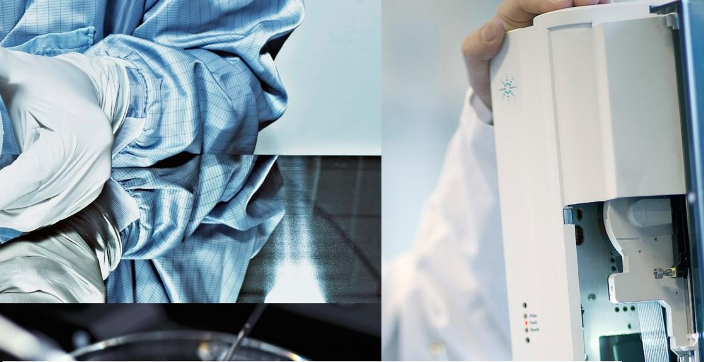


SINTEF

Three-Dimensional Low Voltage Silicon Detectors

Marco Povoli [1] A. Kok [1] O. Koybasi [1] A. Summanwar [1]
L. Tran [2] A. Rosenfeld [2]

[1] SINTEF MiNaLab,Gaustadalleen 23 C, 0314, Oslo, Norway
[2] Centre for Medical Radiation Physics, University of Wollongong, Wollongong, Australia

TEC-EPS Final presentations: Space environment and radiation effects
ESTEC, Noordwijk, Netherlands, May 15th, 2018

Outline

SINTEF MiNaLab

(Micro- and Nanotechnology Laboratory, Oslo)

- The new laboratory opened in 2005
- Shared facility with the University of Oslo
- Two separate cleanroom floors:
  - SINTEF: 800 m^2
  - University of Oslo: 600 m^2
- SINTEF:
  - Silicon production line with annual capacity of 10.000 wafers
  - 150mm wafers
- Situated on the University of Oslo campus
- QA System apprved ISO 9001:2008

SINTEF MiNaLab Space Heritage

- Gas monitor development for future manned space flight based on diffraction micro optics (ESA - CDOE project)

- Photodiode chips for AME/OSIO space detectors 1988 - 2010:
  - Star sensor for ISO mission (operating at 2 °K)
  - Virgo LOI detector for SOHO mission
  - Sun sensors for European and Indian communication satellites (several deliveries 1991 – 2009, new delivery expected 2011/12)
  - Detectors for European and Indian Metrological satellites
  - VIS and NIR detectors for NPOES (US) and GalileoSat missions
  - VIS SLSTR detector units for Sentinel-3 mission (launch 2012)
  - VIS and NIR detectors for Aeolus mission (expected launch 2013)
- Strip detectors for INFN Trieste for Pamela mission

- MEMS sensor chips for PRESENS space qualified pressure transducers:
  - Low pressure transducer for Aeolus mission
  - High pressure transducer for Prisma (S) and Aeolus Mission

SINTEF

Three Dimensional Low-Voltage Silicon Detectors

ESA SINTRA project

- Project funded by ESA within the Technology Research Program (TRP)
- The work is carried out at SINTEF MiNaLab in Oslo
- Consulting offered by ESA and by some of our other partners
- **Objectives:**
  - To develop a sensor prototype that is:
    - » Based on 3D technology
    - » Low mass, low cost and low power
    - » Intended for use in radiation monitoring for space applications
  - To verify the performances of the developed prototype using radiation sources

SINTEF — CENTRE FOR MEDICAL RADIATION PHYSICS — UNIVERSITY OF WOLLONGONG AUSTRALIA

Sensor requirements and possible improvements

Radiation in space

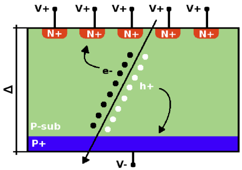
- The sensor must be able to work in a mixed radiation environment
- Charged particles (e.g. electrons and protons)
- X-rays and γ-rays
- Neutrons

Additional requirements

- Compact and low weight
- Low power consumption
- Radiation hardness (e.g. long lifetime)

Standard sensor technologies cannot always satisfy some of these requirements

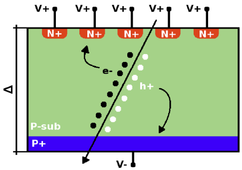
3D sensor technology



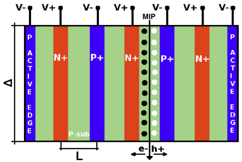
Planar (standard)

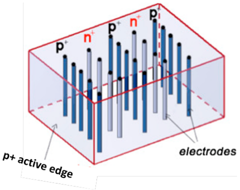
- Well know fabrication process
- Excellent detectors with high yield
- Thicknesses in the range 300μm - 1mm (2mm possible but not standard)
- Inter-electrode distance limited by the wafer thickness
- Large operating voltages
- Sensitive to radiation damage
- Relatively inexpensive

3D sensor technology



Planar (standard)





3D technology

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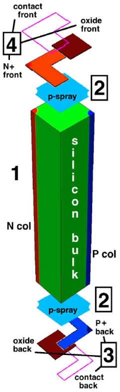
- Excellent detectors with high yield
- Thicknesses in the range 300μm - 1mm (2mm possible but not standard)
- Inter-electrode distance limited by the wafer thickness
- Large operating voltages
- Sensitive to radiation damage
- Relatively inexpensive

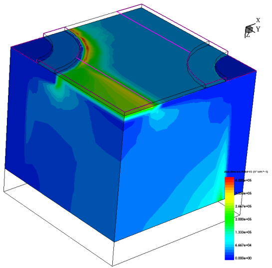
- First proposed by S. Parker in the mid ’90s [NIMA 395 (1997), 328]
- Decouple the inter-electrode distance from the wafer thickness
- Low full depletion voltage (<10V)
- Short charge collection distance (<50μm)
- Increased radiation hardness
- Expensive and complicated fabrication
- Available at SINTEF(Norway), FBK(Italy), CNM(Spain), Stanford(USA)
- Particle tracking in harsh environment (e.g CERN experiments)

3D detectors for space applications

Optimisation of sensor design

Numerical simulations

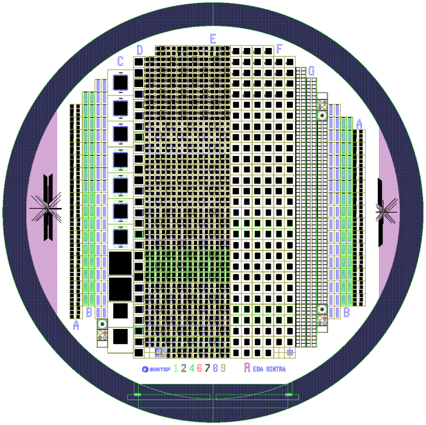


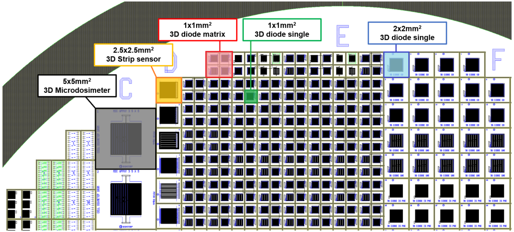


Numerical simulations

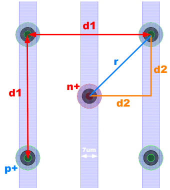
- Modern simulation tool allow for a great level of detail
- Both process and device simulation
- **PROCESS:** Diffusion of doping profile during processing
- **DEVICE:** Include all the structures part of the device
- Electrical properties (currents, capacitance, electric field distribution etc...)
- Sensor response to radiation (alpha particles, heavy ions, lasers etc...)

Final wafer layout and sensor geometries



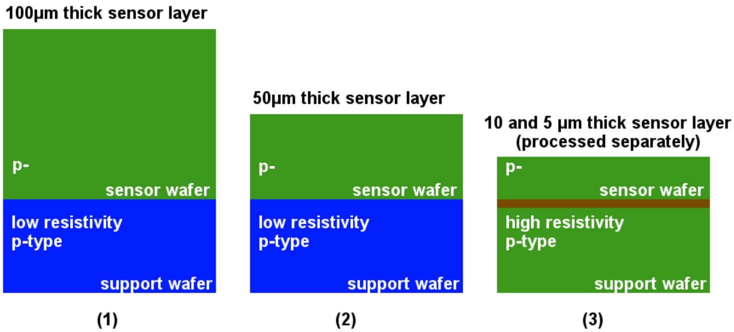


- Square basic cell (1 n^+ and 4 p^+ electrodes)
- Variable inter-electrode distance (d1 = [25, 50, 100] μm)
- Multiple sensor sizes to account for different radiation fluxes
- PAD diodes and strip detectors
- Additional test diodes with non-standard structures (cylindrical cells, slim-edges etc...)
- > 1500 device per wafer



Fabrication

Starting wafer material

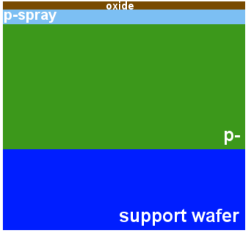


- 3D detector fabrication requires a support wafer
- Main choice: Si-Si wafers from ICEMOS, 50 and 100 μm active layers
- Additional option: SOI wafers from ICEMOS, 5 and 10 μm active layers (to test innovative structures)
- Support wafer thicknesses of 300 and 500 μm

Fabrication (1)

Isolation layer

- First oxidation
- Uniform Boron implantation
- Necessary to ensure electrode isolation



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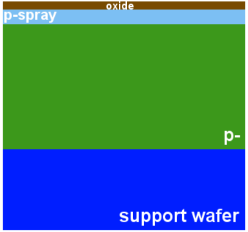
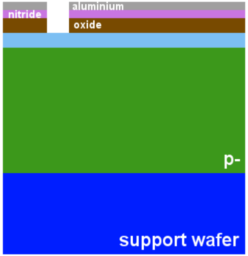


First Photolithography (n$^+$ electrodes)

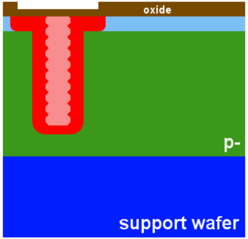
- Deposit nitride and aluminium layer to protect the wafer surface during etching
- Creation of opening corresponding to the desired electrode position and diameter (d = $3\mu m$)

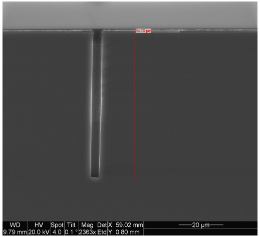


Fabrication (2)

Creation of n-type electrodes

- Deep Reactive Ion Etching (DRIE)
- Doping using Phosphorus gas diffusion
- Polysilicon filling and etching
- Final oxidation
- NOTE: n-type electrodes are not etched all the way through!

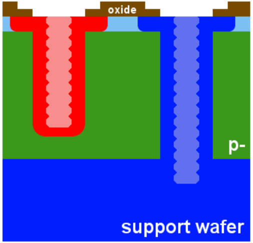




Fabrication (3)

Creation of P-type electrodes

- Same as for the N-type electrodes
- Doping using Boron gas diffusion
- Etched all the way through



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- Doping using Boron gas diffusion
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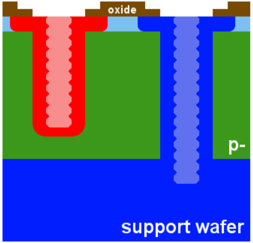
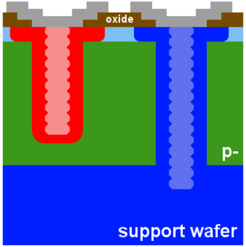
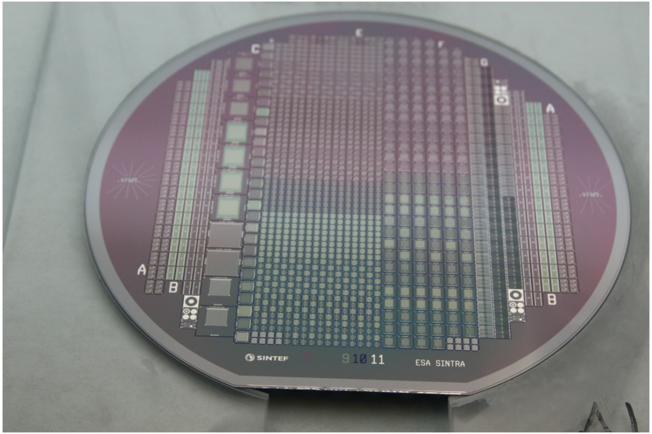


Contact opening, metal deposition and etching

- The contacts are opened over the electrodes with a standard photolithography
- Aluminium sputtering performed uniformly on all wafers
- Metal lithography and etching
- The final passivation layer is deposited after preliminary electrical verification

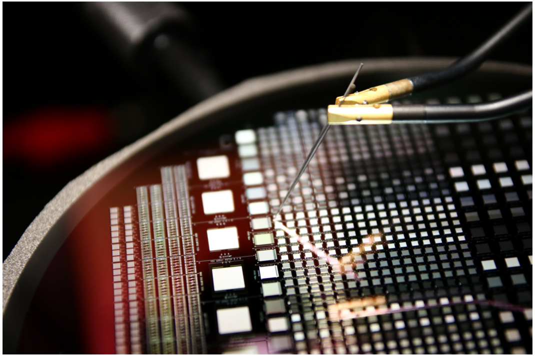


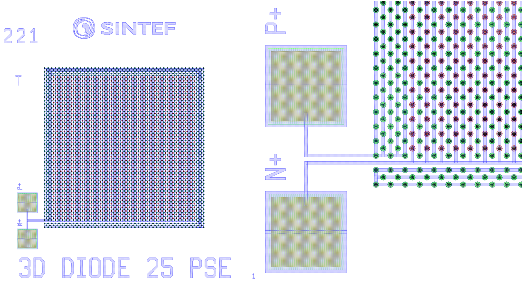
Completed wafer



Electrical characterisation

Testing configuration

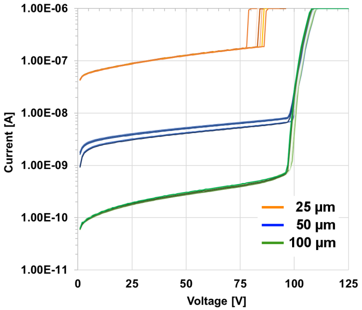




- Electrical characterisation performed at wafer level using a manual probe station
- Needles are positioned using micro-manipulators to contact the sensor pads (140x140 μm^2)
- The probes are connected to a semiconductor parameter analyser

Electrical characterisation

Preliminary results

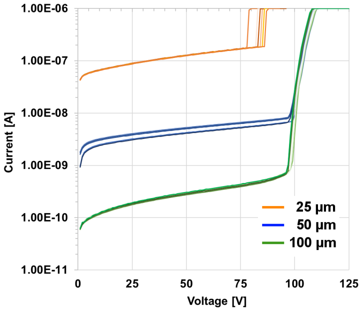


Current-Voltage (I-V)

- Scaling correctly with electrode pitch
- 25μm pitch exhibits some criticality
- Breakdown voltage >85 V

Electrical characterisation

Preliminary results



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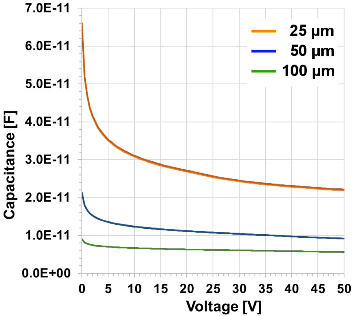
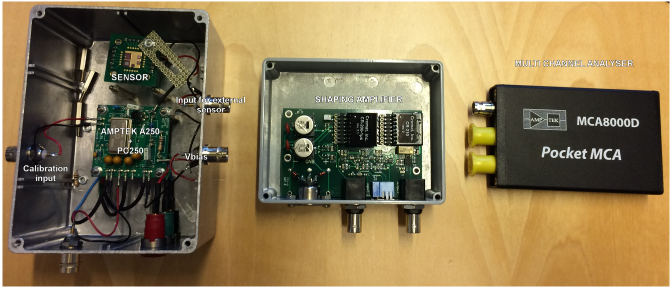
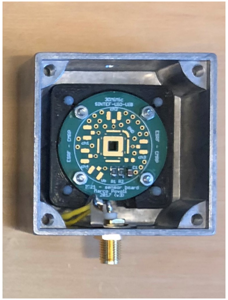


Capacitance-Voltage (C-V)

- Capacitance values scale correctly with electrode pitch
- P-spray makes it difficult to extract full depletion voltage
- Clear change in curve trend before 5-10 V

Functional characterisation
Testing setup

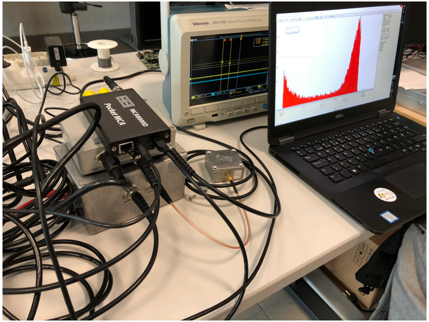




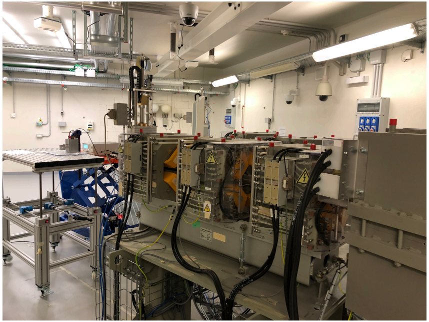
- Sensor is AC coupled to the AMPTEK A250 charge sensitive amplifier
- Semi-gaussian shaping amplifier from Cremat (shaping time 25ns to 1μs) with baseline restorer
- Multi Channel Analyser ”Pocket MCA” from AMPTEK
- Relatively inexpensive setup / easily accessible / good noise characteristics can be achieved

Functional characterisation

Two different experimental setups



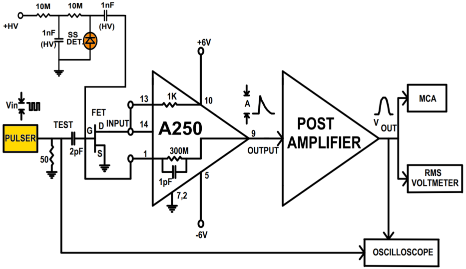
- Setup for alpha particle measurements (^{241}Am)
- Source inside the sensor shielding to minimize distance
- MCA is connected to the PC over USB



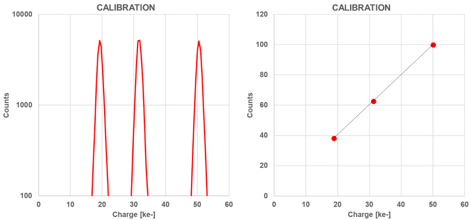
- Experimental beam line at the proton therapy center in Trento, Italy (TIFPA - INFN)
- Same readout configuration
- Data readout from the control room over ethernet

Functional characterisation

Calibration and noise



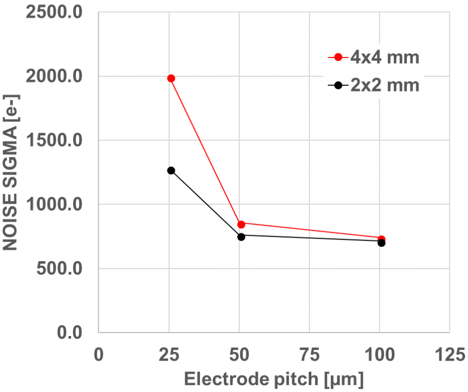
- Bias filter and AC coupling
- Calibration charge injected with a pulse generator
- Input charge: $dQ_{in} = dV_{in} \cdot C_{test}$
- First stage output: $V_A = dQ_{in}/C_F$
- Shaping amplifier filters excess noise (τ=1μs)
- The histogram of V_{OUT} is constructed with the MCA

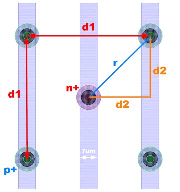


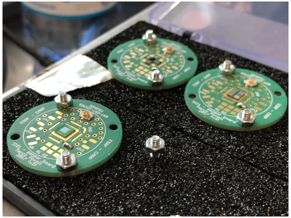
- Inject different amounts of charge
- Fit the resulting peaks with a Gaussian
- Possible to find the input/output characteristic
- Linearity over a large dynamic range is necessary
- **The sigma of the Gaussian fit is the system noise**

Functional characterisation

Calibration and noise





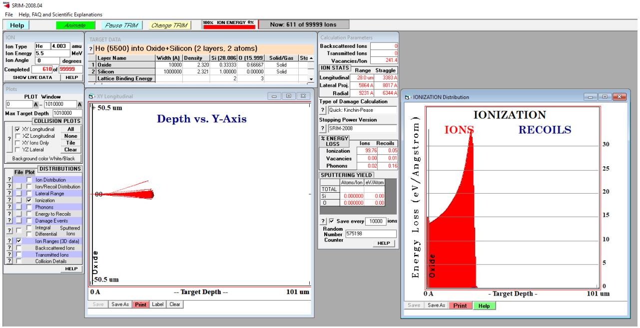


Sensor ID	Size [mm^2]	d1 [μm]	d2 [μm]	r [μm]	noise [ke^-]	noise [keV]
D33	4x4	25	12.5	17.7	2.00	7.20
D51	4x4	50	25.0	35.4	0.86	3.10
D56	4x4	100	50.0	70.7	0.73	2.67
D228	2x2	25	12.5	17.7	1.28	4.61
D328	2x2	50	25.0	35.4	0.76	2.74
D386	2x2	100	50.0	70.7	0.71	2.57

Functional characterisation

Charge collection studies

- Two different type of radiation:
  - ^{241}Am: alpha particles, 5.5 MeV
  - Proton beam: 70, 119, 202 MeV
- Measurements performed on all sensors with increasing bias voltage
- Numerical simulations (SRIM) to estimate expected ionisation in the sensor



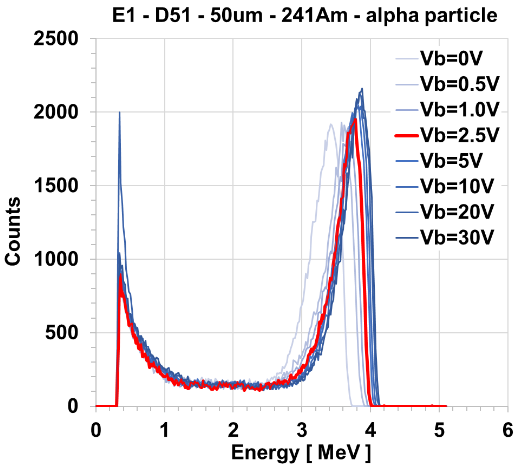
Alpha Particle tests - ^{241}Am

Functional characterisation

^{241}Am alpha particle source (5.5 MeV)

Results

- Experiment carried out in air (some energy loss in air)
- Acquisition at multiple bias voltages
- Very little effect of the voltage on the collected charge
- Source to sensor distance about 1 cm
- **SRIM simulation show main peak at 4.4 MeV**
- **The measured peak is at about 3.9 MeV**
- Uncertainty on source to sensor distance
- Some of the sensor regions are masked by aluminium (energy loss)
- Non-negligible amount of low energy events
  ⇒ hits in the edge region

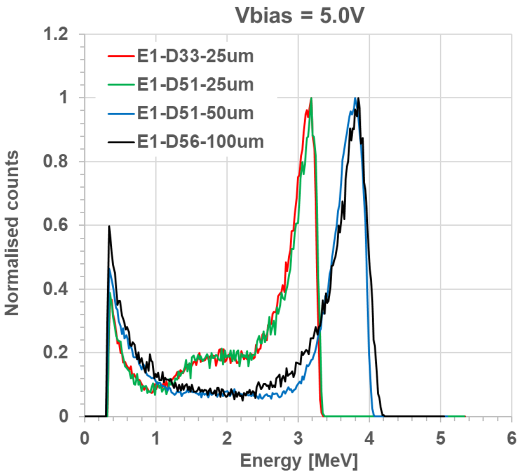


Functional characterisation

^{241}Am alpha particle source (5.5 MeV)

Sensor comparison

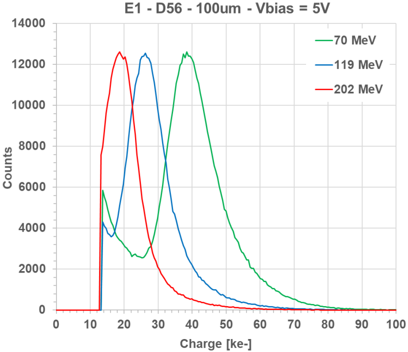
- Bias voltage 5V for all sensors
- Comparable behaviour for pitches 50 and 100μm
- Considerable reduction for 25μm pitch
- Electrode density too high?
- Electrodes are effectively ”dead” volume so particle crossing them have less ionisation in the silicon bulk
- Simulations are being carried out to further understand this issue

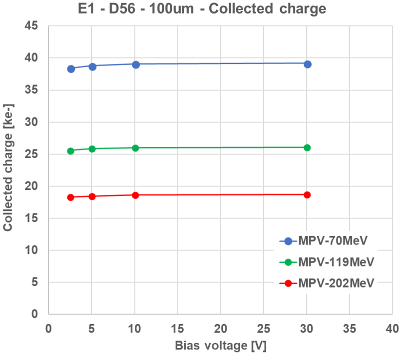


Proton beam test (70, 119, 202 MeV)

Functional characterisation

Proton beam: 70, 119 and 202 MeV

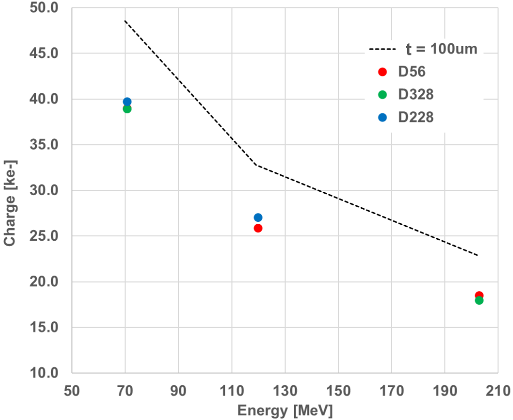




- Excellent separation between different proton energies even for very low bias voltage
- Landau fit to extract the Most Probable Value (MVP)
- Charge saturation at around 5V for 100μm pitch sensor (earlier for others)
- Higher energies have lower SNR
- Minimum Ionising Particle should deliver roughly 8000 electrons, undetectable with self-triggering due to noise
- But... Something is not completely as expected here...

Functional characterisation

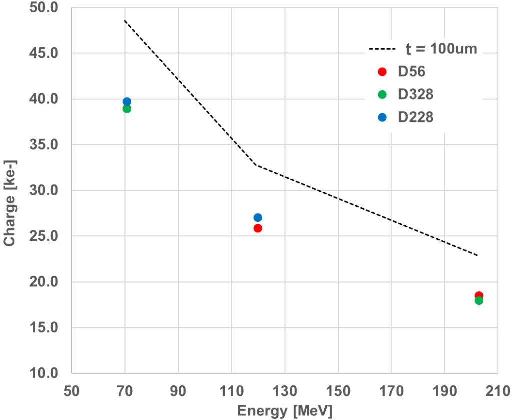
Proton beam: 70, 119 and 202 MeV

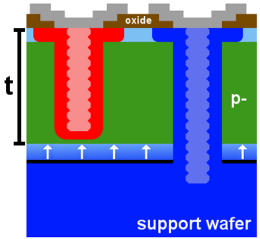


- Measurements do not agree with simulations
- SRIM suggests higher charge for 100μm thick sensors

Functional characterisation

Proton beam: 70, 119 and 202 MeV

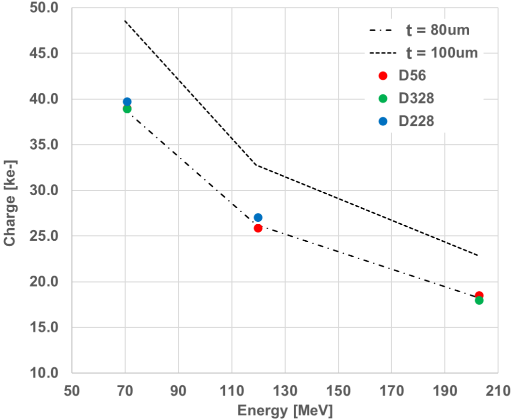


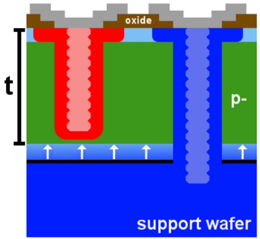


- Measurements do not agree with simulations
- SRIM suggests higher charge for 100μm thick sensors
- These are Si-Si wafers $\Rightarrow$ there is "back-diffusion" of the doping of the support wafer into the sensor wafer
- Loss in active thickness is estimated at 20μm

Functional characterisation

Proton beam: 70, 119 and 202 MeV





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- SRIM suggests higher charge for 100μm thick sensors
- These are Si-Si wafers $\Rightarrow$ there is "back-diffusion" of the doping of the support wafer into the sensor wafer
- Loss in active thickness is estimated at 20μm
- Simulations repeated with 80μm thickness are in much better agreement

Functional characterisation

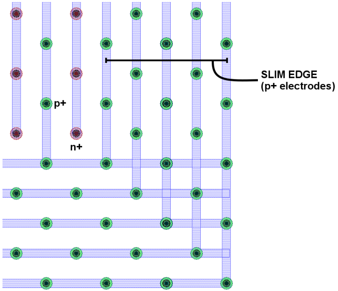
NOISE CONSIDERATIONS

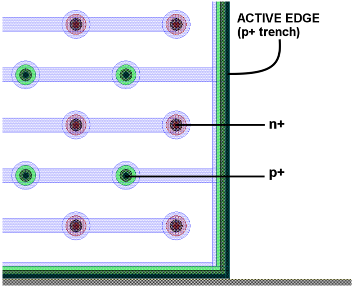
Sensor ID	Size [mm^2]	d1 [μm]	d2 [μm]	r [μm]	noise [ke^-]	Signal - 202MeV proton [ke^-]	SNR
D33	4x4	25	12.5	17.7	2.00	18.3	9.15
D51	4x4	50	25.0	35.4	0.86	18.3	21.23
D56	4x4	100	50.0	70.7	0.73	18.3	25.07
D228	2x2	25	12.5	17.7	1.28	18.3	14.27
D328	2x2	50	25.0	35.4	0.76	18.3	24.08
D386	2x2	100	50.0	70.7	0.71	18.3	25.77

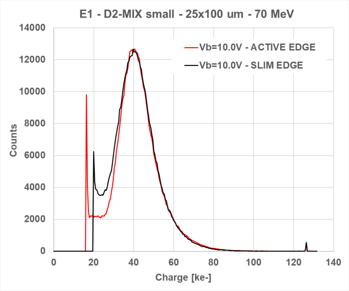
- Sensors with 25μm electrode pitch show much larger noise figures
- This is due to the high electrode density and reduced distance
- This is problematic when detecting low ionisation levels
- The sensor with 50μm pitch is the sensor of choice for reduced electrode pitch a good noise performance
- **All noise related issues can be solve by using 3D sensors in strip or pixel configurations**
- **This will also allow to cover larger areas (counting rates) and will offer position sensitivity**

Functional characterisation

Consideration on edge termination



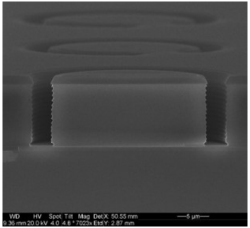


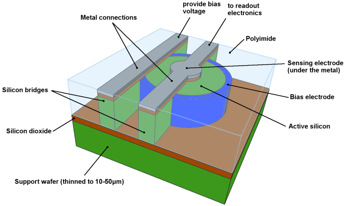


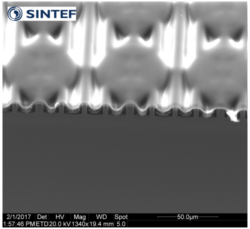
- The edge termination can affect the measured radiation spectrum
- Two types of termination are available in this sensor run
- SLIM-EDGE: fence of p+ electrodes
- ACTIVE-EDGE: p+ trench surrounding the sensor very close to the active area
- The ACTIVE-EDGE delivers much less low-energy events
- The ACTIVE-EDGE also allows for seamless tiling of multiple sensor chips for coverage of larger areas

Outlook and future activities...

Tissue Equivalent 3D Micro-dosimeters



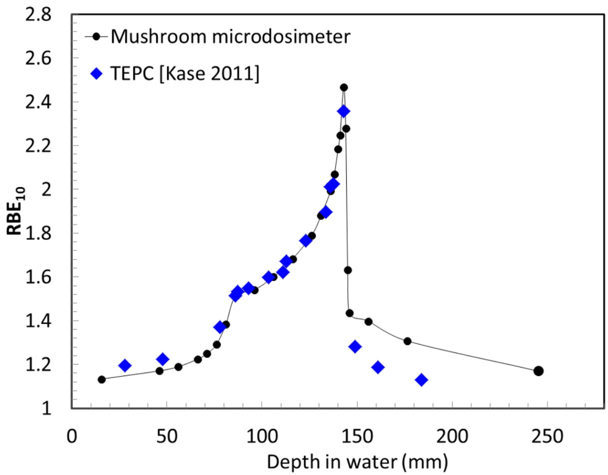




- Developed in collaboration with CMRP (Wollongon, Australia)
- Create isolated structures comparable in size to human cell
- Remove the excess silicon by plasma etching
- Replace silicon with a tissue-equivalent material (PMMA, polyimide...)
- Allows operation in mixed radiation field
- Allows to calculate all microdosimetry quantities and extract the Radio Biological Effectiveness of the radiation field
- Based on a patent from CMRP (US patent No. 8421022 B2)
- This technology is in its early stages and requires additional development

Characterisation of early device implementation

Microdosimetric Kinetic Model (MKM) - Measurements courtesy of CMRP



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

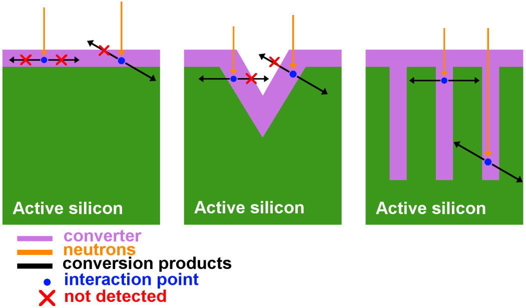
$$\alpha = \alpha_0 + \frac{\beta}{\rho \pi r_d^2} y^*$$

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

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

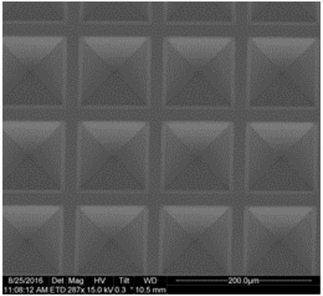
- $\alpha_0 = 0.13\ Gy^{-1}$; $\beta = 0.05\ Gy^{-2}$;
- r_d=0.42 μm is the radius of sub-cellular domain in MK model, V_0=150 keV/μm
- Where $D_{10,R}$=5 Gy is 10% survival of 200 kVp X rays for HSG cells

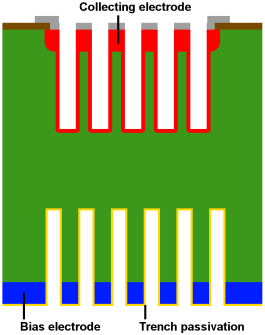
Neutron detectors



- Bare silicon is not able to detect neutrons
- Converting materials are needed: ^{10}B, LiF, B_4C etc...
- Planar films do not offer very high detection efficiencies
- Advanced micro-machining techniques can provide high aspect ratio micro-structures to house the converter for improved neutron detection efficiency

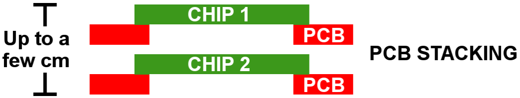
Neutron detectors

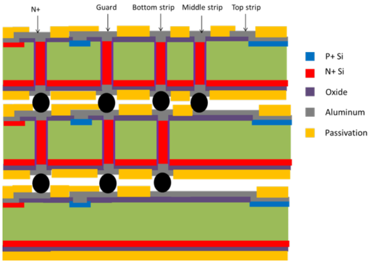




- SINTEF has previously produced sensors with pyramidal micro-structures coupled with neutron converters
- Detection efficiency was roughly 20%
- Higher efficiency can be achieved with high aspect ratio structures
- Best efficiency in literature is about 50%
- There is room for improvement

Advanced chip stacking for compact sensor modules

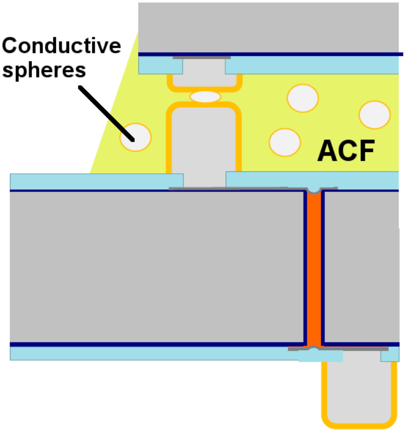




- Stacking multiple chips can offer several advantages
- Stacking strip sensors can offer 2D position sensitivity
- Many approaches rely on multiple support boards (bulky sensor module)
- Using Through Silicon Vias (TSV) and bump bonding, the sensor module can become very compact
- Each layer can be tuned to detect a specific type of radiation
- TSV technology is available at SINTEF but needs further development

Advanced chip stacking for compact sensor modules

- Anisotropic Conductive Film (ACF)
- Can replace Bump Bonding
- Considerable simplification of the bonding process
- Adhesive film with randomly dispersed conductive spheres
- The chips pressed together and some of the spheres will be ”trapped” between chip pads
- ACF is available at SINTEF but needs additional testing, especially on sensor applications



Conclusions

- We have produced a batch of 3D silicon radiation detectors with an optimised fabrication process
- The devices exhibit very good electrical characteristics and the yield is high
- Radiation detection tests show correct sensor operation
- It was possible to identify an optimal sensor configuration in terms of noise, charge collection capabilities and operating voltage
- Similar sensors are currently being irradiated with high energy protons and neutrons up to extremely high fluences to estimate radiation damage effects (results to be presented at the IEEE NSS later this year)
- Additional funding is being sought for the development of other sensor technologies for space applications

SINTEF

Technology for a better society

BACKUP SLIDES

PROTON TEST WITH ALUMINIUM SHIELDING

4.52 g/cm^2 Aluminium