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Design and operation of a 2-D thin-film semiconductor neutron detector array for use as a beamport monitor

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ABSTRACT

Silicon-based diodes coated with a thin film of neutron reactive materials have been shown to produce excellent low-efficiency neutron detectors. This work employs the same technology, but groups 25 equally sized and spaced diodes on a single 29 mm by 29 mm substrate. A 5×5 array was fabricated and coated with a thin film of ^{6}LiF for use as a low-efficiency neutron beam monitor. The 5×5 neutron detector array is coupled to an array of amplifiers, allowing the response to be interpreted using a LabVIEW FPGA. The 5×5 array has been characterized in a diffracted neutron beam. This work is a part of on-going research to develop various designs of high- and low-efficiency semiconductor neutron detectors.

1. Introduction

Coated semiconductor diodes have been used as neutron detectors for many decades. The typical design consists of a Schottky barrier or *pn* junction diode that has a neutron reactive coating, such as ^{10}B or ^{6}LiF, applied over the top of the device. Low cost, compact size, low power requirement, ruggedness and adaptability for the end user are advantages that coated diodes have over many other types of neutron detectors [1–3].

The following work describes the development of a *low-efficiency* 2-D silicon-based neutron detector array for use as a nuclear reactor beam port monitor. The detector is operated upstream of other instrumentation in order to monitor the neutron beam in real time while performing experiments in the beam. The low efficiency allows the neutron beam to remain relatively unperturbed as it proceeds through the detector to the experiment station, hence neutron beam attenuation is negligible. The detection array yields valuable real time and time-averaged information about the neutron flux as a function of position.

2. Theory

Thin-film-coated semiconductor neutron detectors are generally configured as planar semiconductor diodes with a thin film of neutron reactive material deposited upon the diode surface. Detector operation is straightforward. Neutrons are absorbed in the neutron reactive film, which spontaneously releases ionizing reaction products. The most commonly used "converter" films rely either on the ^{10}B(n,α)^{7}Li reaction or the ^{6}Li(n,t)^{4}He reaction.

The ^{10}B(n,α)^{7}Li reaction releases a 1.47 MeV α particle and a 840 keV ^{7}Li ion with 94% branching, or a 1.78 MeV α particle and a 1.05 MeV ^{7}Li ion with 6% branching. Pure ^{10}B has a microscopic thermal neutron cross-section of 3840b, which translates into a macroscopic thermal neutron cross-section of 500 cm^{-1}.

The ^{6}Li(n,t)^{4}He reaction releases a 2.73 MeV triton and a 2.05 MeV α particle. Pure ^{6}Li has a microscopic thermal neutron cross-section of 940b. Unfortunately, pure ^{6}Li is hygroscopic and highly reactive, hence not easily handled as a neutron converter material. However, the stable compound LiF has proven to be easily handled, and can be applied to the surface of a diode by a variety of methods [1]. Pure ^{6}LiF has a mass density of 2.54 g cm^{-2}, which translates into a macroscopic thermal neutron cross-section of 57.5 cm^{-1} [1].

Of the two main candidate films, ^{6}LiF has the most energetic ionizing reaction products, thereby, being easier to detect and discriminate from background radiations. For thermal neutrons, conservation of mass and energy demands the reaction products to be ejected in opposite directions, hence only one of the particles can enter the diode active region (see Fig. 1). The overall thermal neutron detection efficiency varies with the film thicknesses, reaching an optimum value of approximately 4.5%, depending upon the lower-level discriminator setting of the detection system [1]. In the present case, the device is designed to operate with low efficiency, hence application of the ^{6}LiF thin film is straightforward.

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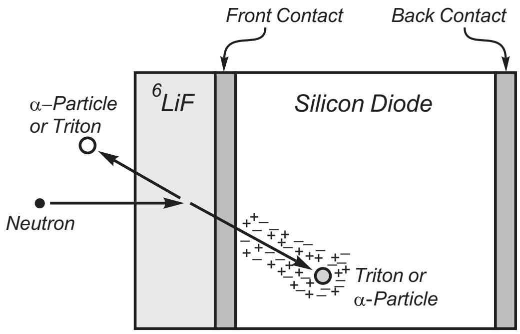

Fig. 1. Thin-film thermal neutron detector concept. Only one reaction product can enter the semiconductor detector.

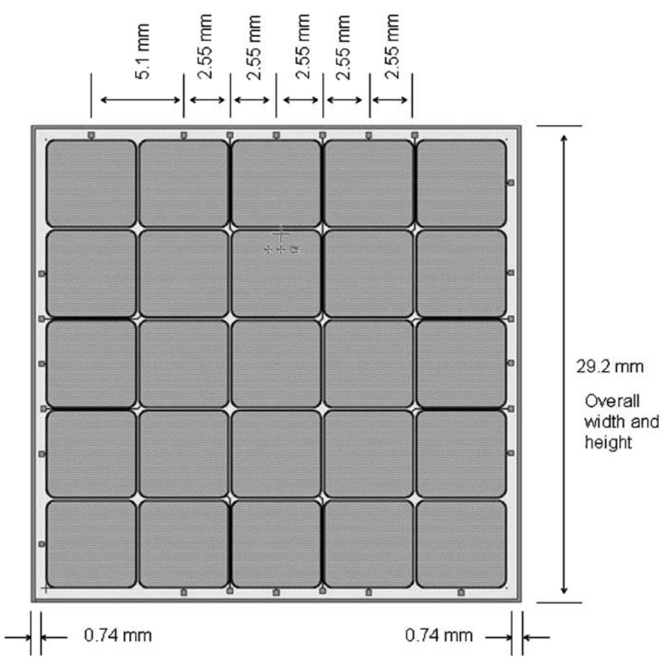

Fig. 2. The layout of the 2-D ^{6}LiF-coated real-time beam port monitor.

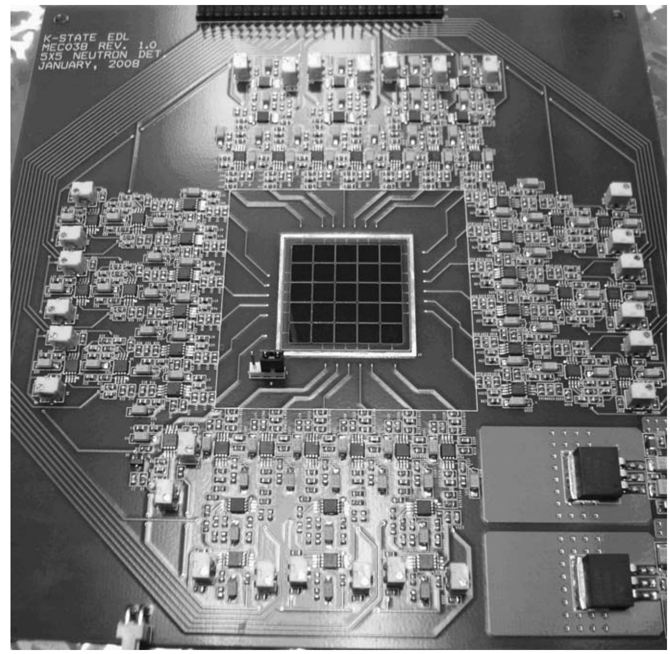

Fig. 3. Assembly of detector array and amplifier board.

3. Chip design and detector assembly

The size of the 2-D detector was designed such that the active area of each pixel is approximately 0.25 cm^2. The spacing between pixels was kept to a minimum, allowing only enough room for the signal output traces (Fig. 2).

Devices are fabricated in float zone, single-side polished, $>10\,\mathrm{k}\Omega\,\mathrm{cm}$, and n-type silicon wafers 76 mm in diameter and approximately 400 μm thick. The detectors are processed with common VLSI processing steps (described elsewhere [2,3]). The diodes are subsequently coated with a thin film of ^{6}LiF approximately 1 μm thick with physical vapor deposition, a thickness that yields approximately 0.5% thermal neutron detection efficiency [1]. The detector array chip is then coated with Humiseal®. Afterwards, the device is mounted on an amplifier board (Fig. 3).

The amplifier board consists of 25 identical amplifier circuits, each with an adjustable threshold voltage that allows for individual adjustments of each channel to compensate for different noise levels between channels. The overall threshold voltage for the entire chip can also be changed via a single potentiometer. The amplifier board is designed to allow a bias to be applied, however the built-in potential of the detectors is enough to operate the detectors, hence for all testing the detector array was operated with no bias applied. The center of the amplifier board is cut out at the chip location so that the neutron beam will not interact (scatter or activate) with the amplifier board.

The output of the amplifier board is connected to a LabVIEW field-programmable gate array (FPGA). A LabVIEW program displays the data as a 2-D array. The data is then shown on three intensity graphs with accompanying 5×5 matrices, where each location represents a pixel on the detector. Each channel in the program can be assigned a scaling factor so that any non-uniformities in detector efficiency between pixels can be adjusted and corrected.

The program has three different display modes, one of which shows the cumulative counts, another the instantaneous counts per second, and the last display shows the average counts per second over a user selected time interval. The intensity graphs are user selectable between color and black/white and feature nearest neighbor, bilinear, bicubic, and bicubic spline interpolation routines for easier interpretation. Fig. 4 shows images for accumulated counts, the spontaneous count rate (cps), and the average count rate (cps) for cases without interpolation, noting that the different gray scale intensities indicate results recorded for each pixel. Fig. 5 shows black and white images for the accumulated counts, and the spontaneous and average count rates, with bicubic $4\times$ interpolation. Note that the detector was moved during the measurement, which caused the lower bulge in the real time cps image.

4. Experimental setup

4.1. Uniformity calibration

The 2-D neutron detector was tested in a 12.7 mm diameter diffracted neutron beam located at the Kansas State University TRIGA Mark II nuclear reactor. The flux at this position is approximately $2\times10^{4}\,\mathrm{n\,cm^{-2}\,s^{-1}}$. The detector was positioned with the center pixel in the center of the neutron beam and a measurement of the neutron flux was recorded. The detector was then translated such that each remaining pixel was repositioned

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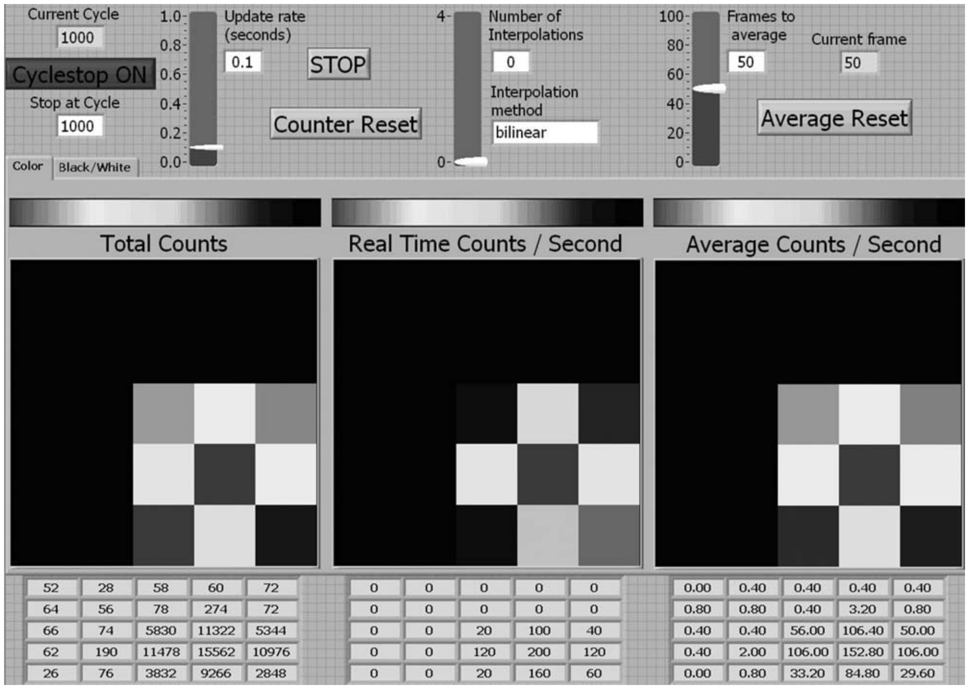

Fig. 4. LabVIEW program displaying beam image with no interpolation.

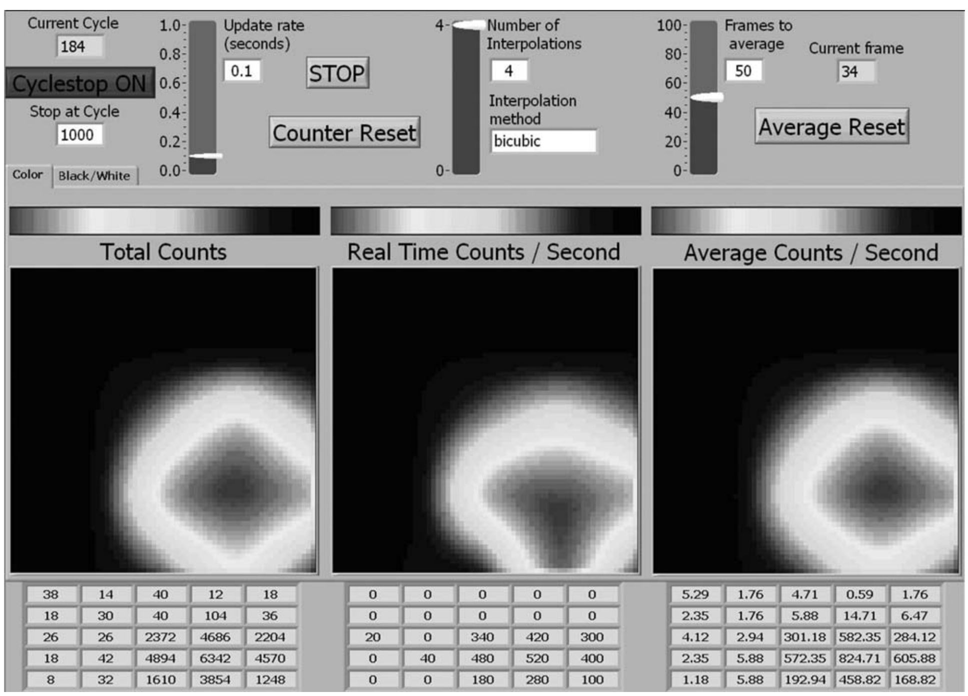

Fig. 5. LabVIEW program displaying beam image with bicubic $4\times$ interpolation.

in the beam center at the same initial location of the first pixel such that each pixel witnessed virtually the same neutron beam flux. The counting efficiencies for each pixel were recorded and appropriate scaling factors were assigned to the individual pixels in the LabVIEW program.

4.2. Calibrated uniformity test

With scaling factors assigned to each channel, the 2-D detector was retested in the neutron beam using the same procedure as before. After repositioning and testing each pixel, they were all found to record counts within 2% error of each other.

5. Conclusions

A 5×5 pixelated neutron beam monitor has been designed, constructed, and tested in a thermal neutron beam from a TRIGA Mark II nuclear reactor. Scaling factors have been programmed into each pixel to yield a real time, uniform, 5×5 neutron detection array. This basic tool allows for real-time beam port

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imaging and monitoring for neutron irradiation experiments (Figs. 4 and 5).

6. Future work

Detector construction is straightforward with common VLSI fabrication techniques, indicating that the basic design can be scaled up and larger beam port imaging array in-line monitors can be fabricated. Using the same concept and advanced perforated semiconductor detector technology [4–6], a high efficiency 1-D 1024 channel array is nearing completion, and will be installed at the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory for use in small-angle neutron scattering experiments [3].

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References

[1] D.S. McGregor, M.D. Hammig, H.K. Gersch, Y.-H. Yang, R.T. Klann, Nucl. Instr. and Meth. A 500 (2003) 272.
[2] W.J. McNeil, S.L. Bellinger, T.C. Unruh, E.L. Patterson, J.K. Shultis, D.S. McGregor, Perforated diode fabrication for neutron detection, in: IEEE NSS Conference Record, 2006, p. 3732.
[3] W.J. McNeil, et al., Preliminary tests of a high efficiency 1-D silicon pixel array for small angle neutron scattering, in: IEEE NSS Conference Record, October 2007.
[4] S.L. Bellinger, W.J. McNeil, T.C. Unruh, D.S. McGregor, Angular response of perforated silicon diode high efficiency neutron detectors, in: IEEE Nuclear Science Symposium, Waikiki, Hawaii, October 28–November 3, 2007.
[5] D.S. McGregor, R.T. Klann, US Patent 7,164,138, allowed January 16, 2007.
[6] D.S. McGregor, R.T. Klann, US Patent 6,545,281, allowed April 8, 2003.