CHARACTERIZATION OF A NEUTRON SPECTROMETER BASED ON A P-I-N PHOTODIODE

S. Agosteo[1,2], A. Castoldi[1,2], P. Colautti[3], G. D'Angelo [1,2], L. De Nardo[4], A. Foglio Para [1], I. Lippi[4], A. Pola[1,2], G. Tornielli[4], P. Zotto[4,5].

[1] Dipartimento di Ingegneria Nucleare, Politecnico di Milano, via Ponzio 34/3, 20133 Milano, Italy.

[2] INFN, Sezione di Milano, via Celoria 16, 20133 Milano, Italy.

[3] INFN, Laboratori Nazionali di Legnaro, via Romea 4, 35020 Legnaro, Italy.

[4] INFN, Sezione di Padova, via Marzolo 8, 35131 Padova, Italy.

[5] Dipartimento di Fisica, Politecnico di Milano, piazza Leonardo da Vinci 32, 20133 Milano, Italy.

ABSTRACT

A proton-recoil spectrometer for neutrons was realized by coupling a commercial P-I-N photodiode with a polyethylene radiator. The minimum and maximum neutron energies which can be detected depend on the thickness of the depletion layer (i.e on the diode bias voltage). It is worth mentioning that the detector has proved to work unbiased, exploiting the field funnelling effect. This effect is due to a local distortion of the electric field in the depletion layer, leading to the collection of pairs produced in the substrate. The response functions were measured by irradiating the spectrometer with monoenergetic neutron beams, generated at the Van De Graaff accelerator of the Legnaro National Laboratories. Monte Carlo simulations were also performed with the FLUKA code. The effect of secondary charged particles produced by thermal and fast neutrons interactions in the silicon device was also investigated.

KEYWORDS

Photodiode, neutron spectrometry, neutrons.

INTRODUCTION

The feasibility of employing a commercial photodiode (Hamamatsu S3509-06) as a proton-recoil neutron spectrometer, by using a polyethylene layer as a proton radiator was discussed in refs. [1,2]. Neutrons are detected through the energy deposited in the depletion layer by the recoil protons generated in the polyethylene radiator. In this application, the field funnelling effect [3] demonstrated to be useful. The field funnelling effect is a local distortion of the electric field of the p-n junction induced by high LET particles, leading the collection of electron-hole pairs produced in the substrate. Therefore, most of the substrate is available for collecting the charge deposited by the recoil protons. In principle this fact allows avoiding to bias the device, and simplifies the electronics. This work discusses the characterization of a neutron spectrometer based on a windowless p-i-n photodiode 0.5 mm thick.

EXPERIMENTAL

Preliminary measurements aimed at characterizing the response of the neutron spectrometer versus bias voltage. Since the range of 8 MeV protons in silicon is about 0.5 mm, this photodiode, when fully depleted, should allow performing neutron spectrometry up to about 8 MeV. The photodiode capacitance and the nominal thickness of its depletion layer are plotted against bias voltage in Fig. 1.

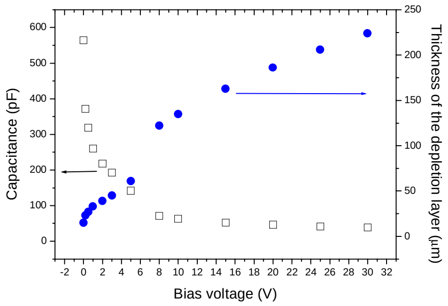

Figure 1: Capacitance and thickness of the depletion layer of the photodiode versus bias voltage.

The spectrometer biased at different voltages was irradiated at LNL with 4.8 MeV monoenergetic neutrons generated by 6.5 MeV protons striking a thin LiF target. The results are shown in Fig. 2.

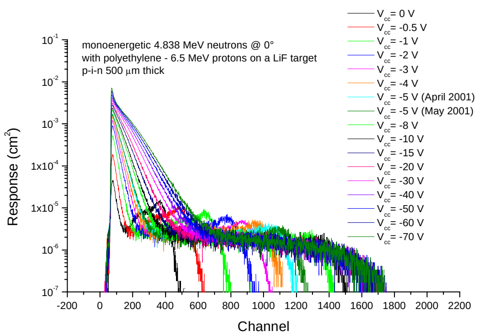

Figure 2: Response of the p-i-n photodiode 0.5 mm thick, covered with the polyethylene radiator, for 4.8 MeV neutrons against bias voltage.

It should be pointed out that the range of the recoil protons from 4.8 MeV neutrons in silicon is about 0.2 mm. The shift of the proton recoil spectra shown in Fig. 2 is less pronounced for bias voltages below -20 V, corresponding to a depleted layer thickness of about 0.18 mm. Below -5 V the shape of the spectrum tends to become irregular, indicating that the field funnelling is no more effective in collecting the charge in the substrate for recoil protons with maximum energy 4.8 MeV. The curves shown in Fig. 2 led to set the bias voltage at –15 V, providing a shape of the proton recoil spectrum which agrees with the simulations and the analytical calculations described in the following. This voltage corresponds to a nominal dead layer thickness of 163 μm. The response functions resulting from irradiation with monoenergetic neutrons generated with the reaction $^{7}Li(p,n)^{7}Be$ at the LNL Van De Graaff are shown in Fig. 3.

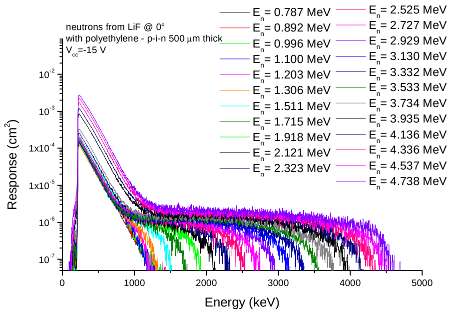

Figure 3: The response functions of the neutron spectrometer.

The edge from about 1 MeV up to the maximum energy of the neutron beam is due to recoil protons generated in the radiator. Below 1 MeV the neutron response is completely overwhelmed by low LET events, probably due to secondary photons and X rays generated in the LiF target and in the detector. This limits the lower detectable energy of the neutron spectrometer. The photon component (and therefore the minimum detectable energy of neutrons) can be lowered by decreasing the bias voltage (down to 0 V) and therefore the thickness of the depletion layer. The consequent reduction of the energy deposited by secondary (low-LET) electrons from gamma interactions is very effective, since they do not give rise to the funnelling effect. By contrast a thinner depletion layer reflects in a limitation of the maximum detectable energy, ruled by the efficacy of the field funnelling effect against bias voltage.

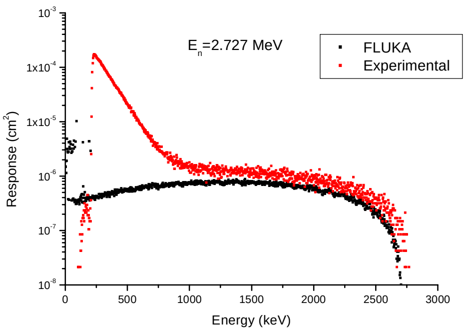

Figure 4: Simulated and experimental response function for 2.7 MeV neutrons.

Monte Carlo simulations of the detector response functions were performed with the FLUKA code. The response function for 2.7 MeV neutrons is shown in Fig. 4, together with the experimental data. Since the target assembly was not simulated, the distribution of secondary photons is not observable. The agreement of the simulation results with the measurements is satisfactory also for all the other neutron energies considered.

Preliminary measurements for investigating the effect of secondary charged particles produced in the structural materials of the photodiode were performed by irradiating the bare detector (i.e. without the polyethylene converter) with monoenergetic neutrons. In the neutron energy range investigated up to now (up to about 5 MeV), secondary charged particles can be produced mainly from $^{27}Al(n,p)^{27}Mg$ (threshold energy E_{th}=1.90 MeV), $^{28}Si(n,\alpha)^{25}Mg$ (E_{th}=2.75 MeV) and $^{28}Si(n,p)^{28}Al$ (E_{th}=2.75 MeV). The detector was not biased and was shielded against light. The measured spectra are shown in Fig. 5. It should be noted that below the lower threshold energy for secondary particle production (E_{th}=1.90 MeV for $^{27}Al(n,p)^{27}Mg$, bottom curve in Fig. 5) the edge due to charged particles is very poorly populated. Some events may be due to secondary particle production in the target assembly (the distance of the detector from the target was 10 cm), in the shield against light (black paper) and in the air. As expected, the charged particle edge becomes more pronounced by increasing the energy of the impinging neutrons, because of the contribution of a larger number of secondary charged particles produced at higher thresholds.

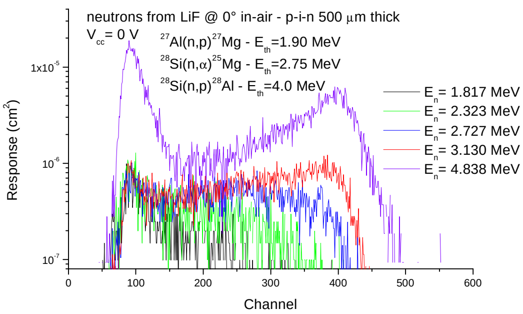

Figure 5: Energy distribution of secondary charged particles generated by fast monoenergetic neutron in a p-i-n photodiode.

Charged particle production by thermal neutrons through the reaction $^{10}B(n,\alpha)^{7}Li$ on the silicon dopant was investigated by irradiating the bare photodiode in the thermal column of the ENEA-TAPIRO reactor in Rome. The spectrum of the energy deposited by the reaction products is shown in Fig. 6.

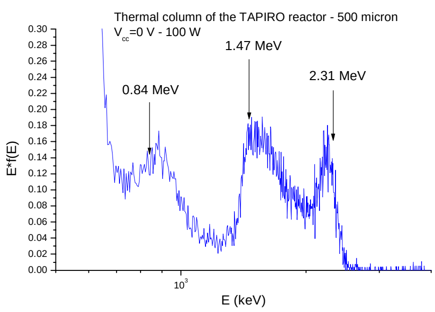

Figure 6: Photodiode response for thermal neutron irradiation.

The reaction Q-value is 2.31 MeV, shared between ^{7}Li (0.84 MeV) and the α-particle (1.47

MeV). Since the range in silicon of ^{7}Li and of the α-particle is 2.5 μm and 5 μm, respectively, and the thickness of the depletion layer is about 20 μm (diode not biased), the probability of partial energy deposition is not negligible. Such events are observable in the structures at the left of the 2.31 MeV full-energy peak (Fig. 6). The spectral shape of these events is due to the distribution of the energy deposited along the tracks of the reaction products, which is not uniform. The contribution of thermal neutrons to the detector response is of the order of 10^{-6} cm^2.

THEORETICAL MODELLING

The response functions of the spectrometers were also determined analytically, for parallel beams of monoenergetic neutrons. The polyethylene radiator was considered thicker than the range of the recoil protons of maximum energy ($E_{p.max}$), which is equal to that of the impinging neutrons (E_n) in a head-on collision ($E_{p.max} = E_n$).

The range-energy relation has been described with a power law:

$$R_p = R_0 \cdot E_p^{ß} \qquad (1)$$

where R_p is the range of the recoil protons in polyethylene, R_0 is a constant (approximately 20 μm in polyethylene), ß is dimensionless (1.77 for proton energies from a few hundreds of keV up to some MeV) and E_p is a number expressing the ratio of the proton energy to the unit energy in MeV. From expression (1) and from the identity $R_{total} = R_{radiator} + R_{detector}$ (where R is the proton range), the energy E_d deposited in the detector is given by:

$$E_d = [(E_n \cdot \cos^2\theta)^{\beta} - h/(R_0 \cdot \cos\theta)]^{1/\beta} \qquad (2)$$

where h is the distance from the point of elastic collision in the radiator to the detector surface and θ and $E_p = E_n \cdot \cos^2\theta$ are the direction (with respect to that of the impinging neutron) and the energy of the recoil proton, respectively.

Expression (2) holds if: i) the scattering and energy degradation of the neutron beam in the interactions with carbon nuclei in polyethylene and ii) the scattering of the emitted protons are assumed to be negligible.

The spectral distribution $p(E_d)$ of the energy E_d deposited in the photodiode was calculated by assuming that: i) the interaction probability of neutrons is uniform inside the very thin useful layer of polyethylene; ii) the angular distribution of the recoil protons is uniform with respect to a $\cos^2\theta$ law (i.e. the elastic scattering is isotropic in the centre-of-mass system). Thus, E_p is uniform in the interval ($0 - E_n$). Under these approximations $p(E_d)$ can be expressed as:

$$p(E_d) = 2/3 \cdot ß \cdot (E_d/ E_n)^{ß-1}/E_n \cdot [\, 1 - (E_d/ E_n)^{3/2}] \qquad (3)$$

It should be underlined that expression (3) is normalised to one interacting neutron. The response functions calculated for 2.73, 3.53 and 4.34 MeV neutrons are compared with the corresponding experimental data in Fig. 7. The agreement is very satisfactory also from a quantitative point of view, since the analytical curves were calculated independently from the experimental data.

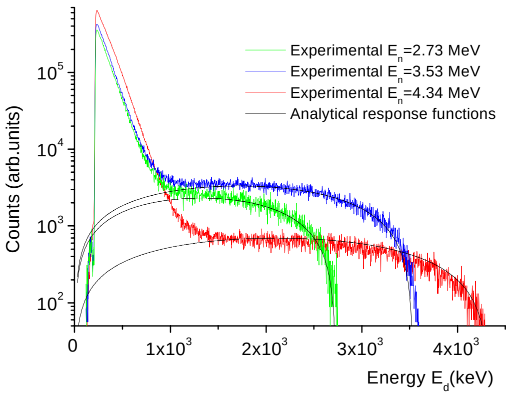

Figure 7: Experimental and analytical response functions for 2.73, 3.53 and 4.34 MeV neutrons.

CONCLUSIONS

The response functions of the neutron spectrometer, based on a P-I-N photodiode, were characterized both experimentally and analytically. The code for unfolding the experimental data is under development and the first test measurements with continuous neutron spectra will be performed soon.

The minimum detectable energy of the spectrometer is limited by the energy deposited by low LET events generated by secondary photons. The possibility of reducing the detection limit by discriminating the rise-time of pulses is under investigation. Measurements for characterising the spectrometer for neutrons up to 14 MeV will be performed during 2002.

REFERENCES

[1] S. Agosteo, A. Castoldi, L. Castellani, P. Colautti, G. D’Angelo, L. De Nardo, A. Favalli, I. Lippi, R. Martinelli, G. Tornielli, P. Zotto, A Feasibility Study of a Single Event Spectrometer Based on Semiconductor Devices, Radiation Protection Dosimetry, in press.
[2] S. Agosteo, L. Castellani, G. D’Angelo, A. Favalli, I. Lippi, R. Martinelli, P. Zotto, Feasibility Study of a Silicon Detector for the Spectrometry of Single Event Effects, INFN-LNL Annual Report 2000, LNL-INFN(Rep.) 178/01 (2001) 197-198.
[3] C.M. Hsieh, P.C. Murley, R.R. O’Brien, A Field-Funneling Effect on the Collection of the Alpha-Particle-Generated Carriers in Silicon Devices, IEEE Electron Device Letters, EDL-2 (1981) 103-105.