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

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Outline

Si-3D-MiMic Collaboration
Background
Development of novel micro-dosimeters
Numerical Simulations
Fabrication
Functional testing
Latest developments
Conclusions
Si-3D-MiMic Collaboration

• Silicon-based 3D Mini and Microdosimetry
• 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 ⇒ Solid-state microdosimetry
CMRP solid-state dosimetry
SOI planar technology


Development of novel micro-dosimeters

SOI - Active thickness 5 and 10 $\mu$m

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

Planar benchmark (TREDI 2015)

- Planar core electrode
- 3D cylindrical trench electrode
- P-spray (only front)
Development of novel micro-dosimeters
SOI - Active thickness 5 and 10 \(\mu m\)

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

- 2D cross-section
- Use cylindrical coordinates

Layout

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

Electrical simulation
Numerical simulations

- 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
Fabrication and layout variations

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- 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
- Major concerns related to metal lines crossing trenches

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:
  - $2.7 \mu m @ 2.5 keV$
  - $51.0 \mu m @ 7.2 keV$
- Beam spot: $0.94 \times 0.35 \mu m^2 (\text{at } 7.2 \text{keV})$
- 1D scans → readout Keithley
- 2D scans → readout V2F (speed)
- Data post-processing required (account for possible beam variations)
ESRF ID21 beam line
Planar n+, 3D p+, $V_{\text{bias}} = 30\text{V}$, Energy = 7.5 keV

- 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 20$\mu$m, as designed
• Heavy Ion micro-probe
• Raster scanning 5.5MeV He$^{2+}$ ions
• 1 $\mu$m focal diameter
• Plot signal as a function of beam position
ANSTO (Australian National Technology and Science Organisation)  
5.5MeV He$^{2+}$ ions

- 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$_{H_2O} = 148$mm)
RBE$_{10}$ obtained with 3D microdosimeter and TEPC

Microdosimetric Kinetic Model (MKM)

\[ S = \exp\left(-\alpha D - \beta D^2\right) \]
\[ \alpha = \alpha_0 + \frac{\beta}{\rho \pi r_d^2} y^* \]
\[ y^* = \frac{y_0^2 \int_0^\infty (1-\exp(-y^2/y_0^2))f(y)dy}{\int_0^\infty yf(y)dy} \]
\[ RBE_{10} = \frac{2\beta D_{10,R}}{\sqrt{\alpha^2 - 4\beta \ln(0.1)} - \alpha} \]

- $\alpha_0 = 0.13 \text{ Gy}^{-1}$; $\beta = 0.05 \text{ Gy}^{-2}$;
- $r_d = 0.42 \mu\text{m}$ is the radius of sub-cellular domain in MK model, $V_0 = 150 \text{ keV}/\mu\text{m}$
- Where $D_{10,R} = 5 \text{ Gy}$ 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 - optimized 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.
Technology for a better society