Designs for Thin-Film-Coated Semiconductor Thermal Neutron Detectors

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Abstract—Thin film coated semiconductor detectors have been studied and used as neutron detectors for decades. Unfortunately, with front-irradiated devices, the basic design limits the thermal neutron detection efficiency to only 3.95% for $^{10}$B-coated devices and only 4.3% for $^6$LiF-coated devices. Presented in the following work are several straightforward methods to increase the thermal neutron detection efficiency for thin-film-coated semiconductor thermal neutron detectors.

INTRODUCTION

Thin-film-coated semiconductor devices have been investigated for thermal neutron detection by a variety of research groups [1-7], all of which have generally used $^{10}$B, $^6$Li, $^6$LiF, and Gd coatings as the neutron reactive layer. Each has advantages and disadvantages regarding neutron detection efficiency and background gamma ray discrimination.

I. BACKGROUND AND THEORETICAL CONSIDERATIONS

Since neutrons hold no electronic charge, methods used to recognize neutron interactions within a detector generally rely on second-order effects. Two very common neutron interactions that are used for a variety of thermal neutron detectors are the $^{10}$B(n,α)$^7$Li reaction and the $^6$Li(n,α)$^3$H reaction [1,2,4,7,8]. The $^{10}$B(n,α)$^7$Li reaction results in the following reaction products [9]:

$$^{10}\text{B} + n \rightarrow \begin{cases} 6\%: & ^7\text{Li}(1.015\text{MeV}) + \alpha(1.777\text{MeV}), \\ Q = 2.792 \text{MeV(t to ground state)} \\ 94\%: & ^6\text{Li}^*(840\text{keV}) + \alpha(1.470\text{MeV}), \\ Q = 2.310 \text{MeV(1st excited state)} \end{cases}, \quad (1)$$

which are released in opposite directions when thermal neutrons (0.0259 eV) are absorbed by $^{10}$B. After absorption, 94% of the reactions leave the $^7$Li ion in its first excited state, which rapidly de-excites to the ground state (~$10^{-13}$ seconds) by releasing a 480 keV gamma ray. The remaining 6% of the reactions result in the $^7$Li ion going directly to its ground state. The microscopic thermal neutron absorption cross section is 3840 barns. Additionally, the microscopic thermal neutron absorption cross section decreases with increasing neutron energy, with a dependence proportional to the inverse of the neutron velocity ($1/v$) over much of the energy range [10,11].

The $^6$Li(n,α)$^3$H reaction results in the following products [9]:

$$^{6}\text{Li} + n \rightarrow ^3\text{H}(2.73 \text{MeV}) + \alpha(2.05 \text{MeV}) \quad , \quad (2)$$

$Q = 4.78 \text{MeV}$

which again are oppositely directed if the neutron energy is sufficiently small. The microscopic thermal neutron (0.0259 eV) absorption cross section is 940 barns. The thermal neutron absorption cross section also demonstrates a $1/v$ dependence, except at a salient resonance above 100 keV, in which the absorption cross section surpasses that of $^{10}$B for energies between approximately 150 keV to 300 keV [10,11].

Fig.1. The fundamental approach to a thin-film-coated semiconductor neutron detector. The film thickness should not exceed the maximum range of the “long range” reaction product. The reaction products are emitted in opposite directions.
The $^{157}$Gd(n,γ)$^{158}$Gd reaction leads to the emission of low energy gamma rays and conversion electrons, most of which are emitted at energies below 220 keV[3,5,6]. The appeal of using $^{157}$Gd is due to its large thermal neutron cross section of 240,000 barns [10,11]. Even natural Gd is attractive since the percent abundance of $^{157}$Gd is reasonably high (15.7%). Unfortunately, the neutron-induced low energy conversion electron and gamma-ray emissions are difficult to distinguish from background gamma rays in a mixed radiation field, thereby reducing its practical use. Therefore, the following presentation is restricted to films utilizing variations of $^{10}$B, $^{7}$Li, and $^{6}$LiF films. All device results are from coated semi-insulating bulk GaAs Schottky diode detectors [7,12,13].

A. The Basic Concept

Thin-film neutron detectors consist of semiconductor diodes, preferably with very thin contact layers, upon which a layer (or layers) of neutron reactive material has been deposited. As shown in Fig. 1, neutrons absorbed in the neutron-reactive film release charged particle reaction products in opposite directions. Only one reaction product may enter the semiconductor detector. Charged particles entering the detector lose their energy through Coulombic scattering, thereby creating a high-density plasma cloud of columnar ionization in the form of electron-hole pairs. The semiconductor diode detector is voltage biased to separate the electron-hole pairs and drift the charges to their respective contacts. The mobile charges each induce an image charge on the contacts as they move through the device, and the induced charge is integrated and measured by an external preamplifier and accompanying electronics.

B. Considerations Regarding $^{10}$B and $^{6}$Li Coatings

1) $^{10}$B Coatings

The average range for a 840 keV $^{7}$Li ion in boron is 1.6 µm, and the average range for a 1.47 MeV alpha particle in boron is 3.6 µm [14]. The energy absorbed in the detector is simply the total energy minus the energy lost in both the boron film and the detector contact during transit. At any reaction location within the $^{10}$B film, the maximum detector entrance energy will be retained by either particle should it enter the detector in an orthogonal trajectory.

Given a lower level discriminator (LLD) setting for minimum energy detection, the average effective range (L) for either particle can be determined [7,8]. For instance, an LLD setting of 300 keV gives $L_d$ as 0.810 µm and $L_\alpha$ as 2.648 µm [7]. With a microscopic thermal neutron absorption cross section ($\Sigma$) for $^{10}$B of 3840 barns and an atomic density of 1.3 x 10$^{23}$ atoms/cm$^3$, the resulting macroscopic absorption cross section ($\Sigma$) is 500/cm. At 300 keV, the $\Sigma L$ product for 840 keV $^{7}$Li ions is 0.0405 and the $\Sigma L$ product for 1.47 MeV alpha particles is 0.1324. Relatively high $\Sigma L$ products are desirable for good detection sensitivity.

2) $^{6}$LiF Coatings

One popular form of $^{6}$Li is the stable compound of $^{6}$LiF. The molecular density of $^{6}$LiF is 6.118 x 10$^{22}$ molecules/cm$^3$, hence the atomic density of $^{6}$Li atoms within amounts to the same. The mass density of $^{6}$LiF is 2.541 g/cm$^3$. With a microscopic thermal neutron cross section for $^{6}$Li of 940 barns, the resulting macroscopic thermal neutron cross section is 57.51/cm.

The average range for the 2.73 MeV triton in $^{6}$LiF is 32.1 µm, and the average range for the 2.05 MeV alpha particle in $^{6}$LiF is 6.11 µm [14]. An LLD setting of 300 keV gives $L_\alpha$ as 4.64 µm and $L_d$ as 29.25 µm. At 300 keV, the $\Sigma L$ product for 2.05 MeV alpha particles is 0.0267 and the $\Sigma L$ product for 2.73 MeV tritons is 0.1682. Hence, the long-range particle (triton) for the $^{6}$Li(n,$\alpha$)$^{3}$H reaction in $^{6}$LiF gives a higher $\Sigma L$ product than that realized by the long-range particle ($\alpha$-particle) for the $^{10}$B(n,$\alpha$)$^{7}$Li reaction in pure $^{10}$B. Conversely, the short-range particle ($\alpha$-particle) for the $^{6}$Li(n,$\alpha$)$^{3}$H reaction in $^{6}$LiF gives a lower $\Sigma L$ product than the short-range particle ($^{7}$Li ion) for the $^{10}$B(n,$\alpha$)$^{7}$Li reaction in pure $^{10}$B. The similar $\Sigma L$ values for $^{6}$LiF and pure $^{10}$B films indicate that the maximum achievable thermal neutron efficiencies for these films will differ only slightly.

3) Pure $^{6}$Li Coatings

Pure $^{6}$Li can also be used as a neutron reactive coating, although its corrosive and reactive nature results in cumbersome handling procedures. The average range for the 2.73 MeV triton in pure $^{6}$Li is 136 µm and the average range
II. DEVICES COATED ON A SINGLE SURFACE

Single-side-coated detectors can be irradiated from either the front or the back. There is an optimum thickness to maximize the neutron detection efficiency if the devices are irradiated from the front. The efficiency will decrease if the film is less than or greater than the optimum thickness [7,8]. The decrease in efficiency for thick coatings is due to neutron absorption in a region too far away for the reaction products to reach the detector. As a result, the film region beyond the particles’ ranges absorbs neutrons without any probability of detecting them [7,8].

If irradiated from the back, then only the substrate can interfere with the neutron measurement, and a careful choice of substrates can limit the problem. For instance, Si has a microscopic thermal neutron absorption cross-section of only 160 millibarns. GaAs, although higher, has a relatively low microscopic thermal neutron absorption cross-section of approximately 4 barns. For backside irradiation, the reactive film is no longer between the source and the detector; hence the films can be thicker than the particle ranges without adverse effects. Furthermore, the highest neutron reaction rate is at the detector/film interface, whereas in the previous case the highest reaction rate is at the upper film surface. Hence, irradiating thin film coated detectors is best performed with the detectors facing away from the neutron source. The general equations describing the efficiency of single-coated devices can be found in the literature [7,8,16].

III. THE SANDWICH DESIGN

Using “sandwich” designs, in which two films are adjacent to a detector active region, is an obvious choice to improve efficiency. Two such configurations will be briefly discussed; the double-sided film design and the double-inward-facing design.

The double-sided version consists of a semiconductor detector in which a neutron sensitive film is deposited on the front and back sides. Such a choice seems obvious, but does have drawbacks. The advantages include high neutron detection efficiency and a very low probability of reaction product coincidence counts (from a single neutron) during a measurement. Disadvantages include higher operating voltages (for full depletion) and higher gamma ray background interference in the larger active region.

An alternative is the double detector design in which two front-coated devices are attached back-to-back. The device outputs can be connected to a common input preamplifier. The required operating voltage is less and the gamma ray background is less, but the capacitance will double. The device efficiency is almost doubled over the single-coated design for such a scheme.

It is the double-inward-facing design that yields the highest
efficiency. It does not rely on the full depletion of the detectors and can still be operated with modest operating voltages. If the neutron-reactive film thickness between the devices is thinner than the summed reaction product ranges, both detectors can simultaneously measure coincident charged particle emissions from a single neutron absorption event. Erroneous coincident recordings, in which counts occur in both devices when only one neutron interaction actually occurred, can be avoided by simply connecting the output of both devices to a common input preamplifier. A straightforward method for producing such a device is to simply fasten two front-coated devices together face-to-face. Figure 4 shows comparison neutron reaction spectra between a single-coated device (count-time corrected) and a double-inward-facing device, both having $^6$LiF as the film. As with the front irradiated single-coated detectors, there is an optimum film thickness to achieve the maximum thermal neutron detection efficiency.

The coincident counting feature for the double inward facing detector configuration allows for a simple gamma ray discrimination method, however the devices must then be operated separately [17]. The total film thickness between the two detectors must be less than the summed reaction product effective ranges. Utilizing coincident counting with the inward-facing sandwich allows for counts to be recorded only when both devices detect a pulse. Gamma rays can be discriminated effectively, but at the price of much lower thermal neutron detection efficiency (see Fig. 5).

The compound design takes advantage of all of the aforementioned techniques, in which two via hole devices with double coatings are assembled together in the double-inward facing detector design. Figure 8 shows comparison neutron reaction spectra between a single-coated device with 10% via hole coverage (filled with $^{10}$B) and a $^{10}$B/6LiF double layer, double-inward-facing detector that also has 10% via hole area coverage (filled with $^{10}$B) on each device. The compound device parameters are not optimized, yet the efficiency has more than tripled. In such a case, larger via holes (30 µm diameter) are used for the $^6$LiF, and smaller via holes (3.1 µm diameter) are used for the $^{10}$B film as well. However, energy loss occurs, thereby shifting the detected energy spectrum. Since the $^{10}$B film has a higher neutron interaction cross section than $^7$LiF or $^7$Li films, a net gain in efficiency is realized. Hence, the short range and high cross section material is deposited closest to the contact while the long range and low cross section material is placed atop the first film. The opposite case renders no improvement and in fact actually decreases efficiency. Figure 6 shows comparisons between devices with single coatings of $^{10}$B and $^7$LiF, and double coatings of $^{10}$B/6LiF and $^{10}$B/6Li.

![Fig. 6. Comparison neutron reaction product spectra from a $^{10}$B single-coated device, a $^7$LiF single-coated device, and two double-coated devices using $^{10}$B/6LiF and $^{10}$B/6Li systems.](image)

V. THE VIA HOLE DESIGN

Discussed elsewhere [18], the via hole design allows for the efficiency to increase by covering the semiconductor surface with small holes. The holes are subsequently filled with neutron reactive material. The geometry allows for the reaction products to enter the device with greater probability than a flat detector (see Fig. 7), with some indication that a $^{10}$B-coated device with 40% of the surface area covered with 10 µm deep holes (filled) can reach approximately 10% thermal neutron detection efficiency [18].

VI. THE COMPOUND DESIGN

The compound design takes advantage of all of the aforementioned techniques, in which two via hole devices with double coatings are assembled together in the double-inward facing detector design. Figure 8 shows comparison neutron reaction spectra between a single-coated device with 10% via hole coverage (filled with $^{10}$B) and that of a $^{10}$B/6LiF double layer, double-inward-facing detector that also has 10% via hole area coverage (filled with $^{10}$B) on each device. The compound device parameters are not optimized, yet the efficiency has more than tripled. A higher density of via holes along with optimized $^{10}$B and $^7$LiF layers can increase the thermal neutron detection efficiency above 20%. In such a case, larger via holes (30 µm diameter) are used for the $^6$LiF, and smaller via holes (3.1 µm diameter) are used for the $^{10}$B film as well. However, energy loss occurs, thereby shifting the detected energy spectrum. Since the $^{10}$B film has a higher neutron interaction cross section than $^7$LiF or $^7$Li films, a net gain in efficiency is realized. Hence, the short range and high cross section material is deposited closest to the contact while the long range and low cross section material is placed atop the first film. The opposite case renders no improvement and in fact actually decreases efficiency. Figure 6 shows comparisons between devices with single coatings of $^{10}$B and $^7$LiF, and double coatings of $^{10}$B/6LiF and $^{10}$B/6Li.

![Fig. 5. Calculated thermal neutron detection efficiencies as a function of film thickness on each detector for double-inward facing devices operated in coincidence. Operating the devices in coincidence allows for effective discrimination of background gamma rays, but severely reduces the thermal neutron detection efficiency.](image)
of diameter) spaced in and out of the larger via holes are used for the $^{10}\text{B}$. A $^{10}\text{B}$ layer is applied first followed by the $^{6}\text{LiF}$ layer. Two such devices are then fastened together in the double-inward configuration. A system using pure $^{6}\text{Li}$ instead of $^{6}\text{LiF}$ can increase the thermal neutron detection efficiency above 30%. The larger via holes should be approximately 100 $\mu$m in diameter for a $^{10}\text{B}/^{6}\text{Li}$ system.

![Diagram of a single via hole](image)

**Fig. 7.** Diagram of a single via hole with dimensions similar to the added ranges of the reaction products. The geometry increases the reaction product detection probability over flat surface designs since the products can enter the device from many directions.

![Comparison neutron reaction product spectra](image)

**Fig. 8.** Comparison neutron reaction product spectra from a via hole covered (10.6%) $^{10}\text{B}$ single-coated device and a compound device that uses both $^{10}\text{B}$-filled via holes (10.6% coverage) and a $^{6}\text{LiF}$ film combined in a double-coated and double-inward sandwich design.

### VII. CONCLUSIONS

A variety of simple methods are available to increase the thermal neutron detection efficiency of thin-film-coated semiconductor neutron detectors. Individually the methods offer respectable efficiency increases. Yet, if used together, dramatic increases in thermal neutron detection efficiency can be realized. Efforts are now underway to optimize systems using $^{10}\text{B}/^{6}\text{LiF}$ films. Systems using $^{10}\text{B}/^{6}\text{Li}$ are also under investigation with an emphasis on preserving the $^{6}\text{Li}$ layer and preventing its decomposition. Neutron imaging arrays [19] using the improved technology are also under investigation.

### VIII. REFERENCES