Perforated Semiconductor Neutron Detector Modules

D.S. McGregor, S. Bellinger, D. Bruno,
W.J. McNeil, E. Patterson, B.B. Rice

SMART Laboratory, Mechanical and Nuclear Engineering Department
Kansas State University,
Manhattan, KS 66506 USA

Abstract: Compact neutron detectors are being designed and tested for use as low-power real-time personnel dosimeters. The neutron detectors are pin diodes that are mass produced from high-purity Si wafers. Each detector has thousands of circular perforations etched vertically into the device. The perforations are backfilled with $^6$LiF to make the pin diodes sensitive to thermal neutrons. The prototype devices deliver over 4.5% thermal neutron detection efficiency while operating on only 15 volts.

Keywords: Semiconductor Neutron Detectors; Perforated Detectors; Perforated Diodes

Introduction
Coated semiconductor diodes have been studied as neutron detectors for many decades [1]. The basic configuration consists of a common Schottky barrier or pn junction diode, upon which a neutron reactive coating, such as $^7$LiF, has been applied. Such devices are compact, easily produced, and have low power requirements. However, they are restricted to low thermal neutron detection efficiencies, typically no greater than 4.5% intrinsic efficiency, due to reaction product energy self-absorption in the neutron sensitive coating [2].

In the present work, the coating is based on the $^4$Li(n,t)$^4$He reaction. When thermal neutrons are absorbed in $^6$Li, a 2.73 MeV triton and a 2.05 MeV alpha particle are ejected in opposite directions. The reaction products from the $^4$Li(n,t)$^4$He reaction are more energetic than those of the $^{10}$B(n,$\gamma$)$^7$Li or $^{157}$Gd(n,$\gamma$)$^{158}$Gd reactions and, hence, are much easier to detect and discriminate from background radiations. $^6$Li has a relatively large microscopic thermal neutron absorption cross section of 940 b, although it is less than $^{157}$Gd and $^{10}$B. The absorption cross section for $^6$Li follows a 1/$v$ dependence [3,4]. Although devices have been fabricated with enriched $^6$Li metal as the converter film [2], pure Li is highly reactive and difficult to prevent from decomposing, even when using encapsulants. It is the stable compound LiF that is used more often. The mass density of $^6$LiF is 2.54 g cm$^{-3}$, and the resulting macroscopic thermal neutron absorption cross section is 57.5 cm$^{-1}$.

The advantages of coated diodes as neutron detectors include compact size, a low power requirement, low cost VLSI mass production methodology, and ruggedness. Yet, since basic planar thin-film coated diode detectors can only achieve practical maximum thermal neutron detection efficiencies of approximately 4.5% [2], they have experienced only modest utilization as neutron radiation detectors.

Recent advances with high-aspect ratio deep etching (HARDE) techniques have allowed for unique perforated neutron detector structures to be realized [5]. Under such a configuration, the diode is permeated with perforations which are backfilled with neutron reactive materials, such as $^{10}$B and $^6$LiF [5]. As a result, the intrinsic thermal neutron detection efficiencies of perforated diodes can be increased above 30%, more than 5 times that of a common planar thin film coated diode [6]. It was shown in previous work that perforated devices incorporating $^6$LiF as the converter can achieve higher intrinsic thermal neutron detection efficiencies than devices with $^{10}$B as the converter [6]. Hence, of the three main materials commonly used for thin-film coated thermal neutron detectors, the following work concentrates only on devices constructed with $^6$LiF as the converter material.

Detector Fabrication
The perforated detectors were produced as Si $p$-type $\text{pin}$ diodes. The diode fabrication processes were carried out on 3-inch diameter float zone, double-side polished, > 10 k$\Omega$-cm, $n$-type TopSil wafers approximately 325 µm thick. The wafers were cleaned with a two-step wet-chemical process consisting of a 5 minute Piranha etch at 120°C followed by a 5-minute Baker Clean:H$_2$O$_2$:H$_2$O (5:1:25) etch at 70°C. Both steps were followed by a 30-second de-ionized (DI)-water: buffered-oxide-etch (6:1). The wafers were rinsed in a DI water cascade for at least 1 minute.

A thick thermally grown SiO$_2$ layer was generated to provide both a diffusion mask and electrical isolation between die on the wafer. The backside oxide on the wafers was stripped and $n$-type junctions were diffused into the back to produce ohmic contacts. A second oxidation step was performed to protect the $n$-type ohmic contact junctions. Photolithography was used to define 5.6-mm diameter circular junction regions on the front of the wafer. Within these circular regions, 42-µm diameter circular oxide dots were defined to prevent dopant introduction into the perforations sites. Shallow $p$-type regions were diffused into the surface, leaving behind, including effects from
sideways diffusion, 38-µm diameter undoped circular regions arranged in a 60-µm center-to-center matrix over the entire 5.6-mm diameter detector p-type junction.

Photolithography was used to define 30-µm diameter open regions aligned and centered over the 38-µm diameter undoped regions in the 5.6-mm diameter p-type circular rectifying junctions. The 30-µm diameter openings are used for the perforation etching step. Hence, the etched holes will not punch directly through the pin junction region, which could otherwise degrade the quality of the rectifying barrier. An inductively coupled plasma (ICP) reactive ion etching (RIE) system (Oxford Plasmalab System 100) was used etch holes into the Si substrate through the 30-µm diameter photoresist openings. The first-generation devices were constructed from devices with only 20 µm deep holes. Next, a final oxidation step was performed to insulate the hole interiors from damage that might occur during the LiF filling process. Photolithography was used to define annuli perimeters around the p-type pad regions. Then liftoff was used to fabricate conductive contacts within the annuli on the p-type regions, where a 250 angstrom layer of Ti followed by a 2500 angstrom layer of Au were evaporated over the substrate. Lastly, the backside n-type region was coated with 250 angstroms of Ti followed by 2500 angstroms of Au. The entire process was developed to accommodate wafer scale mass production. Presently, over 60 detectors can be produced per 3 inch diameter wafer, as shown in Fig. 3.

The perforations in the first generation devices were backfilled by spreading the LiF powder over the devices and gently pressing the material into the holes (Fig. 2). Afterwards, a 22 µm thick 6LiF cap layer was deposited atop the device with physical vapor deposition (Fig. 2). Identical non-perforated detectors were produced, and the same thickness cap layer was deposited upon them during the same deposition process.

**Figure 1.** Perforations are etched into the Si substrate with ICP-RIE. Shown are holes etched into Si, each 30 microns in diameter and 20 microns deep on a center-to-center pitch of 60 microns.

**Figure 2.** The perforations are backfilled with 95% enriched 6LiF material, over which a final cap layer of 6LiF is deposited.

**Figure 3.** The fabrication process developed to produce the perforated detectors was designed for mass production.

**Module Design**

First-generation perforated detectors were coupled to a simple counting system with a low cost, low power, and a small transimpedance and gain amplifier combination. The amplifiers and a detection diode are located in a sealed 4 pin (14 pin footprint) package widely used in the manufacture of crystal oscillators. The wire bonds between the diode and the transimpedance amplifier are also potted in an electronics grade epoxy to ensure stability. Once packaged, the diode “module” is well shielded from external light, electrical noise, and humidity. The module supplies power for the amplifier and perforated detector bias (nominally around 15 volts), and returns a positive polarity pulse output from neutron interactions between 70 and 130 mV with a pulse width of approximately 4 µs.
(depending on the individual diode). The module requires an operating voltage between 2.7 and 5 volts at 150 µA. The module bias supply uses a charge pump circuit with an external adjustment potentiometer to supply between 10 and 20 volts of positive detector bias. It is based on a LT1615-1 DC/DC step up converter. The bias supply is also contained in a 4 pin crystal carrier for noise isolation.

The module requires an operating voltage between 2.7 and 5 volts at 150 µA. The module bias supply uses a charge pump circuit with an external adjustment potentiometer to supply between 10 and 20 volts of positive detector bias. It is based on a LT1615-1 DC/DC step up converter. The bias supply is also contained in a 4 pin crystal carrier for noise isolation.

The device modules were tested, with an $^{241}$Am alpha particle source, for pulse width and pulse height as a function of bias voltage. The pulse widths, on average, leveled off at approximately 3.7 µs beyond 15 volts bias. The pulse height leveled off in magnitude at approximately 130 mV for voltages exceeding 10 volts bias. Since the depletion region need extend only beyond the holes to produce full charge collection, the voltage needed for optimum operation is actually less than needed for full depletion, observed to be 35 volts from CV measurements.

**Figure 4.** Shown is a perforated detector, with a total active diameter of 5.6 mm, mounted alongside the preamplifier circuit.

**Figure 5.** The detectors operate on minimal voltage. Shown are the internal parts to the package, with the detector, preamplifier/amplifier, power supply and digital display. The entire package is powered by 3 AAA batteries.

Pulses exiting the amplifier circuit are converted into a logic-level pulse for the counting circuits. An adjustable voltage level is set with a potentiometer and connected to the negative input of a low power comparator. The pulse is connected to the non-inverting input of the comparator with an r/c filter to remove a small dc offset introduced by the amplification stage. This allows the device to “discriminate” pulse heights, as well as filter out spurious noise. The prototype arrangement operates on 3 AAA cell batteries (4.5 volts), and uses a low power commercial counter to display neutron induced counts. The unit is constructed using surface mount components and techniques, and is housed in an aluminum box. Module testing was initially performed with an $^{241}$Am alpha-particle source. The aluminum housing has a hole drilled above the perforated detector covered by an aluminized mylar window. The hole allows for the 5.5 MeV alpha particles to enter the detector and produce pulses.

The device modules were tested, with an $^{241}$Am alpha particle source, for pulse width and pulse height as a function of bias voltage. The pulse widths, on average, leveled off at approximately 3.7 µs beyond 15 volts bias. The pulse height leveled off in magnitude at approximately 130 mV for voltages exceeding 10 volts bias. Since the depletion region need extend only beyond the holes to produce full charge collection, the voltage needed for optimum operation is actually less than needed for full depletion, observed to be 35 volts from CV measurements.

**Figure 6.** $^6$LiF-coated calibration detector results. The calibration detector was a simple planar device with a 1400 angstrom coating of 95% $^6$LiF.

**Thermal Neutron Measurements**

The devices were tested in a tangential thermal beamport at the Kansas State University TRIGA Mark II Nuclear Reactor Facility. Each detector was tested in the same electronics box under identical conditions. The electronics box and detector were aligned in the beam port using an indexing holder. A thin film coated calibration detector, which had a coating of only 1400 angstroms of 95% enriched $^6$LiF, was used to determine the average thermal flux at a reactor power of 225 kW, which yielded a flux unit of $1.1 \text{ n cm}^{-2} \text{ s}^{-1} \text{ W}^{-1} \pm 0.75\%$. Hence, at a reactor power of 200 W, the average thermal flux at the indexed detector test location was $220 \pm 1.65 \text{ n cm}^{-2} \text{ s}^{-1}$.

A perforated detector and a planar detector, both fabricated identically during the same fabrication run, were tested at a reactor power of 200 W. The reactor power was held constant during the detector apparatus changes in order to ensure that the flux did not change from one detector to the
For each detector tested, a spectrum was accumulated with the detector exposed directly in the thermalized neutron beam and another spectrum was accumulated with a 1 mm thick Cd shield placed between the beam port and the detector. The Cd sheet was placed at the beam port exit several feet away from the detector to ensure that prompt activation gamma rays did not add to the background. The difference between the two spectra yields the net neutron induced counts.

The efficiency determined for the planar device coated with 22 µm of 95% enriched $^6$LiF was 4.5±0.083%, which compares well to theoretical maximum predictions for planar devices [2]. The perforated device yielded 4.85±0.086% thermal neutron detection efficiency, showing an increase over the planar device. By comparison, calculations using the perforated device parameters yielded an expected efficiency of 5.18% [7].

![Figure 7. Perforated detector results, showing the spectra for the shielded and unshielded measurements.](image)

**Conclusions and Future Work**

Si-based perforated diode detectors have been fabricated and demonstrated in compact low-power packages. The shallow hole device yielded 4.85±0.086% thermal neutron detection efficiency, as compared to an identical planar device (no perforations) that yielded 4.5±0.083% thermal neutron detection efficiency. Although a small increase, an efficiency improvement has been demonstrated. The difference between the means of the planar detector counts and the perforated detector counts exceeded 2σ. Future generation devices will be constructed from diodes with much deeper perforations and a tighter perforation matrix. Both changes will increase the intrinsic thermal neutron detection efficiency, with calculations and models indicating that efficiencies above 30% can be reached [6].

**Acknowledgements**

This work was supported under DTRA contract DTRA-01-03-C-0051, National Science Foundation IMR-MIP grant No. 0412208, and US Department of Energy NEER Grant DE-FG07-04ID14599.

**References**