Towards high efficiency solid-state thermal and fast neutron detectors

2012 JINST 7 C03014

(http://iopscience.iop.org/1748-0221/7/03/C03014)

PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *November 23, 2011*
ACCEPTED: *February 2, 2012*
PUBLISHED: *March 7, 2012*

2nd INTERNATIONAL WORKSHOP ON FAST NEUTRON DETECTORS AND APPLICATIONS,
NOVERMBER 6–11 2011,
EIN GEDI, ISRAEL

Towards high efficiency solid-state thermal and fast neutron detectors

Y. Danon,[1] J. Clinton, K.C. Huang, N. LiCausi, R. Dahal, J.J.Q. Lu and I. Bhat

Rensselaer Polytechnic Institute,
100 8th Street, Troy, NY 12180, U.S.A.

E-mail: danony@rpi.edu

ABSTRACT: Variety of applications of fast neutron detection utilize thermal neutron detectors and moderators. Examples include homeland security applications such as portal monitors and nuclear safeguards which employ passive systems for detection of fissile materials. These applications mostly rely on gas filled detectors such as ^{3}He, BF$_3$ or plastic scintillators and require high voltage for operation. Recently there was considerable progress in the development of solid-state neutron detectors. These operate by detection of charged particles emitted from neutron interactions with a converter material. In order to increase neutron detection efficiency to a usable level, the thickness of the converter material must exceed the range of the charged particles in the converter, which limits the efficiency of planar detectors to several percent. To overcome this limitation three dimensional structured solid-state devices are considered where the converter can be thicker but still allow the charged particles to escape into the semiconductor. In the research described here this was accomplished by a semiconductor device that resembles a honeycomb with hexagonal holes and thin silicon walls filled with the converter material. Such design can theoretically achieve about 45% thermal neutron detection efficiency, experimentally about 21% was observed with a partially filled detector. Such detectors can be fabricated in variety of sizes enabling designs of directional fast neutron detectors. Other converter materials that allow direct detection of fast neutrons were also considered by both simulation and experiments. Because the semiconductor thickness is less than a few hundred microns, the efficiency of these detectors to γ-ray(s) is very low.

With further developments these new solid-state neutron detectors can replace gas ionization based detectors in most applications.

KEYWORDS: Solid state detectors; Neutron detectors (cold, thermal, fast neutrons)

---

[1] Corresponding author.

doi:10.1088/1748-0221/7/03/C03014

Contents

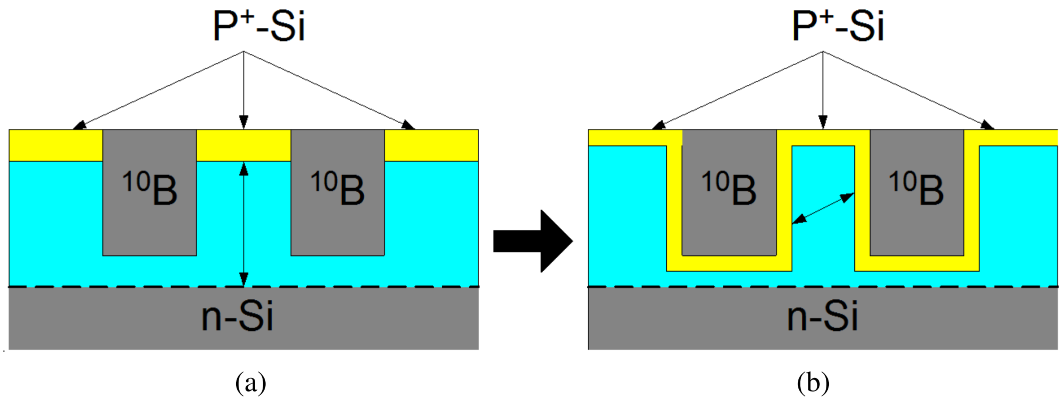
1 Introduction

Traditional thermal neutron detectors mostly utilize gas-based detectors or scintillators and employ a converter material with large total cross section. In these detectors neutrons are converted to charged particles (typically α-particles) which can ionize the detector material and thus indirectly indicate that a neutron interaction occurred. Fast neutron detectors can also employ the kinetic energy of the neutron to cause recoils that are also charged particles and thus provide a conversion process similar to thermal detectors. In various applications thermal neutron detectors and moderators are used to detect fast neutrons. The advantage of some of the existing concepts such as ^{3}He gas-based detector is the high neutron detection efficiency and γ-ray(s) insensitivity. Some of the disadvantages of gas-based or scintillators detectors are the requirement of high voltage bias and the associated detector costs. Recently the inventory of ^{3}He was greatly reduced, which increased the cost of such detectors rendering them unobtainable for most applications.

The purpose of this research is to develop a low cost solid-state based thermal neutron detector that can be produced in small and large sizes, be cost effective and robust, reduce or zero the bias voltage, has a high neutron detection efficiency and low γ-ray(s) sensitivity, and thus provides a good alternative to current neutron detectors. The concept behind such detector is very similar to what was described above by using silicon based detector and boron based converter. The detector is intended to be used in low radiation environment such that radiation damage to the silicon semiconductor is not a concern. It was also attempted to adhere to standard fabrication technologies common in the solid-state industry and thus reduce the cost.

2 Detector construction

Solid-state neutron detectors use a converter with which the neutron interacts to create two charged particles that can be detected by the solid-state device. Planar detectors with a layer of converter coupled to the solid-state device have an efficiency limited by the range of the charged particles in the converter [1]. For the case of ^{10}B the boron layer thickness layer is limited to about 3 μm. When taking the low level discrimination into account the resulting maximum efficiency is about 5% [1]. Methods to overcome this problem were previously described in the literature; they include



(a) (b)

Figure 1. (a) previous designs of a perforated detector, a PIN diode structure with long electron-hole migration paths, (b) the current design is fully depleted with the charge collection layer surrounding the boron layer.

the all boron carbide detector [2–4] and structured geometries [5, 6]. All these detectors attempt to have more converter material embedded in the detector layer. The all boron carbide detector is a homogenous mixture of boron and carbon and the structured devices are heterogeneous adding boron in perforation in the solid-state detector. The boron carbide detectors are currently limited to a thin layer because of the low charge mobility in the material [2]. When using a structured detector the boron is embedded in trenches or holes in the silicon. In previous work [5, 7] the silicon region is operated like a PIN diode which increases the leakage along the silicon/boron interface (see figure 1a) and thus limits the depth of the structure. The device discussed here overcomes this issue by a fully depleted design as illustrated in figure 1b. The charge collection layer surrounds the silicon depletion region and thus provides more efficient charge collection and also enables deeper structures. Because of this higher charge collection efficiency such devices can operate without any bias. For pillar width less than 4 μm such device has capacitance similar to a planar diode, which is important for preventing degradation of the signal.

2.1 Device optimization

Before the devices were fabricated, a series of analytical calculations and GEANT 4 [8] simulations were performed in order to find the optimum device dimensions and geometry [9]. Geometries considered included trenches, square holes, pillars, and hexagonal holes, an example of simulation results is shown in figure 2 for the hexagonal holes which proved to be the geometry of choice. The simulations assumed a thermal neutron beam incident orthogonally to the front side of the detector and an energy deposition discrimination of 200 keV. The results indicate $\sim$45% efficiency for a hole separation (silicon wall thickness) of $\sim$1 μm and boron hole diameter of 2.8μm. It also provides information on the sensitivity of the efficiency to the structure parameters. The calculations presented here were performed assuming boron density of 2.35 g/cm^3, reduction of boron density to 1 g/cm^3 results in about 12% reduction in the efficiency and change of optimal dimensions to favor smaller hole separation.

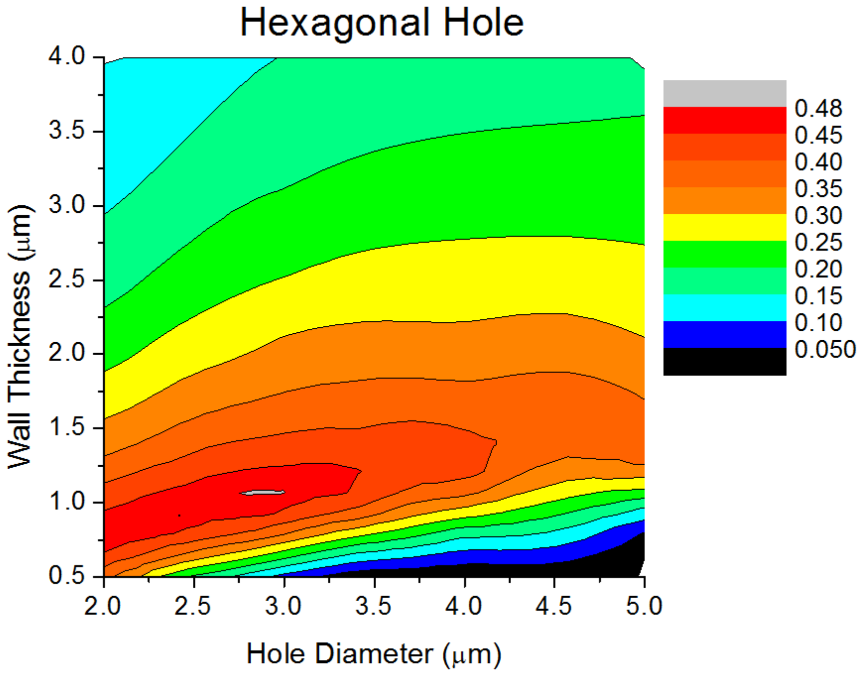
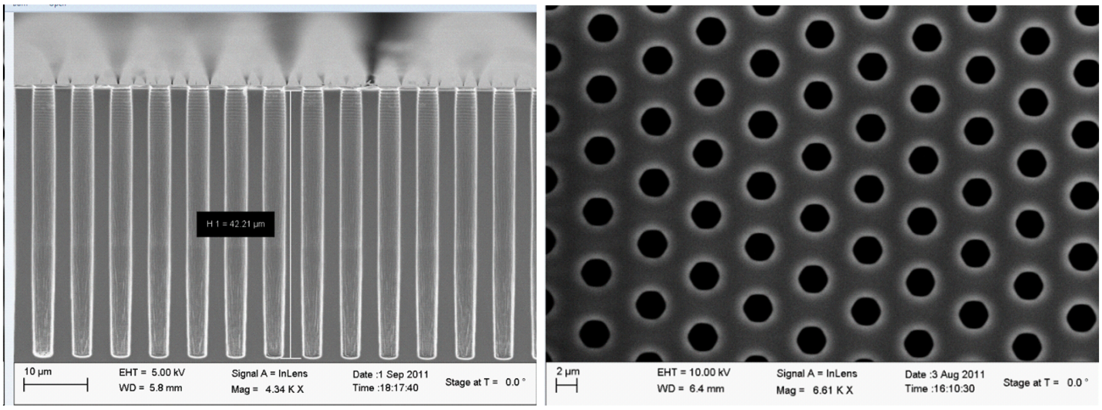


Figure 2. Results of optimization simulations for hexagonal shaped boron holes which are 40 μm deep. The maximum efficiency is about 45% for a hole separation of $\sim$1 μm and boron hole diameter of 2.8μm.



(a) (b)

Figure 3. Example of etched hexagonal holes with depth of 42 μm and hole diameter of 2.5 μm. (a) a cross sectional view through the wafer and (b) is a top view.

2.2 Device fabrication

Device fabrication uses standard clean room equipment consistent with the longer term goal of drastically lowering the cost of these devices. Fabrication starts with a silicon wafer of the proper doping concentration, the wafer is then masked and etched to the desired geometry. The Deep Reactive-Ion Etching (DRIE) process was used and up to 60 μm deep etching was achieved, figure 3 shows an example of etched hexagonal holes.

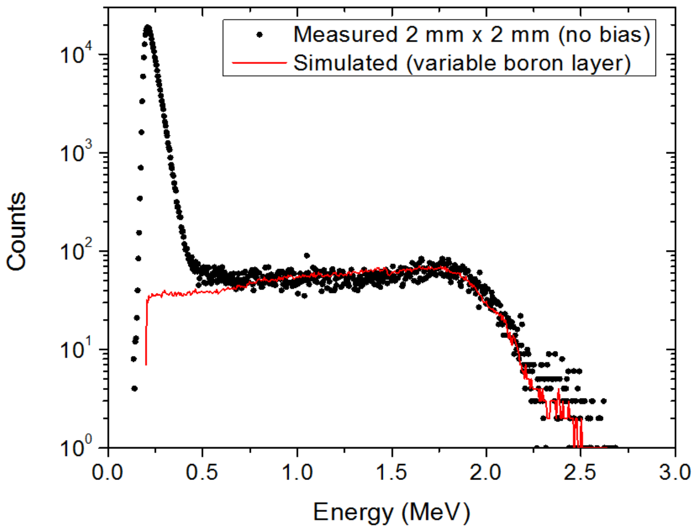


Figure 4. Comparison of the measured and calculated pulse height distribution of the hexagonal solid-state detector. The measurement was performed with zero bias.

The boron fill process is performed using Low Pressure Chemical Vapour Deposition (LPCVD) with variations of pressure and temperature variations with time. In the first phase of this process the temperature is elevated to 900 $^\circ$C for 15 minutes to form the P^+ layer. Boron is then deposited at temperatures in the range 500-600 $^\circ$C, with pressure kept at 300 mTorr. After the boron fill is complete, the top layer is etched using standard DRIE process and contacts are made using aluminium evaporation. The device is then packaged for testing in a standard metal socket. The mask was designed such that multiple devices of different sizes are packaged together and available for testing.

3 Results and conclusions

In order to test the device, a calibrated thermal neutron source was produced. The setup included ^{252}Cf source emitting fission neutrons in a moderated geometry. The moderator size was 61cm x61cm x40cm with the ^{252}Cf source embedded in the centre of the 61cm x 61cm face placed 2.5cm from the face of maximum neutron emission. The flux was measured using gold activation foils, a small Li-Glass detector, and a BF_3 detector. Measurements were taken with and without Cd cover such that the average thermal flux could be determined. The results at different distances from the moderator face were compared with MCNP [10] calculations. At the test distance of 18 cm from the moderator face, the flux was found to be 702±20 n/cm^2/s thermal neutrons (in May 2010).

The detector under test was placed in a cast aluminium box connected to a Cremat [11] modified preamplifier with 45ns time constant and a fast shaper (100ns time constant). The pulse height distribution is shown in figure 4 where the experimental results are compared with GEANT 4 [8] simulations. It was also observed that application of 9V reverse bias slightly reduced the detector noise and thus improved the efficiency.

The best measured efficiency with a detector partially filled with natural boron was 4.5 ± 0.3% and the simulation of the same device results in 4.8% efficiency. Scaling this measured efficiency to a boron fill which is 95% enriched in ^{10}B results in an efficiency of about 21%, which is one of the highest efficiencies reported in the literature for a single detector of this type.

The efficiency measurement and calculations described above were performed for a thermal neutron beam incident on the front side of the detector. When the detector is covered or embedded in a moderator, the neutron flux can enter the detector from all directions and streaming paths along the silicon are removed. The result is a higher detection efficiency compared to the case of a collimated beam hitting the front face which was previously calculated. Calculations indicate that in a moderated geometry the efficiency of a single detector (filled with 99% ^{10}B) increases to about 75%. This efficiency represents the ratio of thermal neutrons detected to the number of neutrons entering the detector volume [12].

Experiments and calculations performed with γ-ray(s) indicate low energy deposition and low interaction probability with the silicon ($\sim$6x10^{-4} for ^{60}Co 1.174 MeV and 1.332 MeV γ-ray(s) and active layer of 40 μm).

Experiments and calculations were also conducted for a detector filled with parylene-n (simulated at C_8H_{10} with density of 1 g/cm^3). Such device provides direct detection of fast neutrons by proton recoil reactions with the plastic. For a hole depth of about 28 μm the measured efficiency measured using fission neutrons from ^{252}Cf was found to be 0.11% compared with a calculate value of 0.14%. Although the efficiency is low such detector could be used in applications where the neutron flux is sufficiently high. However at very high flux rates (inside a nuclear reactor) this detector will suffer radiation damage and is not expected to function.

This research indicates that the concept of zero bias semiconductor neutron detectors is promising and can result in low cost detectors of variable sizes. Future challenges include improvement of the boron fill quality, scaling the detector size by using arrays of detectors on a single wafer and integration of the electronics.

References

[1] D.S. McGregor et al., *Design considerations for thin film coated semiconductor thermal neutron detectors — I: basics regarding alpha particle emitting neutron reactive films*, *Nucl. Instrum. Meth.* **A 500** (2003) 272.

[2] A.N. Caruso et al., *The all boron carbide diode neutron detector: comparison with theory*, *Mater. Sci. Eng.* **B 135** (2006) 129.

[3] D. Emin and T.L Aselage, *A proposed boron-carbide-based solid-state neutron detector*, *J. Appl. Phys.* **97** (2005) 013529.

[4] B.W. Ronertson et al., *A class of boron-rich solid-state neutron detectors*, *Appl. Phys. Lett.* **80** (2002) 3644.

[5] R. Nikolic et al., *Fabrication of Pillar-structured thermal neutron detectors*, *IEEE Nucl. Sci. Symp. Conf. Rec.* **2** (2007) 1577.

[6] J. Shultis and D. Mcgregor, *Efficiencies of coated and perforated semiconductor neutron detectors*, *IEEE Trans. Nucl. Sci.* **53** (2006) 1659.

[7] D.S. McGregor et al., *Perforated diode neutron detector modules fabricated from high-purity silicon*, *Radiat. Phys. Chem.* **78** (2009) 874.

[8] S Agostinelli et al., *Geant4 — A simulation toolkit*, *Nucl. Instrum. Meth.* **A 506** (2003) 250.

[9] J. Dingley et al., *Optimization of a novel solid-state self powered neutron detector*, talk given at the *International Conference on Mathematics, Computational Methods & Reactor Physics (M&C 2009)*, May 3–7, Saratoga Springs, New York, U.S.A. (2009), American Nuclear Society, LaGrange Park, U.S.A. (2009).

[10] *MCNP, a general Monte Carlo code for neutron and photon transport, version 5*, LA-UR-05-8617, (2005).

[11] Cremat, Inc. 45 Union St. Watertown, MA 02472 U.S.A., http://www.cremat.com.

[12] J. Dingley et al., *Directional response of microstructure solid state thermal neutron detectors*, in *Transactions od the American Nuclear Society and Embedded Topical Meeting Isotopes for Medicine and Industry (TANSAO)*, volume 103, November 7–11, Riviera Hotel, Las Vegas, U.S.A. (2010).