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BORON FILM THICKNESS DETERMINATION TO DEVELOP A LOW COST NEUTRON USING MONTE CARLO METHOD

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ABSTRACT

Neutron measurement is important for safety and security of workers at nuclear facilities. As neutron is an uncharged particle, for its detection is necessary to use a converter material that interacts with the neutron and produce a charged particle, which is easy to detect. One of the converter candidates is natural boron composed by about 20% of Boron-10, which capture a low energy neutron ejecting an energetic alpha particle and a lithium ion. A neutron detector can be developed applying a boron thin film over a silicon photodiode, which is charged particle sensitive. For this reason is important to determine the optimal film thickness. We have used an empirical solution for the boron film thickness evaluation; furthermore we developed, using Monte Carlo method (MCNP6), a model to simulate the alpha particles propagation through the detector. Our goal was to ensure the best production and transference of alpha particles to silicon region. The film thickness ranged between 0 to 5.5 µm, the neutron energy was also varied. The optimal thickness value will be used to develop a prototype of a low cost neutron detector.

1. INTRODUCTION

Neutron detection is necessary for safety and security of workers at nuclear facilities, such as research reactors. Recently there is an increasing on demand of neutron detectors and dosimeter to be used in applications [1], such as: detection of nuclear weapons; fissile materials or drugs inspections at customs and airports; boron neutron capture therapy (BNCT), among others. The neutron detectors used in these applications need to be small, portable and reliable.

The neutron detection is a complex task due the absence of charge in this particle. For this purpose it must be used a converter material that interacts with the neutron, by a nuclear reaction, and produces a charged particle as result.

The converters are related with the neutron energy to be measured, due to the neutron cross sections properties each element has, i.e., the converter is chosen according the neutron energy of interest. For individual monitoring, generally, thermal neutron is the most relevant, in this way the most appropriated converters are [2]: ^{3}He, ^{6}Li, ^{10}B and ^{235}U.

For the detection of charged particles that are release in the neutron capture reaction some kind of detectors as gaseous type, scintillators and semiconductor can be used [2]. However due to the practical properties of semiconductors it has, in the last decades, been used for radiation evaluation. Among the benefits of semiconductors are: maintenance free operation, relatively low cost and high Z number.

Nowadays we are experiencing a shortage of ^{3}He [3], considerate one of the best converter materials for neutrons, encouraging the development of solid-state thermal neutron detectors. This devices, typically, consists of a silicon P-N junction filled with neutron converter materials as the ^{6}LiF and ^{10}B [3].

The lithium vaporization temperature is slightly lower than 1700 °C and the cross-section for thermal neutrons is ≈940 b. This type of detector is very compact; however, the products generated in neutron conversion can be absorbed in Li thin film. Causing the phenomenon, known as self-absorption, that limits the neutron detection efficiency [4].

An alternative to the use of lithium as a converter would be the use of boron, which has the advantage of having a greater cross-section (≈3840 b) that the lithium deposited demanding lower converter amounts.

It is under development a prototype of a low cost neutron detector by our group based in a device of silicon P-N junction that will receive a thin film of natural boron (20% of ^{10}B and 80% ^{11}B) that will be deposited by laser ablation.

The nuclear reaction ^{10}B(n,α)^{7}Li, has two main channels, equation 1: grounded state with 6% of frequency (1*) and in the excited state, has 94% of frequency, produces a alpha particle with energy of 1.47 MeV, a ^{7}Li of 0.840 MeV and a gamma-ray of 0.480 MeV (1**) [2].

$$ {}^{10}_{5}B + {}^{1}_{0}n \rightarrow \begin{cases} {}^{7}_{3}Li + {}^{4}_{2}\alpha + 2.792 MeV\,* \\ {}^{7}_{3}Li^{*} + {}^{4}_{2}\alpha + 2.310 MeV\,** \end{cases} \tag{1} $$

Is important to insure that the alphas that are generate in the thin film be able to achieve the photodiode sensitive region without being absorbed in the film, and the size of photodiode has to be thick enough for all the alpha particles be absorbed.

The aim of this study is to specify the optimum boron thin film thickness and to better understand the processes involved.

In order to fulfill both we choose to confront the empirical solution (alpha particle's range) and computational simulation.

This range that alpha particles reach inside a specific material can be calculated using the empirical equations 2 and 3 [5].

$$ R(cm) = 0{,}318E^{3/2} \tag{2} $$

$$ R_A(cm) = \left[0{,}56R(cm)A^{\frac{1}{3}}\right] / [10^{3} \rho \left(\frac{\mathrm{g}}{\mathrm{cm3}}\right)] \tag{3} $$

Where E is the energy given in MeV, R (cm) is empirical range, A is the atomic weight, ρ is the density of the material (g /cm3) and R_A is the range for all kind of nuclides. These equations can be used with a good approach for energies lower than 10 MeV, being a range for alphas particles in the air at 15°C.

The second part of this study, the simulation of the radiation transportation, can be performed using MCNP6 [6]. This allows a comprehension of the alpha particles behavior in the neutron detector (boron thin film + silicon detector) exposed to a thermal neutron flux.

2. METHODS AND MATERIALS

The prototype of neutron detector was modeled, using a silicon photodiode and a thin film of natural boron (natural isotopic ratios) with a thermal neutrons source (Fig. 1). The distance from source up to neutron detector was set to 500 mm.

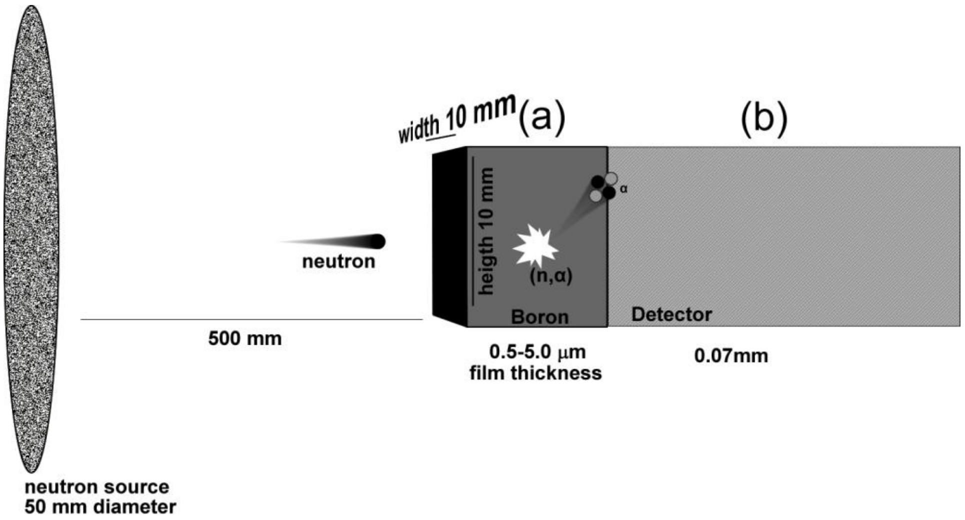

Figure 1: Esquematically illustration of the neutron detector prototype and thermal neutron source modeled for numerical simulations (not scaled).

The silicon photodiode modeled followed the Hamamatsu-S3590-09 (Hamamatsu, New Jersey, U.S.A.) specifications; it has the shape of a parallelepiped, wherein the active region detection area is 1.0 x 1.0 cm, having a dead layer thickness of ≈1 nm and overall thickness of 0.07 mm (silicon chip).

The thin film has the same size and shape of the silicon photodiode. The neutron source is collimated and it has the shape of a circle with 50 mm radius.

The alpha energy in the $^{10}B(n,\alpha)^{7}li$ reaction is 1,47 MeV, using the equations 2 e 3, the range, for this energy was calculated:

For alpha energy particle of 1.47 MeV, the R(cm) =0,56 cm, it was used density of 2.460 g/cm3 (^{10}B) and 2.330 g/cm3 (^{14}Si), resulting in a range of 2.71 µm for ^{10}B. These results show that a film thicker than 2.78 µm will promote self absorption not contributing to the detection.

Based in the analytical range result, the simulation was set to vary the thickness of the film from 0.5 µm to 5.5 µm. The neutron energy was also varied in the thermal region.

It was calculated the fluency (particle/cm^2) at the film and photodiode for alpha particles, using MCNP6 code.

3. SIMULATION RESULTS

It is known [7] that when uncertainties provided by the MCNP code are lower than 5% the results are reliable validating statistically the simulation, and therefore it can be used.

Fig. 2 and 3 shows the results for fluence of alpha particles in function of thickness from thin film for different thermal neutron energy, respectively in the film region (a) and photodiode (b), both illustrated at Fig. 1.

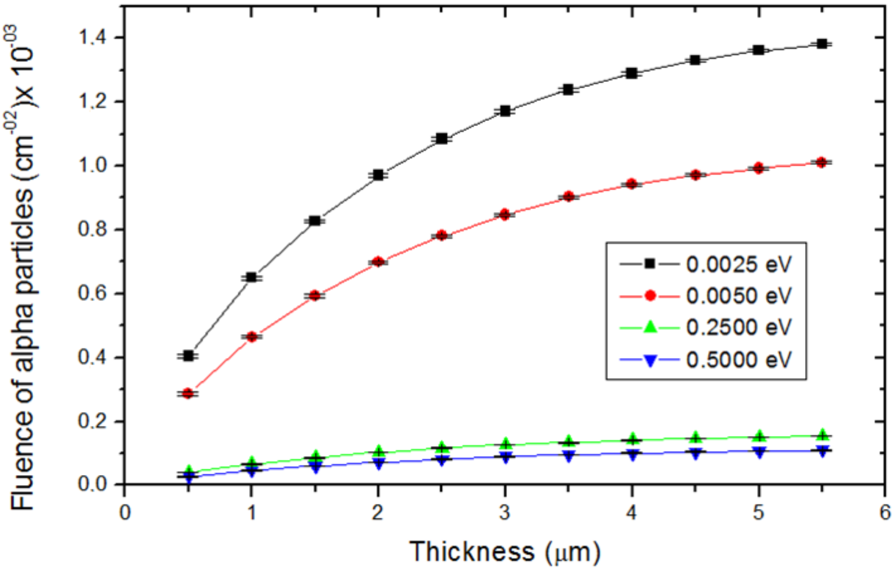

Figure 2: Fluence of alpha particles in function of thickness from thin film for different thermal neutron energy in the boron region (a). The uncertainty bars are comparable to the dots sizes.

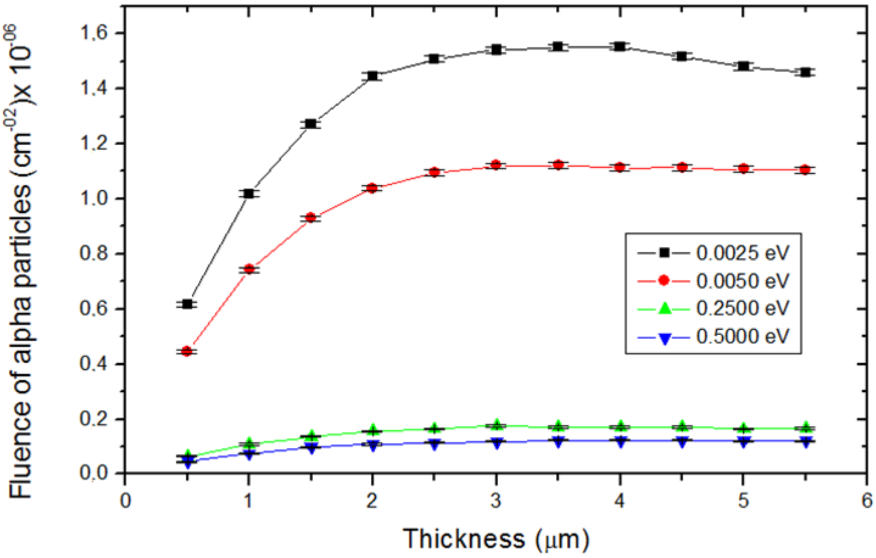

Figure 3: Fluence of alpha particles in function of thickness from thin film for different thermal neutron energy in silicon region. The uncertainty bars are comparable to the dots sizes.

The fluence of alpha particles increases with the thin film thickness, from 0.5 up to 1.5 μm its presents a steep behavior, and for thickness above 2 μm tends to a plateau like saturation, for silicon and thin film regions (Fig.2 and 3).

The population of alpha particles is smaller in the photodiode region due to both: self absorption within the boron film and propagation of the particles toward uninteresting regions (not the photodiode), as expected. Furthermore, the population number depends on the neutron energy in an inversely proportional relationship. The neutrons of interest for dosimetric purposes have 0.025eV, which is the greater contribution in a fission nuclear reactor.

It is noted, as well, a peak around 3 μm, which decays slowly with the film thickness increase. This illustrates, as shown in Figure 4, the shielding that the boron itself is promoting against the neutrons to achieve the useful layer that lies right on of the photodiode.

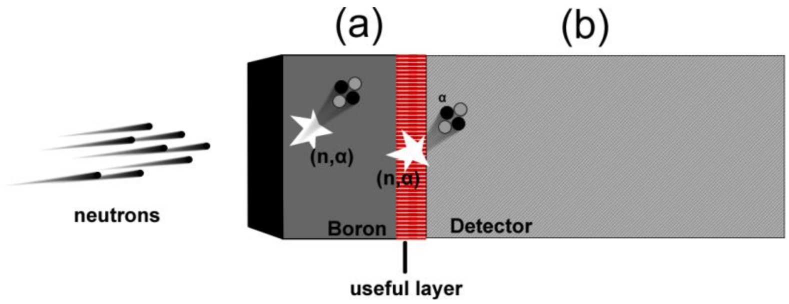

Figure 4: Illustration of the boron shielding and the detector's useful layer.

It is interesting at this point to determine exactly the peak of the alpha particle fluence into the photodiode from the Figure 3, in order to do it; we derivated the curve from Figure 3

(0.025eV) and determined the “zero point”. In this way a polynomial fit was performed and its derivative analyzed (equation 4). The value obtained was 3.18 µm.

$$Y(10^{-06}) = 0.13(3) + 1.13(4) \times X - 0.28(2) \times X^2 + 0.020(2) \times X^3 \qquad (4)$$

Where Y is the fluence of alpha particles given in cm^{-02} and X is the thickness of thin film given in µm.

In order to compare the empirical equation and Monte Carlo methods, the thickness values were replaced in equation 4 and the fluence was calculated for X_1= 3.18 µm and X_2=2.71µm resulting in Y_1=1.57(24).10^{-06} and Y_2=1.55(18).10^{-06}. The value of ratio between, 1.14%, shows a good agreement between the empirical and the simulations.

4. CONCLUSIONS

We have started the study with the analytical result, which determined the optimal film thickness is 2.71 µm, however in order to better understanding the transference process we also performed a simulation based on Monte Carlo method.

The modeling allowed study the behavior of alpha particles in photodiode and thin film regions. For thickness above 2 µm is possible to observe the shaping plateau of saturation.

The polynomial adjustment of fluence of alpha particles in silicon photodiode for 0.0025 eV showed an optimal thickness value of 3.18 µm.

The comparison between the fluence for thickness measured showed that value estimate of analytical fluence it is a good approximation in relation the obtained by the Monte Carlo method.

So is possible to conclude that is necessary at least 3.18 µm thickness of natural boron thin film for development a prototype of a low cost neutron detector and for laser ablation deposition is need to study if there will be any experimental difficult for achieve this value of thickness.

ACKNOWLEDGMENTS

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