Properties of a PIN photodiode as a neutron detector

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Abstract. The properties as a neutron detector of a silicon photodiode of type Hamamatsu S3590-02 in conjunction with a multi-channel analyser Alphatron-3C were investigated in an $^{241}$Am-$^{7}$Be calibration field at the department of nuclear engineering at the University of Madrid. Since the photodiode is sensitive to charged particles, we covered it with two types of converters to enable its response to thermal and fast neutrons. To detect thermal neutrons a 2mm thick $^{6}$LiF converter deposited on aluminium support was used. The detector was placed in the centre of a 25 cm diameter paraffin sphere in front of the neutron source. The response of detector with the $^{6}$LiF converter (understood as the integrated peak count of the alphas produced in the reaction of the Li with thermal neutrons) was compared with the response of a calibration neutron dose rate probe as well as with the more accurate ambient dose equivalent rate based on spectrometric measurements of the calibration field. Good correlation between the detector response and the calibration measurements was found and the calibration coefficient of the silicon detector was determined. For the detection of fast neutrons, a polyethylene converter of 2 mm was employed in order to produce recoil protons. Initially, numerical simulations were performed to predict the efficiency of detection and the shape of the energy spectrum of the recoil protons produced in response to the neutrons emitted by the bare Am-Be source. Subsequently, measurements with the source were carried out in order to determine the sensitivity and applicability of the detector to detect fast neutrons. The counting rate as a function of distance and the angular characteristics of the detector were also determined. We discuss the possibilities of using such a photodiode as a neutron dosimeter.

1. Introduction

A silicon PIN diode can be used to detect charged particles [1, 2] like alphas, tritons, protons. The PIN diode detects charged particles by registering electron-hole pairs produced in its depleted layer during the passage of the particle. In order to register neutrons it is necessary to apply a converter of the neutrons into charged particles [3, 4, 5, 6]. The PIN diode has many advantages like low cost and good energy resolution and it is also fairly insensitive to gamma radiation.

Here we investigate the properties of the PIN as a ambient dose equivalent meter. Two different set-ups were investigated:

(a) Diode with a $^{6}$LiF converter placed inside a paraffin sphere of 25 cm diameter. The paraffin sphere moderates the fast neutrons and so thermal neutrons are detected. The thermal neutrons are captured by $^{6}$Li in the reaction $^{6}$Li(n,$\alpha$)$^{3}$H. The $\alpha$ particle has an energy of 2.05 MeV and the detected tritons 2.7 MeV.

(b) Diode with a polyethylene converter. The fast neutrons produce recoil protons that are detected by the photodiode. The usefulness of such a set-up as a neutron spectrometer is discussed in [7].

In both cases we compared the measurement results with calibration measurements for the source used in the experiment.

2. Experimental set-up

A commercial windowless silicon photodiode Hamamatsu S3590-02, p-i-n junction type with an active area of 10 mm × 10 mm was used. In this work no bias voltage was used. The depth of the
depletion zone is about 200 µm (in section 4.1 it is estimated that the thickness of the depleted zone was equal about 175 µm). This limits the maximum energy that can be deposited in the PIN by the particles emerging from the converter. The signal from the diode was conducted to the charge sensitive preamplifier Hamamatsu H4083 and the spectrum was registered by the portable multi-channel analyser Alphatron 3C\(^1\), specifically designed to analyse the signal from the described diode and pre-amplifier. The photodiode, converter and preamplifier were placed in an aluminium box for light and electromagnetic shielding. The multi-channel analyser allows the registration of the spectrum in 255 channels and its transfer to a PC. The energy calibration was performed with a \(^{241}\)Am and a \(^{232}\)U alpha sources.

The thermal neutrons converter consists of a 2 µm layer of \(^6\)LiF deposited on an 1 mm thick Al support and sealed with a 10 nm thick silver layer.

The fast neutrons converter consisted of 4 mm-thick square of polyethylene placed in front of the photodiode.

The irradiations were performed at the Department of Nuclear Engineering at the Polytechnic University of Madrid. A bare \(^{241}\)Am–\(^7\)Be source was used. Its spectrum extends up to 12 MeV. The strength of the source is about 6.6·10\(^8\) neutrons per second. When not in use the source is stored inside a water and paraffin container. For the measurements, the source is pneumatically transported to the irradiation position about 3 m above the ground. The detector is placed on an Al irradiation bench that allows precise positioning of the detector in relation to the source (see figure 1)[10].

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\(^1\) For more information about the multi-channel analyser contact: DTK Electronics, ATM Center, office 207, Tzarigradsko Shosse Blvd., 7\(^{th}\) km, 1784 Sofia, Bulgaria, e-mail: dtk_electronics@dir.bg.
3. Measurements with the $^6$LiF converter

In this experiment the photodiode was placed in the centre of a paraffin sphere of 25 cm diameter. It is well known that this sphere size with a thermal neutron detector inside behaves nearly as a remmeter [8]. The sphere had a channel into which the box containing the photodiode was inserted. Here our interest is to determine the sensitivity of the dosimeter. The pulse spectrum was registered at different distances from the source. The distance from the source was measured as the distance between the centre of the sphere and the source axis; the accuracy was ±1 mm. The measurement distances were chosen to fit the reference distances at which the neutron field was characterized [10] (plus an additional measurement at 22 cm).

Figure 2 shows an example spectrum, indicating the area of integration, which was chosen to be 2.3-3.0 MeV. The chosen integration interval corresponds to the peak of tritons produced in the reaction $^6$Li(n,α)$^3$H [6].

![Figure 2. An example spectrum obtained with the $^6$LiF converter. The presented spectrum was obtained at the distance of 17 cm from the source. The vertical lines indicate the integration area.](image)

Table I summarizes the obtained numerical results for various distances source-detector. Figure 3 shows the relationship between the counting rate and the distance between the detector and the source. It can be seen that the relationship is inversely square, as expected.

<table>
<thead>
<tr>
<th>Distance [cm]</th>
<th>Count rate [min$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>369±17</td>
</tr>
<tr>
<td>22</td>
<td>259±6</td>
</tr>
<tr>
<td>35</td>
<td>94.1±1.4</td>
</tr>
<tr>
<td>50</td>
<td>46.8±0.8</td>
</tr>
<tr>
<td>100</td>
<td>10.3±0.3</td>
</tr>
<tr>
<td>115</td>
<td>10.2±0.3</td>
</tr>
<tr>
<td>150</td>
<td>6.27±0.15</td>
</tr>
</tbody>
</table>
The results were compared with the dose rates measured with a calibrated neutron ambient dose equivalent $H^{*}(10)$ probe Berthold LB 6411 [11]. The relationship between the counting rate and the ambient dose equivalent rate measurements is linear of the form

$$\text{count rate}[\text{counts min}^{-1}] = (0.1388 \pm 0.0004) \times H^{*}(10) [\mu \text{Sv h}^{-1}]$$ (see Fig. 4).

From the fit it is calculated that the sensitivity of the detector is $60 \times (0.1388 \pm 0.0004) = 8.4 \pm 0.1 \text{ c} \cdot \mu \text{Sv}^{-1}$ (counts per $\mu \text{Sv}$) in the peak interval.

**FIG. 3.** Count rate versus distance of the detector from the source. The diamonds are the measurement points and the line shows a fit of the form $C = 114560 \cdot r^{-2}$. The data was integrated over the energy range 2.3–3.0 MeV.

**FIG. 4.** Count rate versus ambient dose equivalent rate. The straight line represents a linear fit of the form count rate = $(0.1388 \pm 0.0004) \times \text{dose rate}$. 
4. Measurements with the polyethylene converter

4.1. Response of the detector

For the direct detection of the fast neutrons from the Am-Be source, a 4 mm thick polyethylene (PE) converter was placed in front of the photodiode. A 1.7 mm PE layer would have been sufficient but only 4 mm thick sheet of PE was available so this one was used. A 1.7 mm or more PE layer ensures that all possible recoil protons are registered by the photodiode. 1.7 mm corresponds to the range in polyethylene of the most energetic (12 MeV) recoil protons that can be created in the collision with the Am-Be neutrons.

![Graph of measured energy spectrum of recoil protons and simulated energy spectrum for a thickness of the depleted layer of 175 µm.]

**FIG. 5.** a) measured energy spectrum of recoil protons, b) simulated energy spectrum for a thickness of the depleted layer of 175 µm.

The detector was first modelled to predict the response and to estimate the efficiency. The modelling is very similar to that one presented in [7], except that we allowed protons of ranges exceeding the
thickness of the depleted layer. For neutrons whose range exceeded the thickness of the depleted layer (taking into account the proton incidence angle) it was calculated what portion of the energy will be deposited in the depleted zone. The range of protons in PE and Si were taken to be of the form \( R = a \cdot E^b \), where the constants were calculated using [12]. In our program it is possible to use neutron spectra as input and thus allowing the calculation of proton spectra for non mono-energetic neutron sources. Initially a thickness of the depleted layer was assumed to be 200 µm.

In the experiment, the spectrum of the resulting recoil protons was measured. Figure 5 above shows a comparison between the measured proton energy spectrum and the modelled distribution.

It can be seen that the measured and simulated spectra have shapes very close each other. The main difference between the two spectra can be observed in the low energy region. The simulated spectrum decreases to zero for low energies. The low energy background in the measured spectrum extends in the energy region up to approx. 1.6 MeV. The low energy background is thought to originate from secondary electrons generated by photons interacting with the detector assembly [9].

The count rate as a function of distance from the source was determined. Figure 6 shows the relationship obtained. It can be seen that the count rate is inversely proportional to the square of the distance of the detector from the source, as expected. In Figure 7, the relationship between the count rate of the detector and the measured ambient dose equivalent is given. In this way we obtain that the sensitivity of the detector equals 2.07 counts/μSv.

FIG. 6. Count rate of the detector with a PE converter versus distance from the source. The data has been integrated over the region of 1.6..4.8 MeV. The straight line represents the fit with the equation \( C=1.15+26640 \times r^2 \).
4.2. Angular dependence of the response

The disadvantage of the photodiode with a PE converter is that the detector is sensitive to the direction from which the neutrons enter the converter. To assess the influence of the orientation of the detector on the counting rate measurements at different neutron incidence angles were conducted. Two measurements were carried out, at 60° and 30° at 17 cm distance from the source. The relevant spectra are shown in Figure 8.

The integrated count rates for the different incidence angles are 93.3±1.2, 95.6±0.6, 49.3±0.9 counts/min for 0°, 30° and 60° respectively. It can be seen that there is a small difference between the 0° and 30° measurements. The count rate for 60° is much lower.
5. Final conclusions

It has been shown that the photodiode can be used as an ambient dose equivalent meter for an Am-Be source, both placed inside a paraffin sphere with a $^6$LiF converter as well as bare with a PE converter. The relationship between the counting rate and the ambient dose equivalent is linear in both cases.

The sensitivity of the photodiode with the $^6$LiF converter was estimated to be equal 8.4 c/$\mu$Sv$^{-1}$ per cm$^2$ of active diode surface. The photodiode with the PE converter has a lower sensitivity of 2.1 c/$\mu$Sv$^{-1}$ per cm$^2$ (for the Am-Be source) of active diode surface.

The two investigated set-ups have their advantages and disadvantages. In the case of the photodiode inside the paraffin sphere the main disadvantage is its size and weight. The main disadvantage of the photodiode with the PE converter is its sensitivity to the orientation against the measured neutron flux and the necessity to calibrate it for the given source type. The sensitivity is quite low, although this does not depend on the properties of the photodiode but on the nature of neutron interaction with matter.

Acknowledgements

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References