iWoRiD 2022
23rd International Workshop on
Radiation Imaging Detectors
26 – 30 June 2022
Riva del Garda, Italy

Contribution ID: **104** Type: **Oral**

3D silicon detectors for neutron imaging applications.

Tuesday 28 June 2022 17:30 (20 minutes)

Neutron detection has historically been achieved using ^{3}He or BF$_3$ gas detectors. The scarcity of ^{3}He, and the toxicity of BF$_3$, have driven detector research into finding new solutions for efficient neutron detection. For applications in neutron imaging with thermal neutrons, planar silicon detectors coated with neutron converting materials (^{10}B and ^{6}Li) have shown promising results in terms of space and time resolution [1]. The limitations in neutron detection efficiency of planar detectors come from non-optimised converter thickness (self-absorption of the conversion products in the film) and geometrical effects resulting in loss of conversion products [2]. The use of micro-machining promises to eliminate many of these issues, by creating high-aspect ratio micro-structures housing the converter material which should increase both the neutron conversion probability and the chances of detecting the conversion products [3]. Many research groups have investigated 3D neutron detectors by means of single- and double-sided trenches, pillars, and single-sided matrixes of micro-structures in different configurations [4]. Although not all these approaches are compatible with imaging applications, experimental neutron detection efficiency over 40% were reported using the 'stacked' method and the 'pillar' method [4].

Several aspects are cited in the literature as limiting factors of current 3D neutron detectors: (i) non-optimized micro-structure geometry (diameter/width, depth, and pitch), (ii) inactive layers at the silicon/converter interface, and (iii) difficult conformal deposition of the neutron converters.
Our project, "INDET –Improved efficiency for Neutron DETectors", aims at addressing several of these limitations.
The sensors were designed and fabricated at SINTEF MiNaLab, using a N-on-P planar process with a shallow entrance window and p-spray isolation. The wafer layout includes diodes, strip detectors and pixel detectors compatible with the Medipix/TimePix readout chips. The micro-structures housing the neutron converter are etched by means of Deep Reactive Ion Etching - DRIE.
The 3D microstructures are not doped to reduce the extension of the dead layers that could negatively affect the detection of the conversion products. Passivation of the structures is achieved by Atomic Layer Deposition (ALD) of Al$_2$O$_3$, an excellent passivation material with high content of negative trapped charge (>2x10^{12} cm-2) and low interface defects [5]. The ALD process parameters (deposition temperature, thickness, post process anneal etc.) were studied in detail at the University of Oslo by means of QSSPC lifetime measurements and C-V measurements on MOS capacitors with Al$_2$O$_3$ dielectrics before and after irradiation. Optimal passivation was achieved in the presence of native oxide and for Al$_2$O$_3$ thicknesses in the range of 30-90nm, deposited at temperatures spanning wide range (150-300°C) [6]. Successful passivation was maintained after 1MRad γ and β irradiations, with only minimal variation in trapped charge and interface defects density.
The neutron converter of choice is ^{10}B$_4$C, deposited at Linköping university with a newly developed CVD process that will ensure extremely conformal deposition into the high aspect ratio 3D structures [7]. The deposition process was tested on dedicated structures fabricated at SINTEF with excellent results in conformality and step-coverage and will soon be implemented on the sensor wafers.
The final 3D micro-structures implemented on the sensors were designed with the aid of Geant4 simulations using the NCrystal library [8]. Simulations were carried out at the University of Bergen. Different combinations of structure shape, size, depth, and pitch were investigated to study their effect on neutron conversion probability and detection efficiency. The peak simulated efficiency was found to be 31.8% for trenches of width $2\mu m$, filled with converter, with a pitch of $4\mu m$ and etched to a depth of $100\mu m$. The impact of the neutron converter thickness was also studied, and the optimal converter thickness was found to be in the order of $1\mu m$. Many of the investigated structures are being fabricated on wafer to verify the simulation results.
In this presentation, we will report on the details of the design aspects, microstructure geometry and their

fabrication/passivation, neutron converter depositions and electrical measurements. The expected neutron detection efficiency will be discussed. In-depth characterisation of the sensors in neutron beams will be carried out at different facilities. The first results are expected before the end of 2022.

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The authors acknowledge funding from the Norwegian Research Council (Research Project no. 289437 – NANO2021 program).

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Session Classification: Sensors