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1-D Array of Perforated Diode Neutron Detectors

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Elsevier use only: Received date here; revised date here; accepted date here

Abstract

Performance of a 4 cm long 64-pixel perforated diode neutron detector array is compared to an identical array of thin-film coated diodes. The perforated neutron detector design has been adapted to a 1-D pixel array capable of 120 micrometer spatial resolution and counting efficiency greater than 12%. Deep vertical trenches filled with ^{6}LiF provide outstanding improvement in efficiency over thin-film coated diode designs limited to only 4.5%. This work marks the final step towards the construction of a much larger array consisting of 1024 pixels spanning 10 cm. The larger detector array will be constructed with a sub-array of the 64-pixel sensors, and will be used for small-angle neutron scattering experiments at the Spallation Neutron Source of Oak Ridge National Laboratory.

Keywords: Perforated diode, 3D microstructured detector, Solid state neutron detector, Neutron scattering detector

1. Introduction

A 1-D array of thin-film neutron detectors was previously fabricated specifically for small angle neutron scattering measurements at the Spallation Neutron Source (SNS) of Oak Ridge National Laboratory (ORNL). The first prototype array, consisting of 32-channels, demonstrated spatial resolution of 119 μm [1], and also the successful operation of newly developed readout electronics [2]. The simple array also demonstrated the advantage of solid-state detectors in neutron imaging. Benefits include precise micron scale structures and high counting rates in the range of 10^6 cps.

Thin-film coated diode detectors are, however, limited in neutron counting efficiency to 4.5% [3]. Recently-developed perforated diode neutron detectors offer a solution to the low efficiency limit of coated diode neutron detectors and have shown intrinsic efficiency as high as 35% for thermal

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neutron measurements [4]. In the present work, the thin-film detector array design has been modified with perforated diode pixels to achieve a more efficient array. This new sensor has been expanded to 64-pixels from the previous 32-pixel design and marks the final progressive step before tiling multiple sensors into a larger 1024 channel system.

2. Sensor Design and Fabrication

Each pixel is 4 cm long and is just wide enough to accommodate a single trench 30 µm wide that runs the entire length of the pixel. A p-type diffusion is performed on high resistivity n-type silicon (>10,000 Ω-cm) to layout a diode 20 µm wide around the perimeter of the trench (Fig. 1).

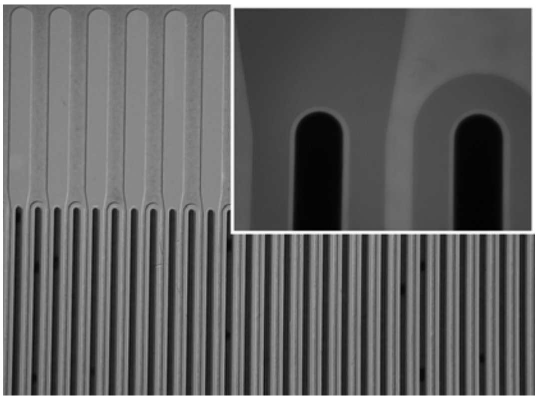

Figure 1: Perforated diode pixel array pattern. Large bonding areas extend from the pixels. Close-up shows the 5 um spacing between trenches (black) and diffused area (dark grey).

With 5 µm buffer spacing between the diffused diode region and the etched trench, the total pixel is 80 microns wide overall. This buffer spacing, in addition to a silicon dioxide passivation in the trench, has been shown to substantially reduce leakage current [5]. Each pixel is separated by 20 µm spacing, making the final array pitch 100 µm.

Each trench was plasma etched to a depth of 90 µm. The etch chemistry was optimized to keep the trench sidewalls as smooth as possible to minimize leakage current from surface damage. Careful attention to etching is imperative since deep structures can create surface damage that can propagate into the bulk region of the device thereby compromising device performance.

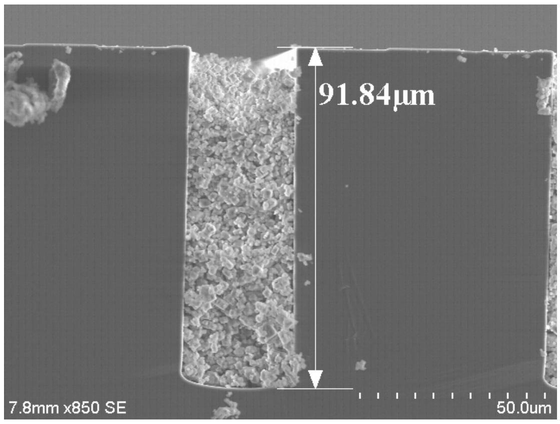

Figure 2: A cleaved devices reveals a trench completely filled with ^{6}LiF powder.

Shallow diffusions only 40 µm wide over a length of 4 cm can provide significant resistance; enough to reduce signal magnitude for radiation interaction events at length from the bonding pad. To alleviate the problem, a metal layer of Al was deposited on top of the diffused region to minimize resistance along the vast length of the pixel. The Al layer also assisted with wire bonding. After the perforated diode array was fabricated with the contacts, ^{6}LiF powder was forced into the trenches (Fig. 2) and a very thin layer of Humiseal® was applied as a protective coating (Fig. 3).

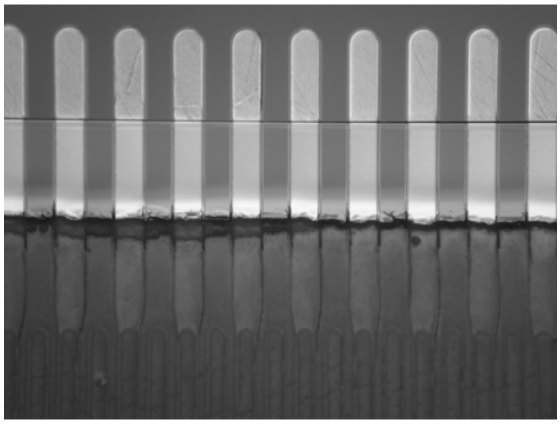

Figure 3: Metalized, coated, and sealed pixel array with exposed bonding pads.

In the final system, the array chip will mount on a small circuit board with traces fanning out to connectors. The connectors allow for a modular design where the sensor array may be easily removed or replaced from the signal processing electronics. Those electronics are all populated on a single large mother-board that provides digital communication to a PC. The mother-board electronics fan out away from the sensor array such that sensitive components conveniently reside outside of the beam path. This design reduces concerns of radiation damage and excessive beam scatter.

3. Experimental Setup

3.1. Efficiency Test

Several 64-pixel chips are to be tested for functionality before being assembled into the 1024-channel system. A failure discovered after mounting 16 chips could be costly and time-consuming to correct. Therefore, a test box was constructed that allows temporary electrical connection to each pixel through two custom probing cards. The alternating pixel design allows for 32 connections from each end of the array, easing the burden of fanning out to larger structures (see Fig. 4).

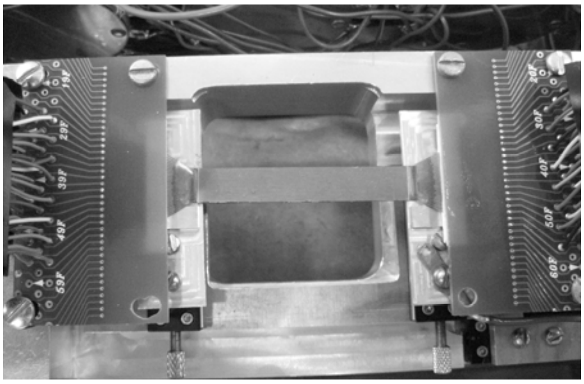

Figure 4: 64-pixel chip test box with two 32-channel probe cards connecting each end of a sensor array chip. The sensor array bridges across a large cavity to minimize beam scatter.

Switches on the test box allow the user to test separate pixels. An Ortec 142 pre-amplifier was connected to the test box and standard NIM electronics were used to collect pulse height spectra from each pixel individually. The pre-amplifier provides an inherent -1.3 volts that is applied to the detector and is sufficient for operating these self-depleting structures. Beam testing was performed in a diffracted beam from the TRIGA Mark II nuclear reactor on-site. The diffracted beam is an excellent source of thermal neutrons at a flux of $2x10^4$ ($cm^{-2}sec^{-1}$), calibrated periodically with a He^3 detector.

With the array located at the center of the neutron beam, a spectral collection was taken on several pixels with and without a Cd sheet blocking the beam. The Cd shielding blocks thermal neutrons, yet will allow for epithermal and higher energy neutrons to pass. Also, the neutron irradiated Cd will produce prompt gamma-rays in a distribution of energies that can extend into the MeV range [6], which can give some indication of the expected sensitivity to background gamma-rays.

3.2. Spatial Resolution Demonstration

The first prototype array was delivered to ORNL for demonstration. On a neutron beam line at the High Flux Isotope Reactor (HFIR), a 300 um slit was placed in beam. The 32-channel system collected counts from all channels simultaneously and plotted them on-screen with a LabVeiw program as they were collected.

4. Results

4.1. Efficiency Test

A typical spectrum collected from a perforated pixel array shows substantial signal formation in the presence of neutrons. The Cd response is quite repressed indicating both that the neutron beam has a low epithermal neutron component and also that the detector is quite insensitive to gamma-rays radiating from the Cd sheet (Fig. 5). The sensitivity of perforated diode neutron detectors to background gamma-rays has been reported elsewhere to be low [7].

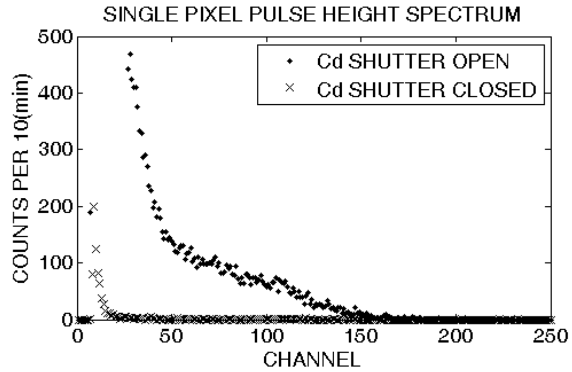

Figure 5: Neutron response from a pixel in the perforated diode array. The difference between the two plots gives true thermal neutron response.

The net sum of thermal neutron counts corrected for the area of the pixel in the beam led to a calculated intrinsic efficiency of 25% for each pixel on average. This is quite remarkable considering that the sensor array is less than 0.5 mm thick.

Previous reports state efficiency of a straight trench perforated neutron detector with 100 µm deep trenches should be 13%, approximately half of the value obtained in this experiment. The difference comes from the way that the pixel array is being biased. The test box was not designed to bias all of the pixels at once. Thus, only the one pixel under test is biased by the pre-amplifier. With neighboring pixels floating, signal charge formed under them is drawn preferentially toward the pixel under test. Considering the perforated design, only half of the counts from a neighboring pixel can be collected by the pixel under test. Thus, a half contribution in counts from two neighbor pixels plus the full contribution from the pixel in test combine to double the counts expected from the single pixel under test.

4.2. Spatial Resolution Demonstration

The 32 channel array was operated for 10 minutes in a HB-2D Future Development beam at HFIR perturbed by a single 300 µm beryllium slit. The slit was approximately 2.5 cm away from the array. Most gas detector arrays offer spatial resolution on the order of millimeters and may have some difficulty resolving such a narrow slit.

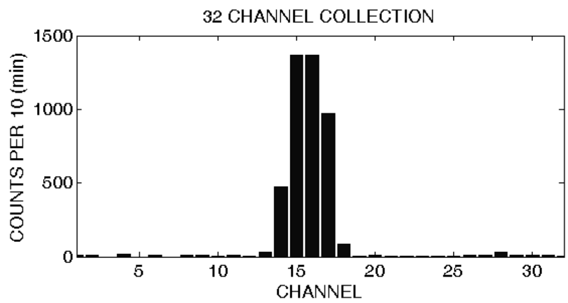

Figure 6: Counts resulting from exposing the array to neutrons passing through a 300 µm slit.

The prototype array however, was able to reveal the presence of the narrow structure accurately. Significant counts accumulated on 4 of the 100 µm wide pixels. Not only is the slit resolved well, it must also have been very well aligned to the long narrow pixel structure. The full-width half-max of the count distribution in the plot was indeed 300 µm.

5. Conclusions

Testing of the new perforated diode pixel array proved to be successful. Pixel chips containing 64 pixels each can be tested on beam line with temporary probing offering very valuable quality tests before permanent mounting in a 1024-channel assembly. The temporary test setup, however, does not provide for accurate efficiency measurement as it is prone to collecting counts from neighbor pixels. Nonetheless, it does verify if a pixel is capable of producing a signal and can be used to easily identify dead pixels before permanent assembly.

The slit experiment proved that this design will be capable of precisely locating diffraction peaks. Such work with this new design will extend capabilities in the study of material stress and strain at the SNS.

6. Future Work

This perforated pixel design holds some unique advantages regarding spatial resolution. In the substantial space between the absorbing trenches, neutrons stream freely through the detector. Additional arrays can be stacked such that trenches align with those streaming paths. The spatial resolution can thus be divided with each stack. In the present case for instance, the spacing between trenches is 70 µm and two identical arrays with trenches 30 µm wide can be stacked beneath the original array so that the trenches occupy 60 µm of the streaming path. Such a structure would offer 40 µm spatial resolution, or one-third of the single array. Furthermore, this increase in spatial resolution could be accomplished with very little loss in efficiency.

Acknowledgements

Dr. Ben Blalock and Dr. Chuck Britton along with their research group at the University of Tennessee, Knoxville, designed the ASIC that provides signal amplification and digital output for the diode array. Dr. Lowell Crowe and his team at Oak Ridge National Laboratory for providing a PC interface card to acquire data from the motherboard, and scheduled beam time at the HFIR. This work was supported by NSF IMR-MIP grant no. 0412208, and DTRA contract DTRA-01-03-C-0051.

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