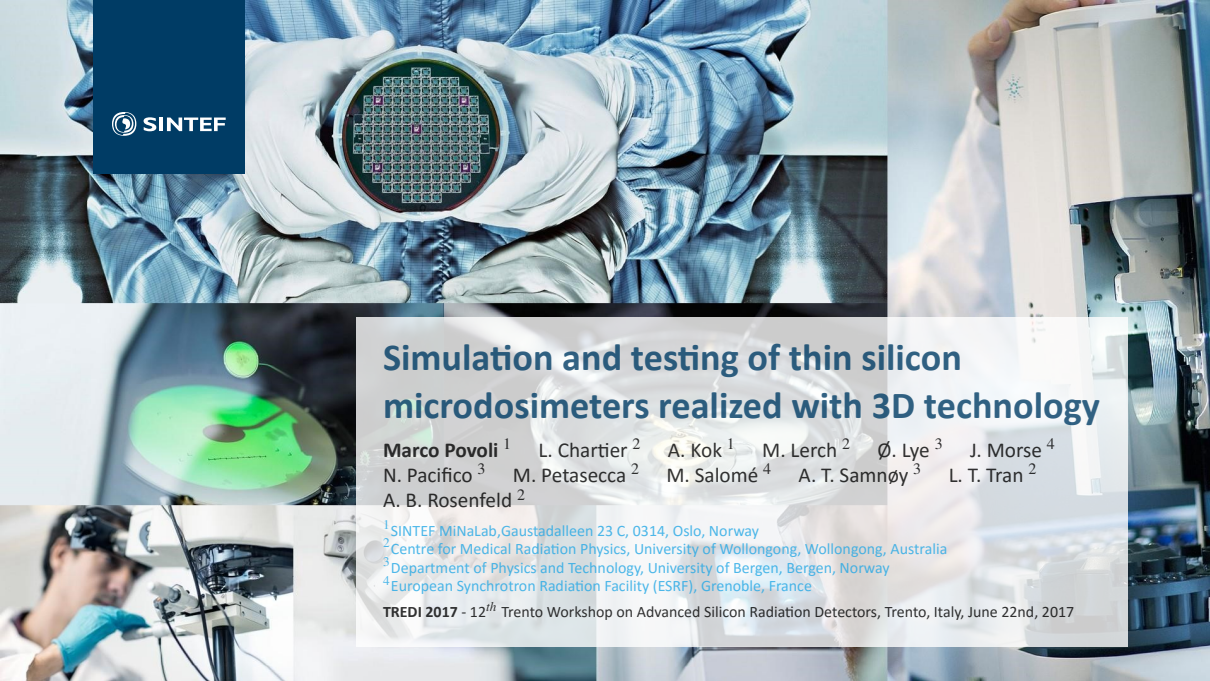

SINTEF

Simulation and testing of thin silicon microdosimeters realized with 3D technology

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N. Pacifico [3] M. Petasecca [2] M. Salomé [4] A. T. Samnøy [3] L. T. Tran [2]
A. B. Rosenfeld [2]

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[2] Centre for Medical Radiation Physics, University of Wollongong, Wollongong, Australia
[3] Department of Physics and Technology, University of Bergen, Bergen, Norway
[4] European Synchrotron Radiation Facility (ESRF), Grenoble, France

TREDI 2017 - 12th Trento Workshop on Advanced Silicon Radiation Detectors, Trento, Italy, June 22nd, 2017

Outline

Si-3D-MiMic Collaboration

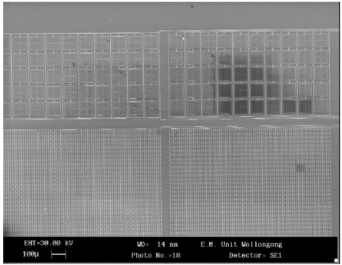
- **Si**licon-based **3D Mi**ni and **Mic**rodosimetry
- 6 project partners (R&D) + users
- Objectives:
  - Development of improved mini- and micro-dosimeters using 3D and micro-machining technologies through prototyping
- Project founded by the Research Council of Norway within the NANO2021 program
- International collaboration:

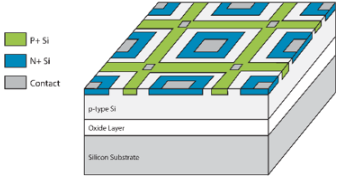
Microdosimetry

- Study of the distribution of the energy deposited in **well-defined microscopic volumes**
- Aims at relating the type and amount of radiation to a **biological effect**
- Required due to the stochastic nature of radiation interaction with small volumes
- Gold standard: ”Tissue Equivalent Proportional Counter”
  - Size limitation (bulky)
  - Requires rather large operating voltages
- To overcome limitations $\Rightarrow$ **Solid-state microdosimetry**

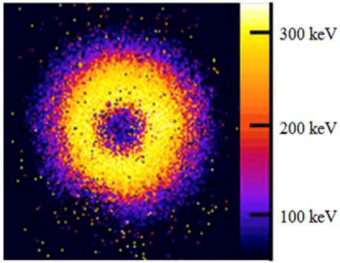
CMRP solid-state dosimetry

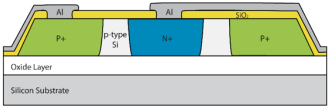
SOI planar technology



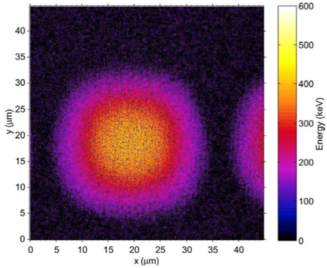


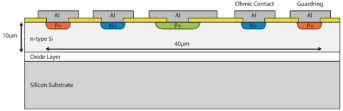
[P. D. Bradley, A. B. Rosenfeld, and M. Zaider, "Solid state microdosimetry," Nucl. Instrum. Methods Phys. Res. B, vol. 184, no. 1-2, pp. 135-137, Sep. 2001.]





[A. L. Ziebell et al., "A cylindrical silicon-on-insulator microdosimeter: charge collection characteristics," IEEE Trans. Nucl. Sci., vol. 55, no. 6, pp. 3414-3420, Dec. 2008.]



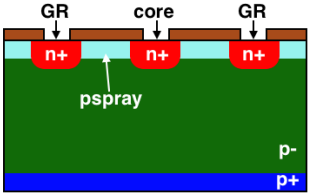


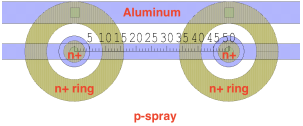
[J. Livingstone et al., "Charge collection in n-SOI planar microdosimeters," IEEE Trans. Nucl. Sci., vol. 60, no. 6, pp. 4289-4296, Dec. 2013.]

Development of novel micro-dosimeters

SOI - Active thickness 5 and 10 μm

Planar benchmark (TREDI 2015)



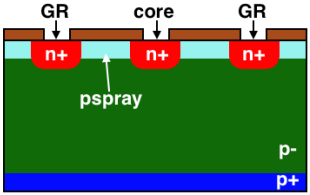


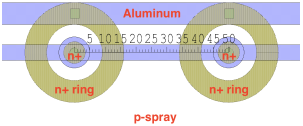
- Planar core and ring electrode
- Uniform back side bias
- P-spray

Development of novel micro-dosimeters

SOI - Active thickness 5 and 10 μm

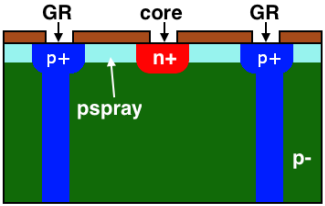
Planar benchmark (TREDI 2015)

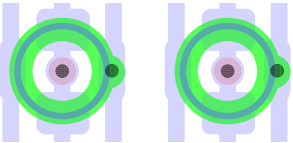




- Planar core and ring electrode
- Uniform back side bias
- P-spray

Planar n+ - 3D p+ (2016)



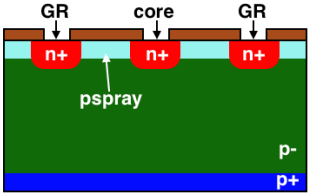


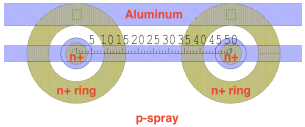
- Planar core electrode
- 3D cylindrical trench electrode
- P-spray (only front)

Development of novel micro-dosimeters

SOI - Active thickness 5 and 10 μm

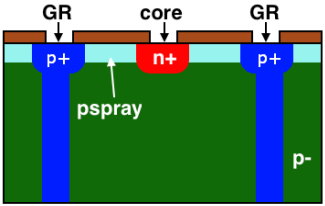
Planar benchmark (TREDI 2015)

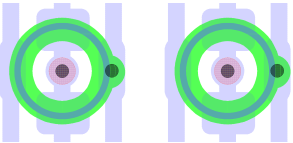




- Planar core and ring electrode
- Uniform back side bias
- P-spray

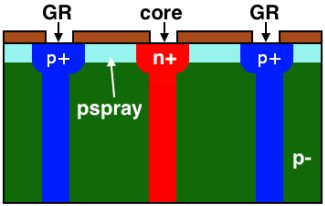
Planar n+ - 3D p+ (2016)

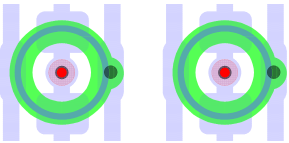




- Planar core electrode
- 3D cylindrical trench electrode
- P-spray (only front)

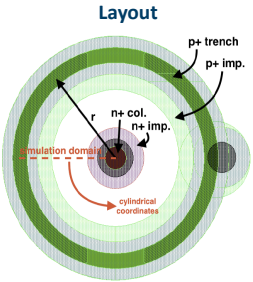
Full 3D (2016)





- 3D core electrode
- 3D cylindrical trench electrode
- P-spray (only front)

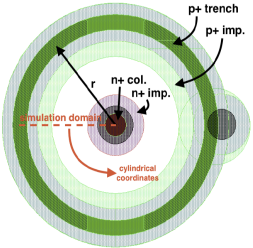
Numerical simulations



- 2D cross-section
- Use cylindrical coordinates

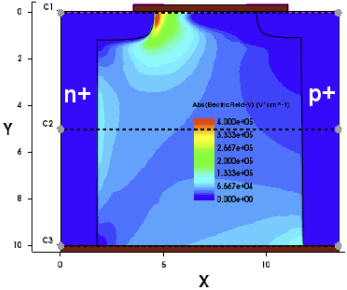
Numerical simulations

Layout



- 2D cross-section
- Use cylindrical coordinates

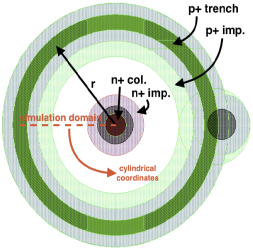
Electrical simulation



- Voltage ramp on p+ electrode
- Distribution of E-field at breakdown
- High field peak due to p-spray
- Smaller peak on the back side

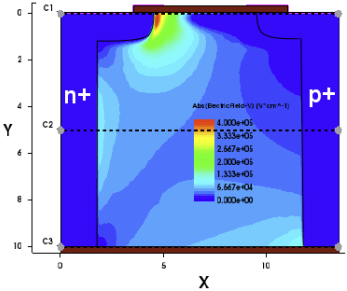
Numerical simulations

Layout



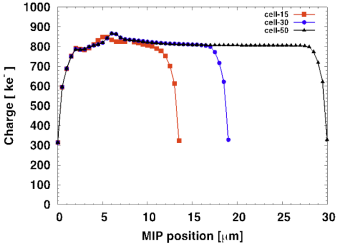
- 2D cross-section
- Use cylindrical coordinates

Electrical simulation



- Voltage ramp on p+ electrode
- Distribution of E-field at breakdown
- High field peak due to p-spray
- Smaller peak on the back side

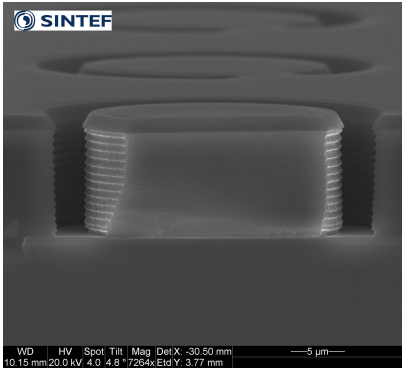
Charge collection (MIP)



- Scan MIP along the radius
- Test for charge collection uniformity
- Perturbation of charge profile near n+ implant
- Well defined active volume

Fabrication and layout variations

- Due to the reduced thickness the etching is not critical
- Major concerns related to metal lines crossing trenches



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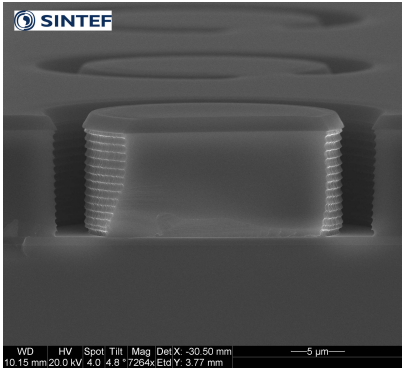
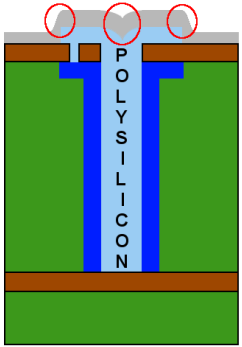


Polysilicon filling



- Over-etching of poly
- Severe topography
- Risk of metal lines breaking

Fabrication and layout variations

- Due to the reduced thickness the etching is not critical
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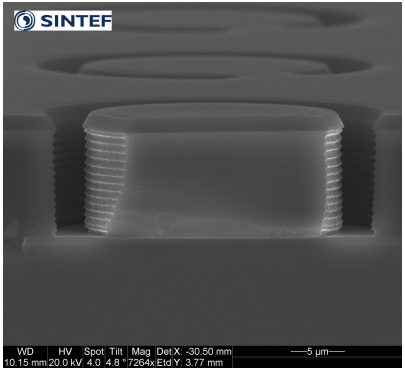
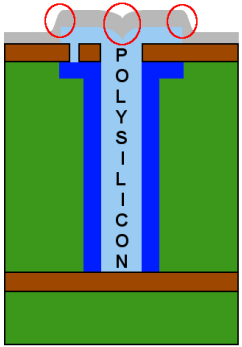
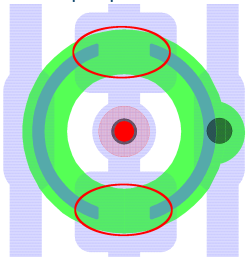


Polysilicon filling



- Over-etching of poly
- Severe topography
- Risk of metal lines breaking

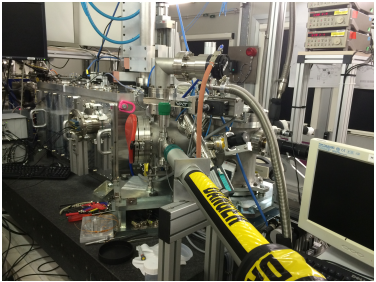
Open p+ trench

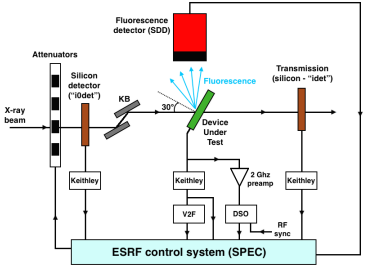


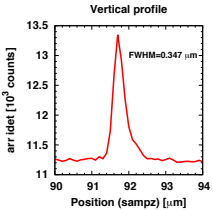
- No risk of metal lines breaking
- Trench empty and implanted
- Slight loss in sensitive volume definition

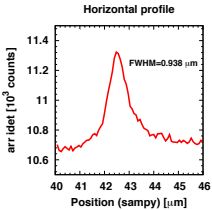
Functional measurements

Beam Line ID21 at ESRF - Scanning X-Ray Microscope (SXM)







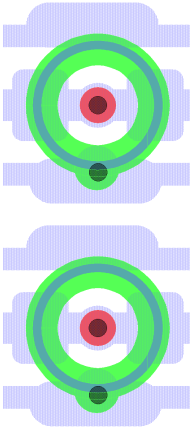


- Beam monitored with many detectors
- Fluorescence detector also available
- Hit angle 30°
- Energy range 2 - 9.2 keV
- Absorption length at used energies:
  - $2.7\mu m$ @2.5keV
  - $51.0\mu m$ @7.2keV
- Beam spot: $0.94 \times 0.35\ \mu m^2$ (@7.2 keV)
- 1D scans $\rightarrow$ readout Keithley
- 2D scans $\rightarrow$ readout V2F (speed)
- Data post-processing required (account for possible beam variations)

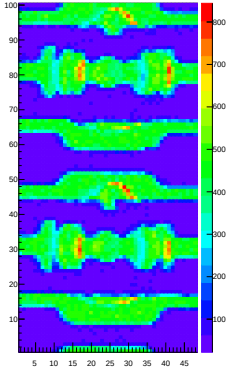
ESRF ID21 beam line

Planar n+, 3D p+, V_{bias} = 30V, Energy = 7.5 keV

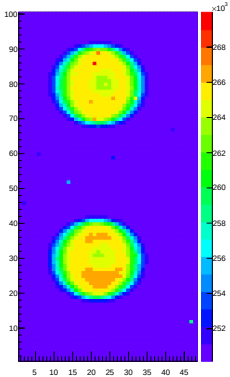
Layout



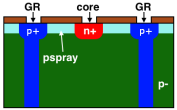
Cell signal



Cell signal



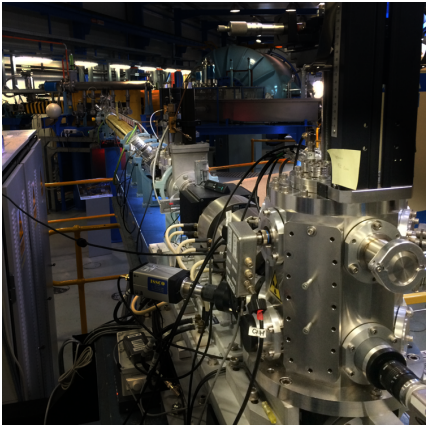
Device type



- Fluorescence detector allows to see the placement of the metal lines
- Slight parallax effect due to the tilt with respect to the beam
- Excellent definition of the sensitive volume
- Slight decrease in efficiency in the middle
- Signal FWHM roughly 20μm, as designed

ANSTO (Australian National Technology and Science Organisation)

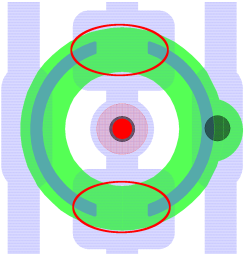
- Heavy Ion micro-probe
- Raster scanning 5.5MeV He^{2+} ions
- 1 μm focal diameter
- Plot signal as a function of beam position

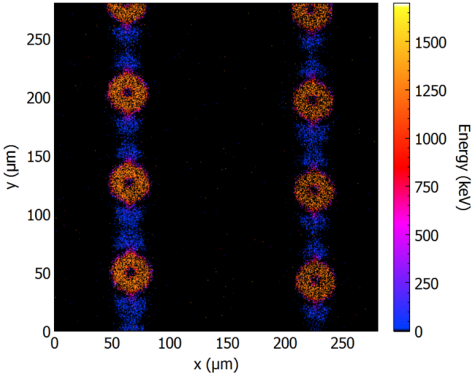


ANSTO (Australian National Technology and Science Organisation)

5.5MeV He^{2+} ions

Device type





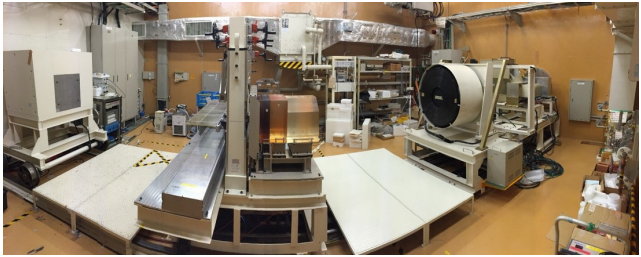
- P+ trench open and not filled with polysilicon
- N+ electrode is 3D (column)
- Acceptable definition of sensitive volume
- No charge collection from the empty n+ column
- The open trench allows carriers generated outside to diffuse inside and be collected

[A. B. Rosenfeld et al., "New 3D Mushroom microdosimeter for RBE studies in passive scattering and pencil beam scanning heavy ion therapy, IEEE NSS 2016]

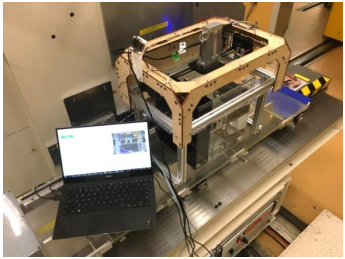
Experiment at Heavy Ion Medical Accelerator in Chiba, Japan

October 2016

- Biological beam port using:
  - 6cm SOBP 290 MeV/u (3.48GeV) ^{12}C ions (Range$_{H_20}$ = 148mm)



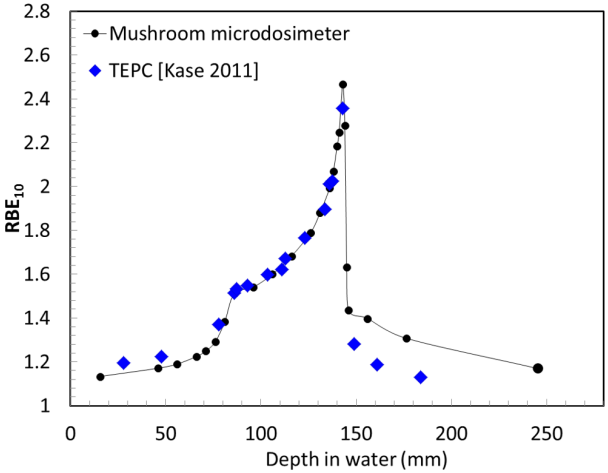
HIMAC Bio-cave beam port with passive scattering delivery



MicroPlus probe with 3D mushroom microdosimeter mounted on XY-movement stage

RBE_{10} obtained with 3D microdosimeter and TEPC

Microdosimetric Kinetic Model (MKM)



$$S = \exp\left(-\alpha D - \beta D^2\right)$$

$$\alpha = \alpha_0 + \frac{\beta}{\rho \pi r_d^2} y^*$$

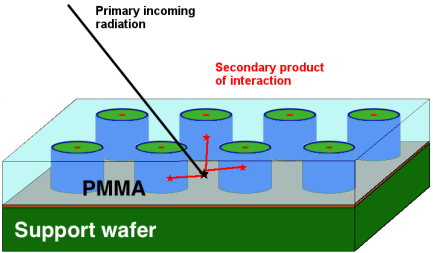
$$y^* = \frac{y_0^2 \int_0^\infty \left(1 - \exp\left(-y^2/y_0^2\right)\right) f(y)\, dy}{\int_0^\infty y f(y)\, dy}$$

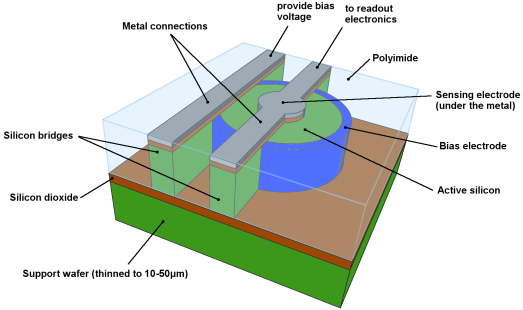
$$RBE_{10} = \frac{2\beta D_{10,R}}{\sqrt{\alpha^2 - 4\beta \ln(0.1)} - \alpha}$$

- $\alpha_0 = 0.13\ Gy^{-1}$; $\beta = 0.05\ Gy^{-2}$;
- r_d=0.42 μm is the radius of sub-cellular domain in MK model, V_0=150 keV/μm
- Where $D_{10,R}$=5 Gy is 10% survival of 200 kVp X rays for HSG cells

Latest developments

Direct integration of Tissue Equivalent materials



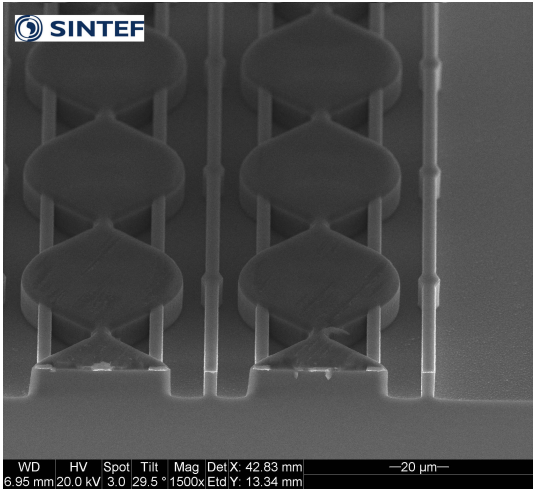


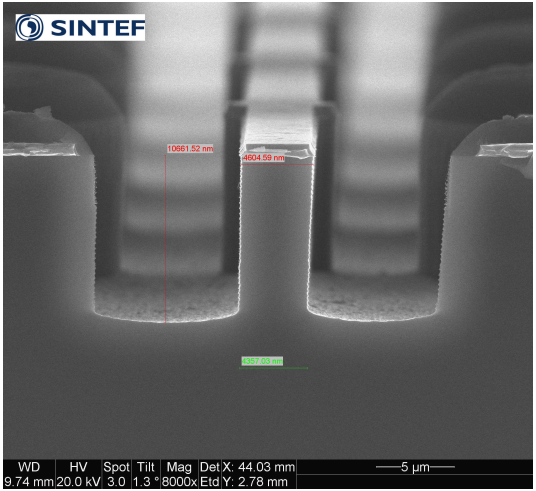
Idea based on CMRP Patented technology (US patent No. 8421022 B2)

- Remove excess silicon outside the cells
- Back-fill with tissue-equivalent material (e.g. Polyimide)
- Mimic interaction of radiation with human cells
- Detect both primary and secondary charged particles produced in the radiation field
- Possible to detect recoils produced by fast neutrons interaction with polyimide

Removal of excess silicon by DRIE

Test wafers (US patent No. 8421022 B2)

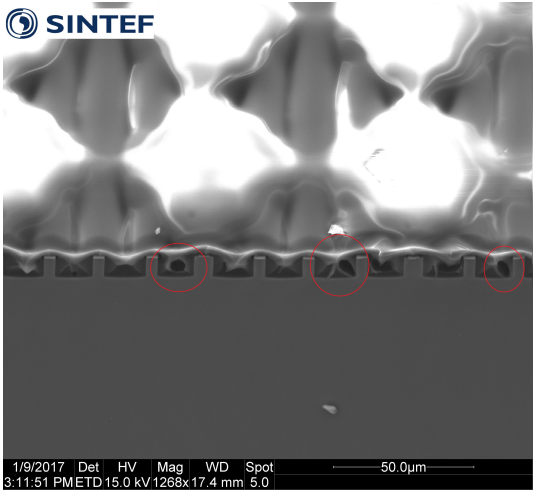




Polyimide deposition

Test wafers (US patent No. 8421022 B2)

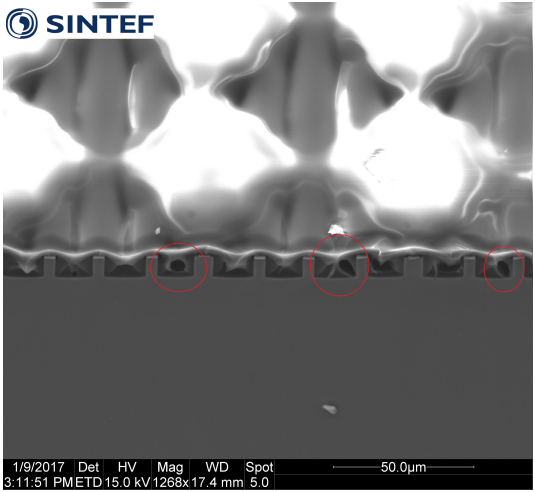
First try - not optimal



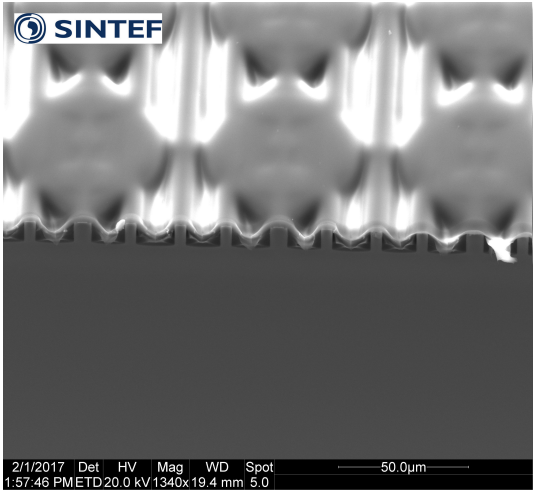
Polyimide deposition

Test wafers (US patent No. 8421022 B2)

First try - not optimal



Second try - optmized procedure



Conclusions

- In the framework of the 3D-MiMic project, we developed a novel generation of solid-state microdosimeters based on 3D technology.
- The layout was aided by results from previous generations and by numerical simulations.
- The devices proved to be operating as intended.
- The charge collection characteristics were found to be excellent.
- The integration of tissue equivalent materials is progressing and devices will be ready to be tested in the coming weeks.

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