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Neutron detection using large area silicon detectors

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Abstract

We present large-area silicon detectors for neutron detection. To detect neutrons, the silicon is coated with a thin reactive layer, such as ^{10}B or ^{6}Li, which has a high probability of interacting with incident thermal neutrons. Each neutron interaction in the reactive layer results in an alpha particle to be detected by the semiconductor, plus a recoil nucleus. A large-area thermal neutron detector of this type was recently constructed at the Naval Research Laboratory by coating a 9.5 cm × 9.5 cm, 0.5 mm thick silicon strip detector with a thin (1.5 μm) layer of ^{10}B. This device was used to detect the 1.47 and 1.78 MeV alpha particles that result from the interaction of incident thermal neutrons with ^{10}B. The device also detected tritons when coated with ^{6}LiF. This has prompted the development of a custom large-area thermal neutron detector. This design is fabricated using Silicon-on-Insulator (SOI) wafers, potentially enabling low-cost and high-volume manufacture of the detector arrays. Furthermore, the SOI technology allows for thinner (7 μm) silicon layers that significantly reduce the instrument's sensitivity to gamma ray backgrounds.

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Keywords: Silicon detector; Neutron detector; Thermal neutron; 3D detectors; SOI

1. Introduction

Semiconductor detectors have been used as neutron detectors for decades. In these detectors, the semiconductor is coated with a converter material such as ^{10}B or ^{6}Li (often in the form of ^{6}LiF), which has a high probability of reacting with incoming thermal neutrons, resulting in an alpha particle and a recoiling nucleus. The alpha particles resulting from the neutron interaction with ^{10}B have an energy of approximately 1.47 and 1.78 MeV and will only travel a short (less than 5.7 μm) distance before depositing the majority of their energy in the detector material. The neutron interaction in ^{6}Li leads to a 2.05 MeV alpha particle and a 2.73 MeV triton. Fast neutrons can be detected in a similar fashion by using hydrogen rich materials as converters and relying on elastic scattering of the neutrons with the hydrogen nucleus. Several research groups [1–3] have done pioneering work in the development of semiconductor neutron detectors. Recently, much progress has been made in increasing the efficiency and performance of thin-film coated GaAs (gallium-arsenide) detectors. Researchers at Kansas State University [2] have worked on optimizing detector parameters such as what thickness of ^{10}B and ^{6}LiF yields an optimal efficiency.

2. Measurements

We have recently demonstrated a neutron detector using existing single-sided silicon strips detectors. The neutron detector was implemented by coating a 64-channel silicon strip detector (similar to those described in Ref. [4]) covering an area of 9.5 cm × 9.5 cm with 99% pure, 1.5 μm thick ^{10}B layer. The strip detector was fabricated on 150 mm diameter high resistivity silicon wafers and is shown in Fig. 1.

The measured alpha particle spectrum resulting from neutron irradiation of this ^{10}B-coated strip detector array is

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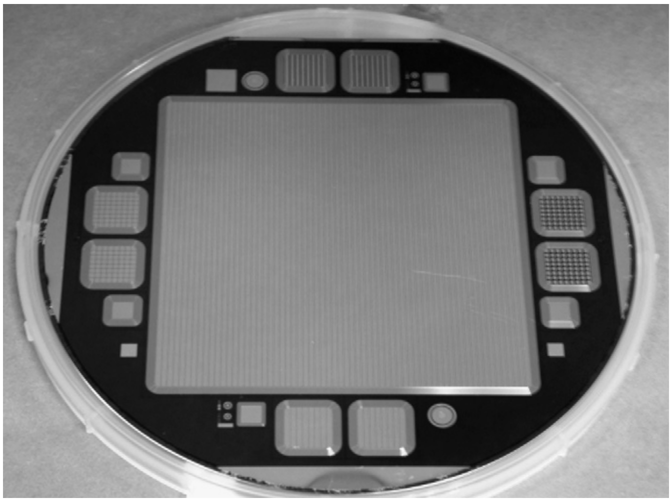

Fig. 1. Photograph of the single-sided silicon strip detector wafer used. The central detector is 96 mm × 96 mm in area and 0.5 mm thick.

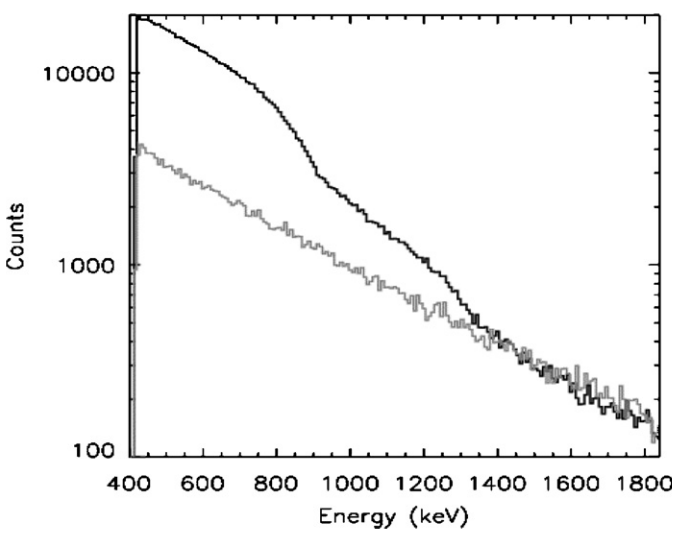

Fig. 2. Measured spectrum under neutron irradiation with ^{10}B (black) and without ^{10}B (gray). The two different alpha energies are clearly visible.

shown in Fig. 2. The bottom curve is the spectrum of background gamma rays. The top curve shows the spectrum resulting from 1.47 and 1.78 MeV alpha particles. The source of neutrons was a 10 Ci AmBe source held in a small barrel filled with paraffin. The source generates a mix of fast and slow neutrons. There is a large flux of gamma rays associated with the source. That gamma ray background is the cause of the steeply falling continuum seen in the spectrum.

An interesting feature of this strip detector is that the capacitance of the detector elements is low enough that it was possible to readout 50 channels having an area of $7\,\text{cm} \times 9\,\text{cm} = 63\,\text{cm}^2$ using one amplifier with good energy resolution for both the 1.47 and 1.78 MeV alpha particles. This is due to the detector thickness of 0.5 mm. If better gamma ray rejection is desired, thinner silicon detectors are

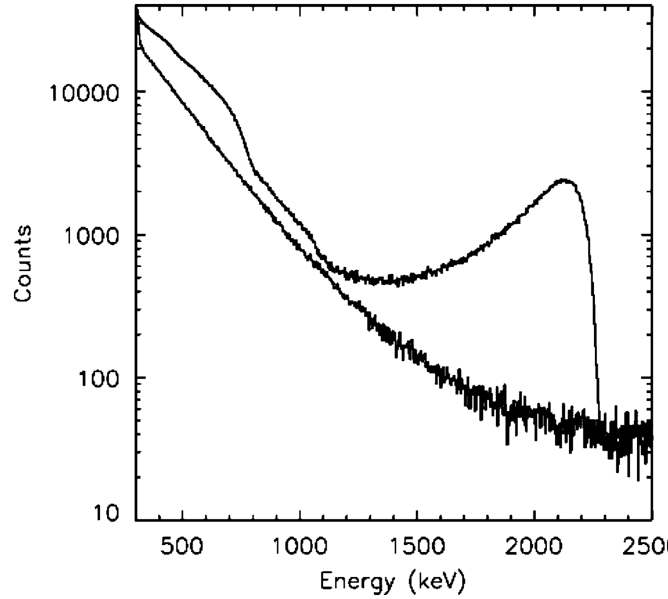

Fig. 3. Measured spectrum under neutron irradiation with ^{6}Li (top) and without ^{6}Li (bottom). The triton peak is clearly visible near 2 MeV.

required and the detector segmentation requirement will increase.

The same detector was then coated with an additional converter layer of ^{6}LiF. The LiF was mixed with a binding agent and then spread over part of the back of the detector shown in Fig. 1. The LiF was spread along ~30 strips, so that the same detector could be used for source and background studies. The spectrum obtained under neutron irradiation is shown in Fig. 3.

The two enhancements from the alpha particles generated in the ^{10}B layer are still visible. The main feature is now the large peak at ~2200 keV. This peak is generated by the triton's recoil nucleus after the alpha particle is emitted from the Li nucleus. Since the triton is only singly charged, it has a longer range than the alpha particle from the same reaction and does not deposit very much energy in the boron and aluminum layers that are between the Li layer and the active silicon. The alpha particle generated in the reaction does not provide a clear peak because its energy is mostly absorbed within the LiF, B, and Al layers.

If a silicon detector was coated directly with a layer of ^{6}Li instead of ^{6}LiF, the alpha particles and the tritons should both reach the active layer. This was modeled in GEANT4 [5] and the expected spectrum for a 3 μm layer of ^{6}Li on top of 0.5 μm of Al and 0.5 μm of inactive silicon is shown in Fig. 4. The high-energy peak in Fig. 4 is from tritons, and the lower peak is from alpha particles. Since the triton and the alpha particles are emitted back to back, a detector covering a 2π solid angle that can detect both species would act like a 4π detector that can only detect the tritons. The device has a potential detection efficiency of ~10% based on the neutron cross sections in lithium and the range of the secondaries in the lithium.