Si3D detectors @ RD50

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Fondazione Bruno Kessler Trento

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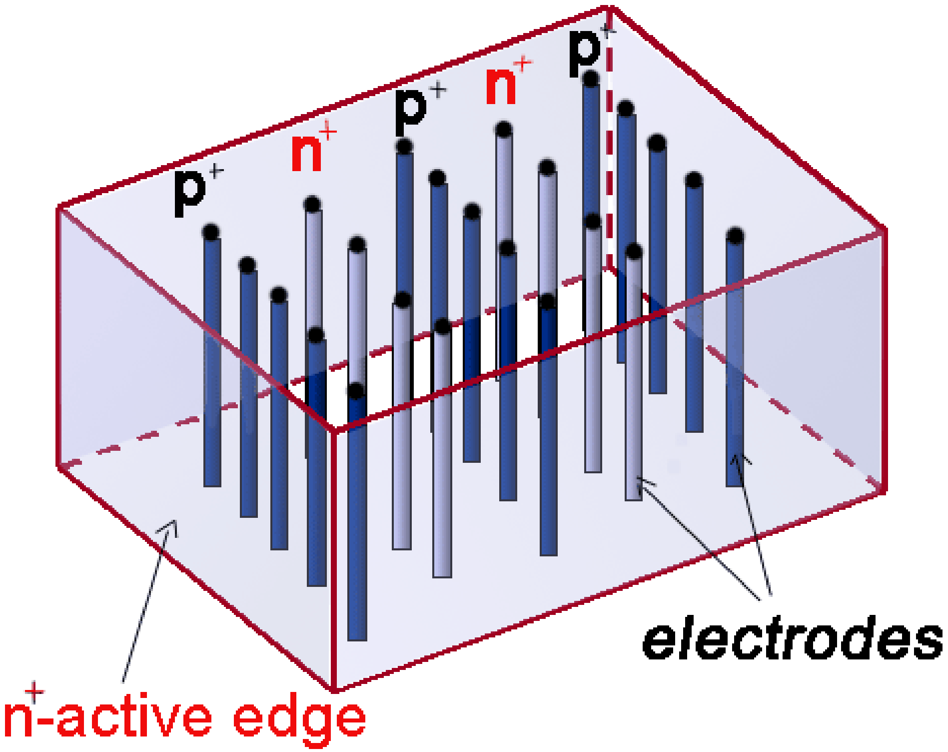
43rd RD50 meeting 27.XI.2023

Introduction: the "usual slide"



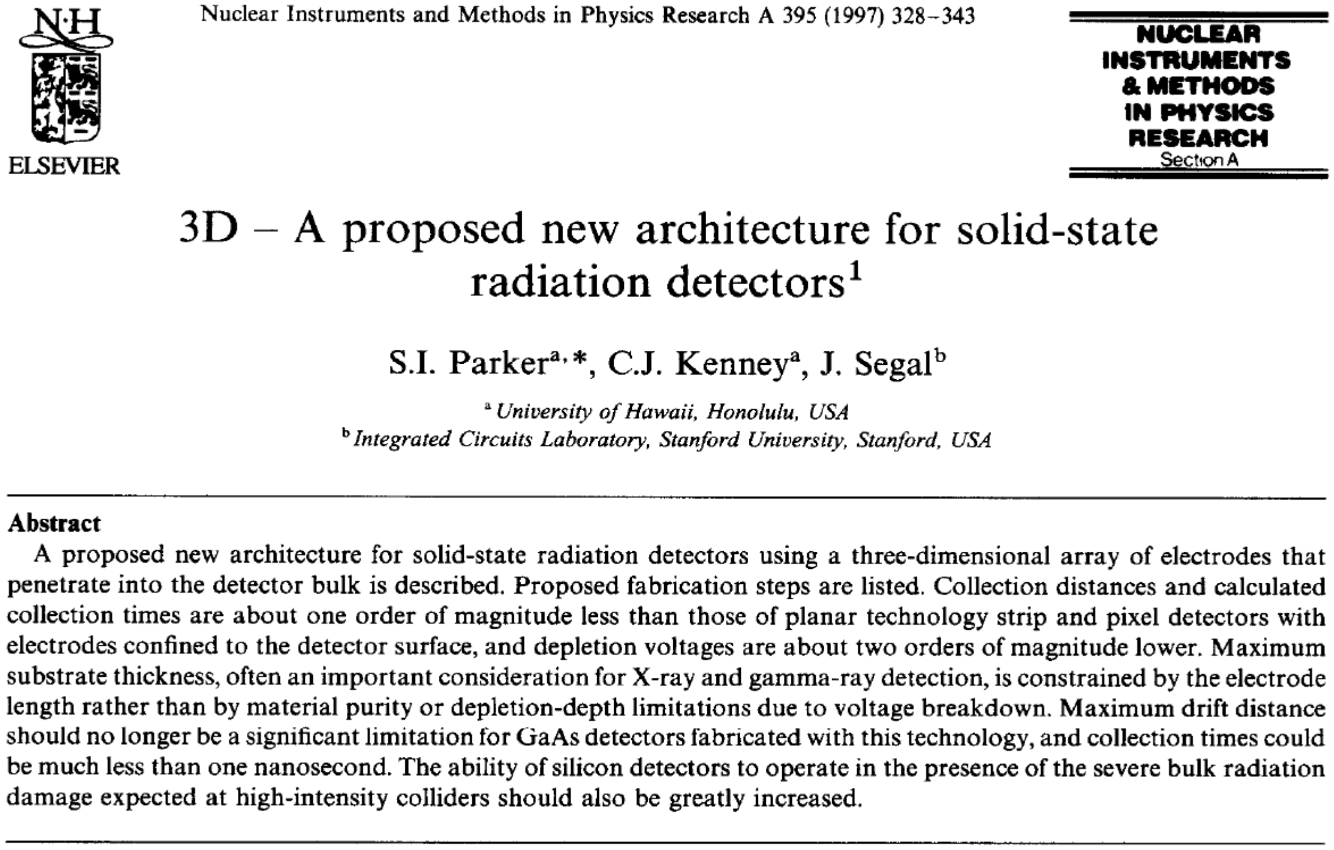
ADVANTAGES:

- Low depletion voltage (low power diss.)
- **Short charge collection distance:**
    - **Fast response**
    - **Less trapping probability after irr.**
- Lateral drift → cell "shielding" effect:
    - Lower charge sharing
    - Low sensitivity to magnetic field
- Active edges

DISADVANTAGES:

- Non uniform spatial response (electrodes and low field regions)
- Higher capacitance with respect to planar (~3x for ~ 150 μm thickness)
- **Complicated technology (cost, yield)**

The first paper



Nuclear Instruments and Methods in Physics Research A 395 (1997) 328–343

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

ELSEVIER

3D – A proposed new architecture for solid-state radiation detectors[1]

S.I. Parker[a,*], C.J. Kenney[a], J. Segal[b]

[a] *University of Hawaii, Honolulu, USA*
[b] *Integrated Circuits Laboratory, Stanford University, Stanford, USA*

Abstract

A proposed new architecture for solid-state radiation detectors using a three-dimensional array of electrodes that penetrate into the detector bulk is described. Proposed fabrication steps are listed. Collection distances and calculated collection times are about one order of magnitude less than those of planar technology strip and pixel detectors with electrodes confined to the detector surface, and depletion voltages are about two orders of magnitude lower. Maximum substrate thickness, often an important consideration for X-ray and gamma-ray detection, is constrained by the electrode length rather than by material purity or depletion-depth limitations due to voltage breakdown. Maximum drift distance should no longer be a significant limitation for GaAs detectors fabricated with this technology, and collection times could be much less than one nanosecond. The ability of silicon detectors to operate in the presence of the severe bulk radiation damage expected at high-intensity colliders should also be greatly increased.

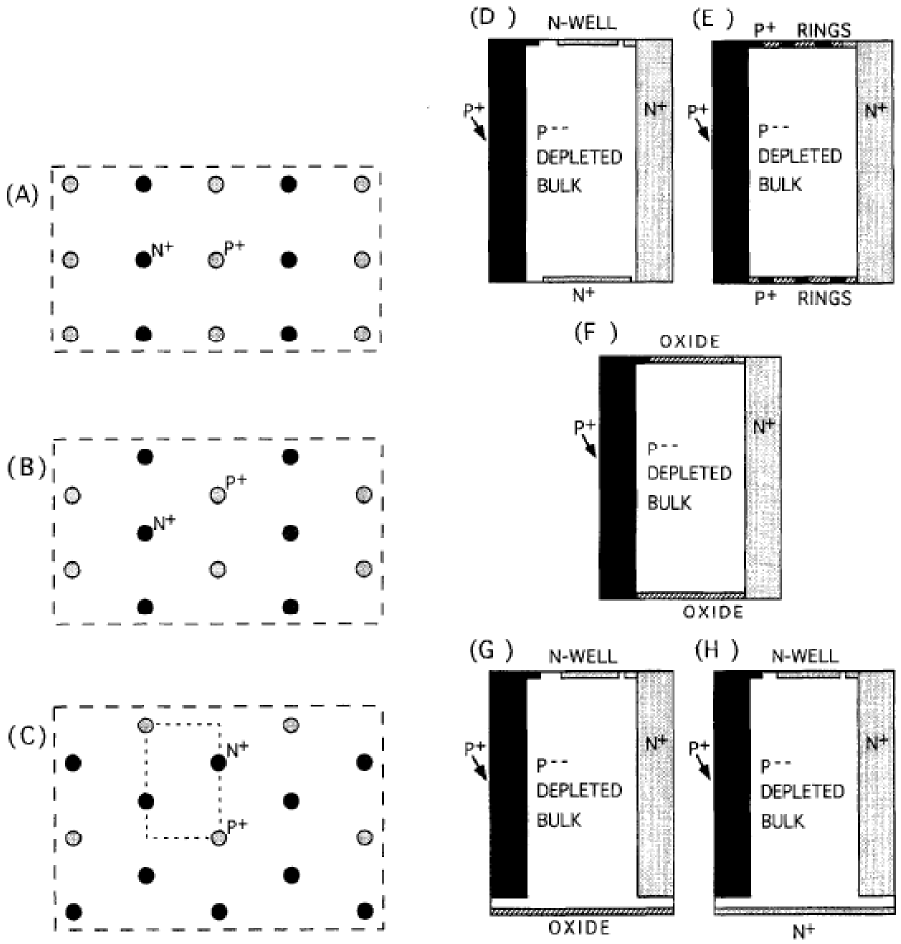
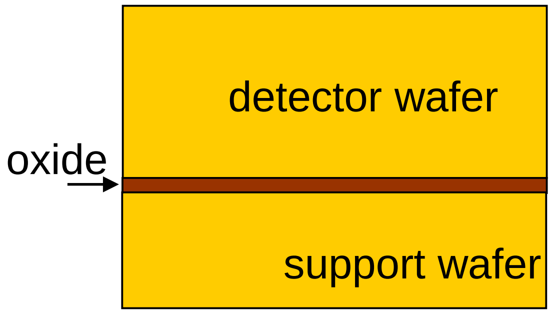
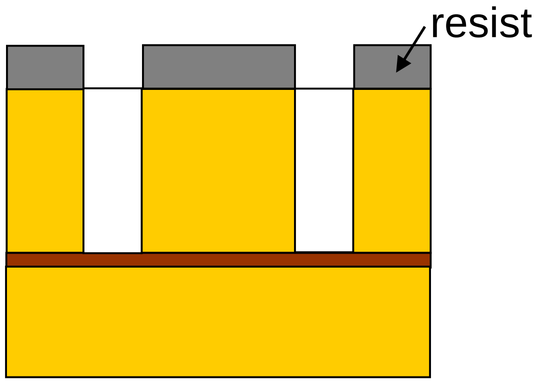


Fig. 10. Top views (a)–(c), and side views (d)–(h) of several possible structures.

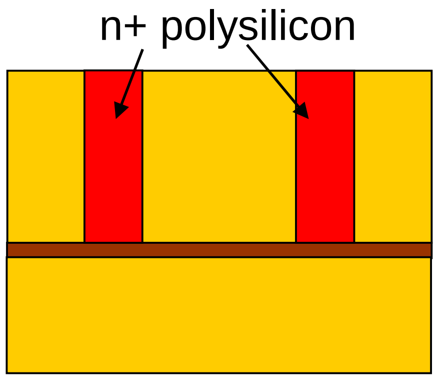
Process scheme



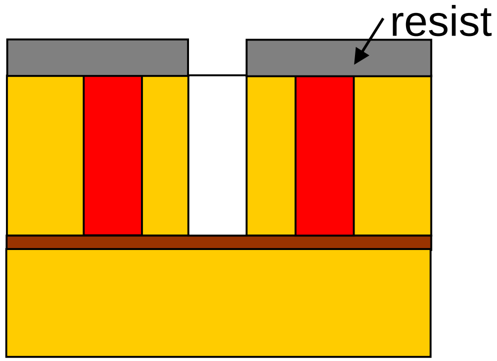
1. wafer bonding



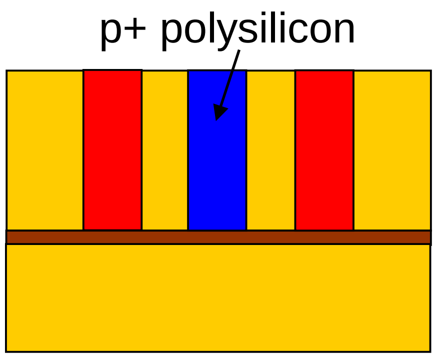
2. n^+ hole definition and etching



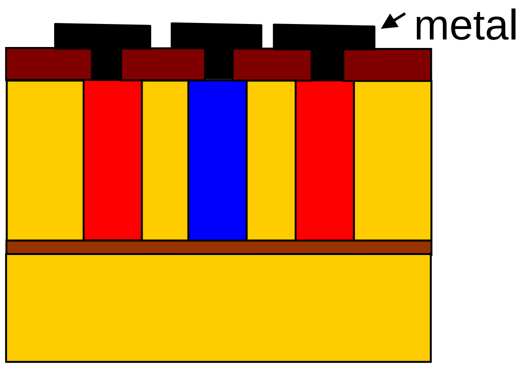
3. hole doping and filling



4. p^+ hole definition and etching



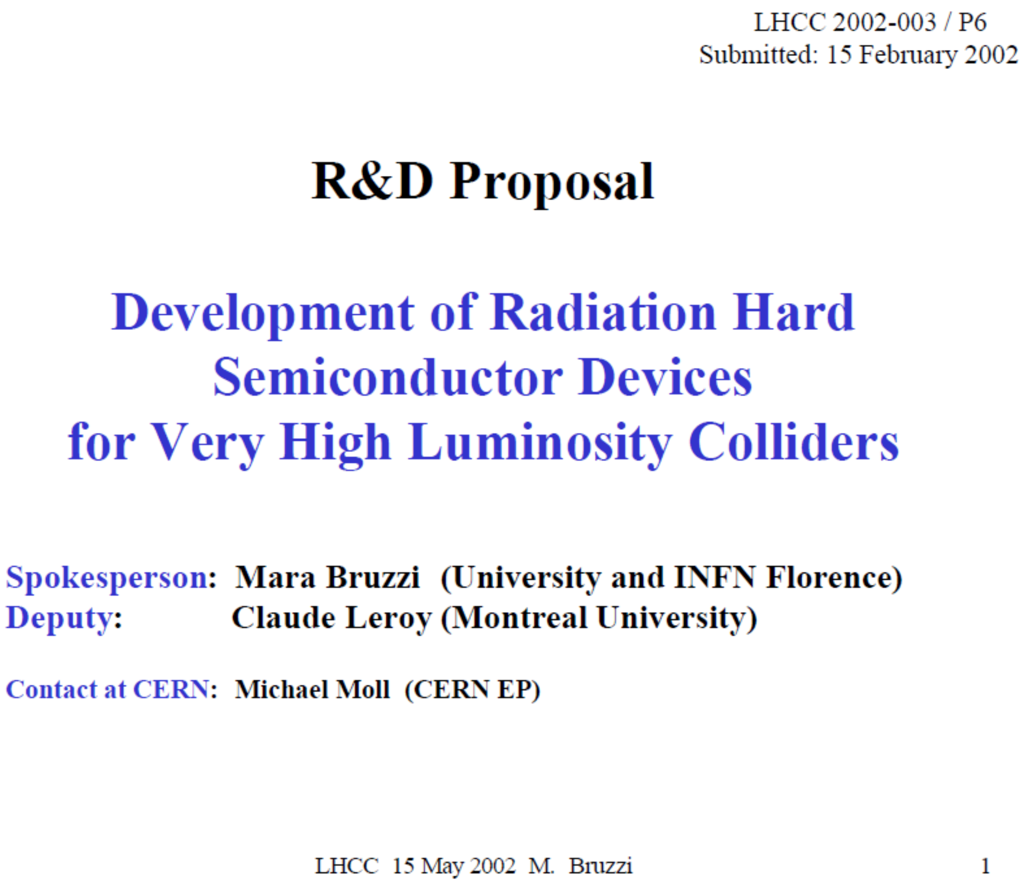
5. hole doping and filling



6. Metal dep. and definition

C. Kenney et al., IEEE TNS, vol. 46, n. 4 (1999) 1224
T.E. Hansen et al., JINST 4 (2009) P03010

RD50 proposal



LHCC 2002-003 / P6
Submitted: 15 February 2002

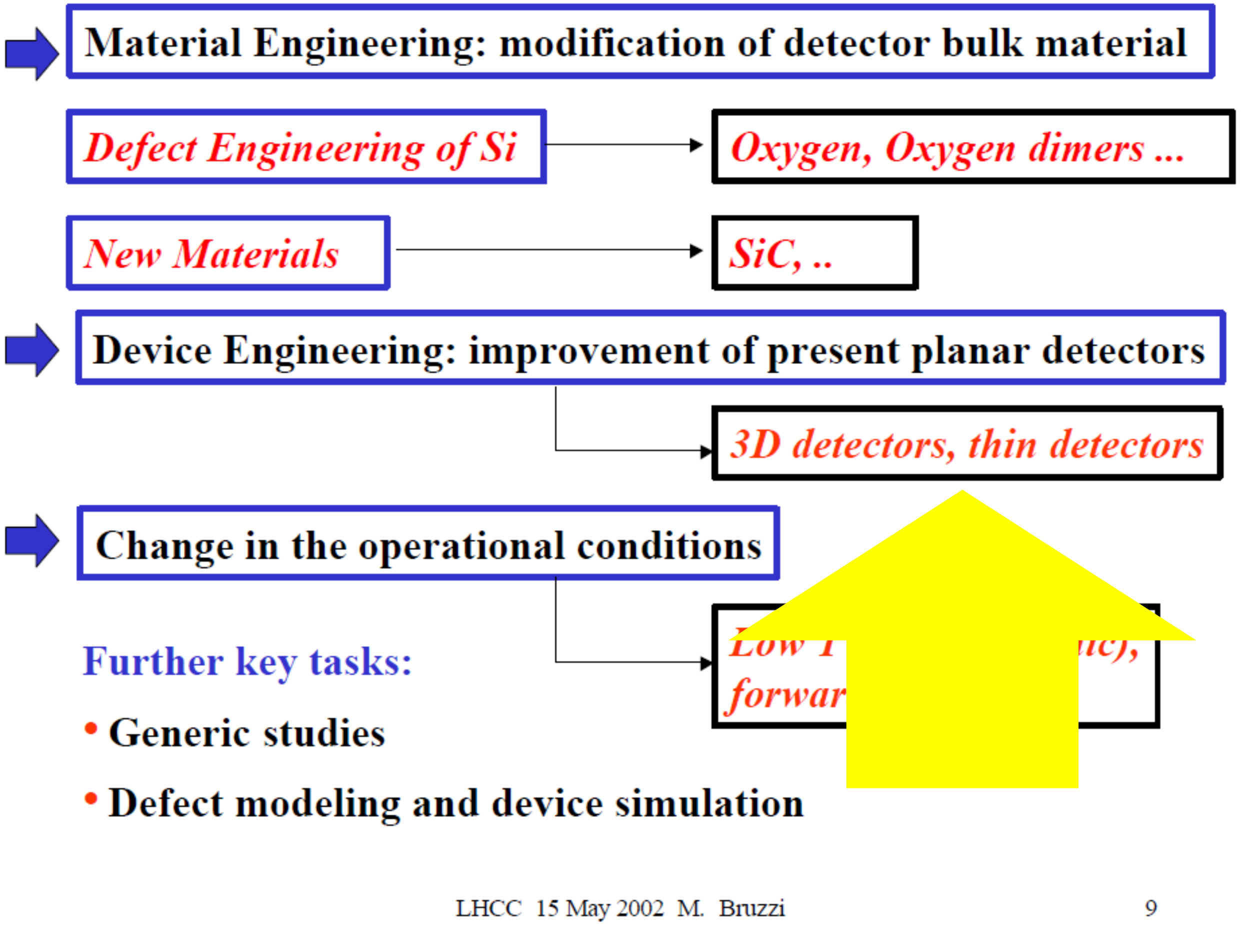
R&D Proposal

Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders

Spokesperson: Mara Bruzzi (University and INFN Florence)
Deputy: Claude Leroy (Montreal University)

Contact at CERN: Michael Moll (CERN EP)

LHCC 15 May 2002 M. Bruzzi 1



Material Engineering: modification of detector bulk material

Defect Engineering of Si → *Oxygen, Oxygen dimers ...*

New Materials → *SiC, ..*

Device Engineering: improvement of present planar detectors

→ *3D detectors, thin detectors*

Change in the operational conditions

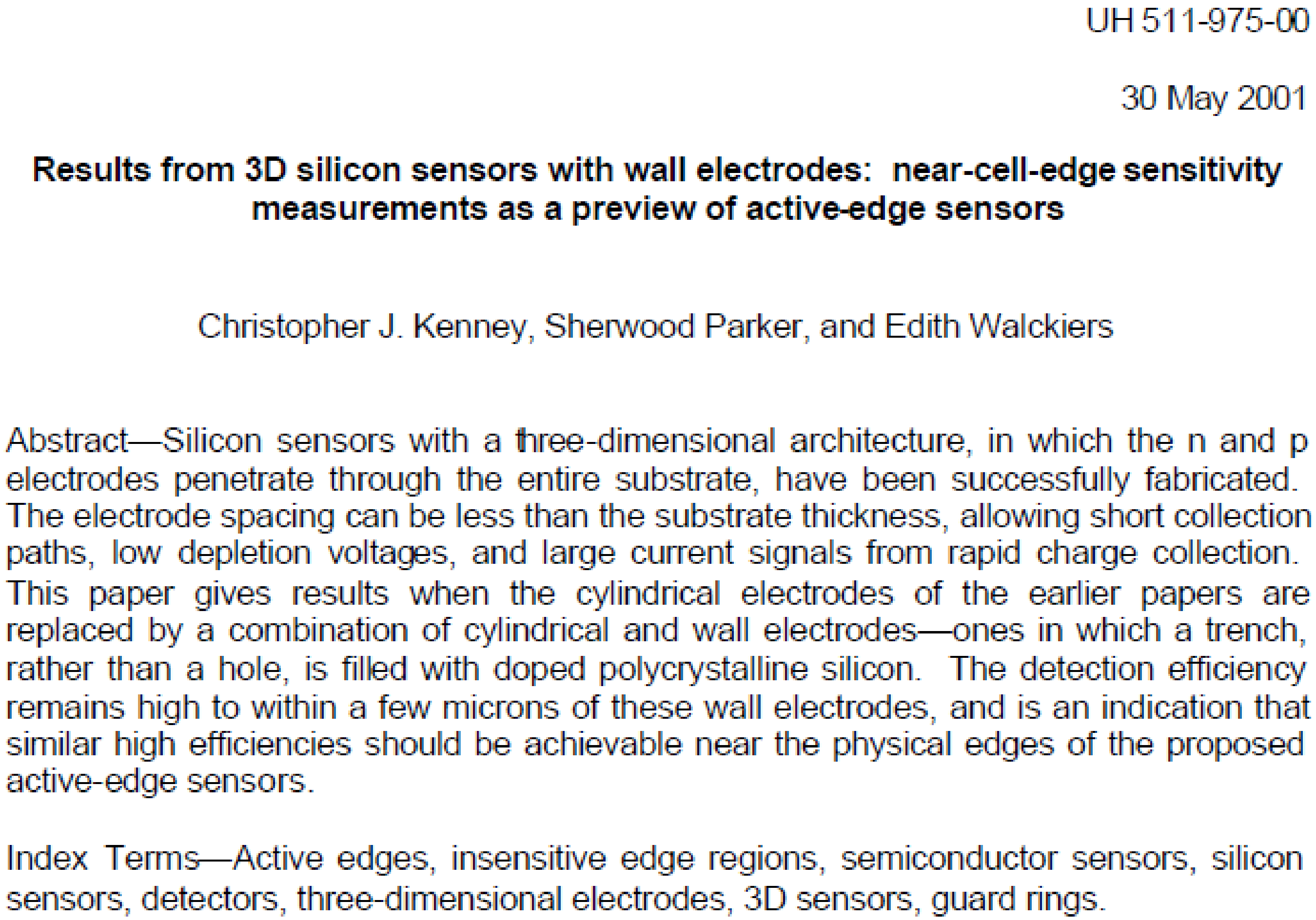
→ *Low T ic), forwar*

Further key tasks:

- Generic studies
- Defect modeling and device simulation

LHCC 15 May 2002 M. Bruzzi 9

1st RD50 workshop
28-30 November 2001



UH 511-975-00

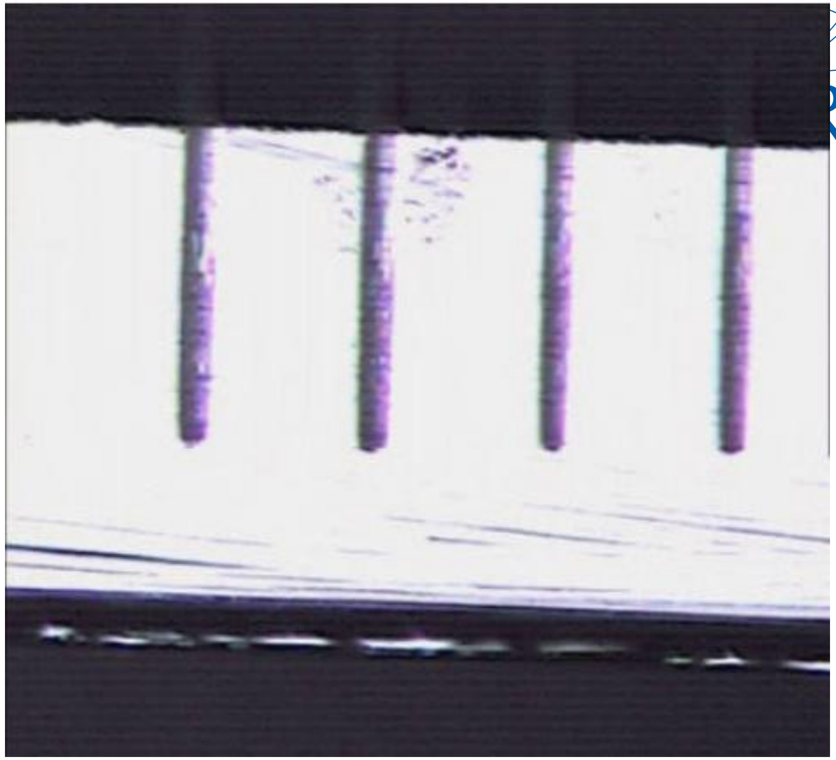
30 May 2001

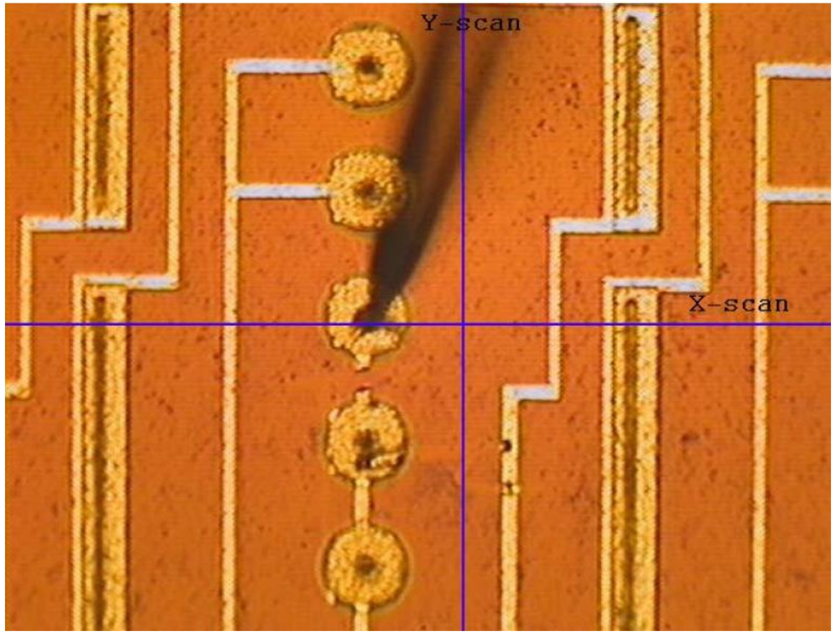
Results from 3D silicon sensors with wall electrodes: near-cell-edge sensitivity measurements as a preview of active-edge sensors

Christopher J. Kenney, Sherwood Parker, and Edith Walckiers

Abstract—Silicon sensors with a three-dimensional architecture, in which the n and p electrodes penetrate through the entire substrate, have been successfully fabricated. The electrode spacing can be less than the substrate thickness, allowing short collection paths, low depletion voltages, and large current signals from rapid charge collection. This paper gives results when the cylindrical electrodes of the earlier papers are replaced by a combination of cylindrical and wall electrodes—ones in which a trench, rather than a hole, is filled with doped polycrystalline silicon. The detection efficiency remains high to within a few microns of these wall electrodes, and is an indication that similar high efficiencies should be achievable near the physical edges of the proposed active-edge sensors.

Index Terms—Active edges, insensitive edge regions, semiconductor sensors, silicon sensors, detectors, three-dimensional electrodes, 3D sensors, guard rings.





1st RD50 workshop
28-30 November 2001

UNIVERSITY of GLASGOW

Fabrication of 3D detectors at The Detector Development Group of The University of Glasgow

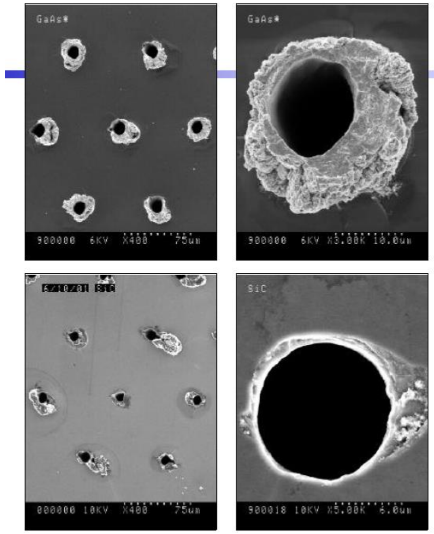
Richard Bates

M. Rahman, G. Pellegrini, P. Roy, K. Mathieson, D. Jones,
V. O'Shea, K.M. Smith, M. Horn, P. Thornton, J. Melone

R. Bates

Laser drilling

UNIVERSITY of GLASGOW



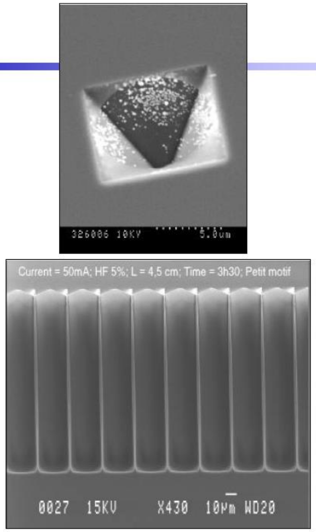
GaAs
- diameter : *10µm.*
- depth : *300-500µm.*

SiC
- diameter : *8µm.*
- depth : *300µm.*

R. Bate

Photoelectrochemical etching

UNIVERSITY of GLASGOW



1) Standard photolithography to create a mask in SiO_2 on the surface.

2) Creation of dimples in hot KOH.

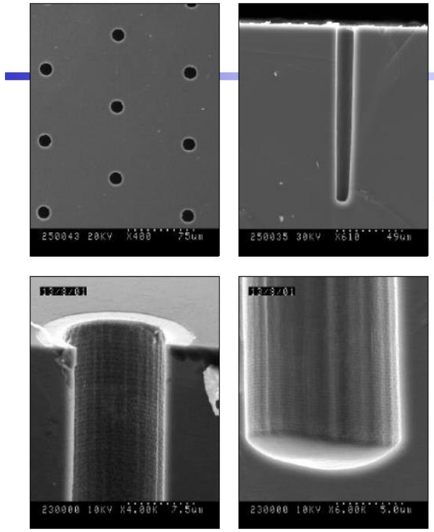
3) The silicon etching process is a primary dissolution reaction of the silicon induced by the hydrofluoric acid and the photogenerated holes.

Royal Institute of Technology KTH Stockholm.

R. Bates

Dry etching

UNIVERSITY of GLASGOW



Inductively coupled plasma
- Plasma etcher : SF_6.
- Mask coating : C_4F_8.

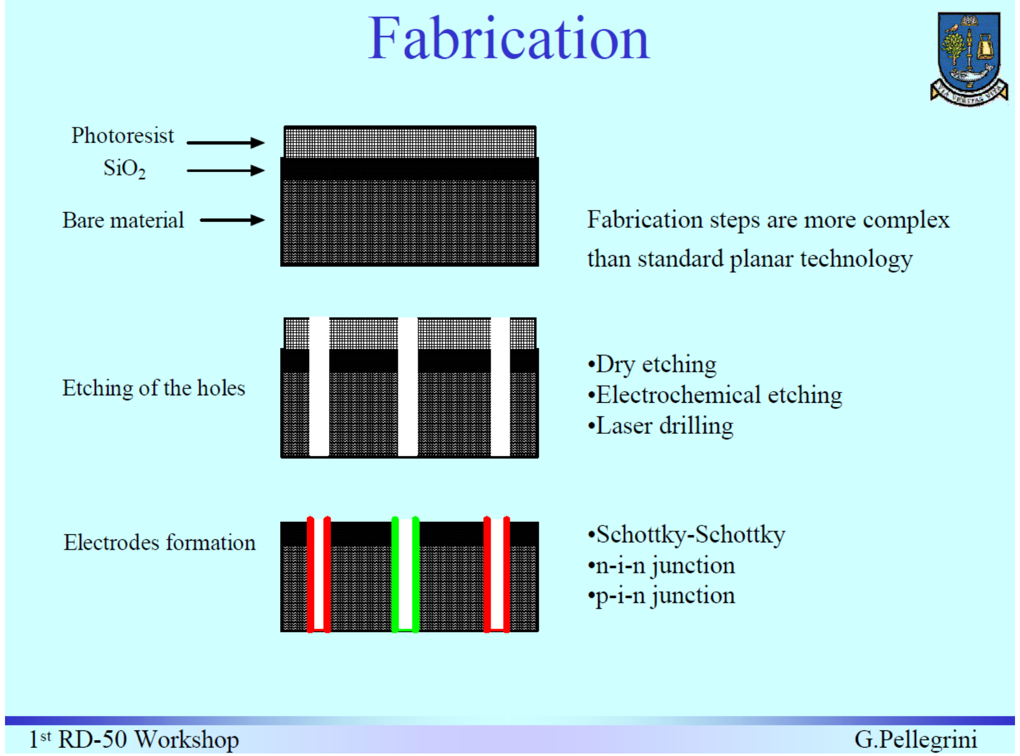
100 minutes of dry etching

⇩

- 10µm holes in diameter
- 130µm deep.

R. Bates

1^{st} RD50 workshop
28-30 November 2001



Fabrication

Photoresist

SiO_2

Bare material

Fabrication steps are more complex than standard planar technology

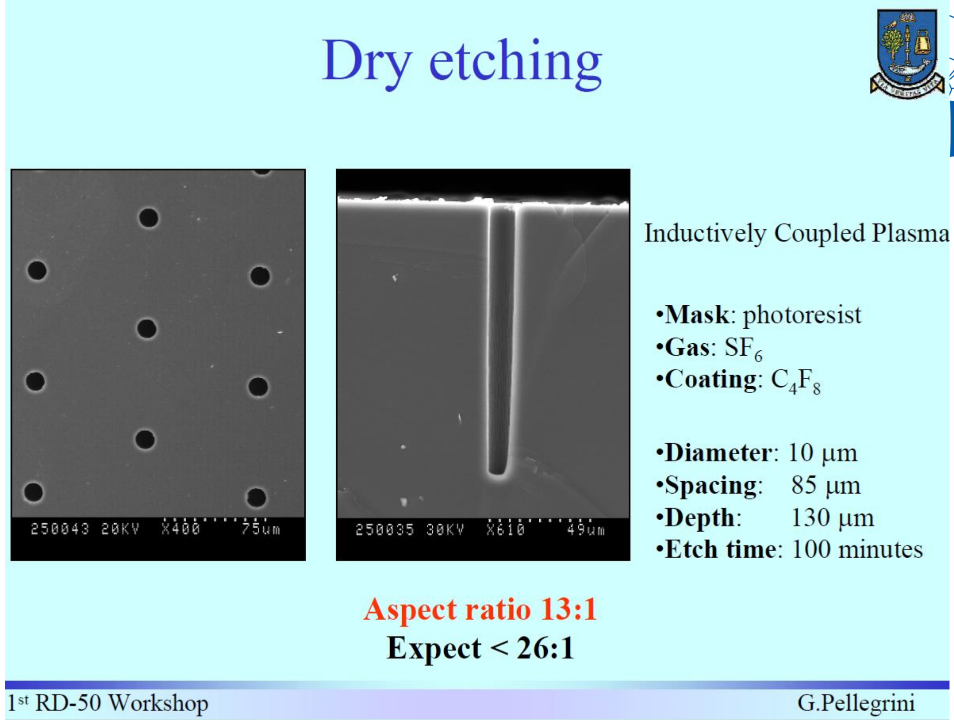
Etching of the holes

- Dry etching
- Electrochemical etching
- Laser drilling

Electrodes formation

- Schottky-Schottky
- n-i-n junction
- p-i-n junction

1^{st} RD-50 Workshop G.Pellegrini



Dry etching

Inductively Coupled Plasma

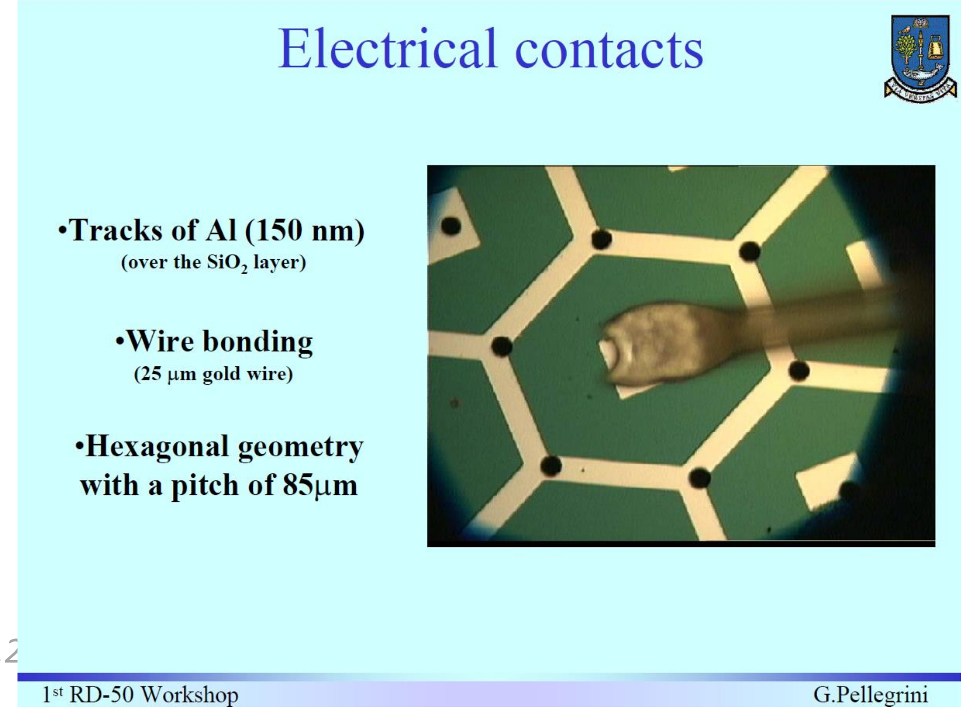
- **Mask**: photoresist
- **Gas**: SF_6
- **Coating**: C_4F_8

- **Diameter**: 10 µm
- **Spacing**: 85 µm
- **Depth**: 130 µm
- **Etch time**: 100 minutes

Aspect ratio 13:1

Expect < 26:1

1^{st} RD-50 Workshop G.Pellegrini



Electrical contacts

- **Tracks of Al (150 nm)**
  (over the SiO_2 layer)

- **Wire bonding**
  (25 µm gold wire)

- **Hexagonal geometry with a pitch of 85µm**

1^{st} RD-50 Workshop G.Pellegrini

4th RD50 workshop
5-7 May 2004

Talk on :

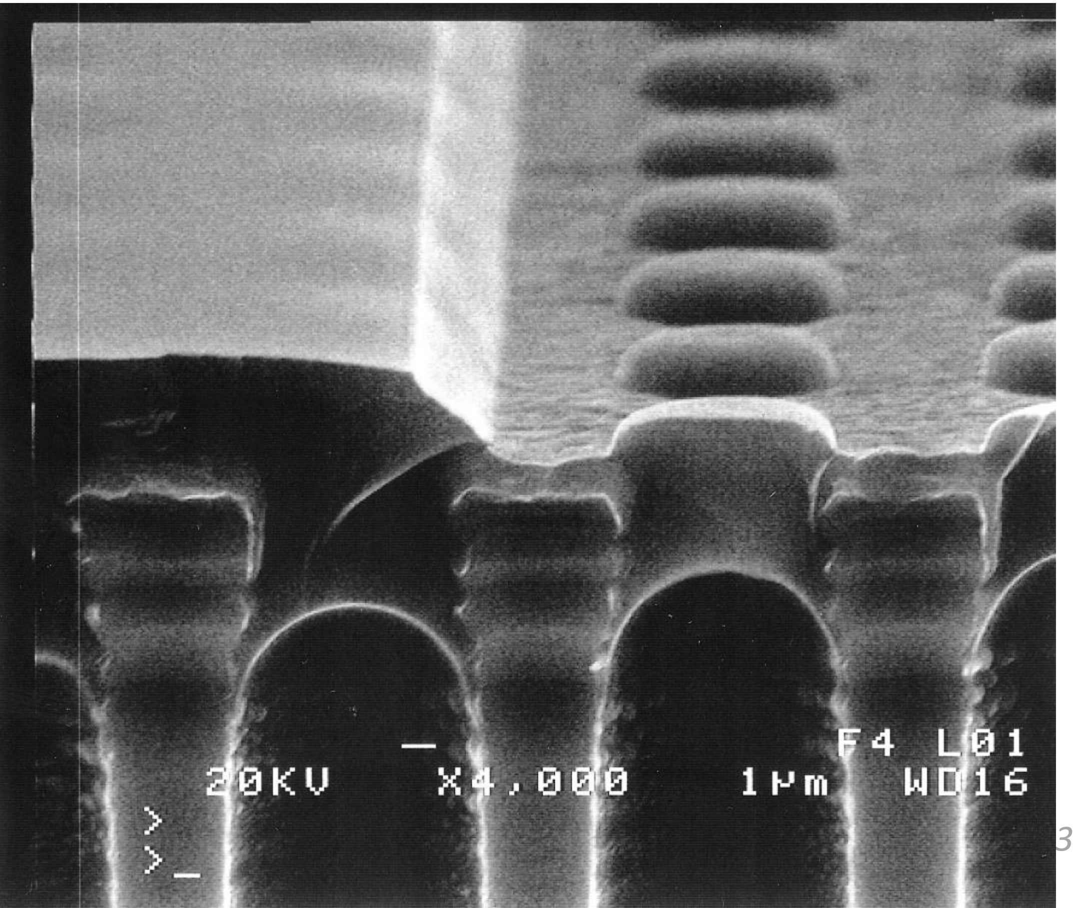
Status of ITC-irst activities in RD50

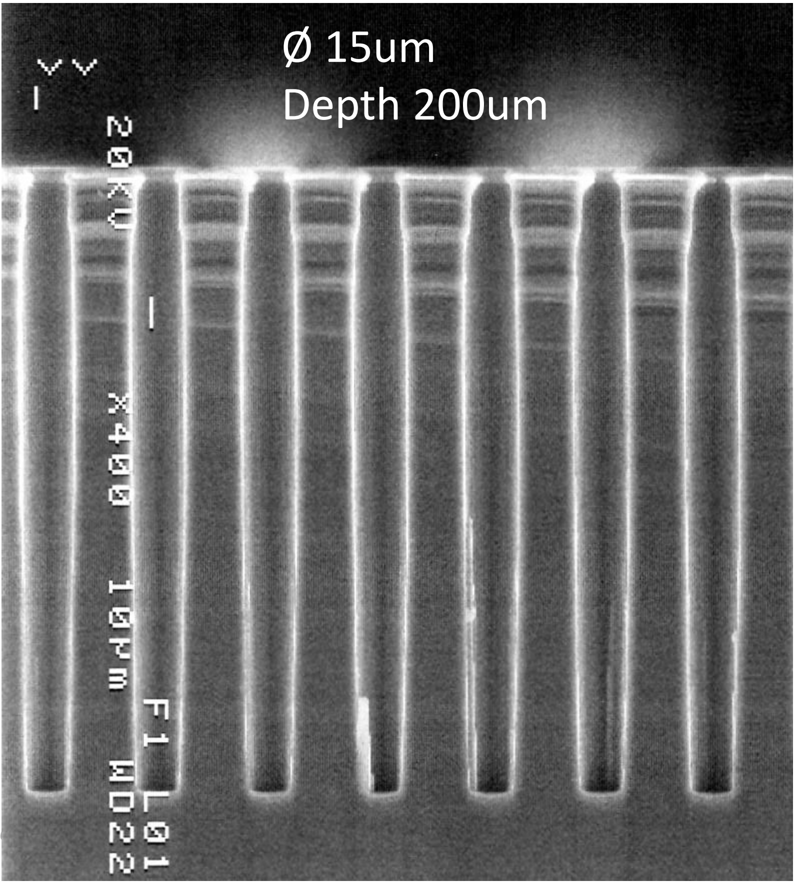
M. Boscardin

- ☐ Mask from Glasgow
- ☐ DEEP Rie Barcellona
- ☐ ITC –Irst process

RD50

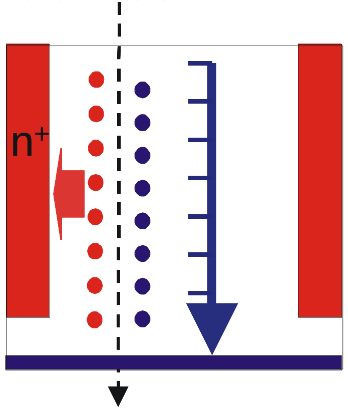
ITC
irst
CENTRO PER LA RICERCA
SCIENTIFICA E TECNOLOGICA



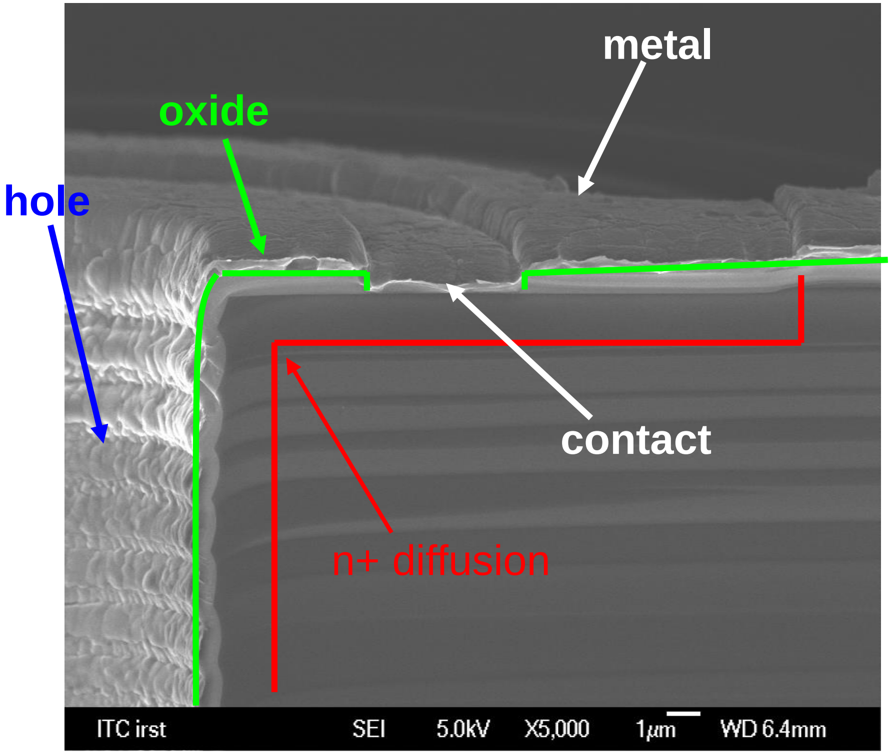

Ø 15um
Depth 200um

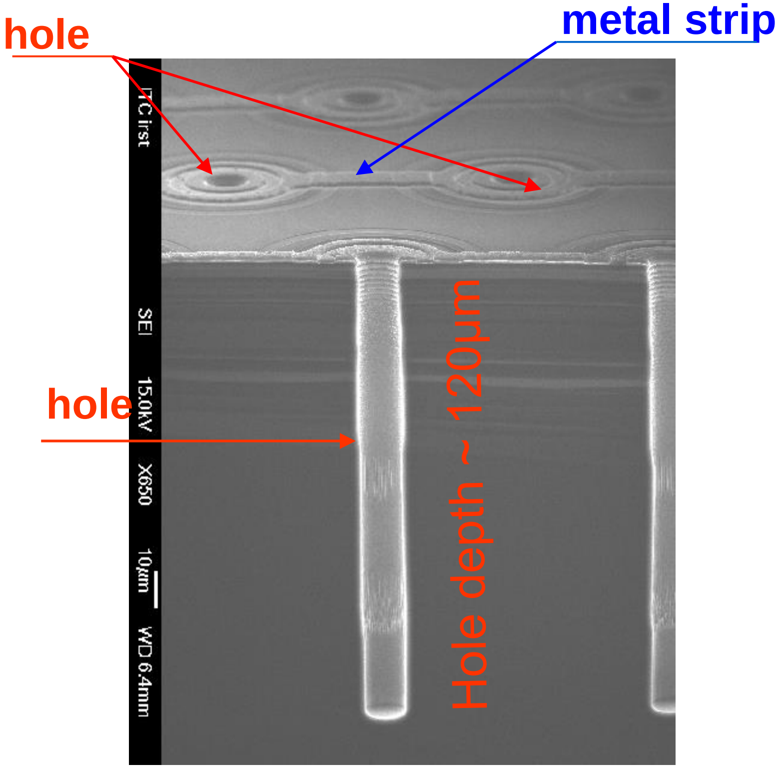
Single-Type-Column 3D detectors - concept

electrons are swept away by the transversal field



holes drift in the central region and diffuse towards p+ contact





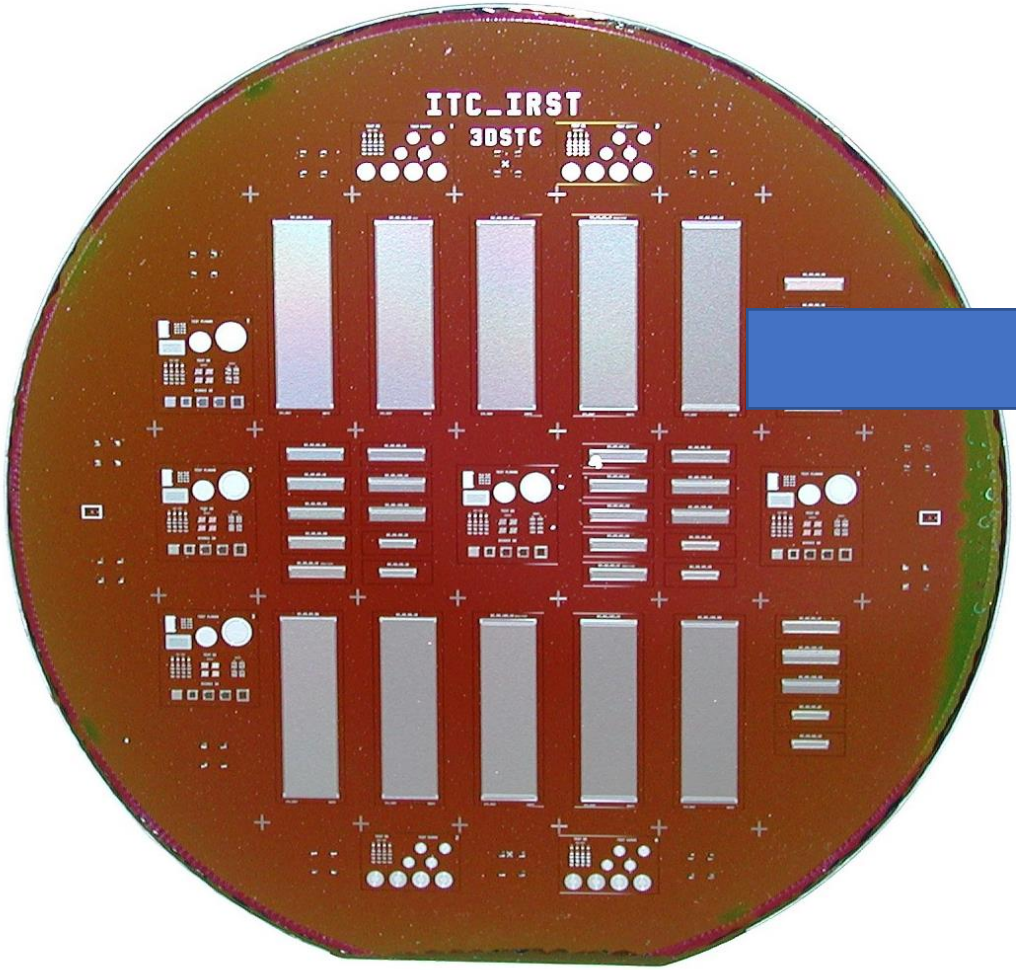
NIM A 541 (2005) 441–448 "Development of 3D detectors .." Piemonte et al

Main feature of proposed 3D-STC:

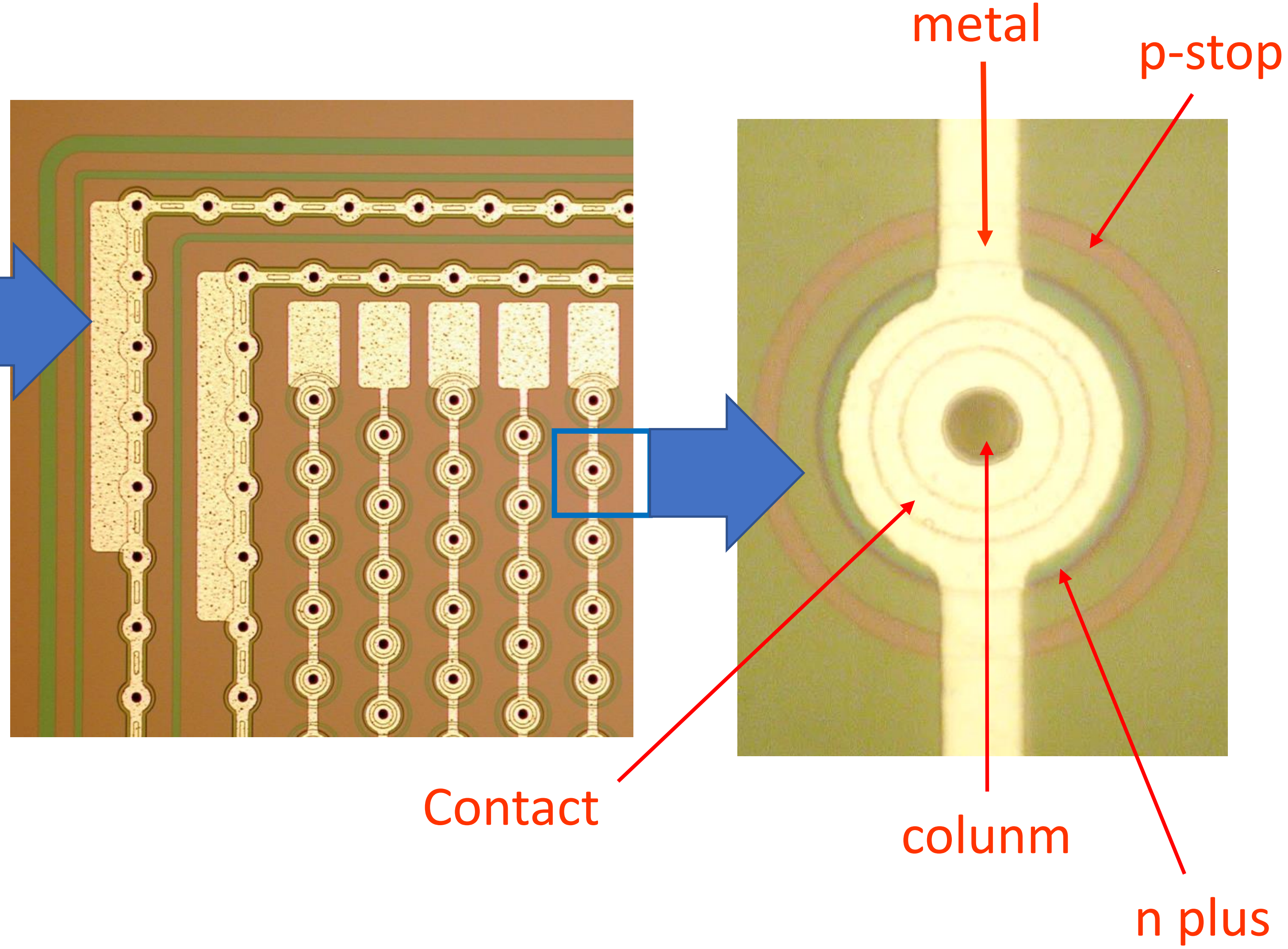
- column etching and doping performed only once
- holes not etched all through the wafer
- bulk contact is provided by a backside uniform p+ implant

7th RD50 workshop
14-16 November 2005

Single-Type-Column
3D detectors



4 inch wafers



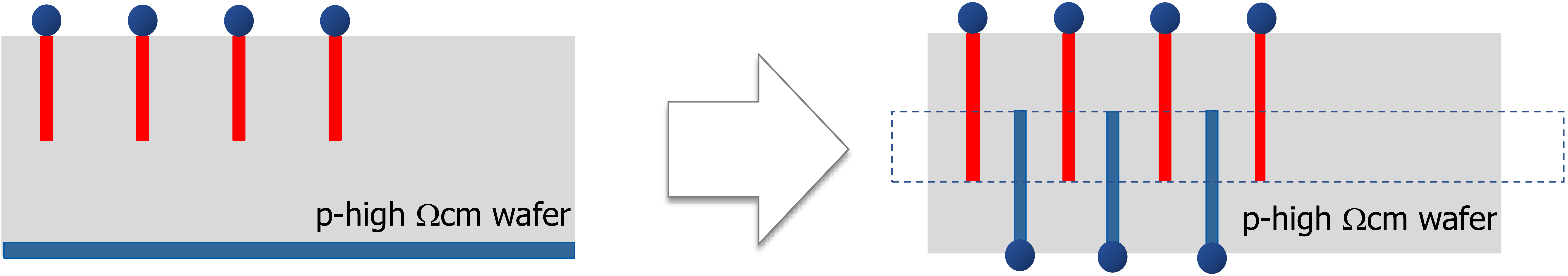
7th RD50 workshop
14-16 November 2005

On going activity

- ✓ University of Glasgow (UK): CCE measurements with α, β, γ on 3D diodes and short strips
- ✓ SCIPP (USA): CCE measurements on large strips
- ✓ INFN Florence (Italy): CCE meas with β,on 3D diodes;
- ✓ University of Freiburg (D); measurements on short strips
- ✓ Ljubljana: TCT and neutron irradiation

High level of involvements of all the collaboration

From single type columns to p&n columns



single side process
Low CE efficiency

Double side process
High CE efficiency BUT only in central region
(overlap between p & n columns)

13th RD50 workshop
10-12 November 2008

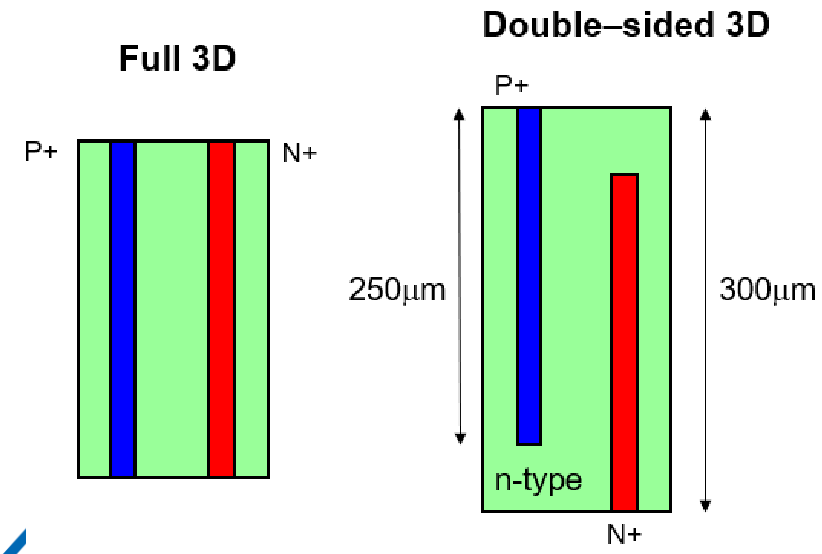
New fabrication run of 3D detectors, np and pn devices

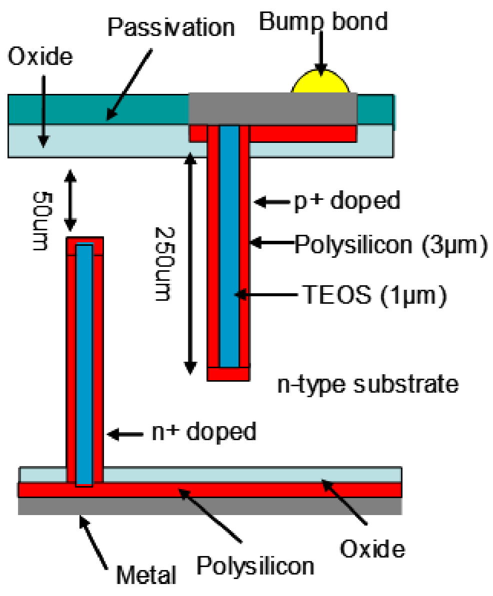
G. Pellegrini, M. Lozano - CNM, Barcelona

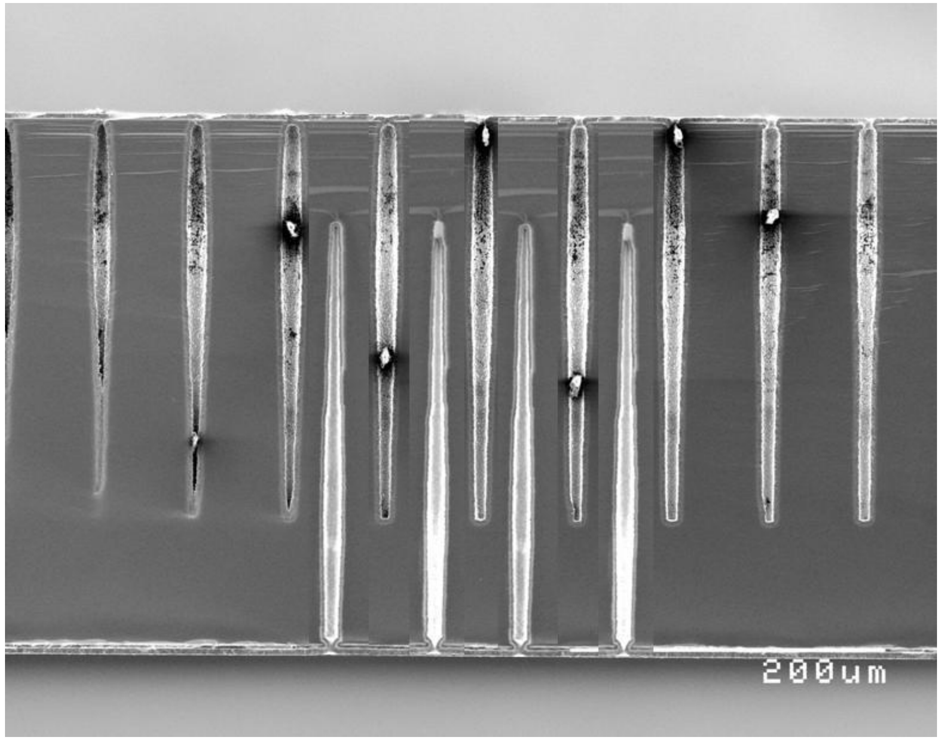
David Pennicard, Celeste Fleta, Richard Bates, Chris Parkes, Lars Eklund, Tomasz Szumlak – University of Glasgow

Double-sided 3D detectors at CNM

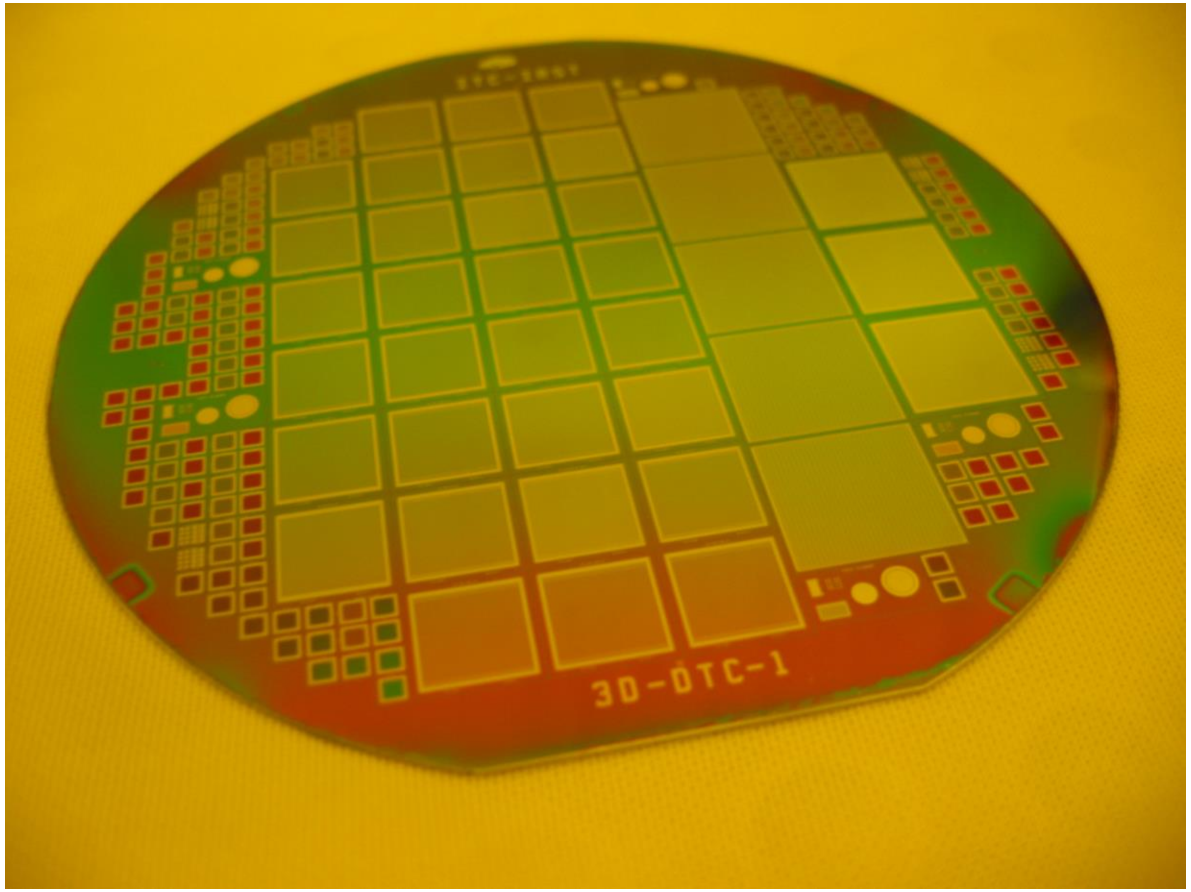
- Detectors fabricated at Centro Nacional de Microelectronica, Barcelona
- Columns are etched from opposite sides of substrate, and don't pass through full thickness
- Column fabrication
  - Reactive ion etching
  - Partial filling with polysilicon then doping







Double Type Columns @ FBK



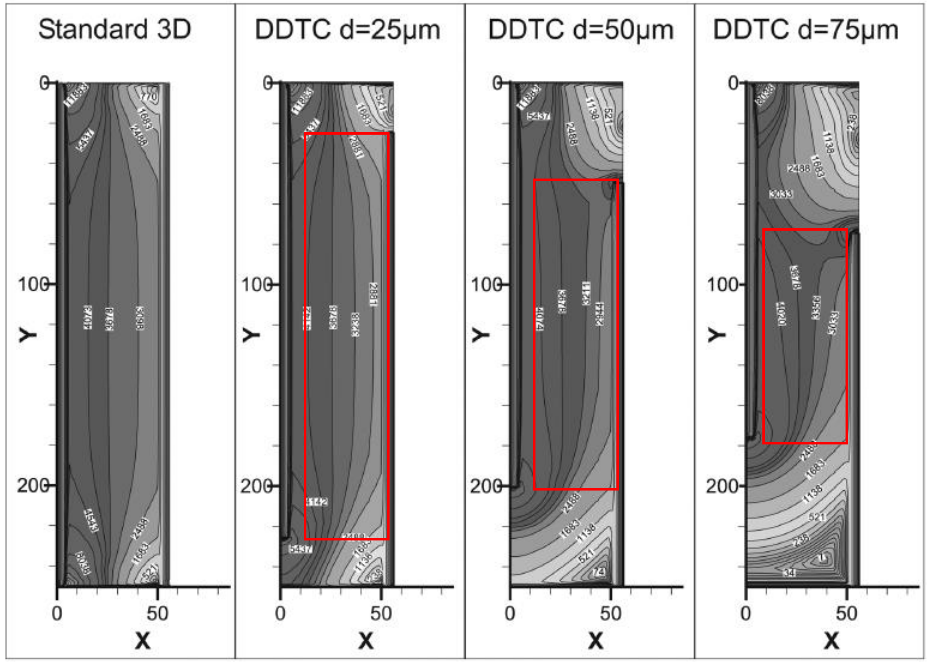
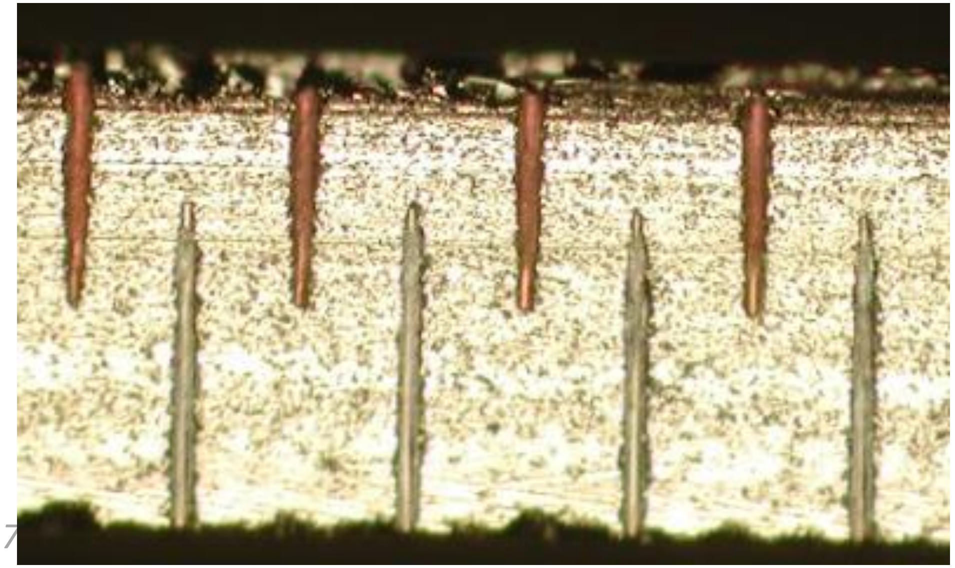


Fig. 2. Simulated electric field distribution in a 2-D cross-section taken along the cell diagonal. X and Y axis units are in μm. The center of the junction column is at $x = 0$, the center of the ohmic column is at $x = 40\sqrt{2}$ μm. The isolines show electric field values in V/cm. Four cases are represented, from left to right: standard 3-D and 3-D-DDTC with d = 25, 50, and 75 μm, respectively.



G. F. Dalla Betta, et al. "New developments on 3D detectors at IRST", IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS - MIC'07), Conference Record, paper N18-3, Honolulu (U.S.A.), Oct. 28 - Nov. 3, 2007

What does it mean to transition from a research phase to production?

specification to be fulfill

Main design specifications

- Two n^+ (read-out) columns per 250 μm pixel (2E)
- Inactive edge width along beam direction (Z) < 225 μm
- Sensor thickness = 230±20 μm

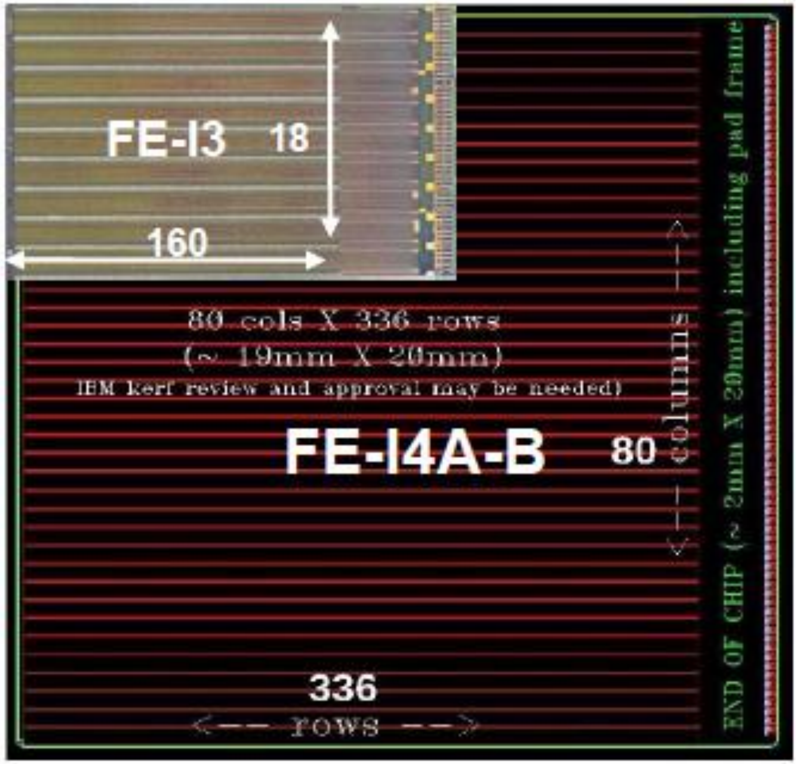
Wafer-level electrical tests

Parameter	Value
Operation temperature [T_{op}]	20 ÷ 24 °C
Depletion voltage [V_{depl}]	< 15 V
Operation voltage [V_{op}]	$\geq V_{depl}$ + 10 V
Leakage current at operation voltage [$I(V_{op})$]	< 2 μa (full sensor) < 200 nA (guard ring)
Breakdown voltage [V_{bd}]	> 25 V
Leakage current "slope" [$I(V_{op}) / I(V_{op} - 5V)$]	< 2

On modules after irradiation at 5×10^{15} n_{eq} cm^{-2}

Parameter	Value
Operation temperature	- 15°C
Operation voltage	<180V
Power dissipation	< 60mW/cm^2
Hit efficiency at 15° tilt angle	> 97%

Device dimension: from FE-I3 to FE-I4

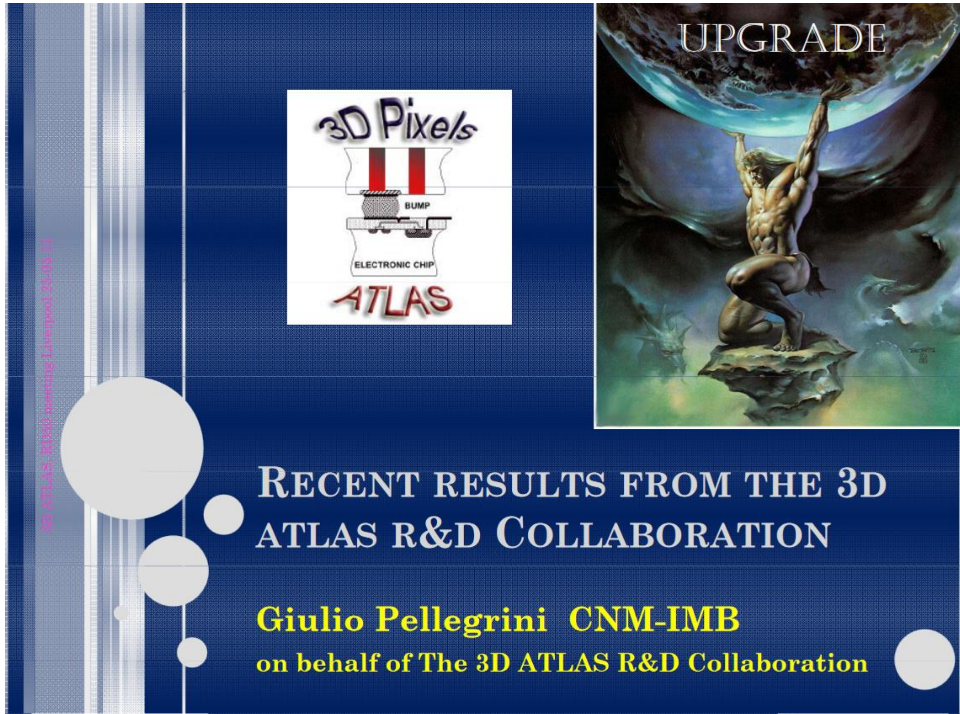


18th RD50 workshop
23 - 25 May 2011

The ATLAS 3D Sensor Collaboration

- Approved in **2007** with the goal of "Development, Testing and Industrialization of Full-3D Active-Edge and Modified-3D Silicon Radiation Pixel Sensors with Extreme Radiation Hardness".
- The Collaboration includes 18 Institutions and 4(+1) processing facilities: SNF, SINTEF, CNM, and FBK

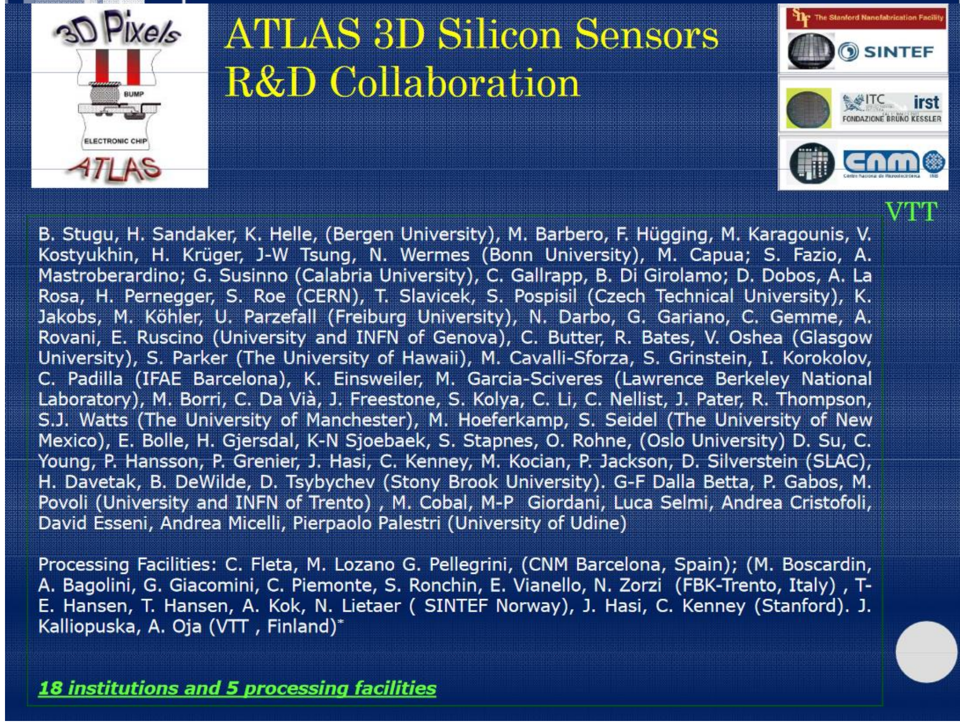
  (VTT joined later).
- Systematic studies on existing 3D samples from different foundries
- Focus on the ATLAS IBL since 2009



RECENT RESULTS FROM THE 3D ATLAS R&D COLLABORATION

Giulio Pellegrini CNM-IMB

on behalf of The 3D ATLAS R&D Collaboration



ATLAS 3D Silicon Sensors R&D Collaboration

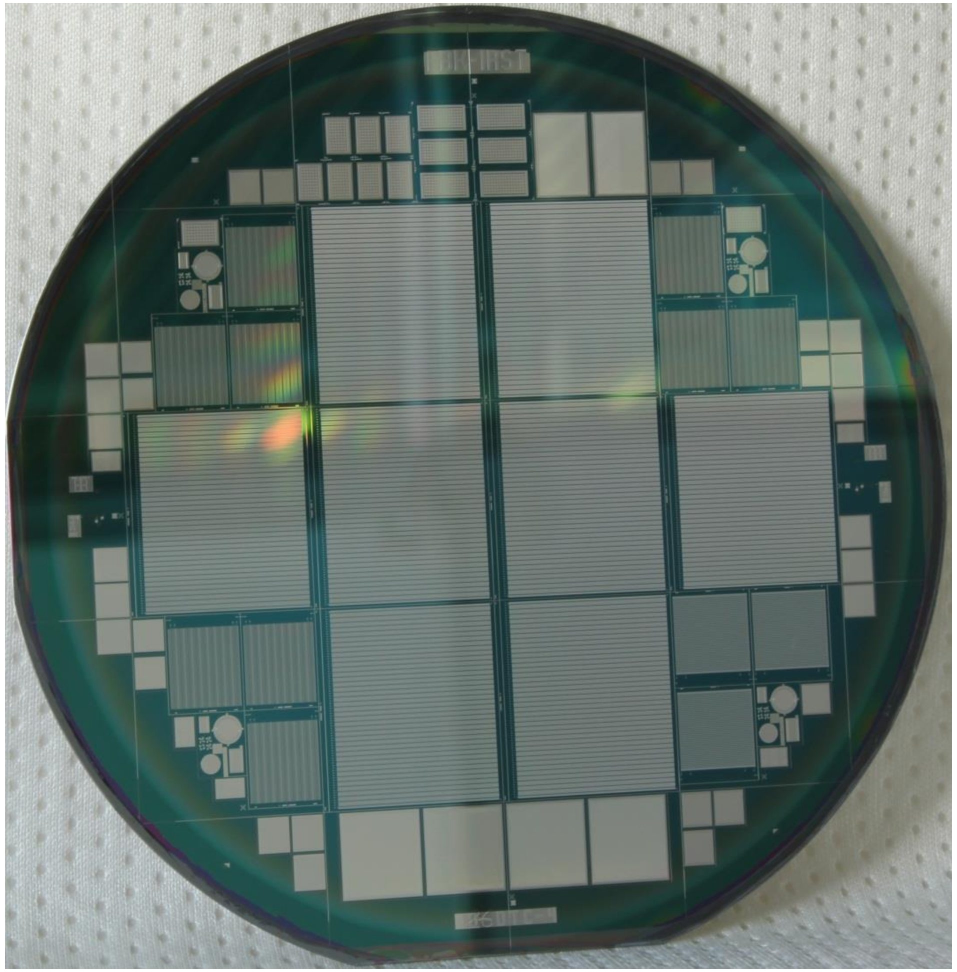
B. Stugu, H. Sandaker, K. Helle, (Bergen University), M. Barbero, F. Hügging, M. Karagounis, V. Kostyukhin, H. Krüger, J-W Tsung, N. Wermes (Bonn University), M. Capua; S. Fazio, A. Mastroberardino; G. Susinno (Calabria University), C. Gallrapp, B. Di Girolamo; D. Dobos, A. La Rosa, H. Pernegger, S. Roe (CERN), T. Slavicek, S. Pospisil (Czech Technical University), K. Jakobs, M. Köhler, U. Parzefall (Freiburg University), N. Darbo, G. Gariano, C. Gemme, A. Rovani, E. Ruscino (University and INFN of Genova), C. Butter, R. Bates, V. Oshea (Glasgow University), S. Parker (The University of Hawaii), M. Cavalli-Sforza, S. Grinstein, I. Korokolov, C. Padilla (IFAE Barcelona), K. Einsweiler, M. Garcia-Sciveres (Lawrence Berkeley National Laboratory), M. Borri, C. Da Vià, J. Freestone, S. Kolya, C. Li, C. Nellist, J. Pater, R. Thompson, S.J. Watts (The University of Manchester), M. Hoeferkamp, S. Seidel (The University of New Mexico), E. Bolle, H. Gjersdal, K-N Sjoebaek, S. Stapnes, O. Rohne, (Oslo University) D. Su, C. Young, P. Hansson, P. Grenier, J. Hasi, C. Kenney, M. Kocian, P. Jackson, D. Silverstein (SLAC), H. Davetak, B. DeWilde, D. Tsybychev (Stony Brook University). G-F Dalla Betta, P. Gabos, M. Povoli (University and INFN of Trento) , M. Cobal, M-P Giordani, Luca Selmi, Andrea Cristofoli, David Esseni, Andrea Micelli, Pierpaolo Palestri (University of Udine)

Processing Facilities: C. Fleta, M. Lozano G. Pellegrini, (CNM Barcelona, Spain); (M. Boscardin, A. Bagolini, G. Giacomini, C. Piemonte, S. Ronchin, E. Vianello, N. Zorzi (FBK-Trento, Italy) , T-E. Hansen, T. Hansen, A. Kok, N. Lietaer (SINTEF Norway), J. Hasi, C. Kenney (Stanford). J. Kalliopuska, A. Oja (VTT , Finland)*

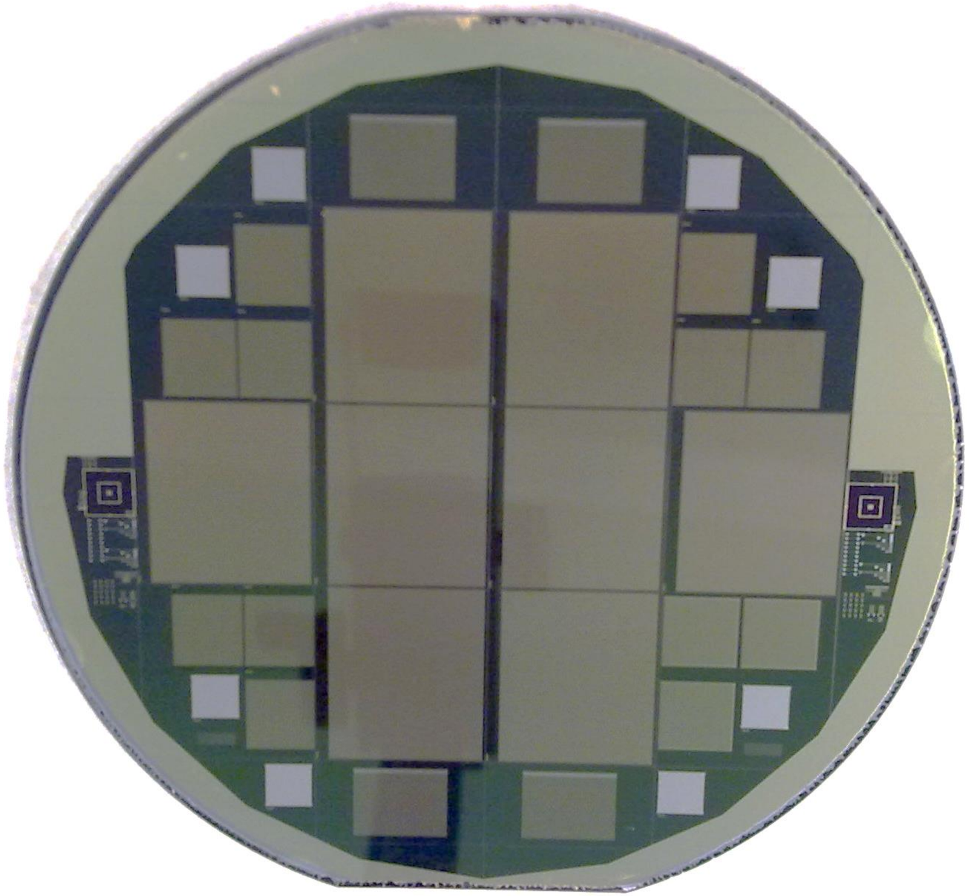
18 institutions and 5 processing facilities

ATLAS IBL: a common flor plan

G. F. Dalla Betta, et al. "The common floor-plan of the ATLAS IBL 3D sensor prototypes", 5th Trento Workshop, Manchester, Feb. 2010

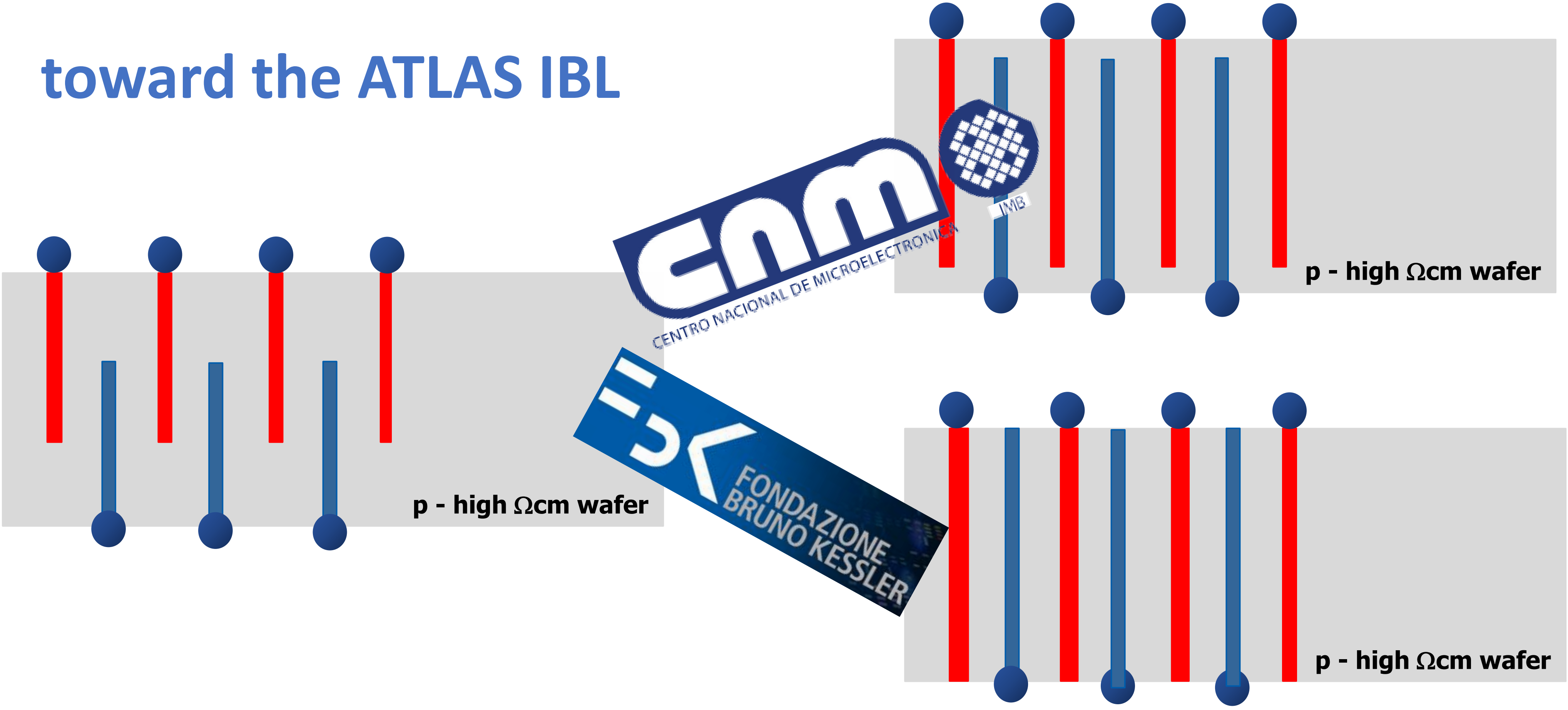


FBK (Trento, Italy)



CNM (Barcelona, Spain)

toward the ATLAS IBL



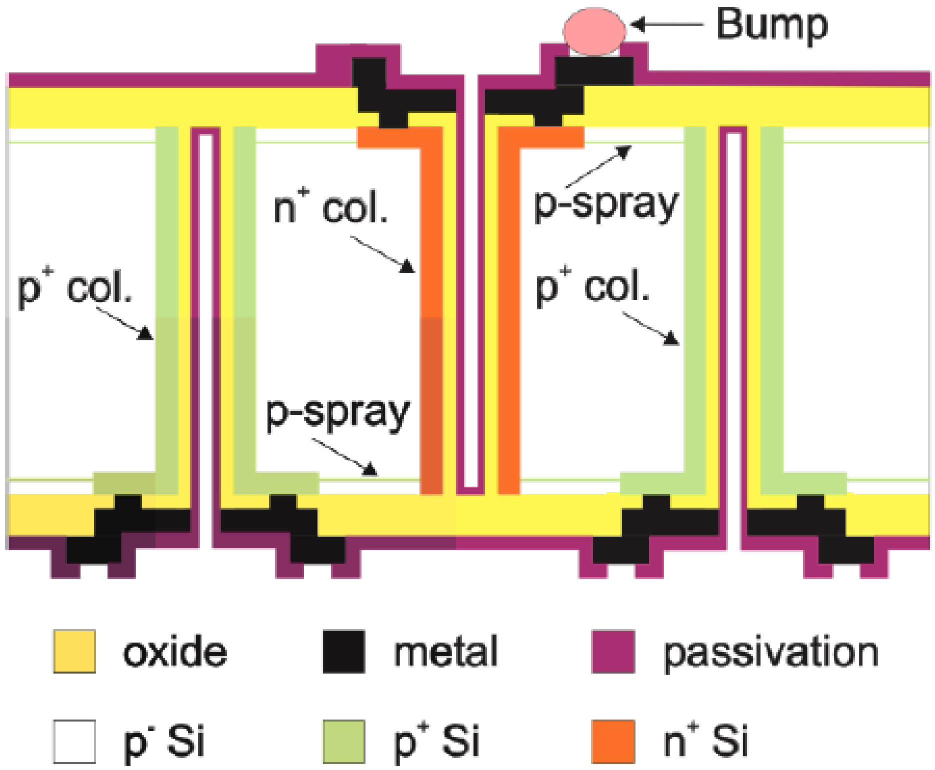
Main difference is the columns depth

FBK = wafers thickness

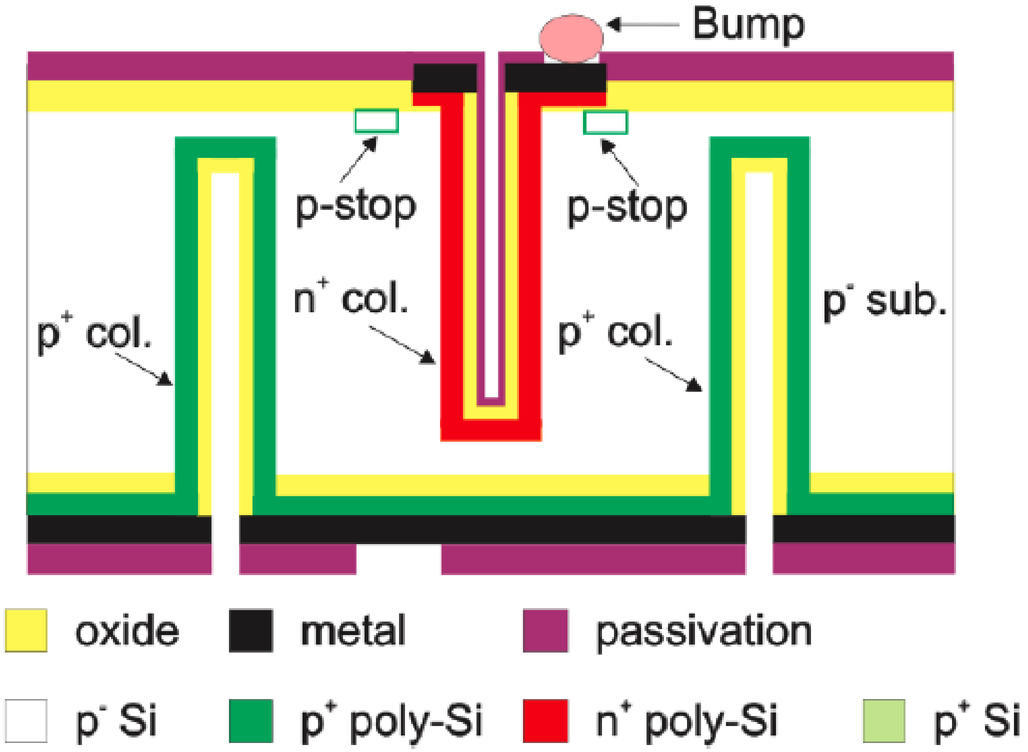
- CNM < wafers thickness

ATLAS IBL: a compatible process

FBK (Trento, Italy)



CNM (Barcelona, Spain)



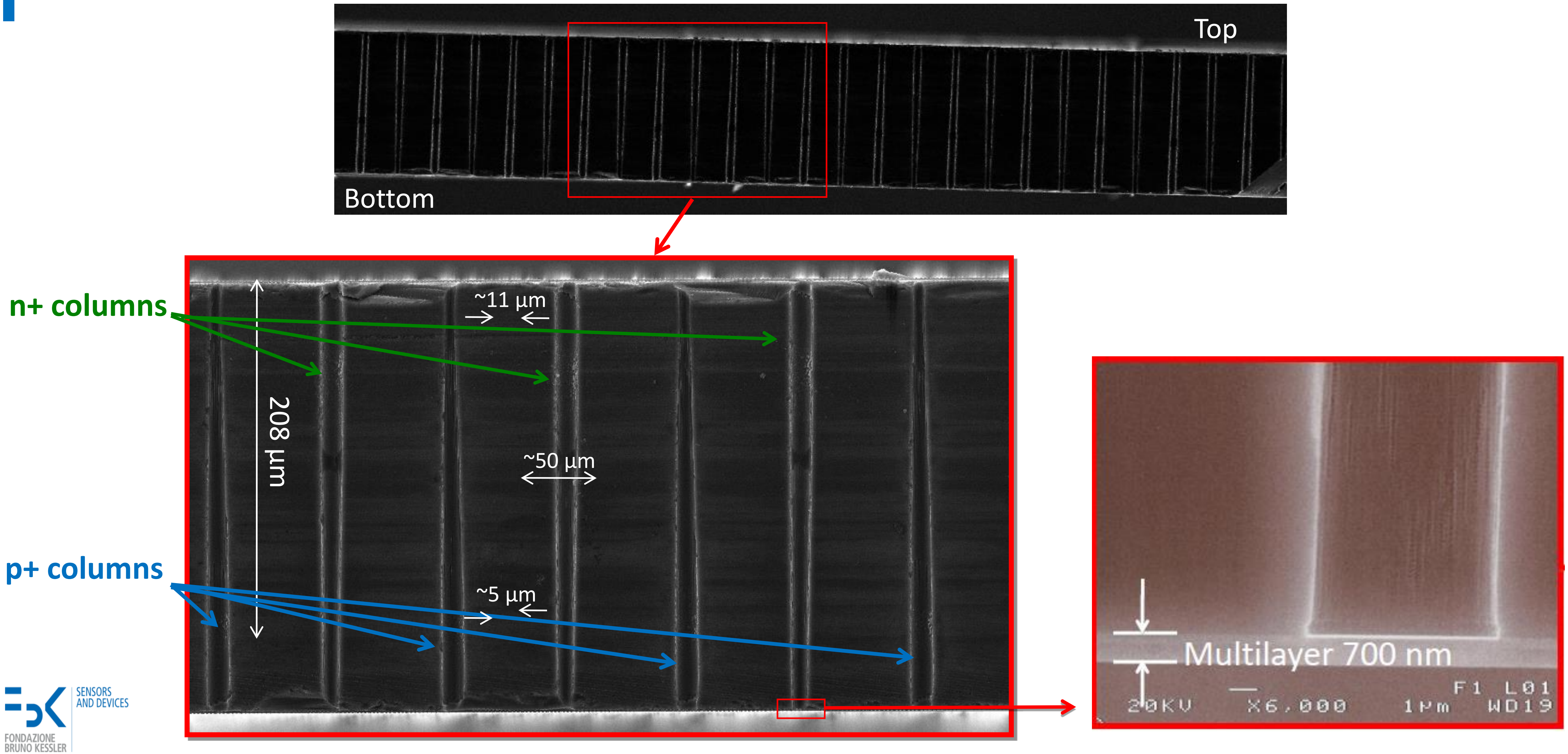
A. Zoboli et. al., IEEE TNS 55(5) (2008), 2775

G. Giacomini, et al., IEEE TNS 60(3) (2013) 2357

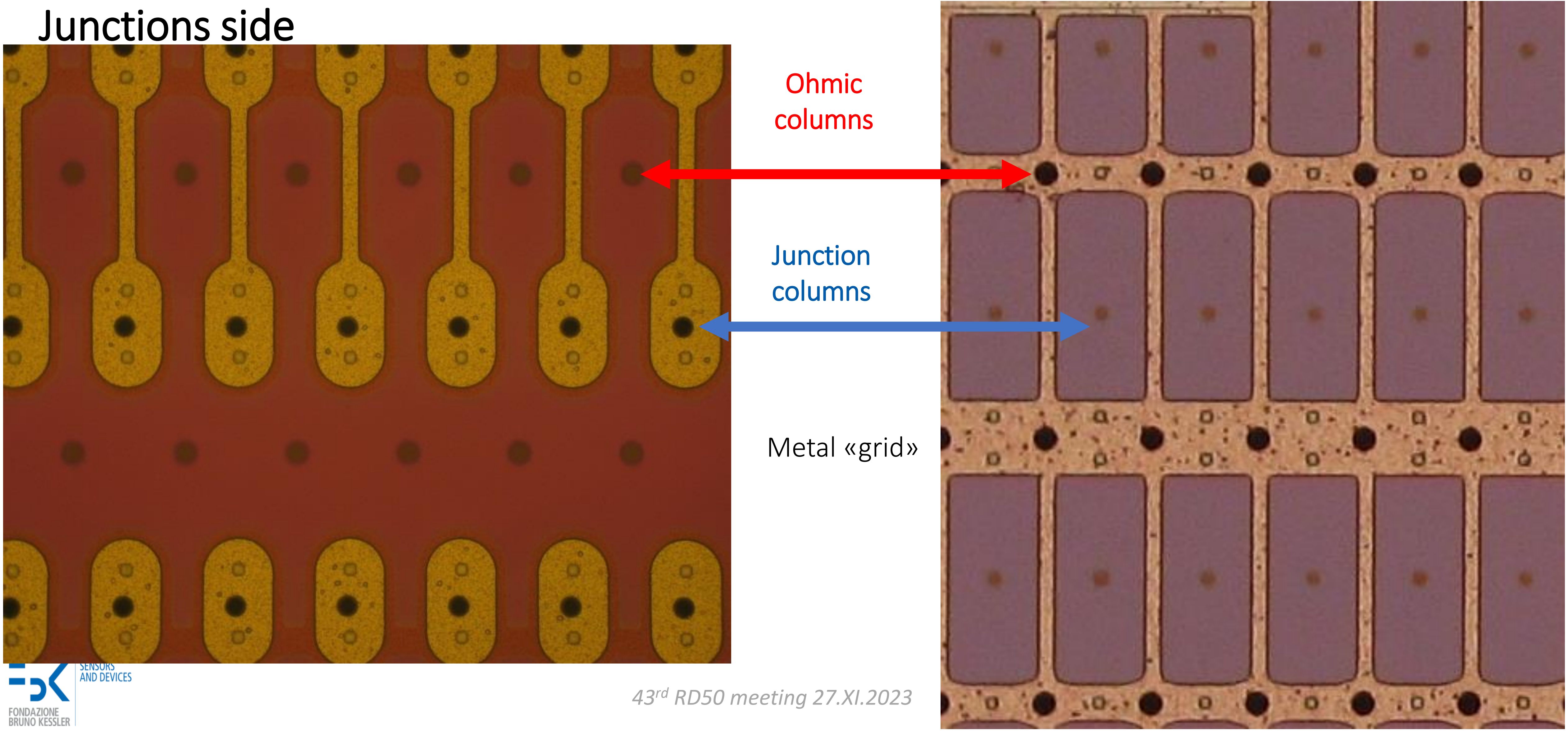
G. Pellegrini et. al. NIMA 592(2008), 38

G. Pellegrini et. al. NIMA 699(2013), 27

FBK SEM pictures

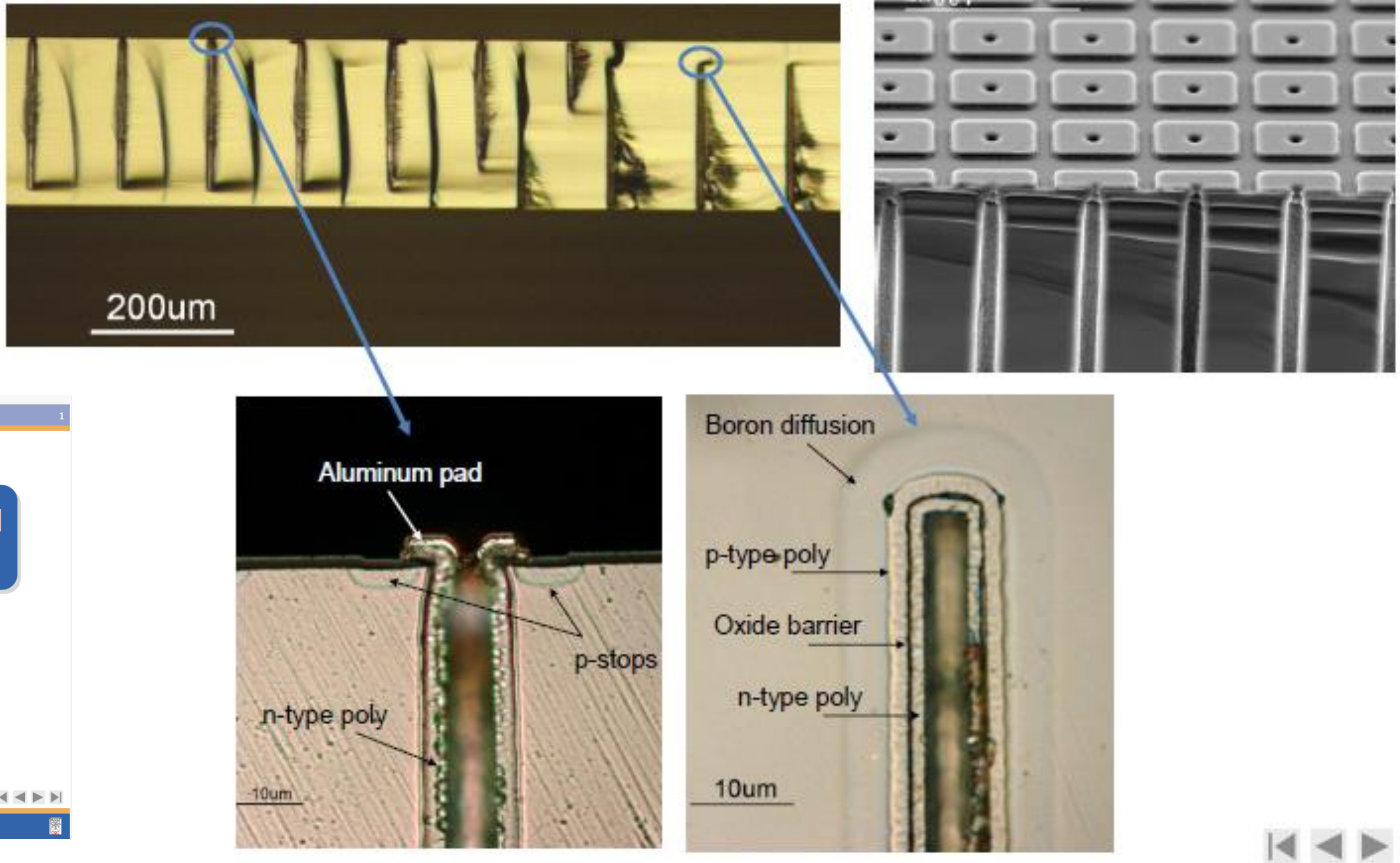


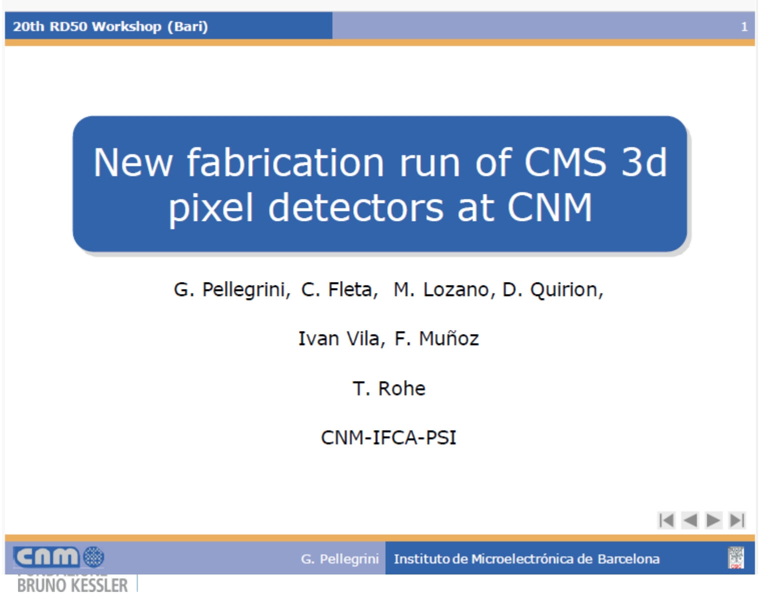
FBK process: full passthrough columns



20th RD50 workshop
30 may – 1 June 2012

3D Technology:





20th RD50 Workshop (Bari)

1

New fabrication run of CMS 3d pixel detectors at CNM

G. Pellegrini, C. Fleta, M. Lozano, D. Quirion,

Ivan Vila, F. Muñoz

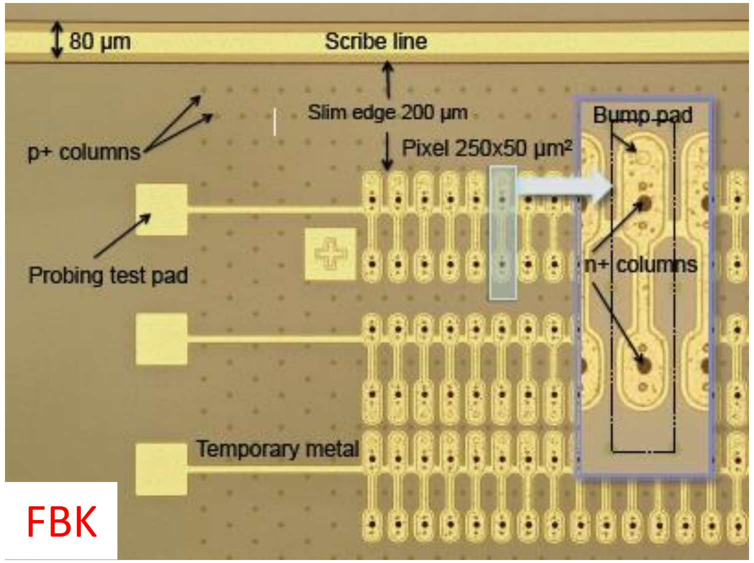
T. Rohe

CNM-IFCA-PSI

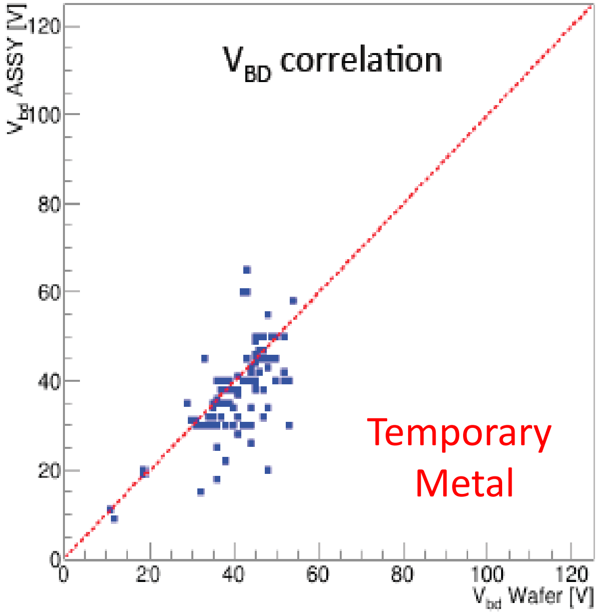
cnm G. Pellegrini Instituto de Microelectrónica de Barcelona

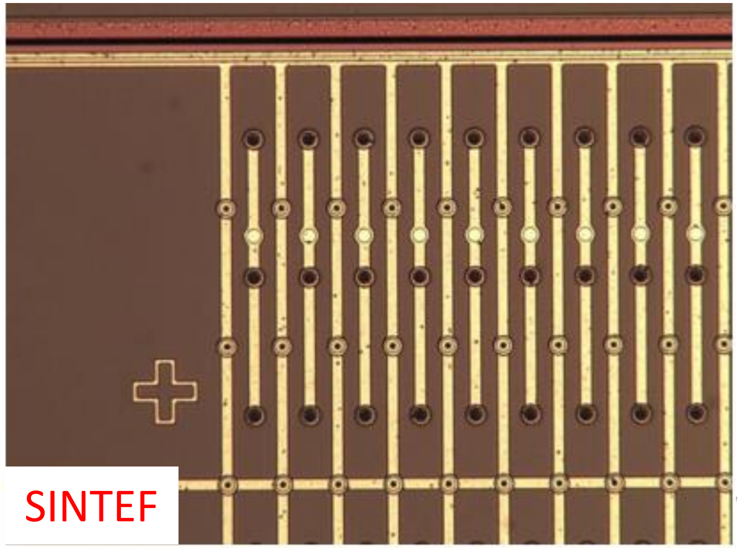
BRUNO KESSLER

Lessons learned from ATLAS IBL: Temporary Metal

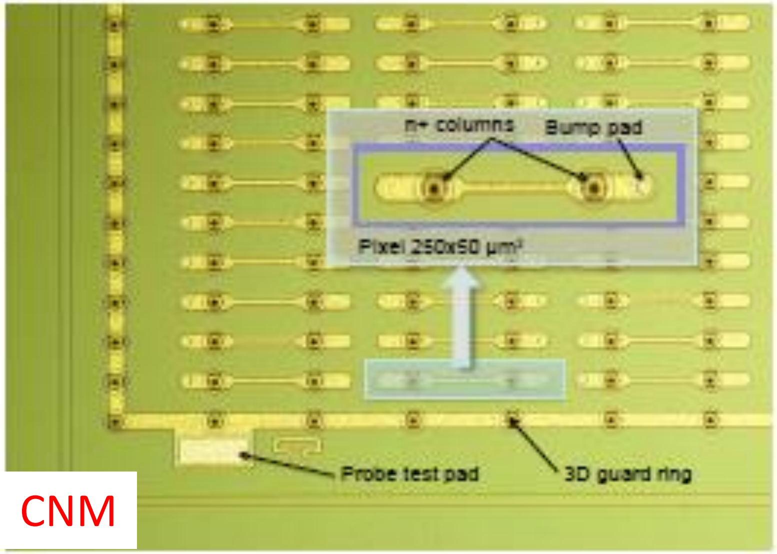


FBK





SINTEF

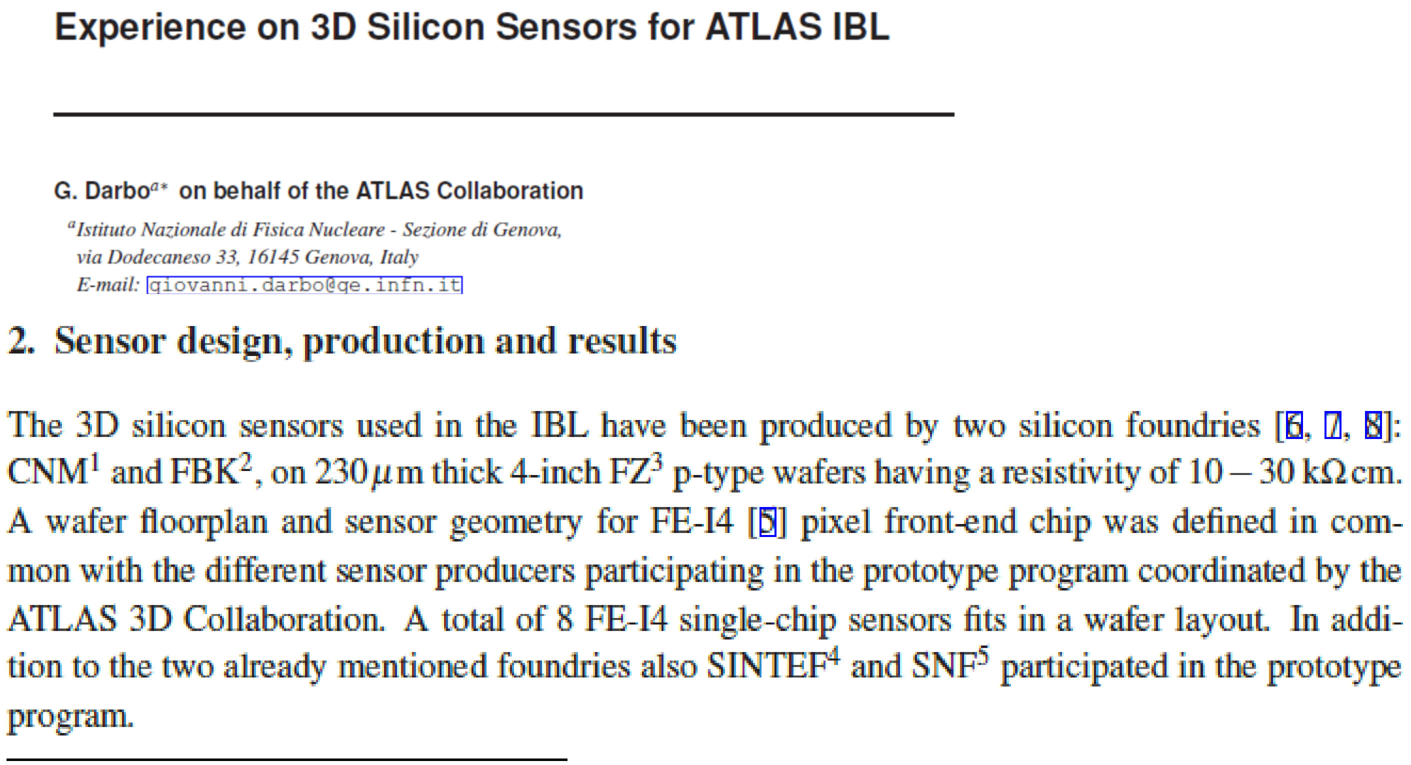


CNM

ATLAS IBL: a successful story

G. Darbo 2015 *JINST* **10** C05001
The ATLAS IBL collaboration 2012 *JINST* **7** P11010

High radiation hardness at relatively low voltage



Experience on 3D Silicon Sensors for ATLAS IBL

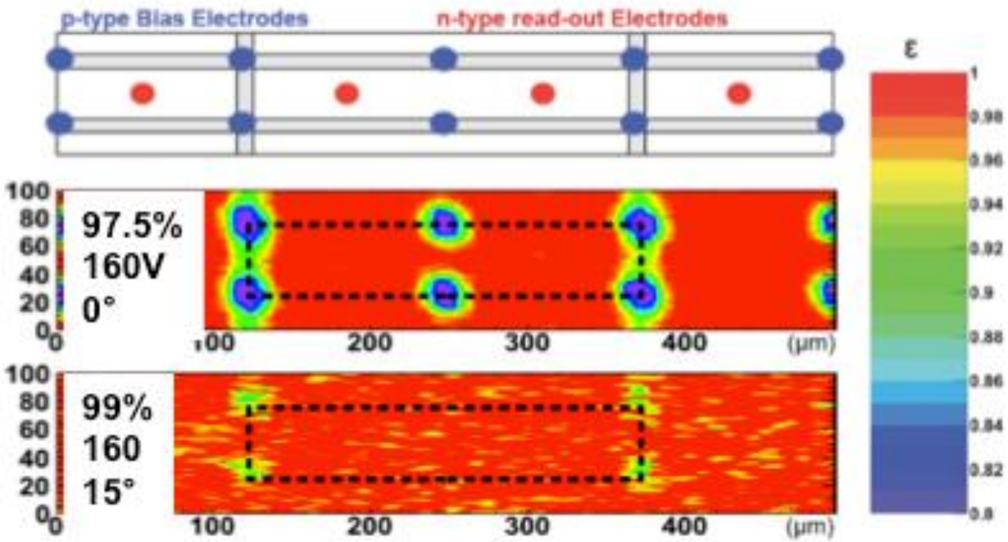
G. Darbo[a]* on behalf of the ATLAS Collaboration
[a]*Istituto Nazionale di Fisica Nucleare - Sezione di Genova,*
via Dodecaneso 33, 16145 Genova, Italy
E-mail: giovanni.darbo@ge.infn.it

2. Sensor design, production and results

The 3D silicon sensors used in the IBL have been produced by two silicon foundries [6, 7, 8]: CNM[1] and FBK[2], on 230 μm thick 4-inch FZ[3] p-type wafers having a resistivity of 10 – 30 kΩ cm. A wafer floorplan and sensor geometry for FE-I4 [5] pixel front-end chip was defined in common with the different sensor producers participating in the prototype program coordinated by the ATLAS 3D Collaboration. A total of 8 FE-I4 single-chip sensors fits in a wafer layout. In addition to the two already mentioned foundries also SINTEF[4] and SNF[5] participated in the prototype program.

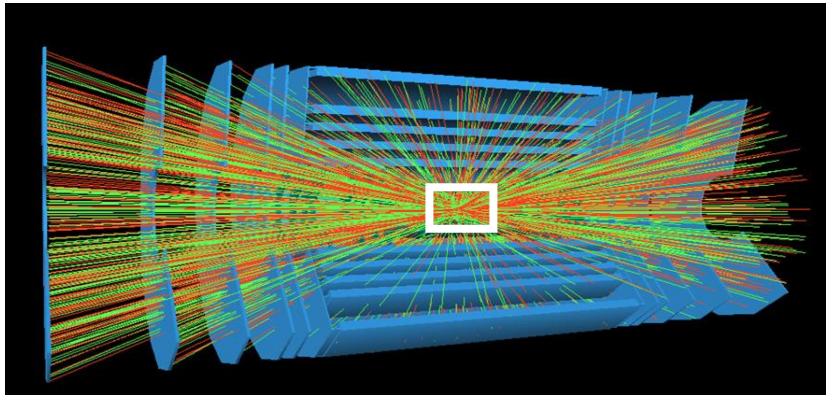
State of the art: ATLAS IBL 3D pixels

- Double-sided 3D (230 μm thick)
- Produced by CNM and FBK
- Excellent performance up to $5\text{x}10^{15}$ n_{eq} cm^{-2}, also pushed to ~$1\text{x}10^{16}$ n_{eq} cm^{-2} in AFP tests

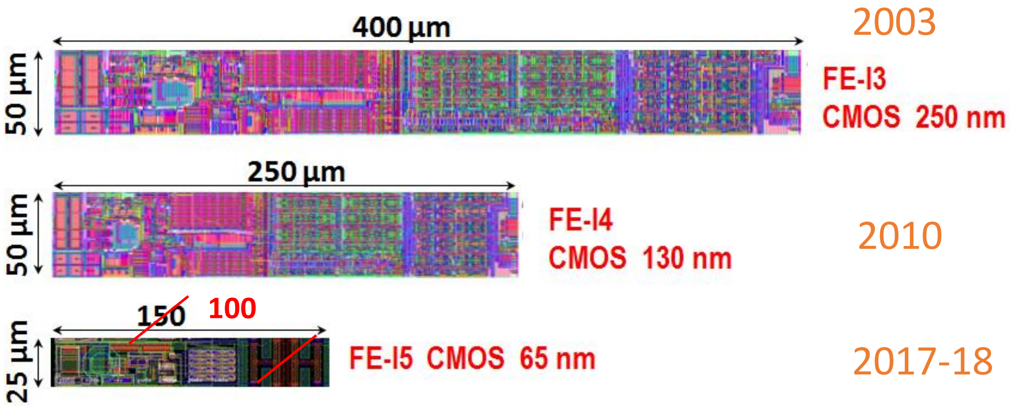


Pixel Roadmap LHC → HL-LHC

N. Wermes, 9th TN Workshop (Genova, 2014)



ATLAS roadmap : Pixel Size



Increased luminosity requires

- higher hit-rate capability
- increased granularity
- higher radiation tolerance
- lighter detectors

Next ROC generation (RD53 65 nm)

50x50 μm^2 and 25x100 μm^2 pixels

$C_{DET} \leq 100$ fF

$I_{leak} \leq 10$ nA/pixel (no amp. comp.)

Threshold: ~1000 electrons

Implications for 3D sensors

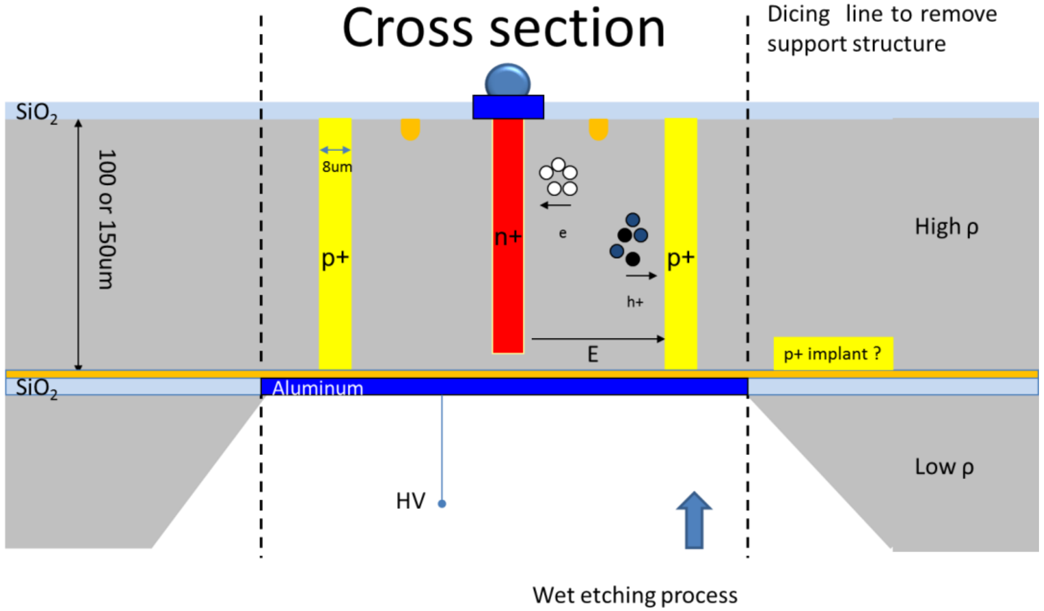
Modified technology/design for:

- thinner sensors
- narrower electrodes
- reduced electrode spacing
- very slim (or active) edges

- HL-LHC ATLAS and CMS Pixel TDR: 2017
- 3D pixels are an option for the innermost layers

27th RD50 workshop
2 – 4 Dec. 2015

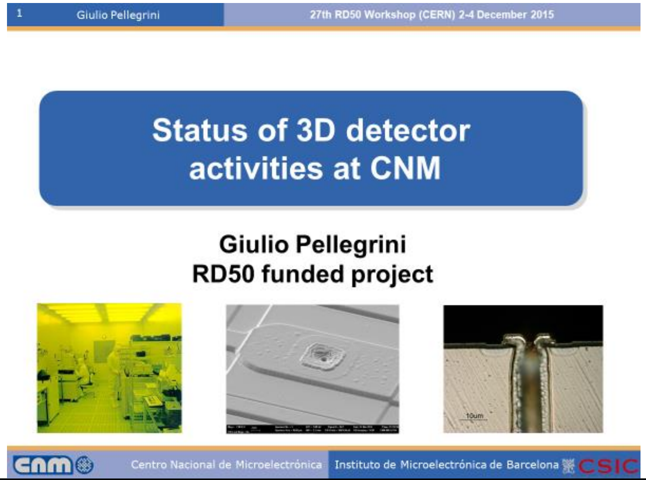
CNM single-side process on SOI wafers


Cross section

Dicing line to remove support structure

Wet etching process

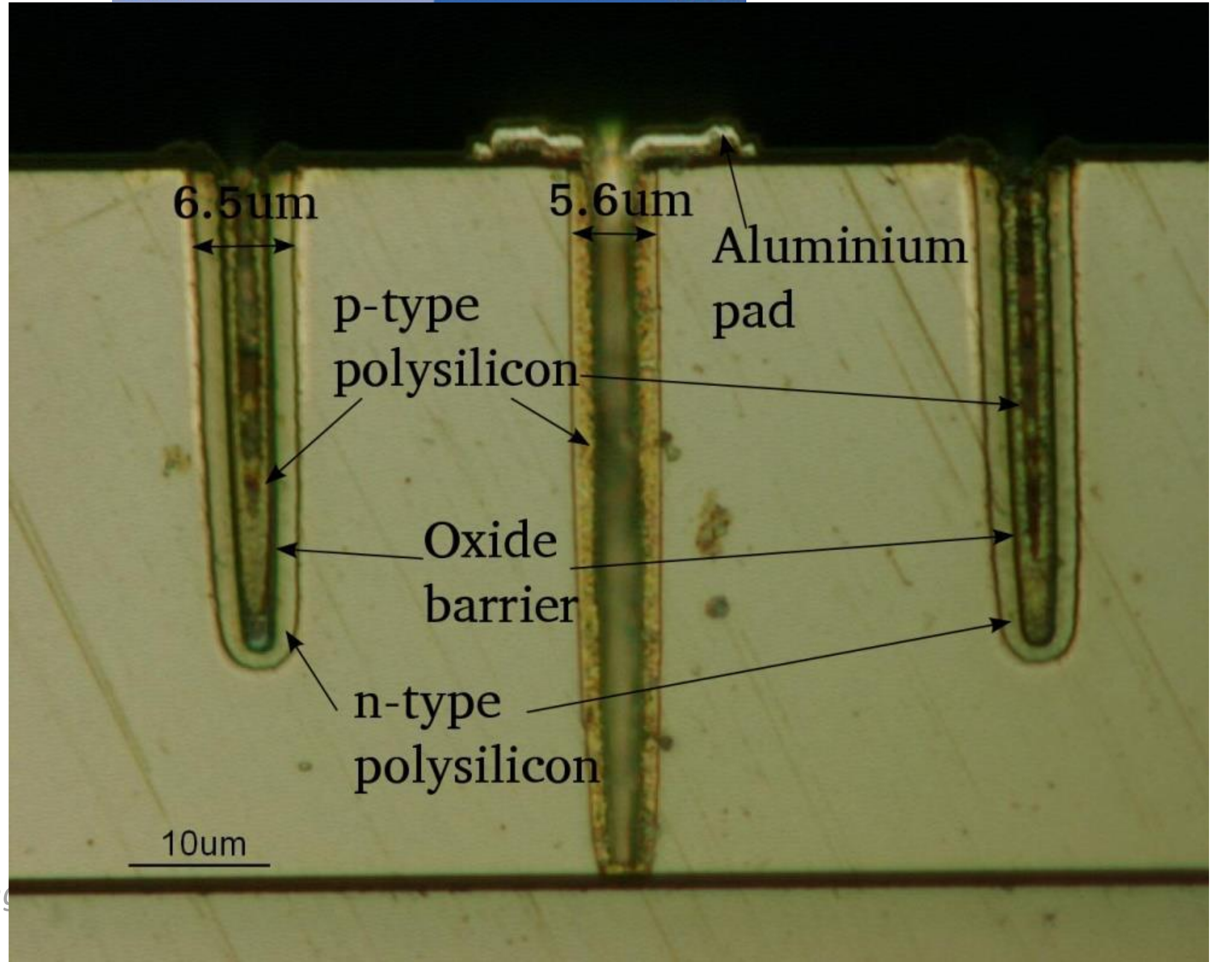
- Single-side process on thin SOI wafers developed at CNM since 2008 for different applications, here modified for back-side bias


1 Giulio Pellegrini 27th RD50 Workshop (CERN) 2-4 December 2015

Status of 3D detector activities at CNM

Giulio Pellegrini
RD50 funded project

cnm Centro Nacional de Microelectrónica Instituto de Microelectrónica de Barcelona CSIC



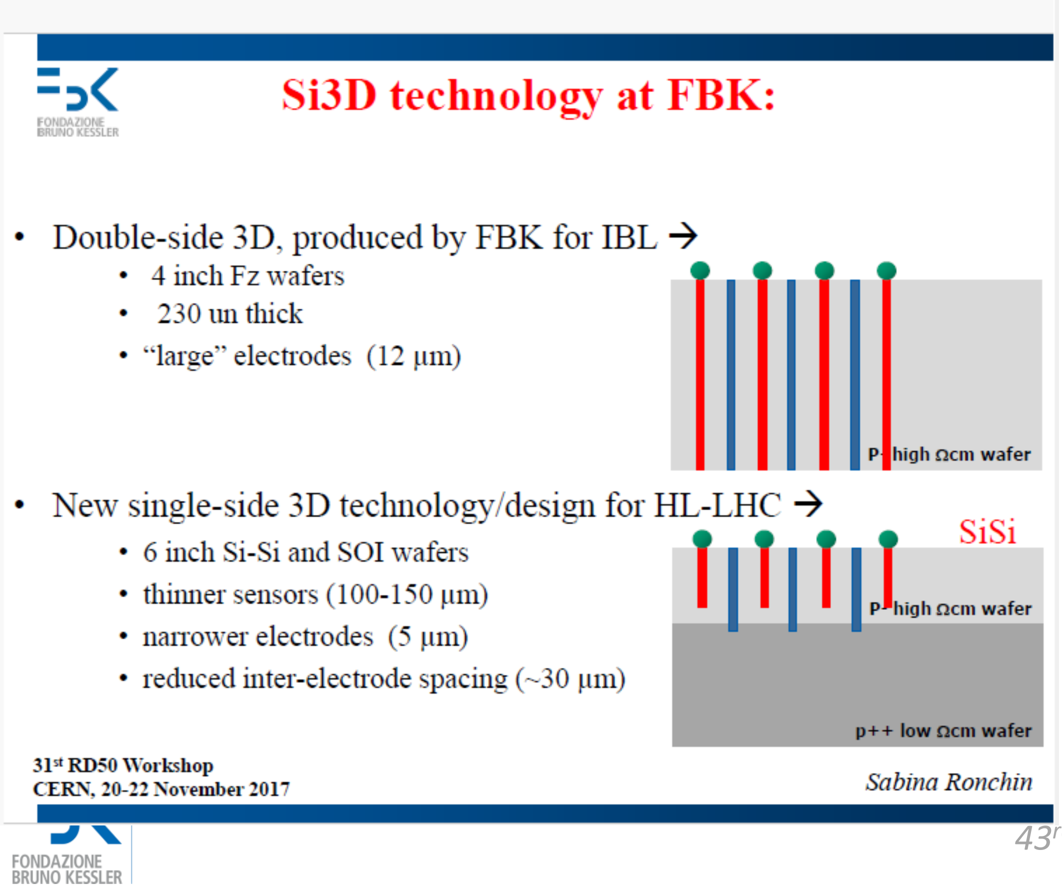
32th RD50 workshop
20 – 22 Dec. 2017

3D silicon sensors at FBK: first results on the last production

Sabina Ronchin

On behalf of the INFN (ATLAS - CMS) - FBK Pixel R&D Collaboration and WP7 - AIDA-2020

31st RD50 Workshop
CERN, 20-22 November 2017

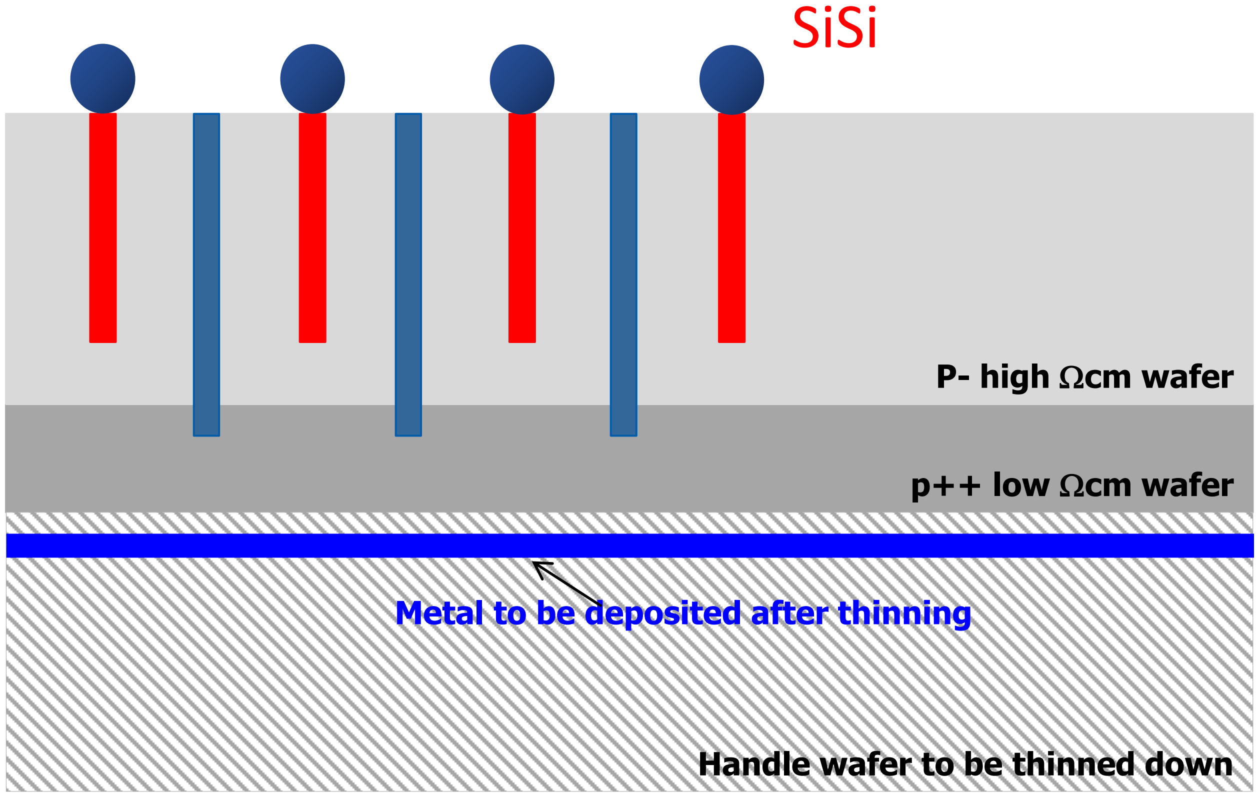


Si3D technology at FBK:

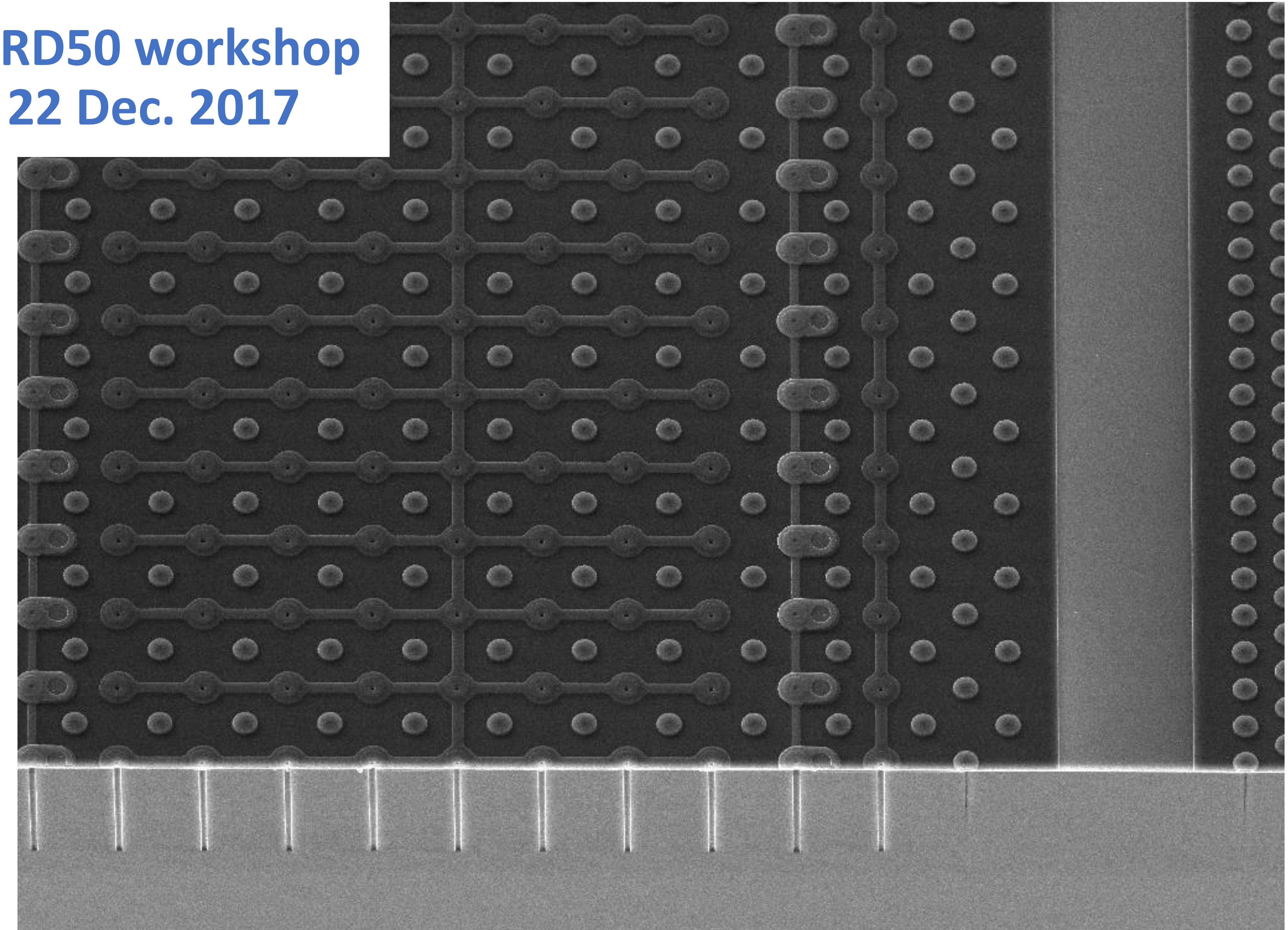
- Double-side 3D, produced by FBK for IBL →
  - 4 inch Fz wafers
  - 230 un thick
  - “large” electrodes (12 µm)
- New single-side 3D technology/design for HL-LHC →
  - 6 inch Si-Si and SOI wafers
  - thinner sensors (100-150 µm)
  - narrower electrodes (5 µm)
  - reduced inter-electrode spacing (~30 µm)

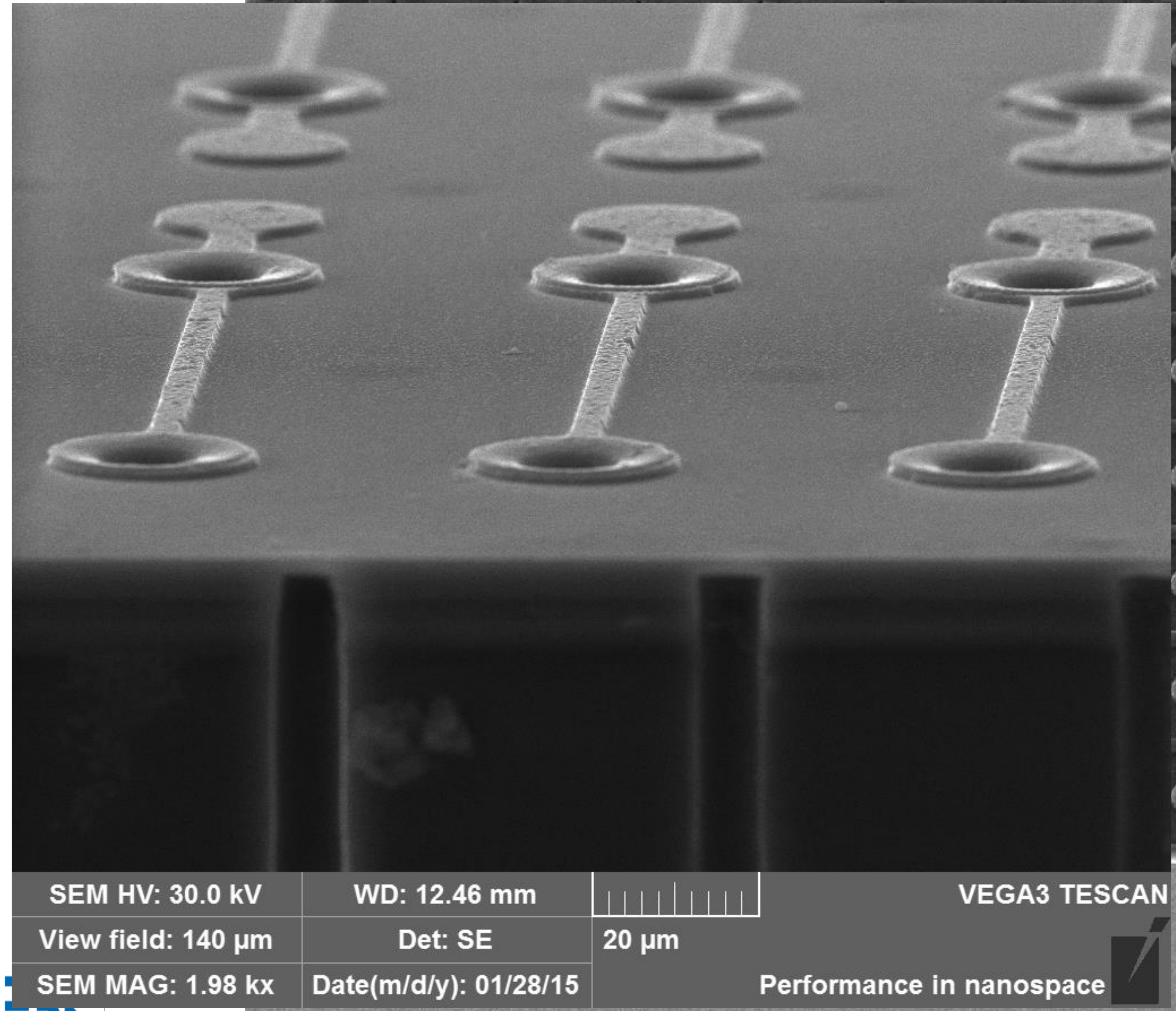
31st RD50 Workshop
CERN, 20-22 November 2017

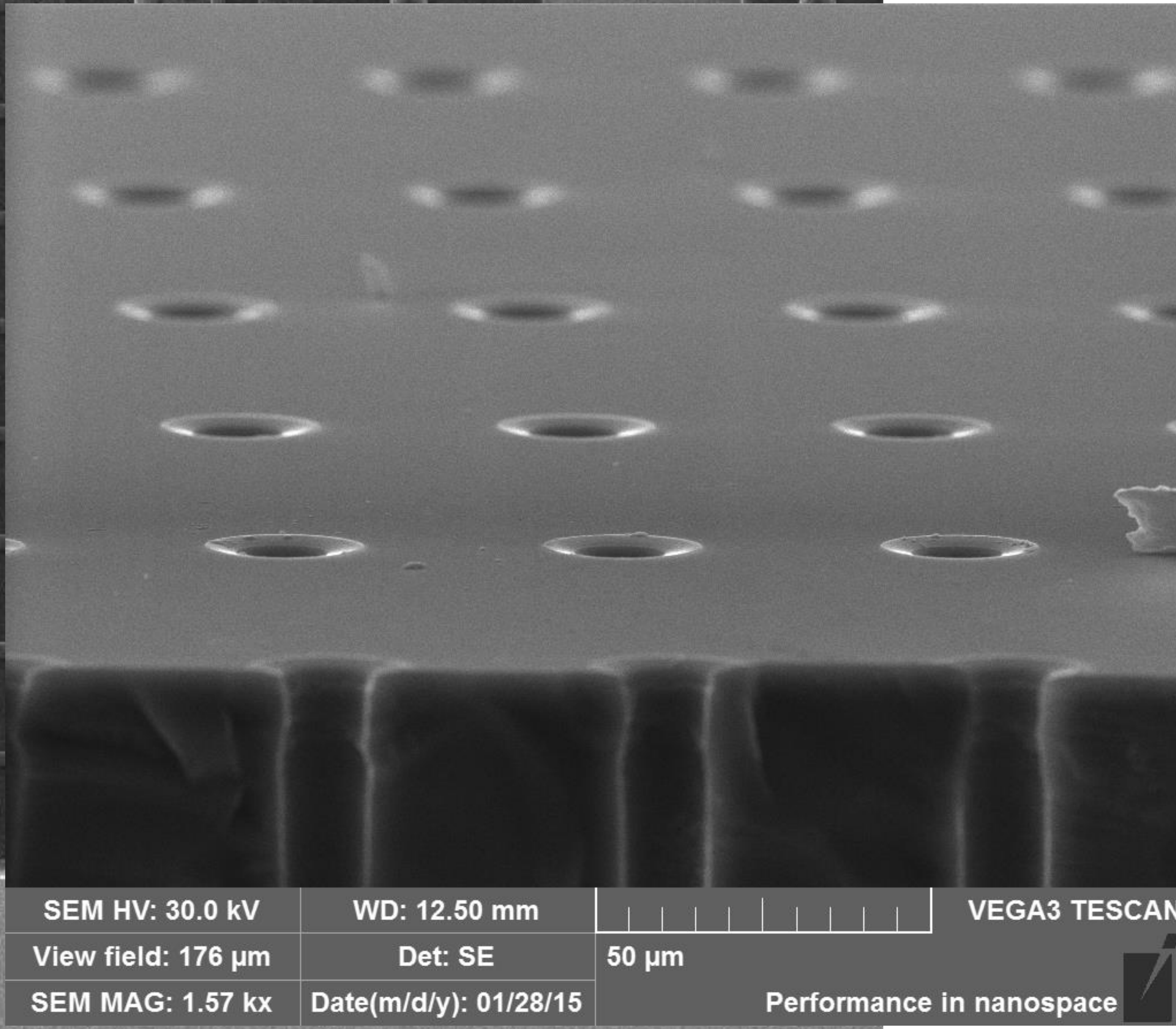
Sabina Ronchin



32th RD50 workshop
20 – 22 Dec. 2017







FONDAZIONE
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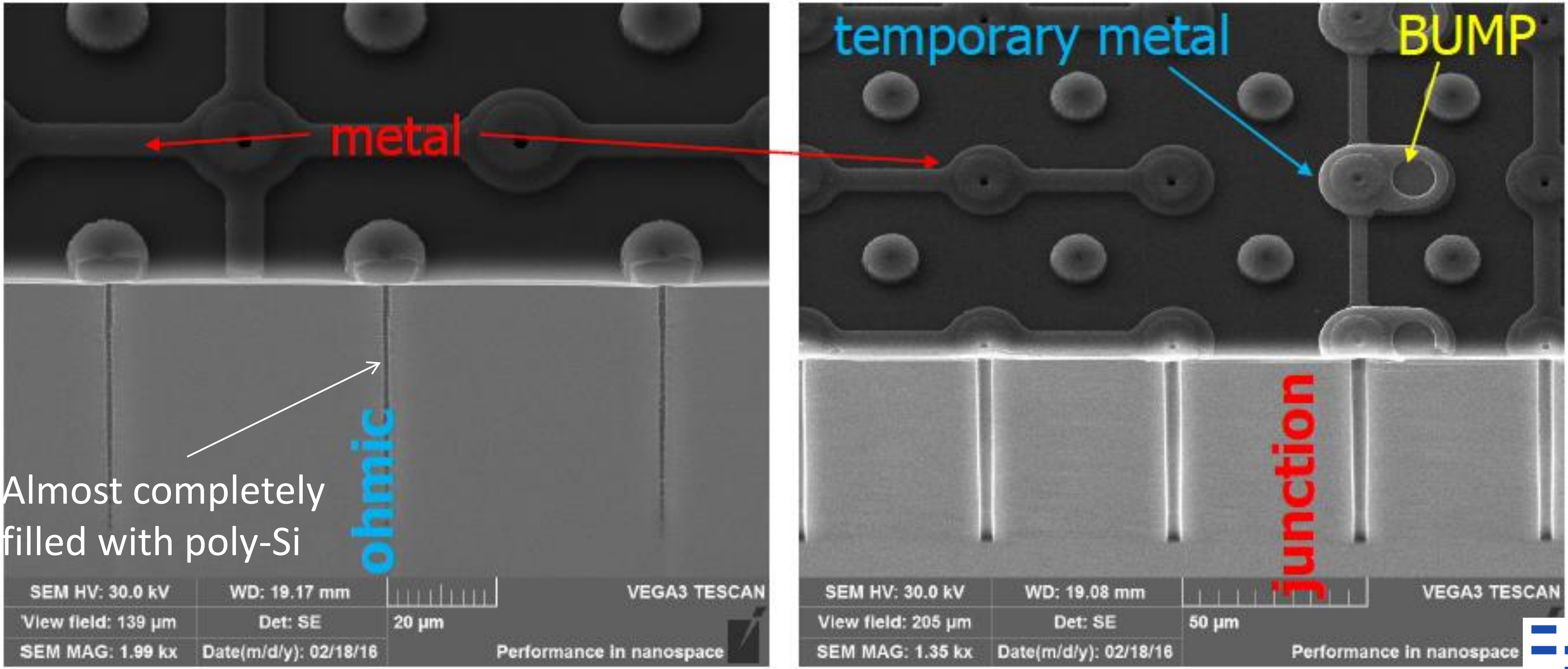
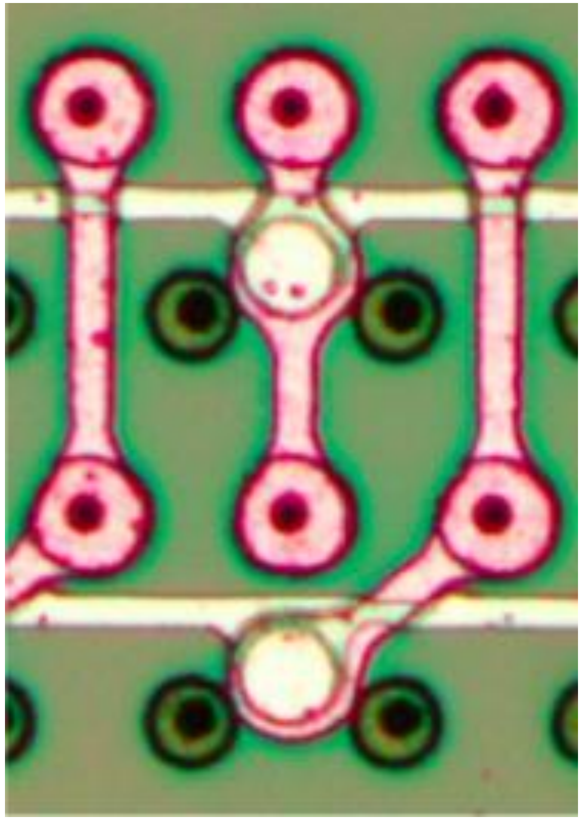
32th RD50 workshop
20 – 22 Dec. 2017

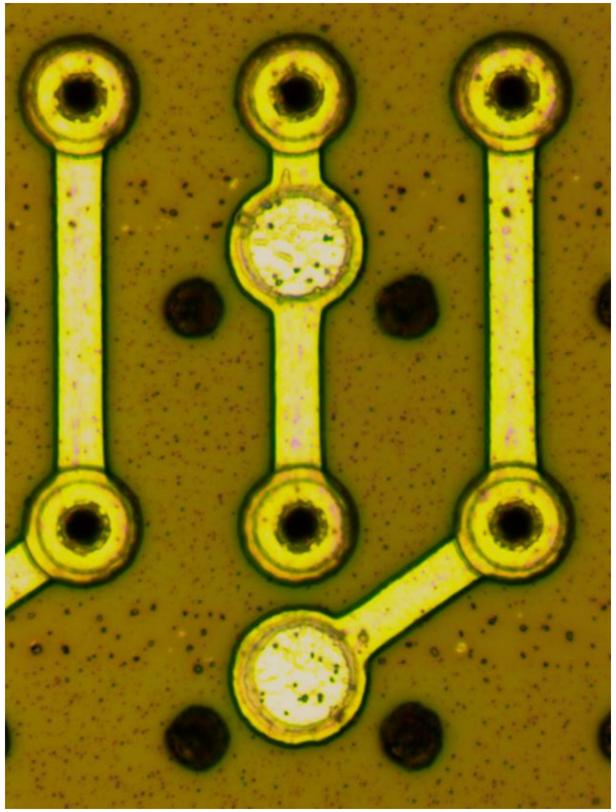


Almost completely filled with poly-Si

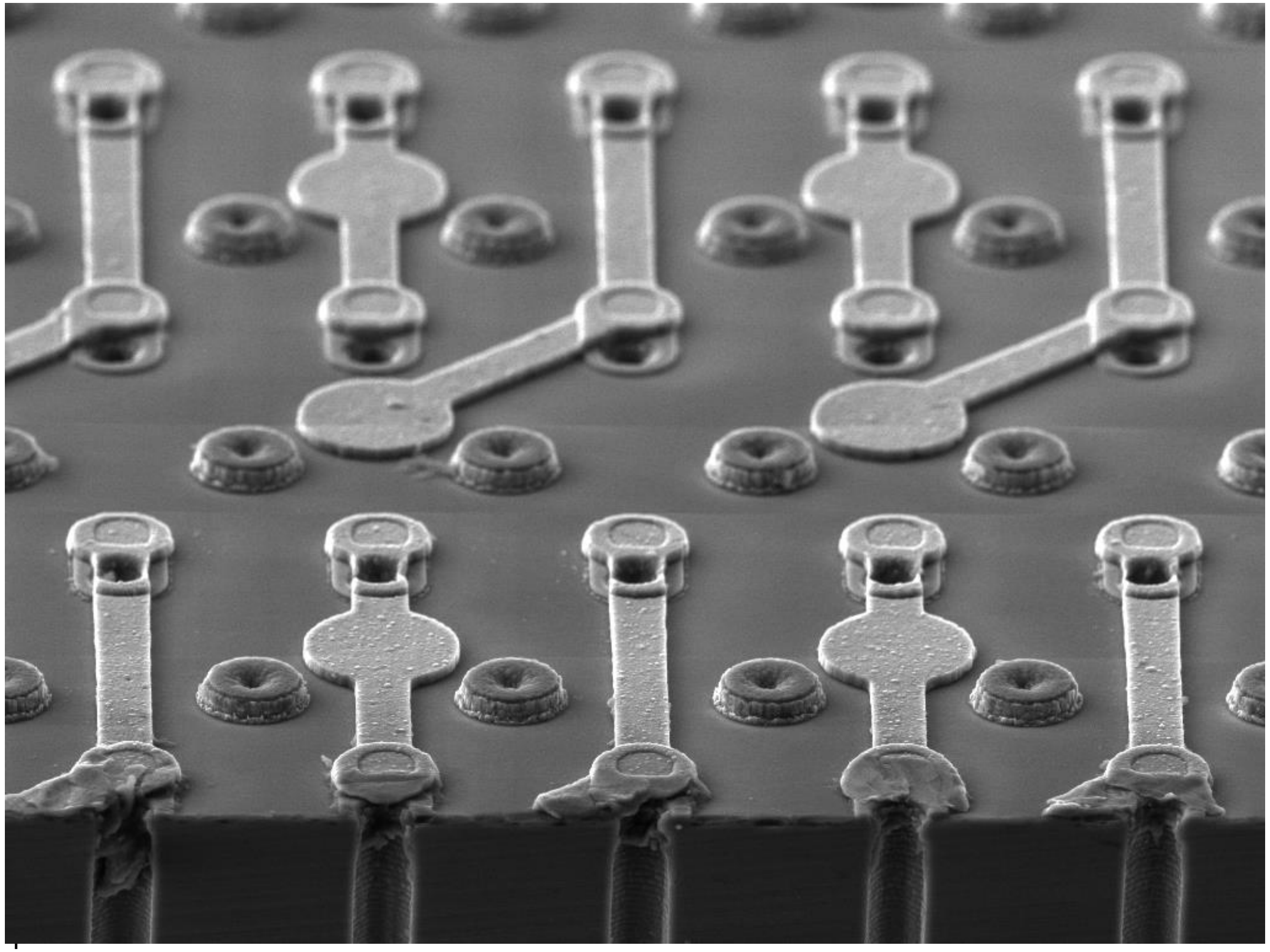
Small pitch 3D pixel layout



Mask Aligner

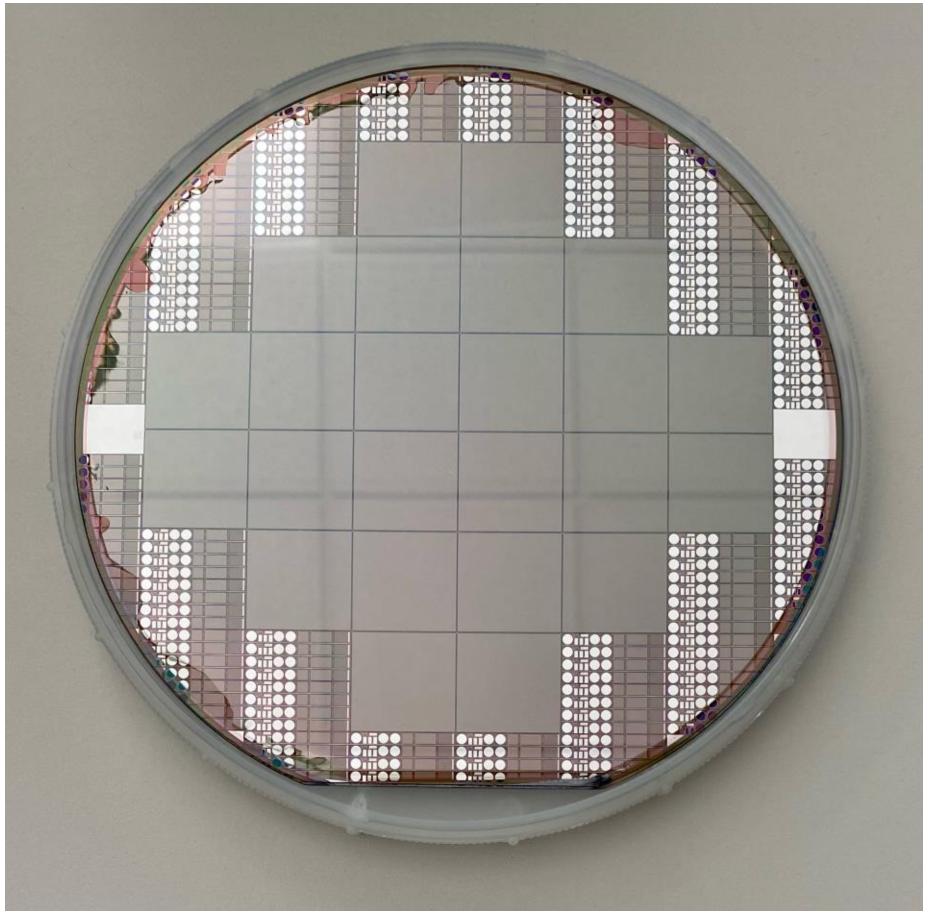


Stepper



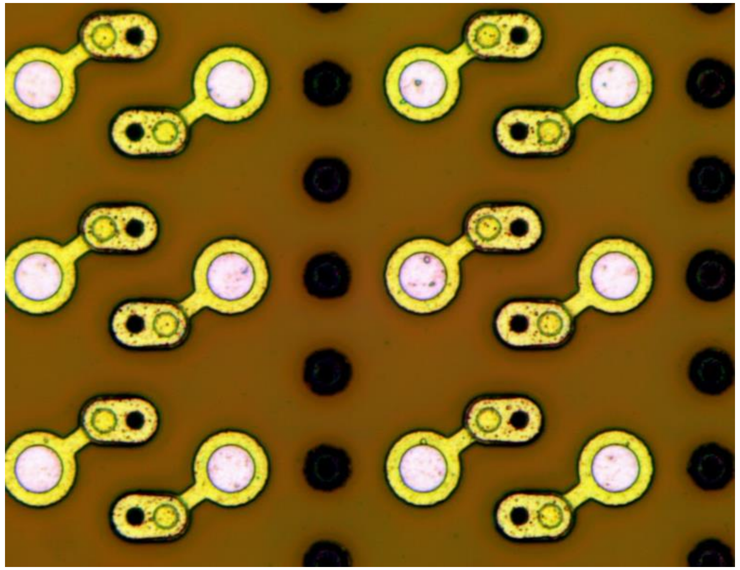
M. Boscardin et al., Frontiers in Physics 8:625275

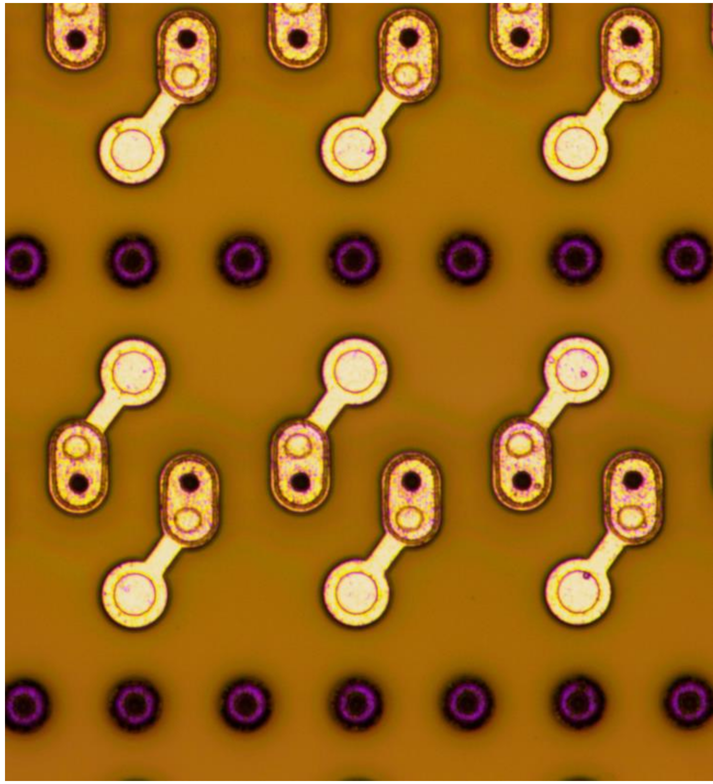
Now: on going production



Production phase for ATLAS Itk

- Barrel (25 x 100 μm^2 - 1E)
  - CNM, 4-inch wafers (~500 sensors)
- Endcap (50 x 50 μm^2)
  - FBK and SINTEF, 6-inch wafers (800 sensors each)



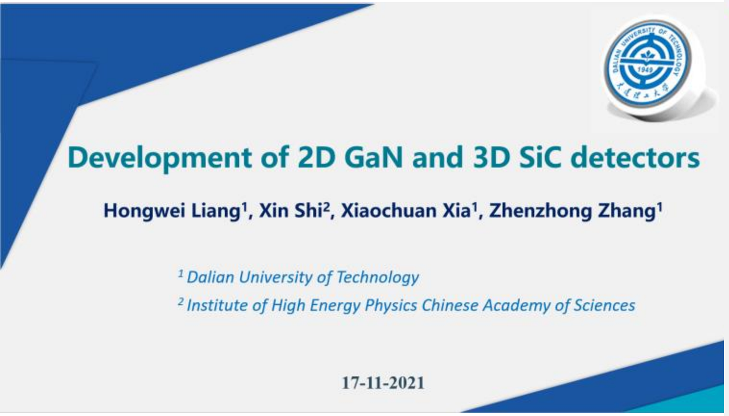


Pre production Phase for CMS

- Fbk, 6-inch wafers (~50 sensors)

Not only silicon : SiC

The 39th RD50 Workshop (Valencia)

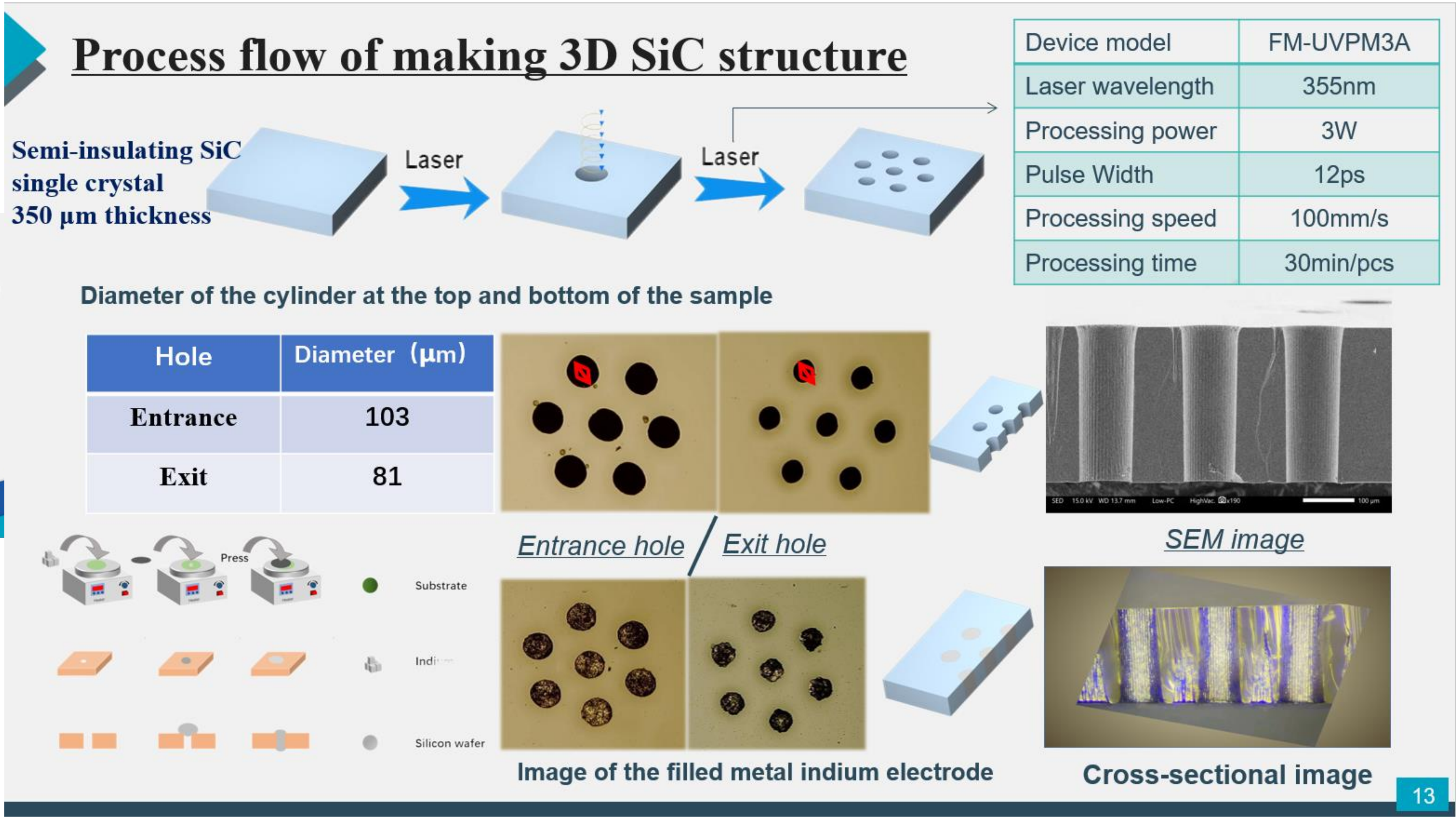


Development of 2D GaN and 3D SiC detectors

Hongwei Liang[1], Xin Shi[2], Xiaochuan Xia[1], Zhenzhong Zhang[1]

[1] Dalian University of Technology
[2] Institute of High Energy Physics Chinese Academy of Sciences

17-11-2021



Process flow of making 3D SiC structure

Semi-insulating SiC
single crystal
350 μm thickness

Device model	FM-UVPM3A
Laser wavelength	355nm
Processing power	3W
Pulse Width	12ps
Processing speed	100mm/s
Processing time	30min/pcs

Diameter of the cylinder at the top and bottom of the sample

Hole	Diameter（μm）
Entrance	103
Exit	81

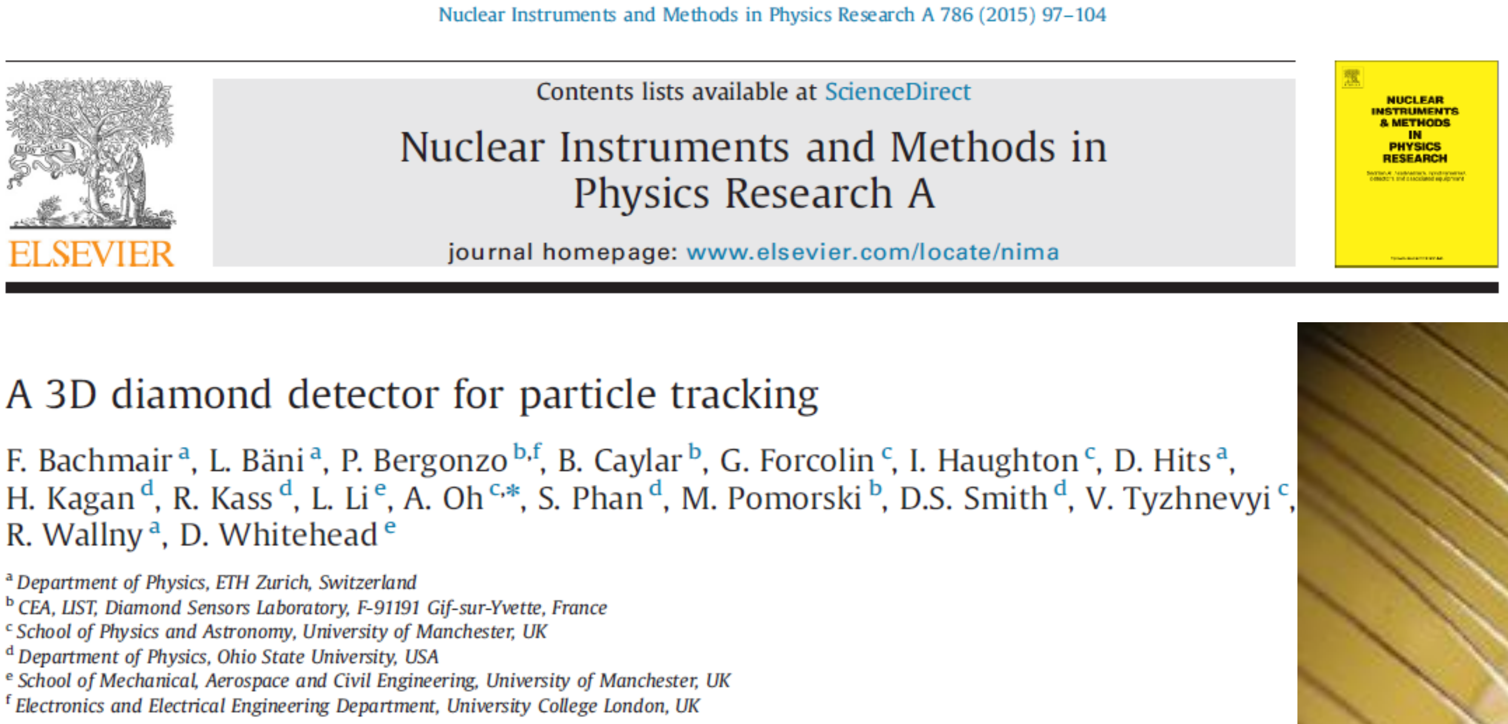
Entrance hole / Exit hole

SEM image

Image of the filled metal indium electrode

Cross-sectional image

Not only RD50 : RD42
Si3D on diamonds



Nuclear Instruments and Methods in Physics Research A 786 (2015) 97–104

Contents lists available at ScienceDirect

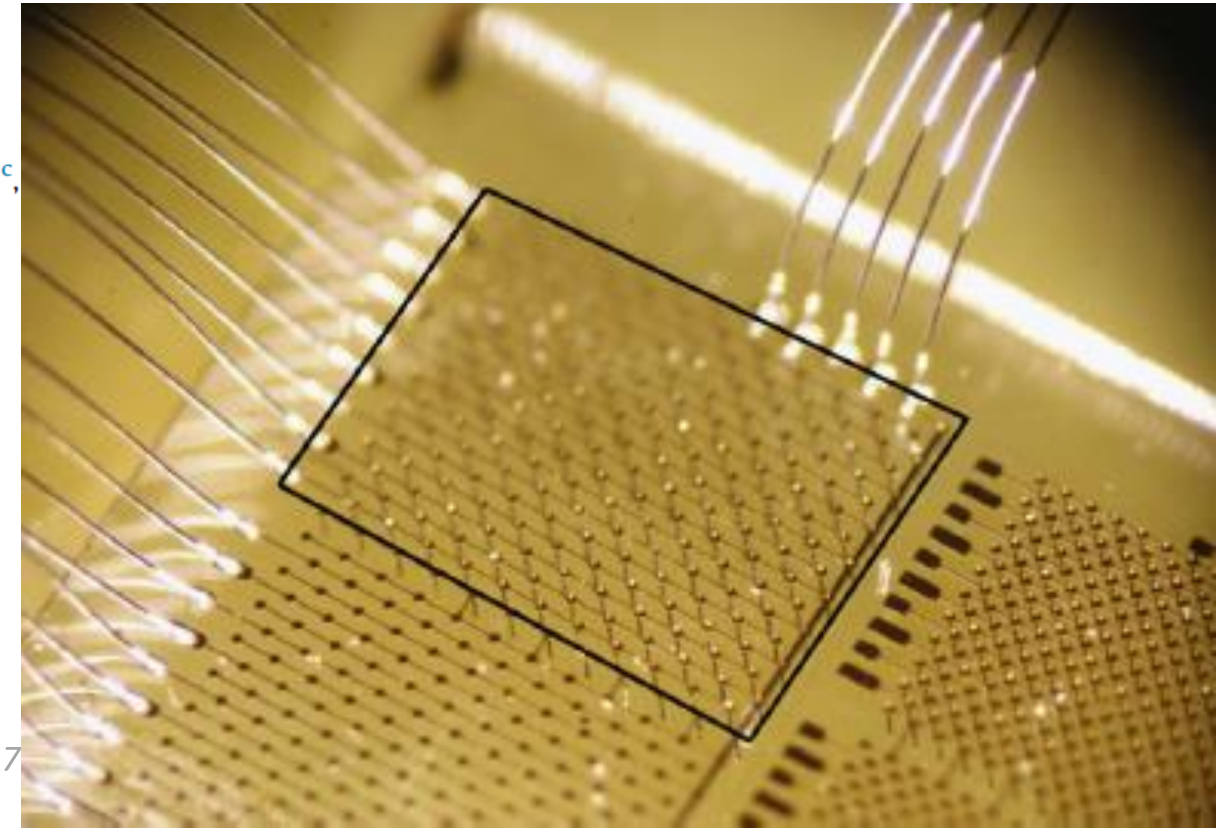
Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A 3D diamond detector for particle tracking

F. Bachmair [a], L. Bäni [a], P. Bergonzo [b,f], B. Caylar [b], G. Forcolin [c], I. Haughton [c], D. Hits [a], H. Kagan [d], R. Kass [d], L. Li [e], A. Oh [c,*], S. Phan [d], M. Pomorski [b], D.S. Smith [d], V. Tyzhnevyi [c], R. Wallny [a], D. Whitehead [e]

[a] *Department of Physics, ETH Zurich, Switzerland*
[b] *CEA, LIST, Diamond Sensors Laboratory, F-91191 Gif-sur-Yvette, France*
[c] *School of Physics and Astronomy, University of Manchester, UK*
[d] *Department of Physics, Ohio State University, USA*
[e] *School of Mechanical, Aerospace and Civil Engineering, University of Manchester, UK*
[f] *Electronics and Electrical Engineering Department, University College London, UK*



NEXT : 3D pixels for timing

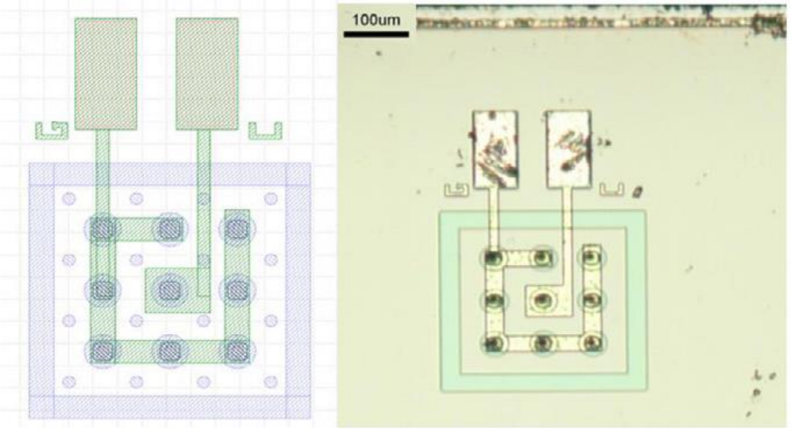
- 3D sensors are also expected to be fast …

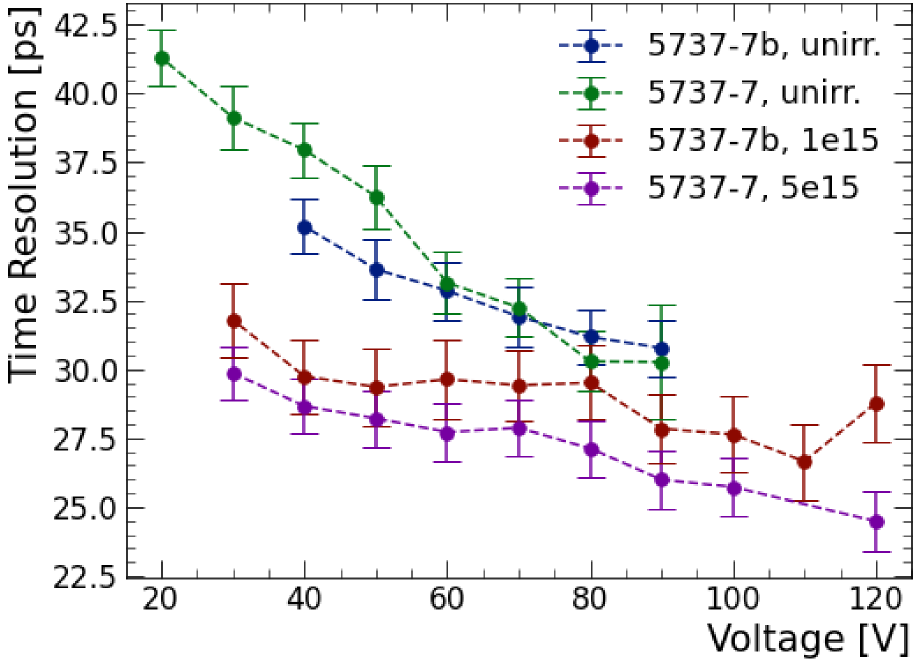
  S. Parker et al., IEEE TNS 58 (2011) 404

- Increasing interest in the past few years
- CNM 50x50 μm^2 single cells DS-3D (230 and 285 μm thick) tested by several groups

  G. Kramberger et al., NIMA 934(2019) 26
  C. Betancourt et al., MDPI Instruments 6 (2022)
  P. Fernandez Martinez et al. Pisa Meeting 2022

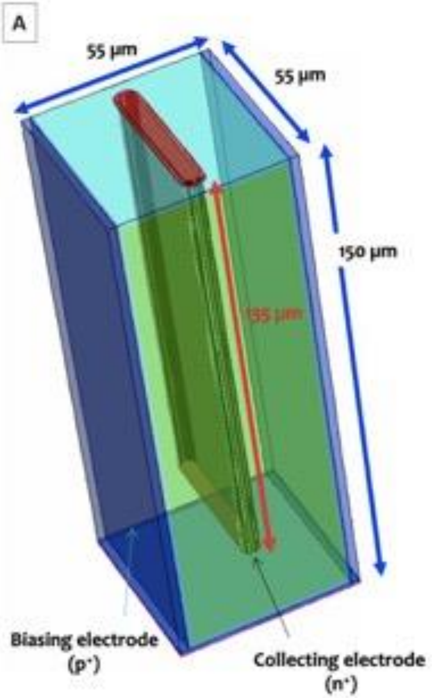
- Beta source setups, LGADs as reference
- Best result ~25 ps timing resolution

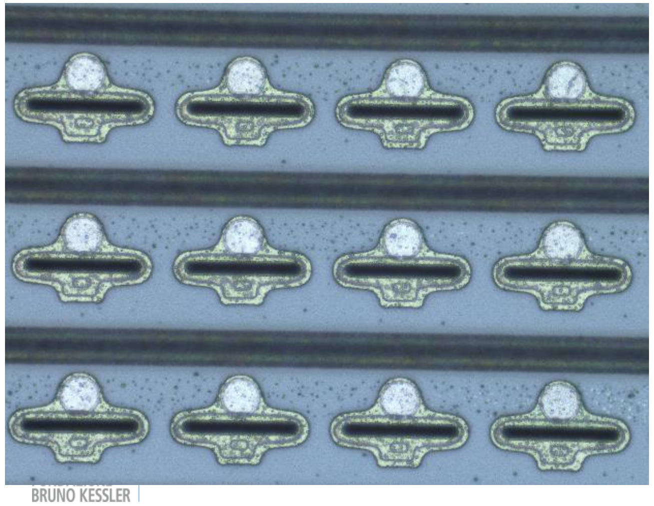


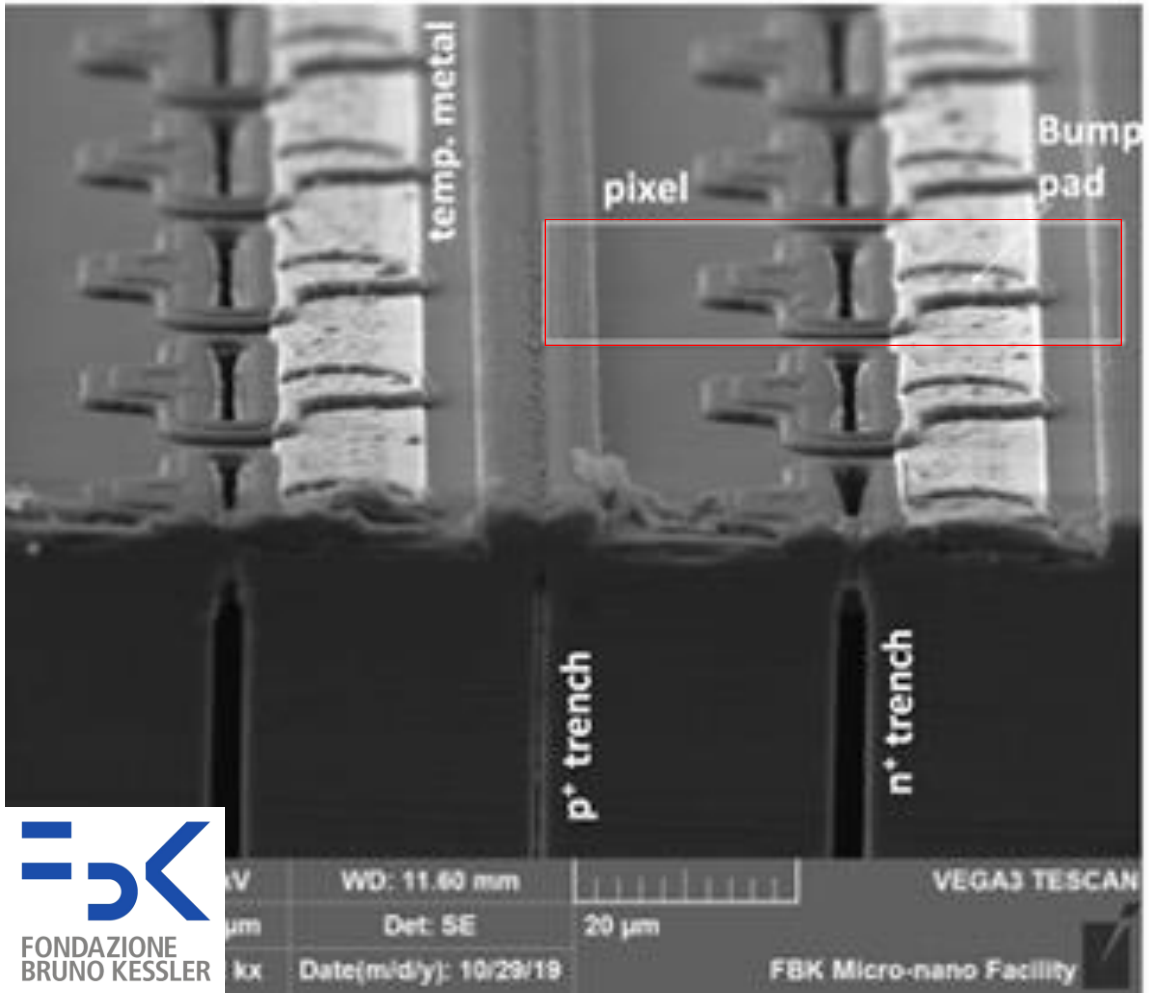


L.-Diehl. et al., Pisa Meeting 2022

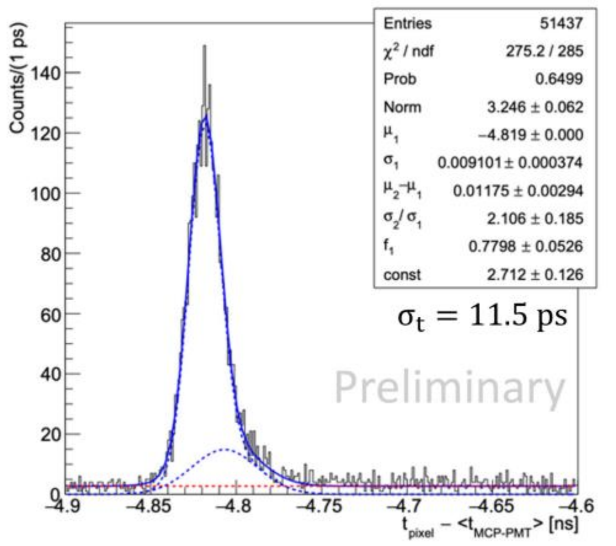
TIMESPOT trench 3D sensors



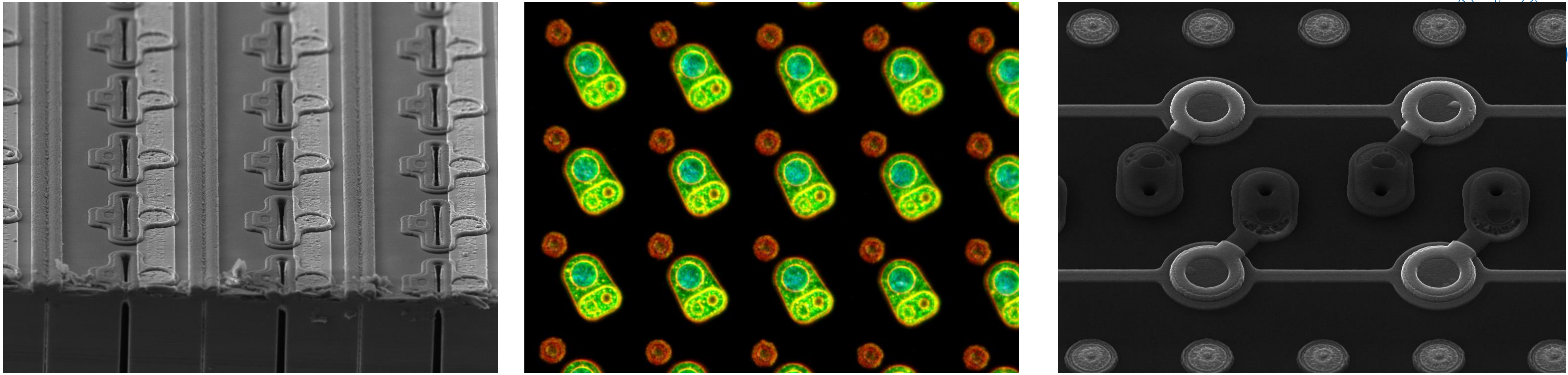




G. Forcolin et al., NIMA 981 (2020) 164437



A. Lampis et al., “10 ps timing with highly irradiated 3D trench silicon pixel sensors”, JINST 18, C01051, 2023



Thank you all for your attention

Thanks to my colleagues at FBK

Thanks to all members of the RD50 collaboration