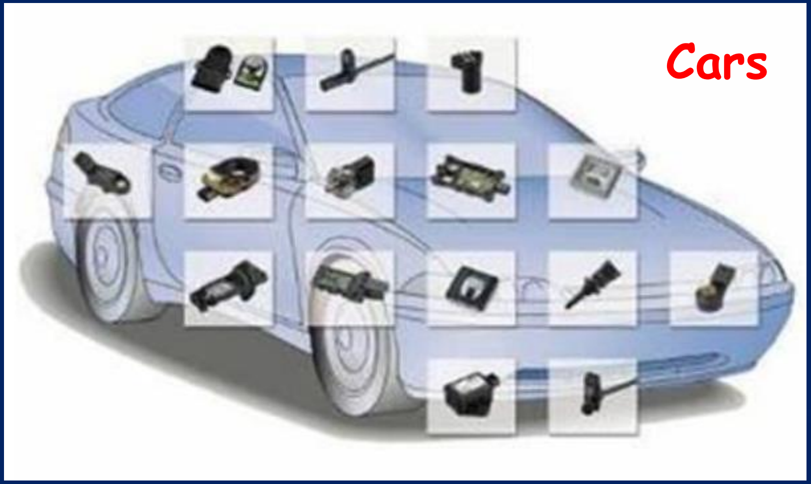
Surface acoustic wave

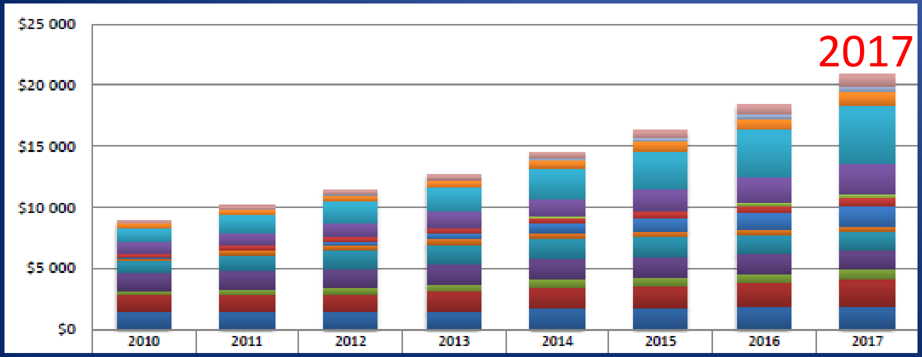
Managing fluids

Emerging MEMS

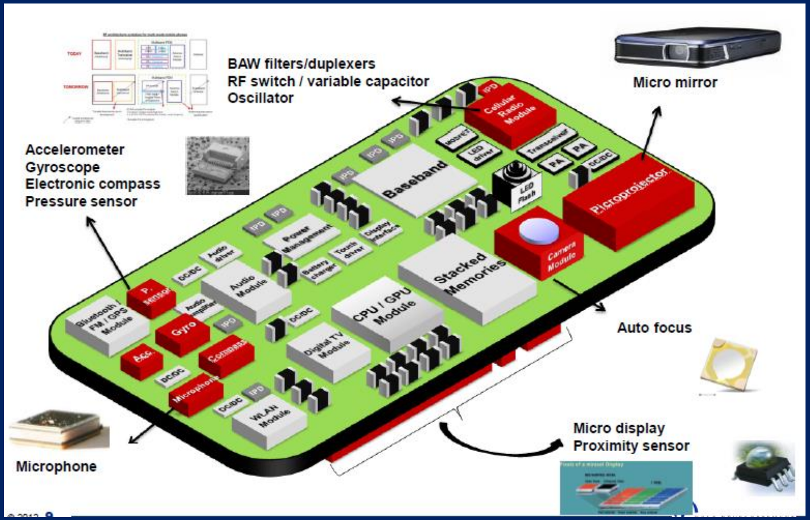
Every Day MEMS & Market driven development

TODAY



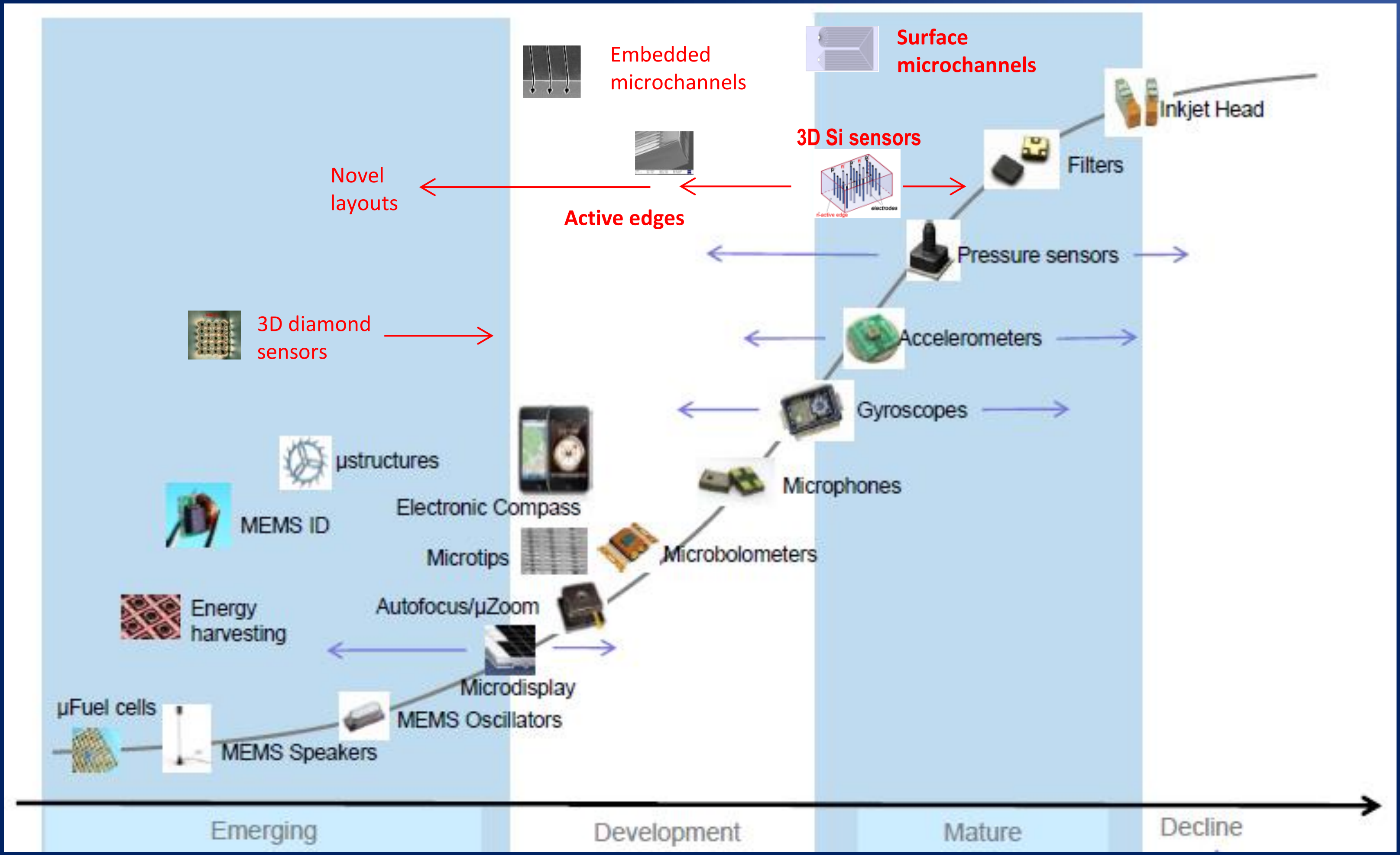


- Others (microstructures, micro tips, flow meter ...)
- Oscillators
- RF MEMS
- Microfluidics
- Optical MEMS
- Micro displays
- Uncooled IR
- Combos
- Compasses
- Gyroscopes
- Accelerometers
- Microphones
- Pressure Sensors
- Inkjet Heads



Smartphones

MEMS Evolution



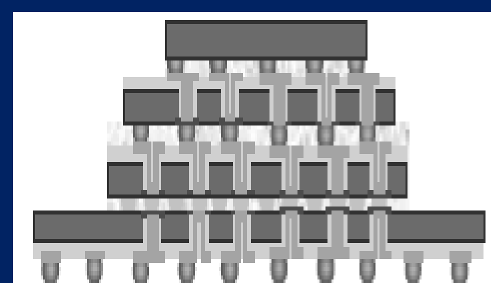
IBL 3D sensors are here

3D vertical integration, Micro-Systems and "More than Moore"

- 3D-"System-in-a-Package" (3D-SIP): Integration on the package level. Where multiple dies are integrated in the same package. The resultant packages are afterwards stacked on top of each other using flip chip technology.

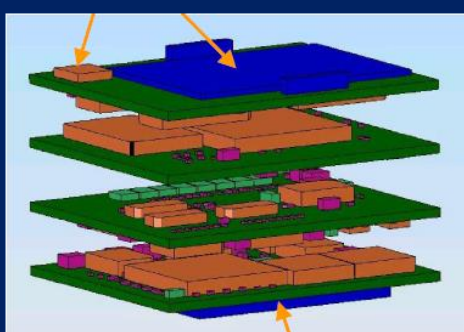
- 3D-"Wafer level packaging" (3D-WLP): Integration at wafer level. Interconnection is usually made by through wafer "vias" with a relatively large diameter of e.g. 150 um

- 3D-"Stacked IC" (3D-SIC): Integration on IC foundry level (see V. Re talk)



3D-WLP

L1-Opto-electronic

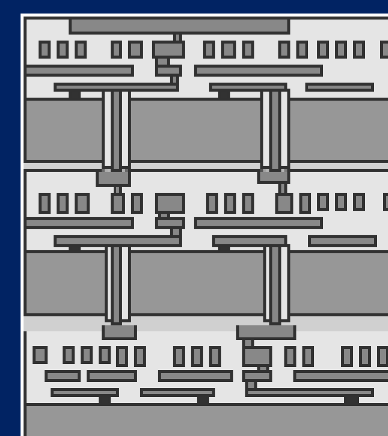


L2-FPGA

L3-Bus

L4-IC

3D-SiP



3D-SIC

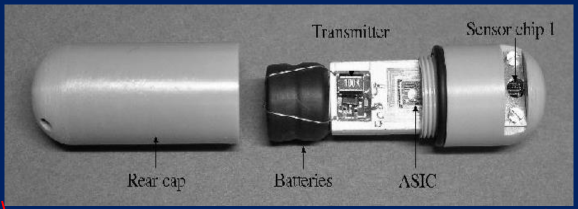
Applications in Bio-Medicine

Source: S. Bhansali

MEMS sensors in the biomedical field maybe used as:

- ❖ Critical sensors, used during operations.
- ❖ Long term sensors for prosthetic devices.
- ❖ Sensor arrays for rapid monitoring,
- ❖ Diagnosis at home.

http://www.spie.org/web/oer/august/aug00/cover2.html
http://www.see.ed.ac.uk/~tbt/norchip2002.pdf



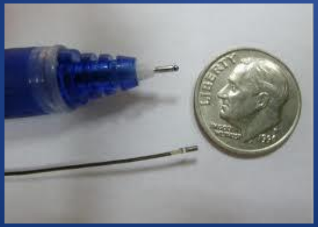
35mm

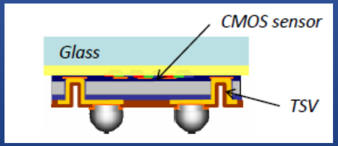
"lab on a pill"

- ❖ Digital camera (CMOS Technology)
- ❖ Light source
- ❖ Battery
- ❖ Radio transmitter
- ❖ Sensors (MEMS Technology)

-The pill is intended to be swallowed like any normal pill.
-Once within the body, the pill's sensors sample body fluids and pick up "meaningful patient data" such as temperature, dissolved oxygen levels and pH.
-The pill is expected to retrieve all data over a 12-hour period and disposed off,
-This data is transmitted wirelessly to a card attached to the wrist of the individual.

"Ultra miniaturized camera for endoscopy with TSVs"





Source: I-Micronews May 2011

"Precision scalpels"

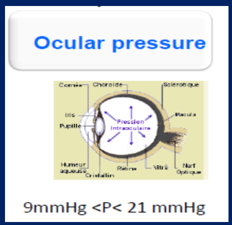
MEMS piezoelectric motor help to accurately position the scalpel.
MEMS pressure sensors incorporated on the scalpel, can help to measure the force exerted on the area operated upon. Accordingly, the scalpel can he handled.

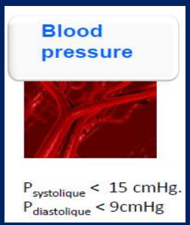
http://www.ee.ucla.edu/~jjudy/publications/conference/msc_2000_judy.pdf

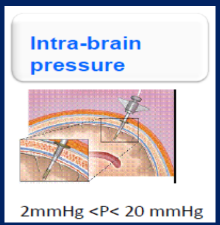
Applications in Bio-Medicine

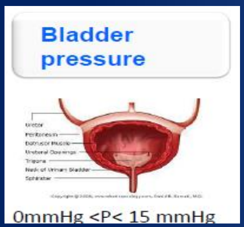
Source: Lami EpoSS 2012

Pressure Sensing

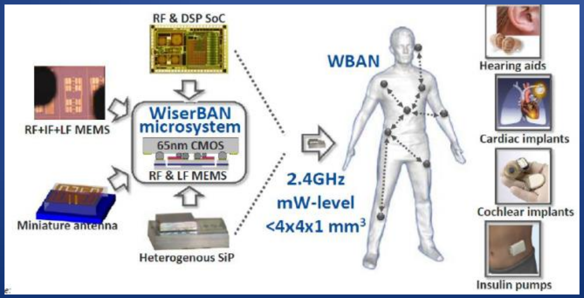








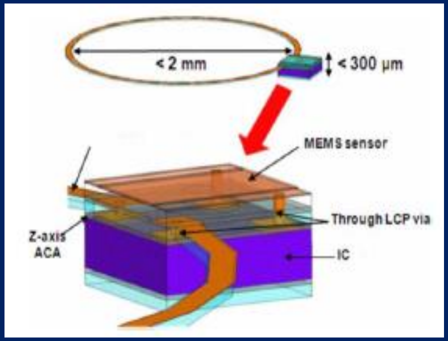
Implantable Devices



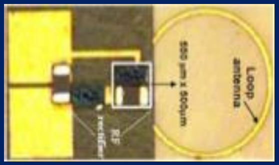
Acceleration monitoring in pacemakers

Glaucoma diagnosis

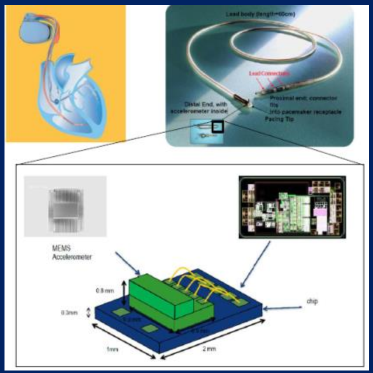
D. Ha et al. IMS 2010

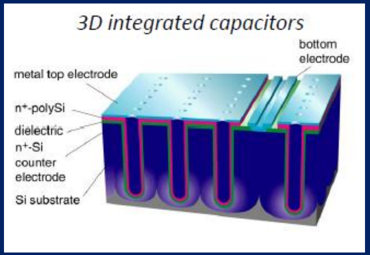


3D IC and MEMS stacking

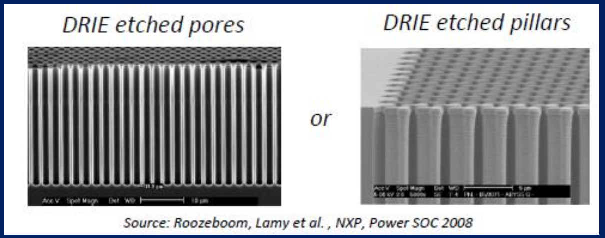


Inserted in a mouse's eye





Energy Management
500 nF/mm
Using high k dielectrics



Source A. Rippart INEMI 2011

Silicon Micro-dosimetry

Mimic Project
A. Kok et al SINTEF
C. Da Via STFC -CLASP proposal

Pioneering work from

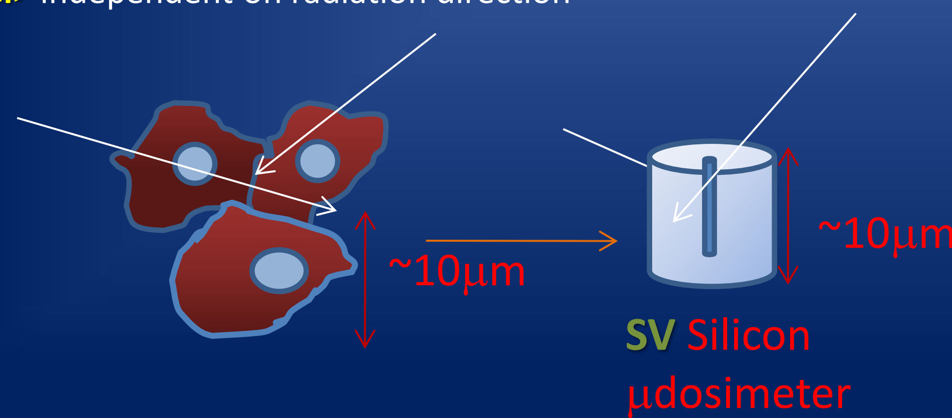
University of Wollongong

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>** independent on radiation direction

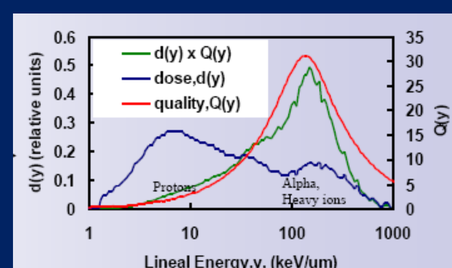
❖**Mixed Field** detection in a small sized array of cell-like elements of well defined Sensitive volume **SV** is required to precisely determine RBE



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

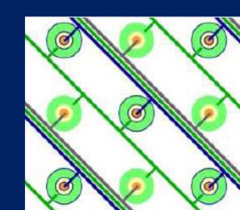
$D_{si} = D_{TE} S_{Si}/S_{TE}$

Dose equivalent $H = Q D_{si}$

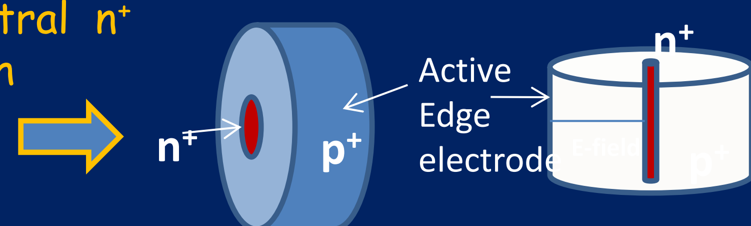


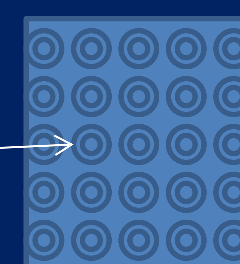
Plot from Rosenfeld et al

Dose distribution d(y)



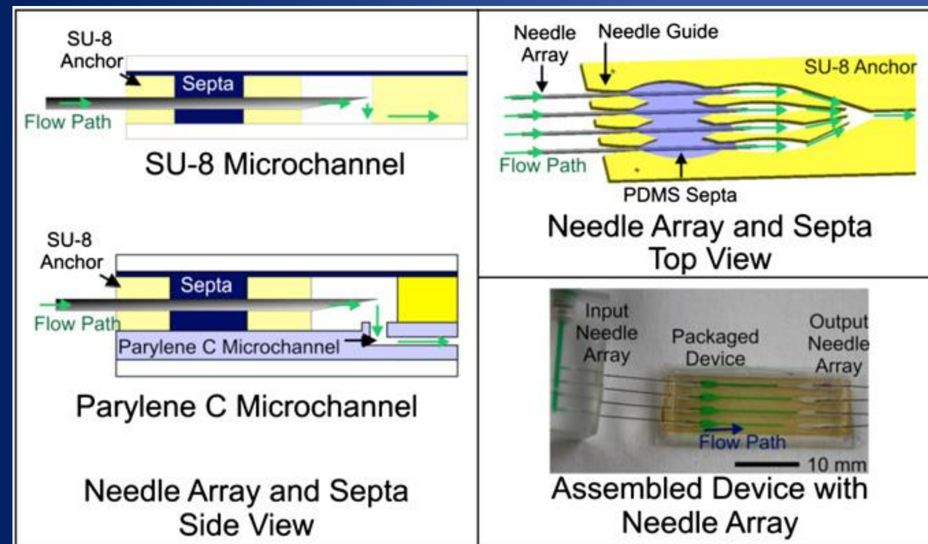
Use array of 3D sensors with central n^+ electrode surrounded by p^+ trench to define cellular size sensitive volume

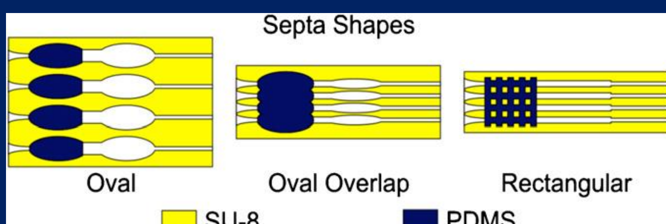


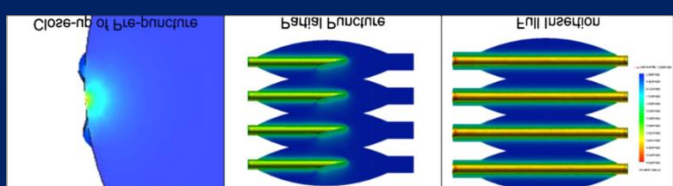


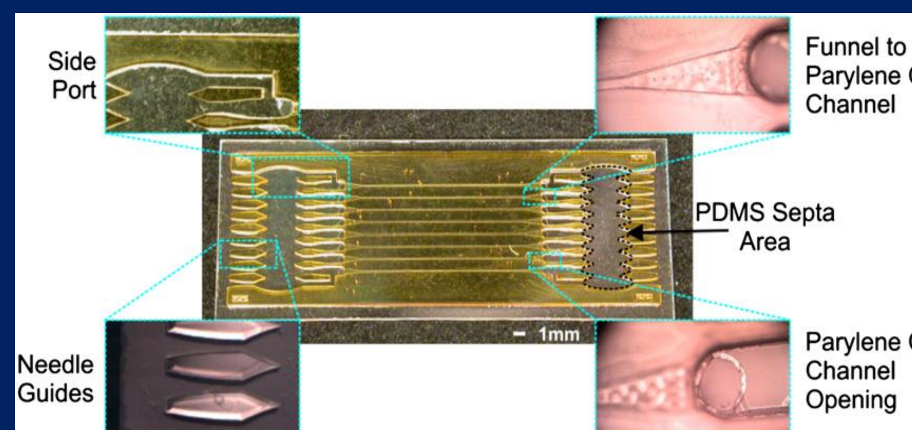
Micro total-analysis systems (μTAS) and lab-on-a-chip (LOC)

- microfluidics are used in applications such as chemical synthesis, genetic analysis, drug screening and single cell/molecule analysis
- in-plane interconnect using a 'pin-and-socket' approach in which a single commercially available non-coring needle (33G) accessed a microfluidic device by puncturing a polydimethysiloxane (PDMS) septum









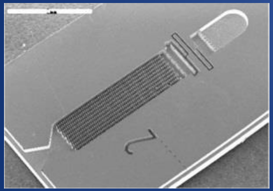
R Lo1 and E Meng
Department of Biomedical Engineering, University of Southern California, 149 Commonwealth Drive, Menlo Park, CA 94025, USA

Applications in Space

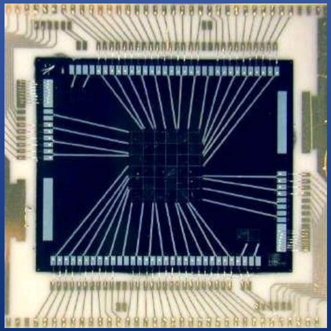
MEMS and Microstructures in A erospace
Applications
Published in 2006 by RC Press Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300 Boca Raton, FL 33487-2742

The MEMS technologies included in the NASA inventory:

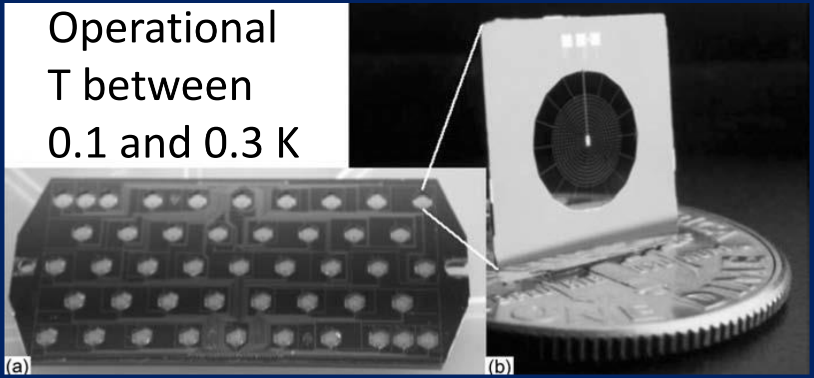
. Stirling coolers
. liquid-metal micro-switches
. inertial sensors
. microwave RF switches and phase shifters
. thrusters
. deformable mirrors
. pressure or temperature sensors
. power supplies
. sensors

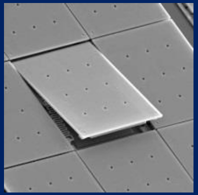


Propulsion thrusters

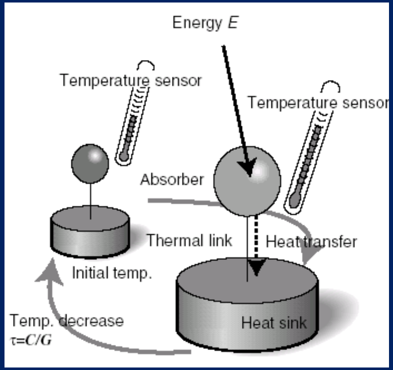


X-Ray sensor being used
For the SUZAKO x-ray
spectrometer





μ-mirrors



Used as a very sensitive T
Sensor T prop to E (x-ray)

microfabricated "Spider Web" bolometers, JPL

high-purity, neutron transmutation doped (NTD), single crystal Ge thermistor chip mounted on a "spider web" suspension comprising metallized, suspended SiN filaments

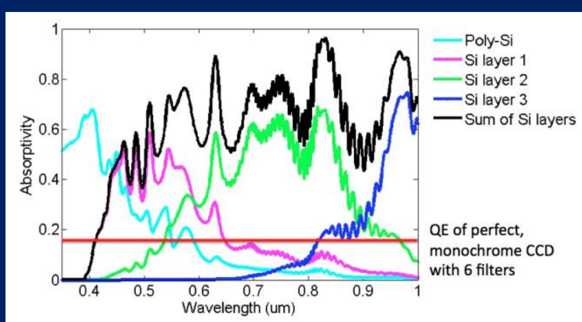
Multi-Layer Polychromatic CCD

Astronomy, Cosmology

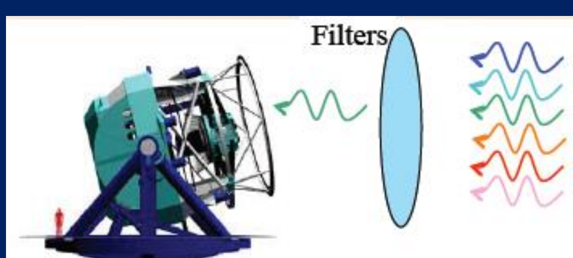
Chu-En Chang, J. Segal, R. Howe, A. Roodman, SLAC
Material from C. Kenney

Imager, which can record the intensity of light within multiple color bands and with high quantum efficiency

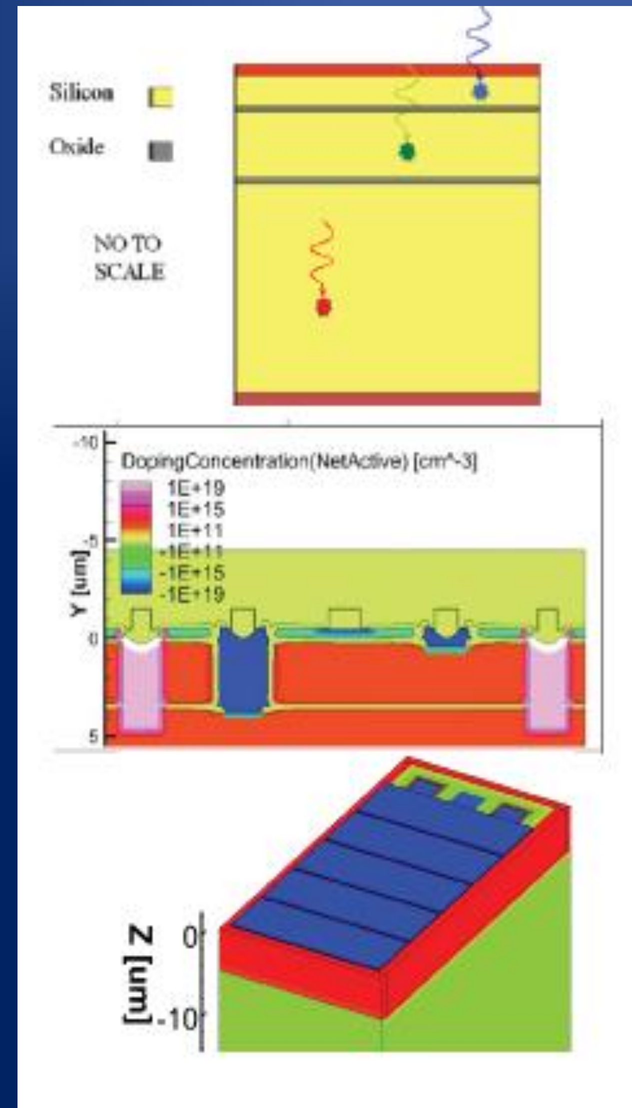
- Basic idea is to make a multi-layer CCD to replace a monochromatic CCD with a 'color-sensitive" device
- All layers are clocked out simultaneously by the same set of gate electrodes
- Each layer readout separately, but simultaneously
- Employ micro-machining technology for channel stops and read-out contacts – similar procedure used for 3D sensors



Simulation of quantum efficiency for Poly-chromatic versus mono-chromatic CCDs



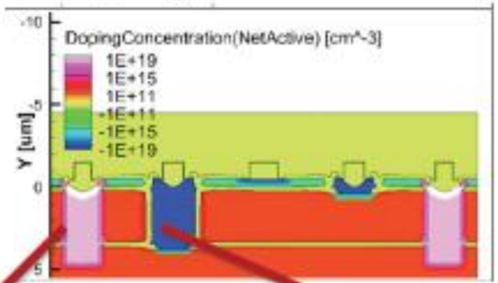
Application in wide-area Optical surveys for cosmology

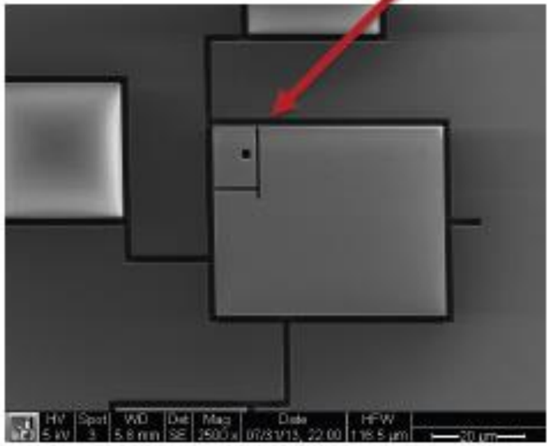


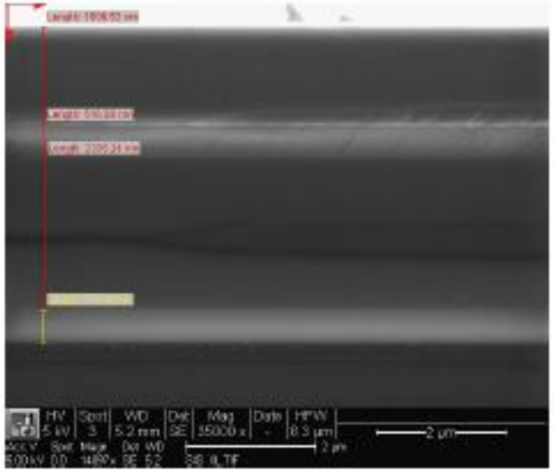
Multi-layer CCDs prototype

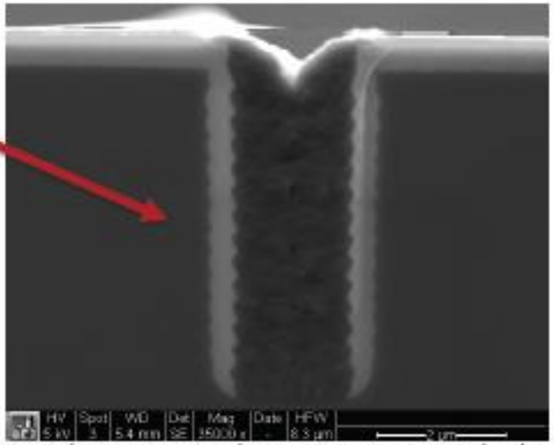
Fabrication of many layers of thin, float-zone silicon separated by oxide films done in partnership with local company

Channel-stop trenches same a used in 3D sensors





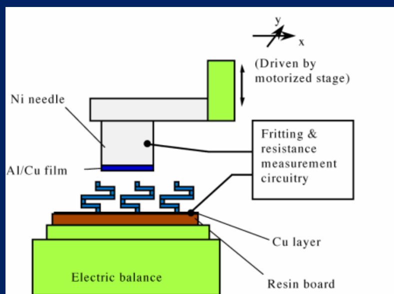


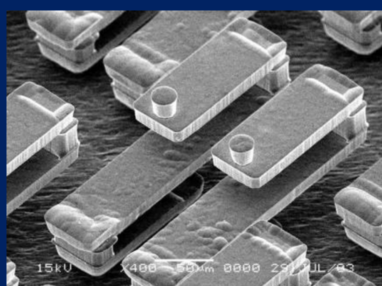


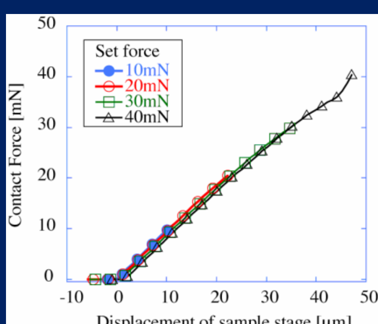
Isolated, conducting vias demonstrated

Cinzia Da Vià. The University of Manchester, UK. Hiroshima Conference , 1-5 September 2013

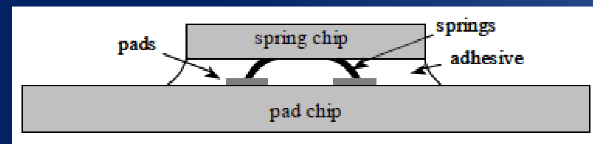
Wire-bonding free electrical connectors

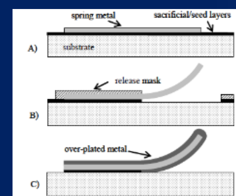


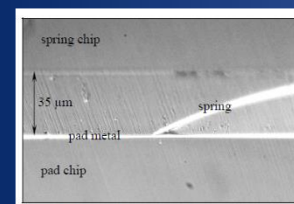


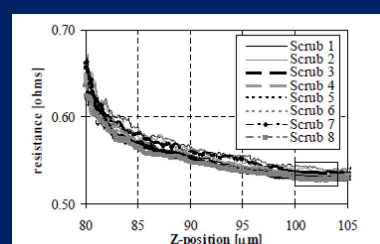


Kenichi Kataoka
Research Center for Advanced Scienceand Technology,
The University of Tokyo



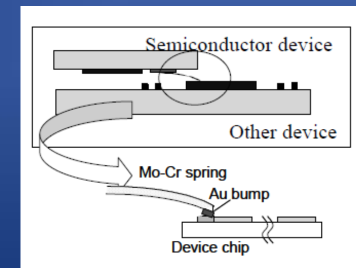






Solder-Free Pressure Contact Micro-Springs in High-Density Flip-Chip Packages

Eugene M. Chow, Chris Chua, Thomas Hantschel, Koenraad Van Schuylenbergh, David K. Fork
Palo Alto Research Center (PARC)



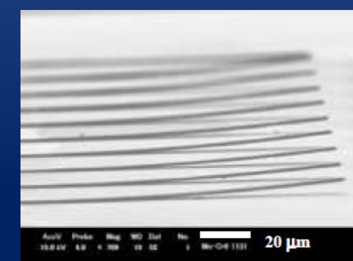


Table I Contact resistance and sheet resistance of metals deposited using various process.

Material	Contact resistance (Ω)	Sheet resistance (mΩ/□q.)	Particle size (nm)
Mo-Cr	0.0628	192.5	-
Au (EB deposition)	0.044	12.8	unable to measure
Au (pulse plating (i))	0.0314	18.15	50-500
Au (pulse plating (ii))	0.0078	9.72	50-500
Au (ultrasonic plating)	0.0035	6.7	250

Chip-Bonding for Integrated Circuit by using Micro-spring Probe

Chinami Kaneshiro, Kohji Hohkawa
Kanagawa Institute of Technology

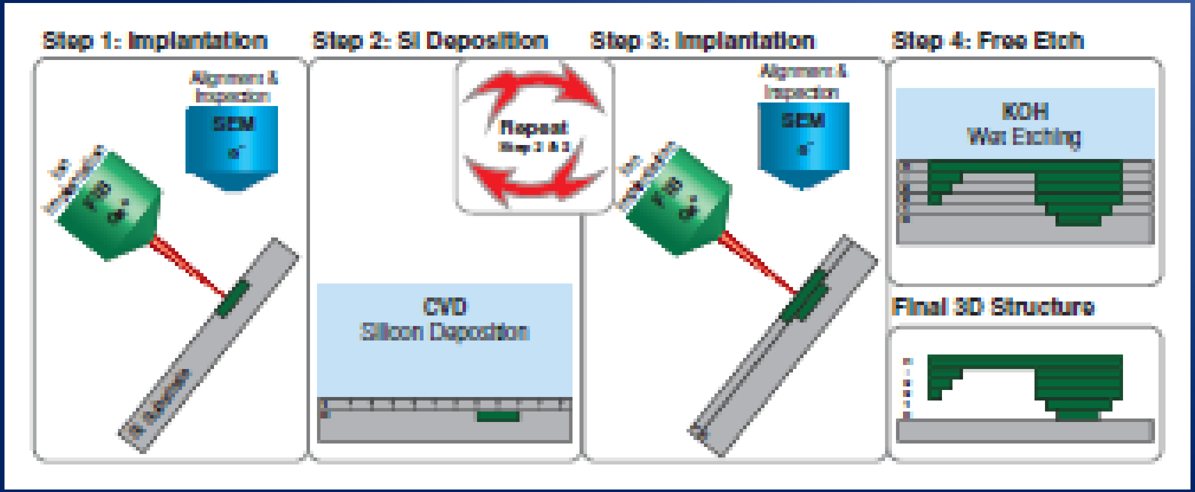
The future: 3D printing

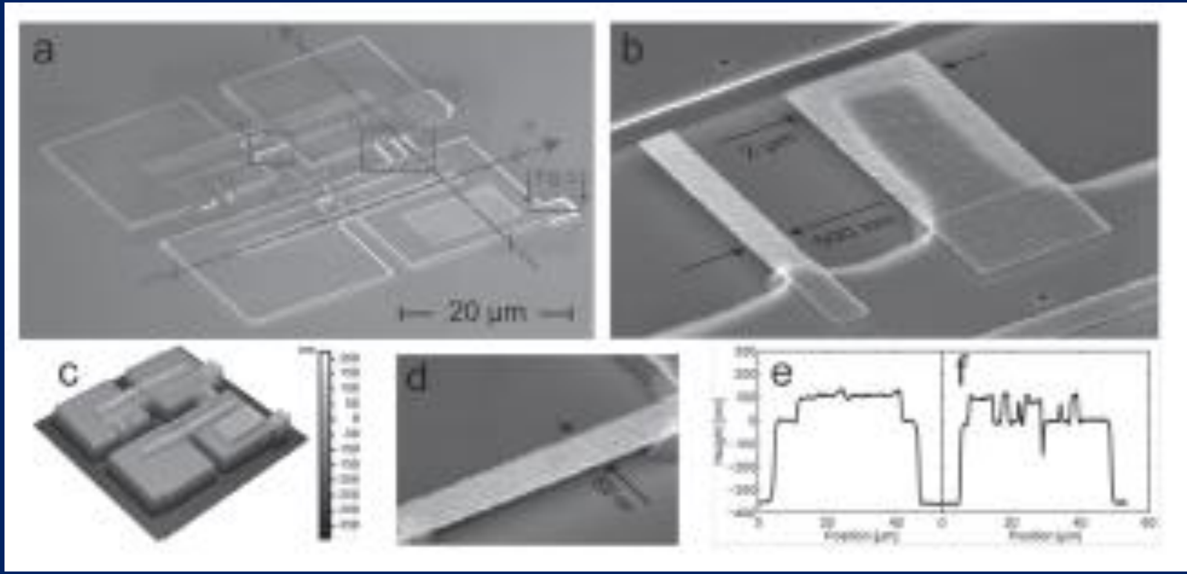
Adv. Funct. Mater. **2012**, *22*, 4004–4008

The layer-by-layer fabrication is based on alternating steps of chemical vapor deposition of silicon and local implantation of gallium ions by focused ion beam (FIB) writing.

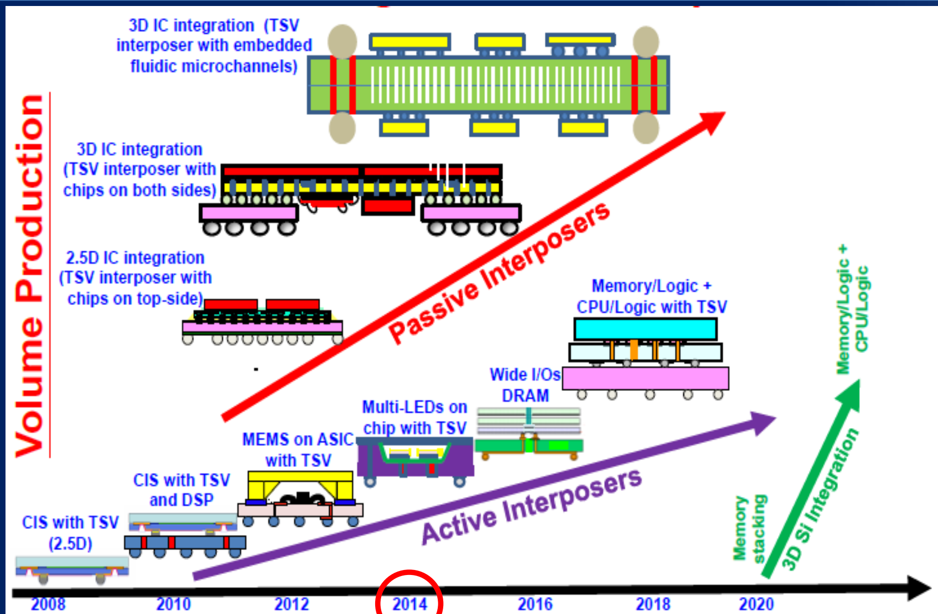
In a final step, the defined 3D structures are formed by etching the silicon in potassium hydroxide (KOH), in which the local ion implantation provides the etching selectivity.

The method is demonstrated by fabricating 3D structures made of two and three silicon layers, including suspended beams that are 40 nm thick, 500 nm wide, and 4 μ m long, and patterned lines that are 33 nm wide.

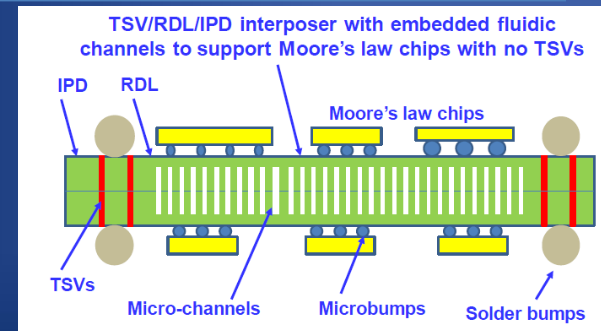




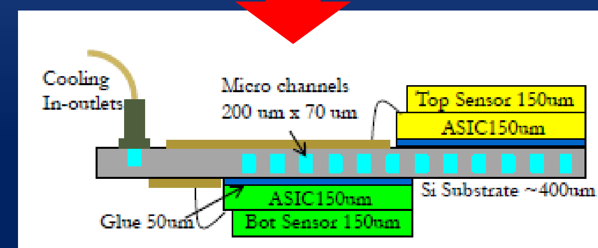
More than Moore: 3D integration roadmap



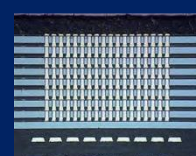
Source: John Lau, ITRI, InterPACK 2011



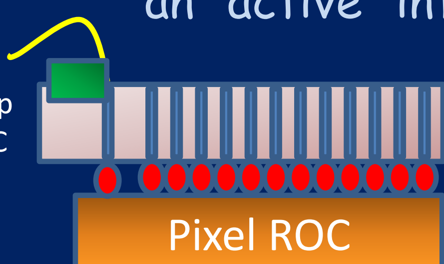
LHCb layout



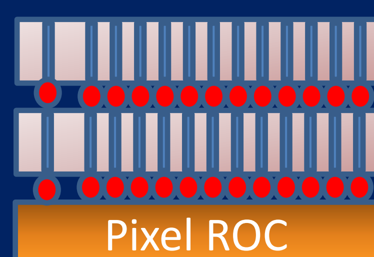
3D sensor can be used as an "active" interposer



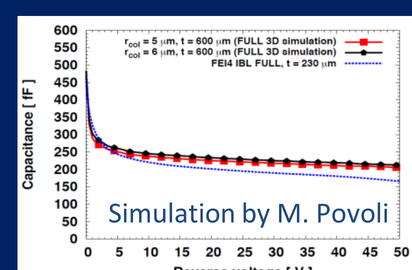
Strip ROC



Dual readout



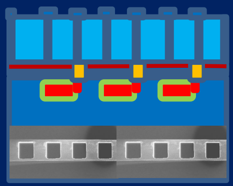
"Stacked " 3D sensors



Applications on momentum Discrimination and "charge-share" free x-ray imaging

A Future Innermost layer in ATLAS?

Rad-Hard sensors +
Micro-channel cooling +
Electro-mechanical connectors on superlight supports

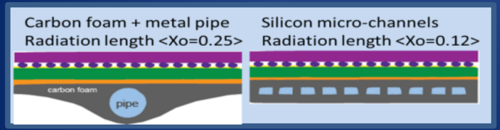


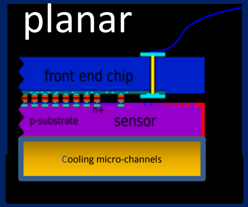
3D

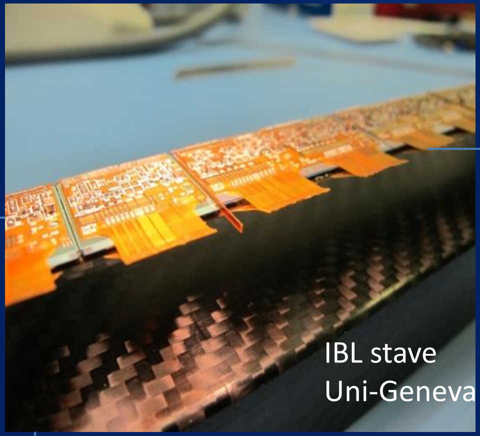
FEC

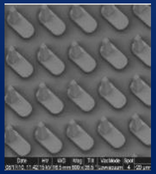
uchannels

Micro-connector

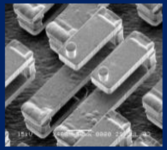




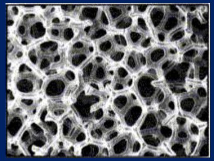




MEMS techniques to produce lithographically printed probe cards capable of 6 µm sq. x 20 µm high probe tips on 40 µm pitch are also possible
@Csacade Microtech

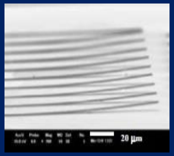


M-probe by Kenichi Kataoka
Research Center for Advanced Science and Technology,
The University of Tokyo



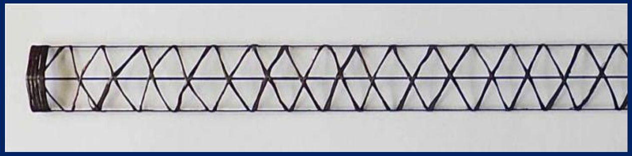
SiC foam

PLUME



Micro-wire spring made of elastic metal materials, coated with Au film
At Kanagawa Institute of Technology

Carbon fiber

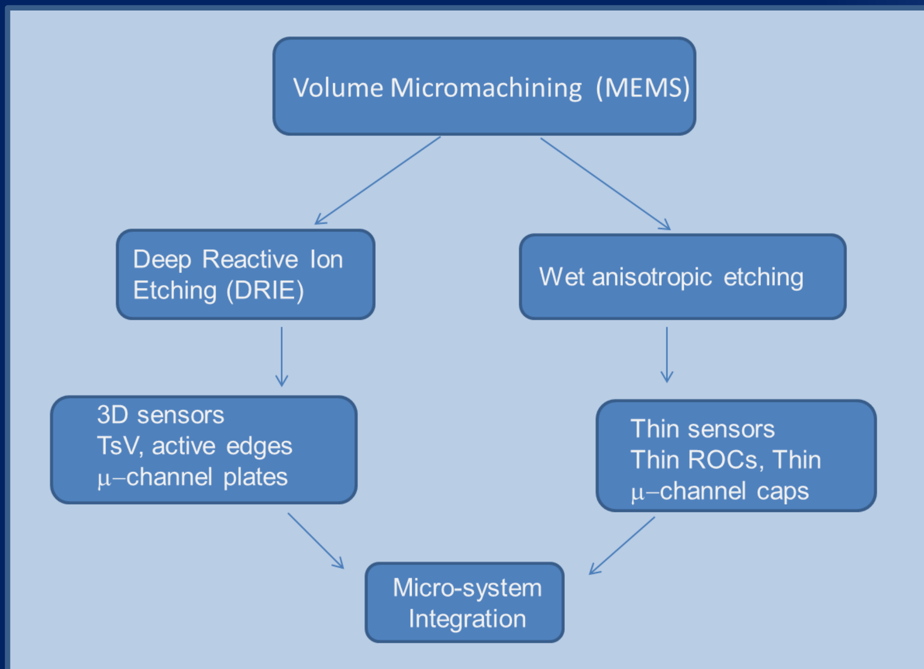


ALICE

Micro-Fabrication is a proposed CERN RD

24 Institutions from all LHC experiments + 7 processing facilities

3D Sensors & MicroFab Systems



This project gathers 7 major facilities with proven skills to perform all the required processing and integration steps of the proposed program

Together we believe we can solve "faster" and "cheaper" technological and production challenges

Potential technology transfer to other fields

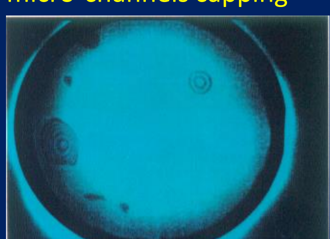
Wafer bonding
mechanical stability
Active edge 3D sensors
Thin electronics
micro-channels capping

3D electrodes and
active edges single side
3D double side sensors

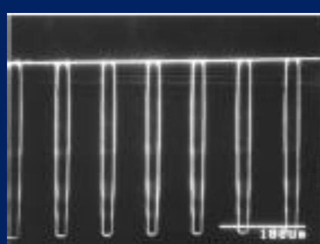
Embedded
micro-challels

Integration , TsV

Superficial micro-
channels



CIS-Stanford



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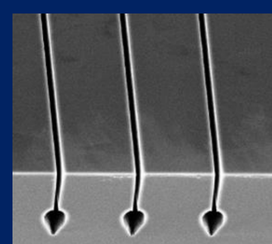

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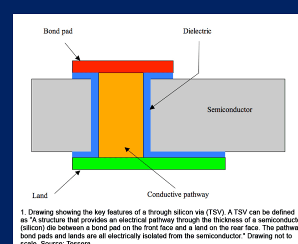

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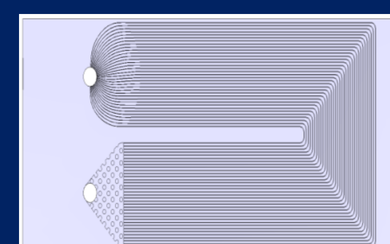


EPFL-CERN-LHCb

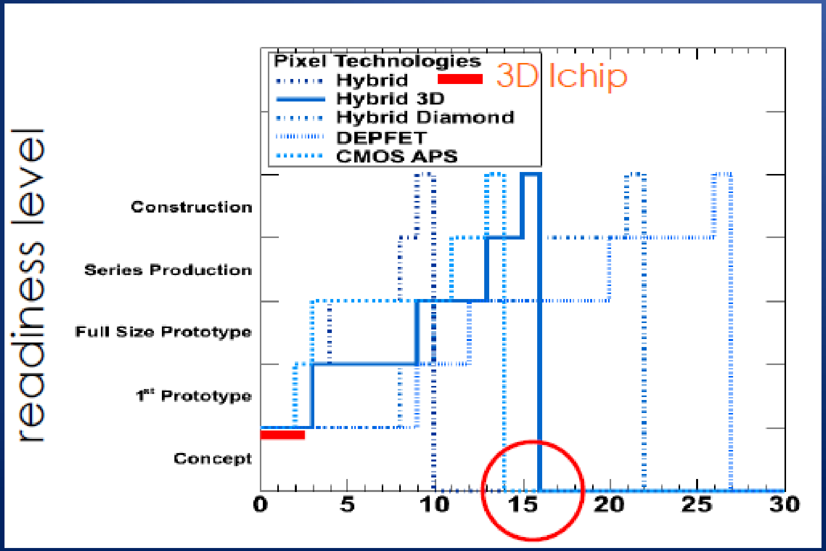
Conclusions and Outlook

❖ Micro-Fabrication is offering good opportunities for future Vertex systems at The LHC beyond 3D sensors, Micro-cooling and TsV.

❖ A lot of the development is Market driven but also research driven in biology , and space applications and we should take advantage of it!

❖ In particular if this involves a new concept since the average time to get to maturity for a new technology is ~15 years.

It seems we will have time..



From A. Cattai