SIMULATION OF A NEUTRON DETECTOR FOR REAL TIME IMAGING APPLICATIONS

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Abstract Monte Carlo Method is used to simulate a double layer gadolinium-amorphous silicon thermal neutron detector. The detector fabricated in pixel array configuration has various applications including neutron imaging. According to the simulation results, a detector consisting of a gadolinium (Gd) film with thickness of 2-4 μm, sandwiched properly with two layers of sufficiently thick (~30 μm) hydrogenated amorphous silicon (a-Si:H) diodes would have the optimum characteristics. At a threshold setting of ~7000 electrons, the detectors would have efficiency of about 42%. The expected average signal size is about 12000 electrons, which is well above the noise. These neutron detectors have very low gamma sensitivity and are very well suited to real time neutron imaging applications.

Key Words Neutron Detector, Imaging, Monte Carlo, a-Si:H

چکیده در این پژوهش یک آشکارساز نوترون حرارتی طراحی شده با استفاده از یک ساختار دو لایه ای از گادولینیوم (Gd) که برروی یک آرایه از دیودهای سیلیکن بی شکل پوشش داده شده به روش مونت کارلو شبیه سازی گردیده است. آشکارساز صفحه ای حاصل با حساسیت مکانی دوبعدی دارای کاربردهای وسیعی از جمله در تصویربرداری های صنعتی با پرتوهای نوترون می باشد. بر اساس نتایج شبیه سازی، آشکارساز متشکل از لایه های ۲ تا ۴ میکرومتر از گادولینیوم و دو دیود Pin از جنس سیلیکن بی شکل با ضخامت لایه i برابر ۳۰ میکرومتر از نظر کارایی بهینه می باشد. این آشکارساز با حد آستانه ۷۰۰۰ الکترون دارای راندمانی برابر ۴۲ درصد خواهد بود. دامنه سیگنال مورد انتظار برای نوترونهای حرارتی حدود ۱۲۰۰۰ الکترون می باشد که به اندازه کافی از میزان نوفه بالاتر است. این آشکارسازهای نوترون از حساسیت بسیار ناچیزی نسبت به پرتوهای گاما برخوردار بوده و برای کاربردهایی چون تصویربرداری با نوترون کاملاً مناسب می باشند.

INTRODUCTION

Real time neutron imaging has important industrial and research applications [1]. In this technology, different kinds of neutron cameras have been used, some with image intensifier tubes having internal neutron sensitive screens, and some with external scintillating screens coupled to video cameras [1,2]. High sensitivity and small pixel size two dimensional pixel arrays of neutron detectors are desirable for a wide range of other applications, which are not possible through other means such as X-rays and electrons e.g. probing biological samples or other materials with low atomic number by neutron scattering. Position sensitive neutron detectros such as proportional-counters, microchannel-plates, and Anger cameras [3] are in use in many neutron scattering facilities. These detectors offer spatial resolutions in the range of 500 μm to a few mm. The position sensitive neutron detectors used in some high resolution experiments consist of ^{6}Li glass scintillators coupled to hamamatsu position sensitive photo-multiplier (PM) tubes (R-2487). The problem with these 55×45 mm^2 PM tubes is that they have a fairly large gamma sensitivity and their gain is also position dependent.

The Presently simulated detector is a modified version of the previously reported detector (Figure 1) [4]. It is a low cost, high resolution and large area position sensitive neutron detector based on hydrogenated amorphous silicon (a-Si: H). Despite its poorer electronic characteristics compared to crystalline silicon, it offers great advantages of large area and much higher radiation resistance. This material has been successfully used as a detector for X-rays, gamma rays, charged particles and neutrons [4,5]. For neutron detection we interfaced amorphous silicon n-i-p diodes with Gd converters. Gadolinium, even in its natural composition, has a large thermal neutron absorption cross section (~46000 barns) and facilitates achievement of much higher neutron detection efficiencies than possible with other converters such as ^{10}B and ^{6}Li [4]. It is more suitable to be used in its metallic form rather than its scintillator compounds, i.e. gadolinium oxisulfate (Gd_2O_2S).

This new design with a maximum neutron detection efficiency of ~53%, consists of two back-to-back-connected a-Si:H diodes integrated with two layers of Gd coatings in a sandwiched configuration (Figure 2). In this manner, not only the probability of neutron absorption is considerably increased, but the chance of detecting internal conversion electrons produced by neutron capture is also enhanced appreciably. The simulation results show that the detection efficiency would increase to a level of 73%, by using Gd layers enriched to 50% in ^{157}Gd isotope which has the highest neutron absorption cross section (2.55×10^{5}). The simulated detector can be used in a pixel array configuration integrated with its readout electronics as a robust two dimensional position sensitive detectror. The details of the array structure and characteristics are given elsewhere [6]. In the present paper only the simulation of an individual pixel, which resulted in a full characterization of the device is discussed.

MONTE CARLO SIMULATION

In the case of radiation detectors, like many other devices, simulation results can be very useful in device optimization before fabrication process. In dealing with radiation transport through different layers of a detector. The Monte Carlo method is a powerful tool which can successfully generate particle

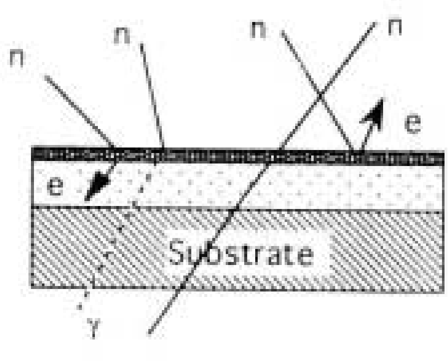

Figure 1. Schematic diagram showing various interactions of incident neutrons on a single layer a-Si:H detector coated with gadolinium.

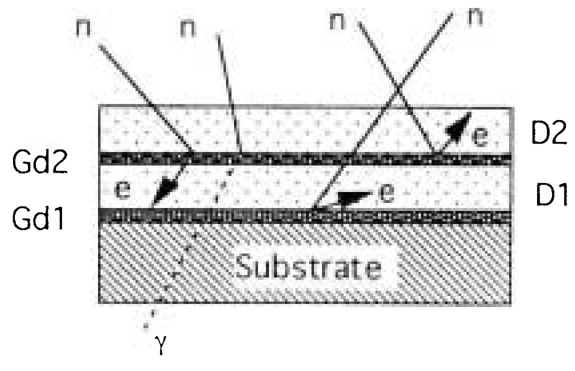

Figure 2. The double layer sandwiched structure a-Si:H neutron detector, and a schematic representation of various neutron interactions.

tracks and histories by simulating the random nature of the particle interaction with the medium. All one needs are complete mathematical expressions of the probability relationships which govern the track length of an individual particle between interaction points, the choice of an interaction type at each such point, the choice of a new energy and a new direction if the interaction is of any scattering types. These are all stochastic variables, and to make a selection of specific values for these variables, a complete understanding of the physics of various processes a particle undergoes during its lifetime, from the time of its birth, until it is either absorbed or leaves the system under consideration is necessary. The process of deciding on a specific value for some stochastic variable is generally based on the selection of a number at random from a uniformly distributed set of integers, produced by random number generator. In the present work, our incident particles are thermal neutrons which are commonly produced in special locations in research nuclear reactors and have an average speed of about 2500 *m/sec*. Interaction of thermal neutrons and the interfacing gadolinium (Gd) layer of the detector produces internal conversion electrons with an average energy of about 70 keV. There is another competing process i.e. gamma emission as shown in Figures 1 and 2. The Gd itself has three isotopes with different interaction probabilities for each of the above-mentioned processes. The electrons generated in the Gd layer lose some or all their energies in the layer. This loss is taken to be signature of neutron stopping in the detector. Only those electrons which are energetic enough to pass through the interface and reach one of the a-Si:H diodes are registered. Therefore, the simulation program has to consider a large number of incident neutrons ($\sim 10^5$) and follow them individually through the Gd layers. For those neutrons stopped, the program should determine both the production of conversion electrons and the energies at which that are produced.. If the conversion electrons can penetrate the Gd layers to reach the diodes, then their associated neutrons will, in fact, be detected. The detection efficiency of the detector, which was intended to be maximized, is defined as the ratio of the number of detected to incident neutrons. The Monte Carlo program can simulate multi-layer Gd-interfaced detectors. The detector has to be planar and is assumed to be thick enough to stop all conversion electrons, otherwise, an electron stopping efficiency should also be incorporated in the final charge collection efficiency and signal size prediction. Our Monte Carlo program takes into account neutron interactions in two most prominent absorbing isotopes of gadolinium i.e.^{155} Gd and ^{157}Gd with 14.8% and 15.7% natural abundances, respectively. The conversion electron energies and transition probabilities for these isotopes are separately computed and used as inputs in the simulation program. Once the program registers stopping of an incident neutron in the detector, it locates its point of absorption in either of the Gd layers, follows the path of conversion electrons produced by neutron capture in Gd isotopes, and determines their energies, emission angles, their path lengths in the Gd converter, and finally their reamining energy upon arrival into either of the n-i-p diodes. The values of these remaining energies are saved as the stored energy in the amorphous silicon diodes and then converted to signal size, assuming that the average energy required to produce an e-h pair (w) for a-Si:H diode is 4.8 eV.

SIMULATION RESULTS

The first device configuration that we simulated had three converter layers, but the Monte Carlo simulation results proved that using a top Gd layer on the structure of Figure 1 would increase neutron stopping efficiency, but drastically decrease both average signal size and the electron event efficiency. Electron events are defined as: "those neutron captures involving internal conversion electron emission (rather than gamma emission), form which at least one of the electrons would be able to escape the Gd films into one of the amorphous silicon diodes." Since only such events would contribute to a count, the electron event efficiency is in fact the real neutron detection efficiency, as long as the signal size is above the noise level. The effects of variation of thickness of the top Gd layer (Gd3) on: (a) neutron stopping efficiency. (b) electron event efficiency, and (c) average signal size are shown in Figure 3. Similar results were obtained when several other values were used for thicknesses of the remaining two Gd layers. As a result of this investigation, we decided to use only two Gd layers. The remaining task for the Monte Carlo simulation was to study the electron event efficiency and the average signal size as a function of thicknesses of Gd1 and Gd2 layers in order to find an optimum configuration. Variation of electron event efficiency as a function of top Gd layer thickness is shown in Figure 4. It is seen that the optimum value for top Gd layer thickness (t_{Gd2}) varies with t_{Gd1}, and also the increase in t_{Gd1} from 4 μm does not result in a significant change in the electron event efficiency. The maxima in these curves, in fact, is a result of a compromise between growing neutron stopping efficiency and declining number of electrons exiting the gadolinium, with thickness increase of the Gd2 layer.

The expected average signal size (Figure 3), on the other hand is larger with the thinner Gd1 layer and declines with increasing t_{Gd2}. This quantity is calculated based on the energy of the conversion electrons upon their arrivals in a-Si: H diode; therefore, it is sensitive to the Gd thickness as the electrons will lose more of their energy in thicker Gd layers.

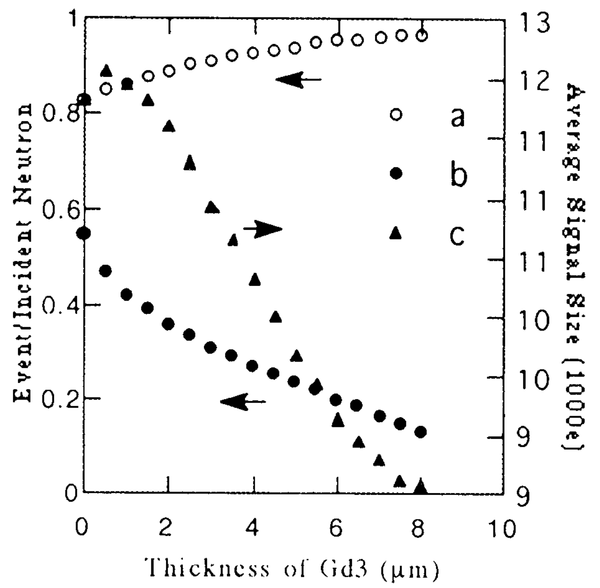

Figure 3. Simulated results on the effect of thickness of Gd3 on (**a**) neutron stopping efficiency (**b**) electron event efficiency, and (**c**) average signal size; for a 2μm Gd2 layer.

Considering these two results, one can see that the optimum choice proves to be a thickness of 4 μm for Gd1 and 2μm for Gd2 layers. For such a detector, our simulation predicts an electron event efficiency of ~53% and an average signal size of about 12000 e⁻.

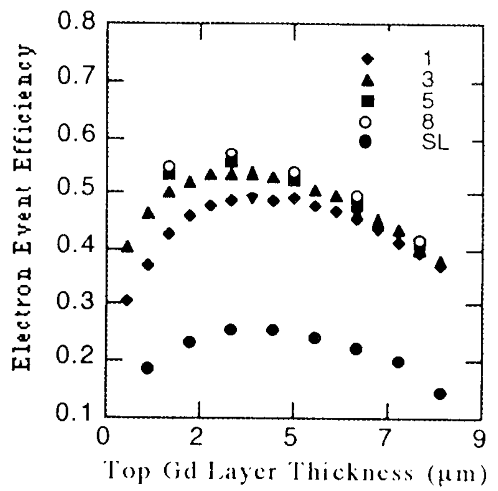

Figure 4. Variation of electron event efficiency vs. thickness of Gd2, for various thickness values of Gd1 layer; the SL curve is for single layer detector of Figure 1.

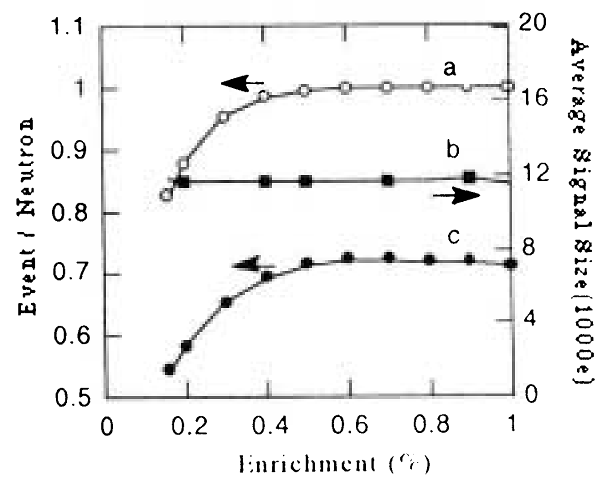

Figure 5. The effect of ^{157}Gd enrichment on (**a**) neutron stopping efficiency, (**b**) average signal size, (**c**) electron event efficiency.

This efficiency would translate into a real neutron detection efficiency provided that the amorphous silicon diodes are thick enough to stop all conversion electrons emitted by Gd converters into them and the noise level is low enough to allow detection of slow conversion electrons. The detector efficiency can be further increased by using an enriched Gd converter. The ^{157}Gd isotope with the highest neutron absorption

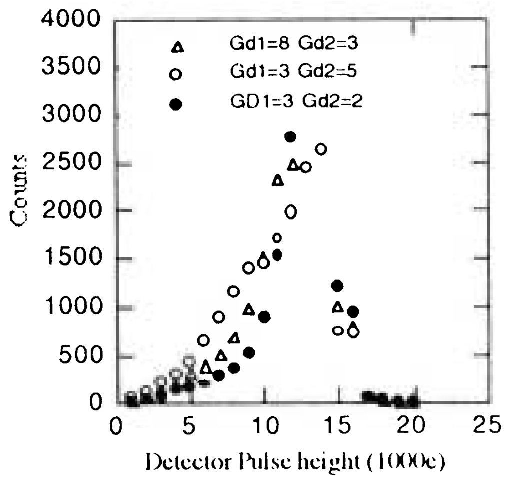

Figure 6. Simulated pulse height spectrum for various thicknesses of Gd1 and Gd2 layers.

cross section (2.55×10^5) has only 15.7% natural abundance. We have studied the effect of using higher enrichment Gd converters by our Monte Carlo program. The results of this study shown in Figure 5 indicate that: (**a**) detector efficiency can be raised to about 73% by using a 50% enriched gadolinium; (**b**) increasing enrichment beyond 59% has no positive effect; and (**c**) gadolinium enrichment does not increase average signal size. The simulated pulse height spectrum for various thicknesses of Gd1 and Gd2 layers is shown in Figure 6.

CONCLUSIONS

We have simulated a neutron detector, using Monte Carlo method. The detector can be used in a pixel array configuration as a position sensitive detector for various applications, including real time neutron imaging. The simulation results provide insights into many important features of the device and defines the optimum design parameters which may be used in the fabrication process.

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