Simulation studies for optimization of geometrical parameters of 3D neutron detectors

Arvind Singh[1] and Anita Topkar[1,*]
[1]*Electronics Division, Bhabha Atomic Research Centre, Mumbai - 400085, INDIA*
* email: anita@barc.gov.in

Introduction

There is an increased demand of neutron detectors for security applications requiring detection of special nuclear materials (SNMs) to prevent proliferation and illegitimate trafficking, for monitoring neutron beams, etc., [1][2]. Commonly, ^{3}He and BF$_3$ gas detectors are being used for such applications due their high efficiencies. However, these detectors suffer from certain issues such as global shortage of ^{3}He, toxicity of BF$_3$, portability, etc.. Therefore, in recent years, there has been a significant interest in the development of semiconductor based, mainly silicon based thermal neutron detectors as an alternative to these gas filled detectors. Silicon detectors have advantages of compactness, low operating voltage requirement and low cost due to well established fabrication technology and possibility of large-scale production [2].

Planar structured silicon based thermal neutron detectors, where a detector is coated or integrated with the converter material/layer (commonly ^{10}B due to high thermal neutron absorption cross section of 3800 barn) are reported to have maximum efficiency in the range 2-3%. This low efficiency is the consequence of limitations on convertor material/layer thickness due to self-absorption of the secondary charged particles produced in the interaction of neutron with converter material (^{10}B (n, α) ^{7}Li). One of the ways for improving the efficiency of silicon based neutron detector is to increase the thickness of ^{10}B by making the trenches or array of pillars filled with ^{10}B. We have initiated the development of a high efficiency 3D structured thermal neutron detector having array of PIN diode pillars filled with ^{10}B. Initial simulation results for optimizing the geometrical parameters of the 3D pillar structured thermal neutron detector are presented in this paper.

Simulation studies

The device structure for the 3D neutron detector was visualized comprising thin PIN pillars with ^{10}B filled in the trenches around them. Considering the range of secondary particles generated due to neutron interaction with ^{10}B, the pillar cross section was considered to be a few μm^2. In order to increase the quantity of ^{10}B, the pillars were considered with height of a few tens of microns (Type I). In the inverse 3D structure, holes in a PIN structure were considered to be filled with ^{10}B (Type II). Considering these device structures, 3D models were generated in FLUKA for carrying out the Monte Carlo (MC) simulation studies. The 3D model for Type I structure is shown in Figure 1(a). In the Type I structure, the thermal neutron interacts with the ^{10}B filled between the pillars and the secondary particle produced will deposit part of its energy in the adjacent PIN diode pillars and the signal from all the pillars can be collected using a common electrode on the top and bottom. In Type II structure which is inverse of Type I, the secondary particle deposit energy in the common PIN structure. The cross sectional top views of two types of structures are shown in Figure 1(b) and (c).

The simulations were carried out for studying the effect of pillar geometrical parameters on the efficiency of the detector for thermal neutron detection. The aim of this study was to optimize the geometrical design parameters such as pillar height (etch depth for ^{10}B filling), pillar cross-section or trench cross section and separation between the pillars or trenches [3].

Based on the simulation results, the energy deposition in active volume (i.e. in PIN diode region) of the Type I detector for varying depth is plotted in Figure 2. This data was generated for varying etch depth or trench depth (^{10}B filling depth) from 2 µm to 100 µm by keeping the trench cross section fixed (4 µm x 4 µm). It can be depicted from the plot that the energy deposition in the detector active volume increases with the increase in the ^{10}B filled trench depth when the cross-sectional area is kept constant. Up to the depth of 50 µm, the energy deposition is observed to increase monotonically. However, further increase in the trench depth beyond 50 µm does not result in significant increase in the energy deposition in the detector active volume. Similar results were also obtained for the Type II detector.

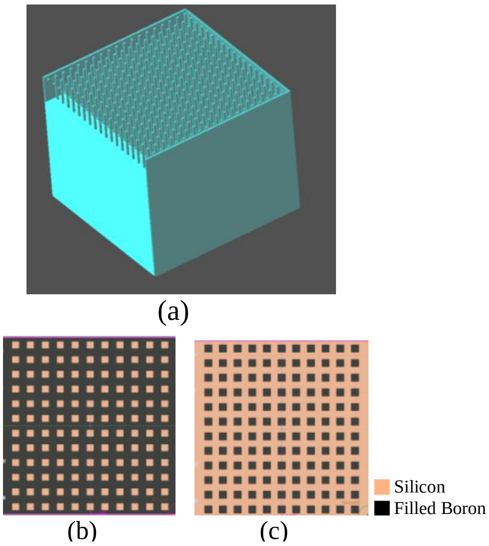

Figure 1. (a) 3D representation of thermal neutron detector of Type I having array of PIN diode pillars the gap between the pillars is to be filled with ^{10}B, **(b)** Top view of Type I detector, **(c)** Top view of Type II detector.

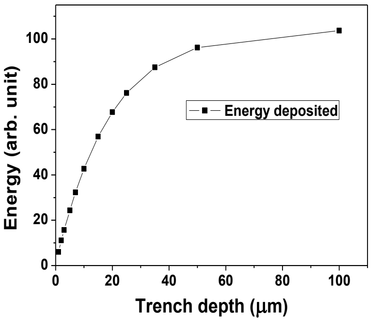

Figure 2. Energy deposition in the Type I detector active volume for a trench size of 4 µm x 4 µm with variable depth.

Further simulations were performed keeping the etching depth fixed at 50 µm and by varying the pillar/trench cross section and distance between the pillars/trenches. Various values of gap (2 µm / 3 µm / 4 µm) between two trenches were simulated along with different cross-sections (4 µm^2 / 9 µm^2 / 16 µm^2). Due to fabrication limitations, cross section below 4 µm^2 was not considered. The consolidated simulation results in terms of detector neutron detection efficiency with various geometrical parameters are presented in Table 1.

Table 1. Simulated efficiency of 3D detector with various geometries.

Pillar/Trench size (Depth 50 µm)	**Spacing between the pillars / Trenches**	**Efficiency (%)**
Geometry of Type I		
2 µm x 2 µm	2 µm	40.75
3 µm x 3 µm	3 µm	31.81
4 µm x 4 µm	4 µm	25.77
Geometry of Type II		
2 µm x 2 µm	2 µm	20.45
3 µm x 3 µm	3 µm	21.26
4 µm x 4 µm	4 µm	19.56

Results and Discussion

Simulation results as presented in Table 1 show that for Type II structure, there is no significant increase of neutron detection efficiency as the trench cross section is reduced. Compared to Type II structure, Type I structure has more efficiency. In this structure, significant increase in the efficiency can be obtained by reducing the cross section of pillars. Based on these simulation studies and fabrication process limitations, a few designs have been finalized for the fabrication of 3D thermal neutron detectors.

References

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