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Experimental determination of gamma-ray discrimination in pillar-structured thermal neutron detectors under high gamma-ray flux

Qinghui Shao [a], Adam M. Conway [a], Lars F. Voss [a], Radoslav P. Radev [a], Rebecca J. Nikolić [a,*], Mushtaq A. Dar [b], Chin L. Cheung [c]

[a] Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94550, USA
[b] King Saud University, Riyadh 11421, Saudi Arabia
[c] Department of Chemistry, University of Nebraska–Lincoln, Lincoln, NE 68588, USA

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ABSTRACT

In this paper, we demonstrate a detector that has a high neutron-to-gamma discrimination of 8.5×10^5 with a high thermal neutron detection efficiency of 39% when exposed to a high gamma-ray field of 10^9 photons/cm^2 s. The detector is based on a silicon pillar structure filled with a neutron converter material (^{10}B) designed to have high thermal neutron detection efficiency. The pillar dimensions are 50 μm pillar height, 2 μm pillar diameter and 2 μm spacing between adjacent pillars.

Helium-3 tubes are the most widely used technology for detecting neutrons due to their high neutron detection efficiency as well as high gamma-ray discrimination, but there are issues with stability, sensitivity to microphonics, and very recently a shortage of helium-3 [1]. In order to find alternatives, solid-state thermal neutron detectors have been investigated that utilize various architectures and material combinations [2–7]. Many solid-state thermal neutron detectors are more sensitive to gamma-rays compared to helium-3 tubes, which can be an issue because the most nuclear materials emit 10 or more times as many gamma-rays as neutrons. For example, in measurements of spent fuel, gamma-ray fluxes of 1000 R/h ($\sim 10^9$ photons/cm^2 s) or more are encountered, and the gamma-ray discrimination of the detector may dominate all other considerations [8]. The electronic pulses generated by gamma-rays can be readily rejected by setting a high low-level-discriminator (LLD). However, a high LLD setting will limit the registration of low-energy pulses created by neutron events. The gamma-ray discrimination and intrinsic neutron detection efficiency are therefore important figures-of-merit for evaluating the performance of a neutron detector. In this paper, we report the performance of our pillar structured thermal neutron detector's gamma-ray discrimination properties under a high gamma-ray flux environment (up to 10^9 photons/cm^2 s). This is more than 10,000 times higher than the typical gamma-ray flux used for determination of gamma-ray discrimination in semiconductor based thermal neutron detectors [4–6,9–12]. This is important because high fluxes can be associated with pulse pile up effects, which can limit the utility of this class of detectors.

^{10}B is selected as the neutron converter material because of its high thermal neutron cross-section of 3840 barns, compared to 940 barns of ^{6}Li, which is also a popular neutron converter in solid-state thermal neutron detectors [2,3]. The thermal neutron capture reaction by ^{10}B can be described as follows [13]:

$$^{10}_{5}\mathrm{B} + ^{1}_{0}n \rightarrow \begin{cases} ^{7}_{3}\mathrm{Li}(1.015\ \mathrm{MeV}) + ^{4}_{2}\alpha(1.777\ \mathrm{MeV})\ (\text{ground state},\ 6\%) \\ ^{7}_{3}\mathrm{Li}^{*}(0.84\ \mathrm{MeV}) + ^{4}_{2}\alpha(1.47\ \mathrm{MeV})\ (\text{1st excited state},\ 94\%). \end{cases} \quad (1)$$

The reaction byproducts deposit their energy into the semiconductor and generate electron–hole pairs. The charge carriers are swept out by an internal or applied electric field and collected by the electrodes for the registration of a neutron event. The selected semiconductor material should have a relative low atomic number (Z) and density (ρ) for the purpose of low gamma-ray interaction [13]. Silicon is used in our pillar detectors because it has both a low Z of 14 and ρ of 2.33 g/cm^3. Murphy et al. reported that Si provides

* Corresponding author.
E-mail address: nikolic1@llnl.gov (R.J. Nikolić).

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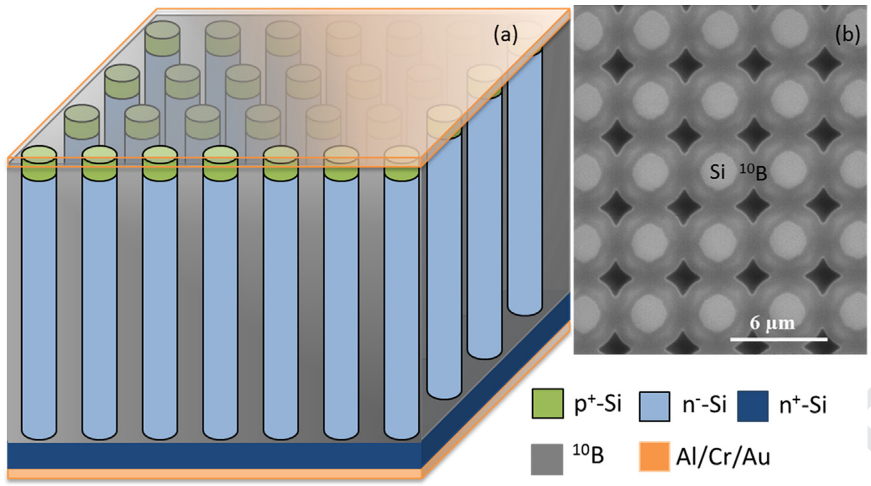

Fig. 1. (a) Schematic of a pillar structured solid-state thermal neutron detector with 2 μm pillar diameter, 2 μm pillar spacing and 50 μm pillar height (the dimensions are not to scale) and (b) scanning electron microscopy image of boron filled pillar arrays (top view).

better gamma-ray rejection compared with other semiconductor materials, i.e. C (diamond), ZnO, GaAs, and CdTe [14].

Our Si–^{10}B detector design uses a three-dimensionally integrated approach. The geometrical constraints on the converter material thickness are decoupled from the limitation of the ion track length [4–7]. The ^{10}B thickness is defined by the pillar height, chosen as 50 μm, which is three times the mean free path of thermal neutrons in ^{10}B. The pillar pitch of 4 μm (2 μm pillar diameter and 2 μm pillar spacing) is designed to allow a high probability of interaction between the energetic ions and the semiconductor pillars, created by nuclear reaction of the neutron with ^{10}B [4]. We have reported a 48.5% of intrinsic thermal neutron detection efficiency using this design [7]. Fig. 1(a) shows a schematic of a pillar structured thermal neutron detector. A silicon wafer comprised of a 3 μm p^+ layer and a 47 μm intrinsic layer (n^-) epitaxially grown on an n^+ substrate was used for device fabrication. The pillar diameter and spacing were defined lithographically followed by deep reactive ion etching to form a 50-μm-tall pillar array. A conformal ^{10}B coating was deposited to fill the gaps in the pillar array by chemical vapor deposition [15]. A Plasma Quest electron cyclotron resonance etcher was used for boron etching on the front side to expose the highly conductive p^+ pillar tops as shown in Fig. 1(b). This was followed by surface planarization using Honeywell Accuflo™ 2027 spin-on-polymer and chemical-mechanical polishing. Finally, metal contacts were formed by sputtering Al/Cr/Au (5000 Å/500 Å/7500 Å) on both sides.

In the pillar detector shown in Fig. 1, neutron absorption only takes place in the neutron conversion material (^{10}B), which is defined by the pillar height. Gamma-ray interaction takes place in the entire Si portion, although only those absorbed in the intrinsic region contribute to the signal. Previously we investigated the effect of the intrinsic layer below the pillars on gamma-ray discrimination in a structure with a 25 μm intrinsic layer [6]. We found that the lowest gamma-ray response occurs when the thickness of intrinsic region below the pillars is reduced to a minimum, which limits the gamma–silicon interaction volume in the active region. Therefore, it is important to select a starting structure where the intrinsic layer thickness is close to the designed pillar height. In this paper, the pillars of the device under test (DUT) were formed by etching completely through the intrinsic region to increase the gamma-ray discrimination.

The experimental setup is shown in the inset of Fig. 2. The DUT was a 2×2 mm^2 detector composed of a 50-μm-tall pillar array. It was attached to the side of a 5 cm-thick high-density polyethylene (HDPE) moderation fixture, which houses a ^{252}Cf source of

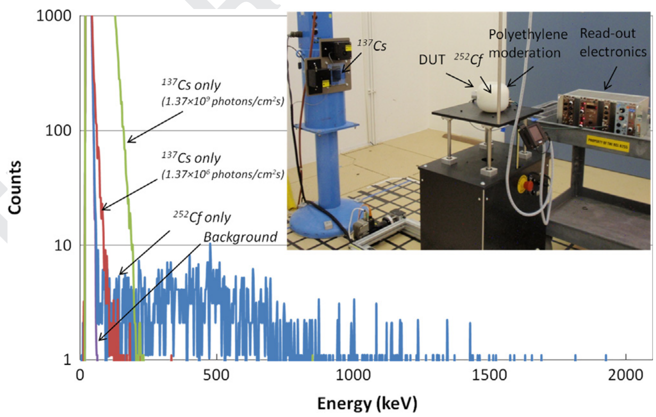

Fig. 2. Measured background spectrum (no source), neutron spectrum and gamma spectrum of a 2×2 mm^2 50-μm-tall pillar detector. ^{137}Cs and ^{252}Cf were used as the gamma-ray source and the neutron source, respectively. The inset shows the experimental setup.

2.5×10^{-2} μg. The ^{252}Cf source primarily emits fission neutrons and had an activity of 13.44 μCi based on NIST calibration. The HDPE fixture moderates the high energy neutrons to produce thermal neutrons (~0.025 eV). The thermal neutron flux on the detector surface was 48 n/cm^{2}s. This is obtained by measuring the neutron spectra of a calibrated pillar detector having the same geometry (2×2 mm^2) with the same experimental setup. The thermal neutron detection efficiency of the calibrated pillar detector was obtained using two techniques as discussed in Ref. [7]. The gamma-ray flux on the detector surface was controlled by varying the distance between the detector and a large 662 keV ^{137}Cs gamma-ray source with an activity of 218.2 Ci. Data acquisition was carried out using an Ortec 142C preamplifier, an Ortec 572 shaping amplifier with a shaping time of 0.5 μs, and an Ortec AMETEK EASY-MCA-2K multichannel analyzer. The measurement live time was set to 20 min. The energy calibration of the electronic readout was performed by using external calibrated capacitors [16,17].

In order to investigate the gamma-ray discrimination at different flux levels, 1.37×10^6 and 1.37×10^9 photons/cm^2 s were obtained by positioning the DUT away from the ^{137}Cs source at distance of 632 cm and 20 cm, respectively. Fig. 2 shows the measured neutron and gamma spectra of the DUT using the geometry shown in Fig. 1. The fractional standard deviation of the neutron counting measurement is 3.2% obtained by $\sqrt{N}/N$, where N is the total number of recorded neutron counts. The