

TEST AND EVALUATION OF SEMICONDUCTOR COMPONENTS IN MIXED FIELD RADIATION MONITORING

José Patrício N. Cárdenas^{*1a}, Tufic Madi Filho^{1b}, Letícia L. C. Rodrigues^{1c}

¹ Instituto de Pesquisas Energéticas e Nucleares, IPEN - CNEN/SP
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
a) ahiru@ipen.br, b) tmfilho@ipen.br, c) lcrodri@ipen.br

ABSTRACT

Silicon components have found extensive use in nuclear spectroscopy and counting, as described in many articles in the last three decades. These devices have found utility in radiation dosimetry because a diode, for instance, produces a current approximately 18000 times higher than any ionization chamber of equal sensitive volume. This reduces stringent requirements from the electronics used to amplify or integrate the current and / or allows approaching the ideal detector point for the mapping of radiation fields. For better performance, in the case of diodes, they are normally used with high inverse polarity to obtain a deeper barrier, less noise and shorter transit time.

The aim of this work was the evaluation of these semiconductor components for application in ionizing radiation fields monitoring, in nuclear research reactors and radiotherapy facilities, for radiation protection and health physics purposes. Experimental configurations to analyze the performance of commercial semiconductors, such as silicon PIN Photodiodes and Silicon Surface Barrier Detectors, were developed and the performance of three different configurations of charge preamplifier with silicon components was also studied. Components were evaluated for application as neutron detectors, using some types of radiators (converters).

The radiation response of these silicon components to neutron fields from nuclear research reactors IEA-R1 and IPEN-MB1 (thermal, epithermal and fast neutrons), from beam holes, experimental halls and AmBe neutron sources in laboratory was investigated.

1. INTRODUCTION

Semiconductor materials have introduced new possibilities in solid-state dosimetry, allowing, for instance, in vivo registration of radiation in real time. Semiconductor detectors are attractive for applications in radiation dosimetry for the following reasons: high density and low energy required for the creation of electron-hole pairs, inducing the same charge as in a gas detector, but with 4–5 orders of magnitude less volume; ability to work in passive (unbiased) and active (biased) mode; high efficiency of radiation induced charge collection under low voltage, owing to the high purity of modern semiconductor materials; reproducibility in large batches, using standard microelectronics technology; the possibility of having the detector and electronics readout integrated in the same chip [1].

The most suitable semiconductor material for room temperature radiation dosimetry is silicon, although other semiconductors have a higher Z that is more attractive for low doses (or energy) gamma detection. Silicon microelectronics technology is highly advanced and silicon detector production is cheaper than for other semiconductor detectors. Semiconductor detectors can be applied in personal dosimetry, accident dosimetry and radiation therapy dosimetry [1].

2. OBJETIVES

The aim of this work is the evaluation of semiconductors under mixed field radiation. The radiation response of silicon components to neutron fields from nuclear research reactors IEA-R1 (thermal and epithermal neutrons) and IPEN-MB1 (fast neutrons), from beam holes, experimental halls and AmBe neutron sources (Laboratory) was investigated.

3. MATERIALS AND METHODS

3.1 Materials

3.1.1 Components – Detectors and electronics for data adquisition

3.1.1.1 The PIN Photodiode

When light strikes on the surface of the photodiode, the electron within the crystal structure becomes stimulated. If the light energy is geater than the band gap energy E_g , the electrons are pulled up into the conduction band leaving holes in their place in the valence band. These electron-hole pairs (e-h) occur throughout the P-layer, depletion layer and N-layer materials. In the depletion layer, the electric field accelerates these electrons toward the N-layer and the holes toward the P-layer. Therefore, the electron-hole pairs that are generated proportionally to the amount of the incident light are collected in the N and P-layers. This results in a positive charge in the P-layer and negative charge in the N-layer [2].

Interactions of fast neutrons with the silicon detector can be classified into two groups: (i) interactions inside the depletion region, (ii) interaction with material surrounding this sensitive region, like epoxy glue, which is mainly required for the mechanical adhesion of the depleted region to the insulating ceramic mounting ring.

The interactions in the sensitive layer include elastic and inelastic processes. When neutrons interact elastically with silicon, the recoil nuclei gain a maximum energy of about one seventh of the incident neutron energy. Therefore, for neutron energy below 5 MeV, the average recoil energy is low (less than 0.7 MeV). For high energy neutrons, near 15 MeV, the average recoil energy is between 1 and 2 MeV. Since the total elastic cross section is relatively large (several barns), and because only deposited energy above background, i.e. about 0.7 MeV, are taken into account in the photodiode sensitive area, silicon recoils cannot be neglected for high energy neutrons.

At high neutron energies, inelastic interactions also start to contribute in the sensitive area. These include, mainly, $\text{Si}(n,p)\text{Al}$ and $\text{Si}(n, \alpha)\text{Mg}$ reactions. Interactions with the epoxy glue are mainly via elastic reactions with the hydrogen content [3]. Fig. 1 shows the semiconductors used in the experiments.

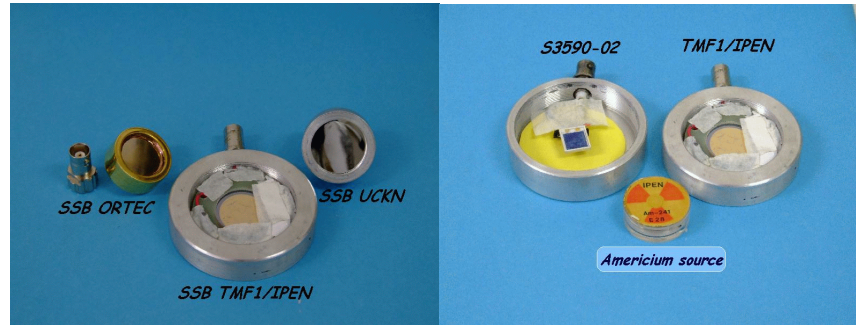


Figure 1. Silicon Surface Barrier Detector, PIN Photodiode (with aluminum assembly to avoid light and interference, without cover) and the ^{241}Am alpha source

3.1.1.2 The Charge Sensitive Preamplifier (CSP)

A large number of applications require extremely low noise detection systems, based on small capacitance and low leakage current detectors. A lot of efforts have been put to date in the development of various circuits implemented in different technologies for the read out system. The charge sensitive amplifier is widely used at the front-end, since its conversion gain is independent from anode capacitance variations. The primary purpose of the preamplifier is to provide an optimum coupling between the detector and the rest of the counting system and, also, to minimize any sources of noise, which will be transmitted along the pulse that would degrade the energy resolution of the system [4]. A charge sensitive preamplifier is used to amplify the photodiode output and a capacitor at the preamplifier input is used to couple a test pulse voltage (ORTEC 448 Research Pulser in our case) to the system and check the calibration made through a ^{241}Am source. We only had four working charge sensitive amplifier (ORTEC 142A, 142AH, 142PC and Soshin 9161) and the best performance was found with ORTEC 142A and 142PC.

3.1.1.3 The Spectroscopy (Shaping) Amplifier (SSA)

Because of the low gain in the charge sensitive amplifier, the shaping amplifier (SSA) follows the CSP to provide an additional gain (ORTEC 142A and 142PC). The shaping amplifier is capacitively coupled to the CSP and uses a RC-CR shaping to achieve a minimal noise and good linearity. To observe the outputs of the CSP and shaping amplifier, we tested the detection channel using an oscilloscope (Tektronix T220) to adjust the gain and shaping time for the best performance (stability and overall noise) of the detectors.

3.1.1.4 The Converter (radiator)

A semiconductor radiation dosimeter can be implemented by placing a converter in contact with a silicon device, providing a charge collection layer of a micrometric thickness. When exposed to a neutron field, the silicon acts as a detector of ionization induced in the sensitive zone by the secondary charged particles generated in the converter [5]. A recoil proton spectrometer was created by coupling a pin diode with a polyethylene converter.

The use of a converter implies in losses and benefits due to the effect of the self-absorption of the produced particle inside the converter material itself [6]. Very slim converters are not efficient due to the small layer of atoms to interact with the incident neutrons. On the other hand, with thicker films, the interaction probability increases and, consequently, a larger amount of charged particles is produced. However, since these particles (alpha or protons) have little range in the materials [7], they can be absorbed or it disappears in the converter itself.

The characterization of the converter thickness is of great importance in the design and construction of neutron detectors. In most scientific approaches, the first step is to establish the experimental expectations in function of the available theoretical studies. In the interactions of the neutrons with the converter material, two items should be considered: 1) the neutron ability to generate the ionizing particles (protons) and 2) the self-absorption process. The detection efficiency depends on the size, format and intrinsic efficiency of the detector [8]. The polyethylene converter (radiator) was fixed on a 2 mm aluminium sheet and the distance between the polyethylene and the silicon sensitive region was 0.5 mm. We assumed a normal incident neutron beam and the converter covering the entire sensitive area (normally used 80 to 85% to avoid edge effects), then edge effects were developed due to protons recoiling toward the surface region.

3.1.2 Experimental facilities description

3.1.2.1 Laboratory CENF

Measurements using an AmBe neutrons and reaction (α,n), acquired from Amersham in 1970 with a nominal activity of 37×10^9 Bq (1 Ci) of Am and neutrons emission rates of 3.1×10^5 n.s⁻¹ were carried out in this laboratory. By calculations, we obtained 2.9×10^5 n.s⁻¹ for the actual emission rate. Fig. 2 shows the detectors used and the CSP [9].

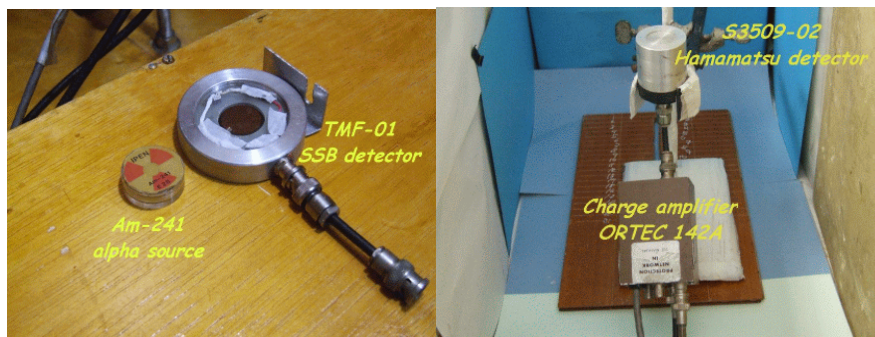


Figure 2. SSB TMF-1 (left) and S3590-04(A) assemblies with the ²⁴¹Am alpha source.

Radiological protection requirements were implemented to work with the AmBe source bench, through a biological shielding structure made with 10 cm paraffin blocks.

3.1.2.2 The IEA-R1 Neutronography facility

At IEA-R1 experimental hall, there is another facility built close to the Beam Hole #8, in order to be used for Neutronography experiments. This irradiation channel is in a radial direction toward the reactor core, with internal diameter of 20 cm. Inside this channel, 2 aluminum tubes are inserted, for assembly of filters, collimators and other components to extract the neutrons beam.

The total factor reduction for the neutrons flux, caused by the filters and collimators is 2.5×10^{-8} , resulting in a flux of $\sim 1.75 \times 10^6$ n/cm².s in the irradiation site, with a gamma dose of ~ 20 mSv/h and ~ 70 mSv/h (dose equivalent rate) for neutrons. Also, there is an external shielding composed basically of paraffin, boric acid, cadmium, lead and high density concrete, together with the reactor biological shielding [10].

Fig. 3 shows the facility assembly and the SSB TMF-01 detector measurement setup. The incident neutrons were estimated previously, using the gold foil activation technique at 2 MW reactor thermal power [11].



Figure 3. Neutronography assembly (left) and the TMF-1 SSB Detector setup (right).

3.1.2.3 IPEN/MB-01 (UCRI) facility Description

The IPEN/MB-01 is a Brazilian nuclear research reactor designed and constructed by researchers and engineers from the institution, with financial support from the Brazilian Navy; its first criticality was on November 5th, 1988. This reactor is a nuclear facility that provides simulation for all parameters of a high power nuclear reactor in scale, without necessity to build a complex system for heat removing. This kind of reactor is known as Zero Power Reactor or Critical Unit; it was designed to operate at a maximum full power of 100 Watts. Fig. 4 shows the reactor core and the detectors measurement setup.

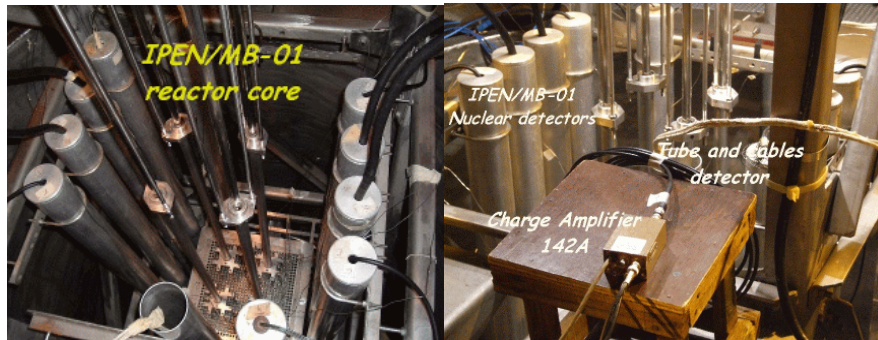


Figure 4. Reactor core (left) and detector measurements setup (right).

3.2 Methods

A nuclear reactor, as a neutron source, generates gamma radiation, which can interfere in the neutron flux measurement. Then, it is necessary that the detecting system be capable to discriminate the gamma interference.

Several techniques have been proposed and two are commonly used: (i) pulse-height analysis applying threshold electronic discriminator and (ii) pulse-shape discrimination. The choice between these alternatives depends, fundamentally, on the pulse height generated from the gamma photon and the neutron particle. If they are similar and overlapping each other, then the pulse shape discrimination can be used, otherwise the technique of electronic discrimination would be preferable.

In this type of reactors, the neutrons generated in the primary process have energies around 20 MeV, which are classified as fast neutrons. Other devices, such as the particle accelerators and AmBe sources, also produce fast neutrons. However, in detector designs, the most used nuclear converters, such as ^{10}B and ^7Li , are not efficient in that energy level, also due to the absence of charge: in order to obtain neutron detection, it is necessary to use a material converter. This limitation can be overcome by using a moderator material to reduce the neutron energy level [9]. Fig. 5 shows the effect of a converter under a neutron beam.

Semiconductor detectors, such as Si, Ge and others, are usually used for detecting ionization radiation due to their low noise/signal ratio and their high energetic resolution performance. But, these semiconductors are made with high atomic numbers that are not efficient to produce useful interactions with neutrons. This limitation can be overcome by using a converter material on sensitive surface semiconductors, transferring the kinetic energy from neutron to proton, as shown in Fig. 5 [12].

The silicon has high sensitivity for proton detection. Additionally, the range of the proton in the silicon varies approximately from 0.09 to 1 mm, for particles ranging from 3 to 12 MeV, what makes thin surface detectors possible to be constructed. Besides, the silicon detector has high mobility of electrons and holes. This characteristic and the small dimension of the detector allow the charge collection in a short time (nanoseconds) and, therefore, a high resolution can be reached [13].

In this work, neutron detection system using silicon semiconductors surface barrier (SSB) type TMF-01 (developed at IPEN) and two ORTEC SSB type BA-040-200-300 (Golden and Silvered model), using polyethylene as (n, p) recoil protons generation converters were developed; as a comparison in performance, a PIN Photodiodes type S3509-04 and a S1223-01, both from Hamamatsu, were also used. In such design, the optimum thickness of the converter is an important parameter to be established and it was determined, experimentally and theoretically, in a past work by Madi et al [9].

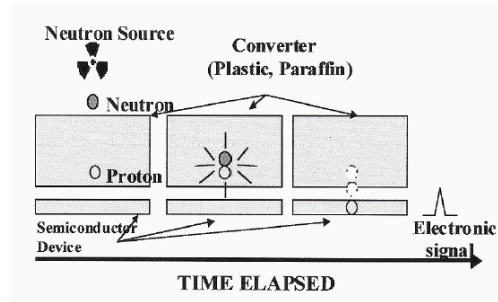


Figure 5. Semiconductor associated with a (n,p) converter to detect a source of neutrons.

3.2.1 The TMF-1 Silicon Surface Barrier Detector

The Silicon Surface Barrier type detectors, developed at IPEN (1999), were made from wafers (Topsil), with resistivity of 50 k Ω .cm, 2.54 cm in diameter - total area 5 cm² and 1mm in thickness, according to Takami et al. [14]. Approximately, 3.14 cm² of the sensitive surface were covered with 80 μ g.cm⁻² Au and the rear face with 40 μ g.cm⁻² Al, in order to form the ohmic electrode, using the vacuum deposition technique. Such assembly presents depletion layer depth of 420 μ m at 40V reverse bias voltage and specific capacitance of 70 pF.mm⁻² [14-15]: Fig. 1 shows the SSB detector.

3.2.2 The ORTEC BA-040-200-300 Surface Barrier Detectors

These SSB detectors are a silvery and a golden type from ORTEC; these detectors have an extremely thin p-type layer in face to a high purity n-type Si wafer. The rated energy resolution of the detectors is 40 keV and the active thickness, when fully depleted, is 300 microns. The detectors have an active area 200 mm², a total resistivity 8700 ohms.cm and operational reverse bias voltage of 50 Volts. Fig. 1 shows the three silicon barrier detectors [16].

3.2.3 The Hamamatsu PIN Photodiode

A PIN silicon photodiode windowless type Hamamatsu S3590-04, sensitive area of 10x10mm covered with foils of polyethylene, thickness of 0,12 mm (experimental data) in front of detector was used. The stray capacitance of the S3509-04 detector was about 70 pF

and its dark current was less than 1.5 nA at a bias voltage of 40 volts. Also a S1223-01 PIN type photodiode was tested and its resin was removed to test its irradiation response [2].

The maximum detectable energy imposed by the thickness of the totally depleted layer (S3590-04 detector, for instance) is 6 MeV, the minimum detectable energy is limited by the contribution of secondary electrons generated by photons in the detector assembly, this limit being 1.5 MeV at full depletion voltage. Fig. 1 shows the Hamamatsu detector.

All Surface Barrier detectors were tested with a reverse bias voltage of 0, 15, 24, 30 and 40 Volts. The best performance for the S3590 type photodiode was achieved with 15 Volts, in the case of the AmBe neutron source.

3.2.4 Set up instrumentation

In order to develop the experimental standard, NIM electronics was used for data processing, as shown in Fig. 6. The instrumentation setup used to detect fast neutrons from the AmBe source and the IPEN/MB-01 reactor, and epithermal neutrons from the facility described above in the IEA-R1 reactor, was as it follows: each sensor was connected to a charge sensitive preamplifier (ORTEC 142A) with a Hewlett Packard Power Supply; the output of this preamplifier was coupled via an RG 75 cable to an amplifier with gain (50 or 100) and shape (2 or 6 microseconds) adjustment (ORTEC 572 and 672 models); the output of this amplifier was connected to a Spectrum Master 919 processing module linked with a PC computer, running in Win 3.11 environment, with Maestro Signal Analyzer software (ORTEC), in order to obtain the acquisition of neutron spectrum. No vacuum chamber was used in any experiment.

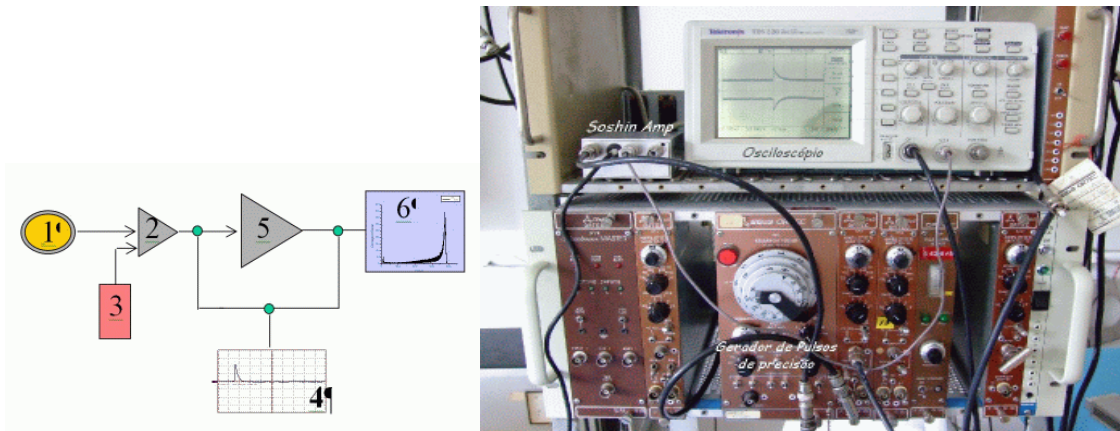


Figure 6. Measurements setup (left) for all the experiments: 1) detector, 2) charge sensitive amplifier, 3) power supply (HV), 4) Oscilloscope, 5) spectroscopy amplifier and 6) Computer with Maestro software (MultiChannel Analyzer) and a picture (right) of NIM instrumentation in the case of Soshin 9161 CSP.

4. RESULTS

4.1 VDG Lab Experimental results.

At first, we began the experiments with several shaping times in order to find which (CSP or SSA) would give us the best FWHM (for resolution); then, we determined that a shaping time of 6 and 2 microseconds was ideal, depending on the type of semiconductor detector coupled to the system. Fig. 7 shows, for instance, the response of S3590 and S1223 detectors to a ^{241}Am alpha source. The distance from the source to the surface detector was 1 mm. The S3590 showed a better sensitivity and resolution than the S1223 one.

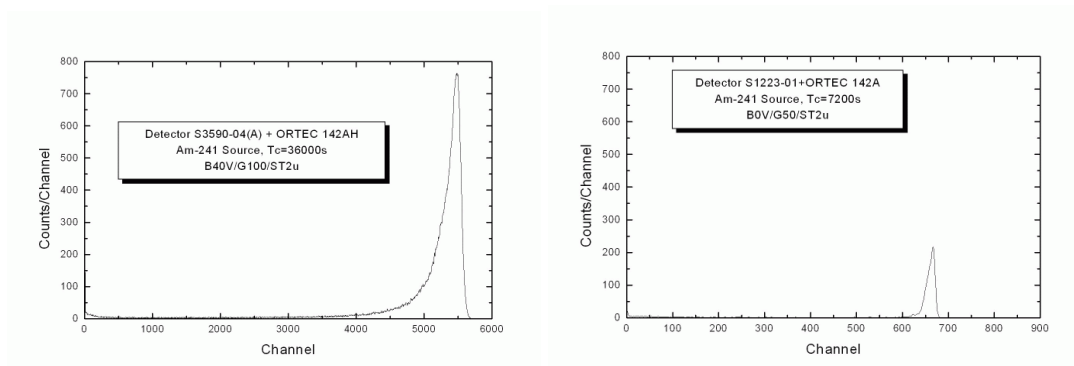


Figure 7. Response of S3590-04 (A) and S1223-01 Hamamatsu PIN photodiode to a ^{241}Am alpha source.

Afterwards, measurements were carried out in the Laboratory using an Am-Be neutron source, in order to obtain a fast neutron detector response (recoil proton spectrum) for the TMF-01 and the S3509-02 detectors, with the instrumentation setup shown in Fig. 8.

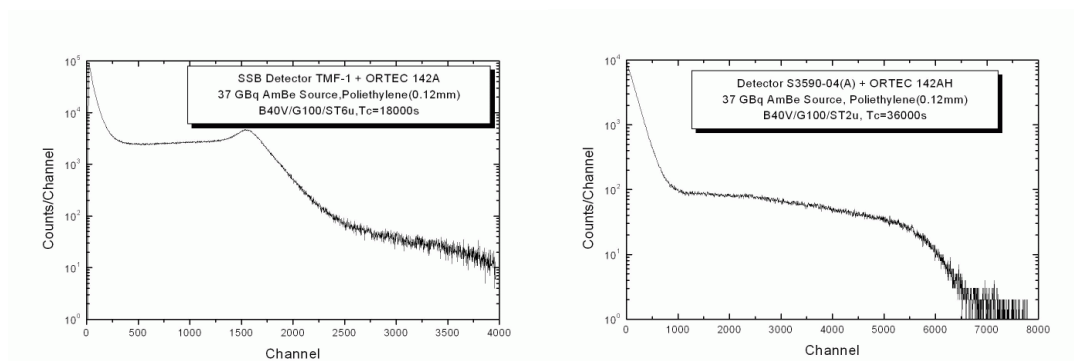


Figure 8. Response of TMF-1 SSB (left) and S3590-04 PIN photodiode (right) to an AmBe neutron source.

For direct fast neutrons detection from the AmBe source, a 0.12 mm (experimental) thick polyethylene converter was placed in front of the photodiode. In this case, the distance from the source to the surface detector was 30 mm and the results for the optimized thickness are shown in Fig. 8.

4.2 Neutronography facility results

In this facility, the following spectra were obtained with the reactor IEA-R1, operating at nominal thermal power of 2 MW, as shown in Fig. 9 (0.12 mm polyethylene converter).

Under thermal/epithermal neutron field, the TMF-1 SSB detector shows (Counts/Channel) a better sensitivity than the S3590, although the latter shows a better response (Channel).

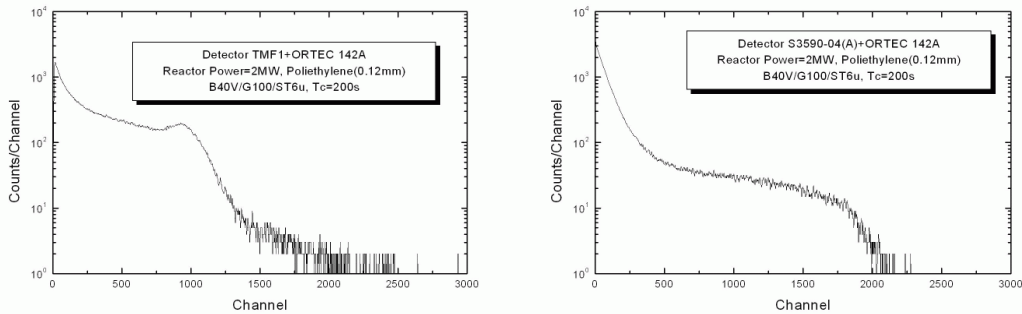


Figure 9. Response of TMF-1 SSB and S3590-04 PIN photodiodes to epithermal neutron in the Neutronography facility.

4.3 IPEN/MB-01 facility results

In the IPEN/MB-01 (UCRI) reactor, the spectra of the recoil protons were obtained. Both detectors, TMF-01 and S3509-04, were placed around the reactor core, then the reactor IPEN-MB01 operated at a thermal power of 1, 2, 4 and 10 Watts, as shown in Fig. 10. In this case, the TMF-1 showed a better performance in sensitivity and range than the S3590; this makes the TMF-1 suitable to be used either as a reactor power monitoring device or as a support tool in the UCRI power calibration.

In this work, we only show the detectors, charge sensitive amplifiers and the spectroscopy amplifier with the best performances. Some detectors, as the ORTEC SSB, presented considerable problems to work with them, because their high sensitivity for handling and to any kind of radio-interference, shielding or grounding problems. This kind of ORTEC SSB detector might need a special enclosure assembly, against interferences. Some Charge

Sensitive Preamplifier presented excessive instability (ORTEC 142AH) or nonlinearity (Soshin 9161), consequently we chose to work with the ORTEC 142A and the 142PC.

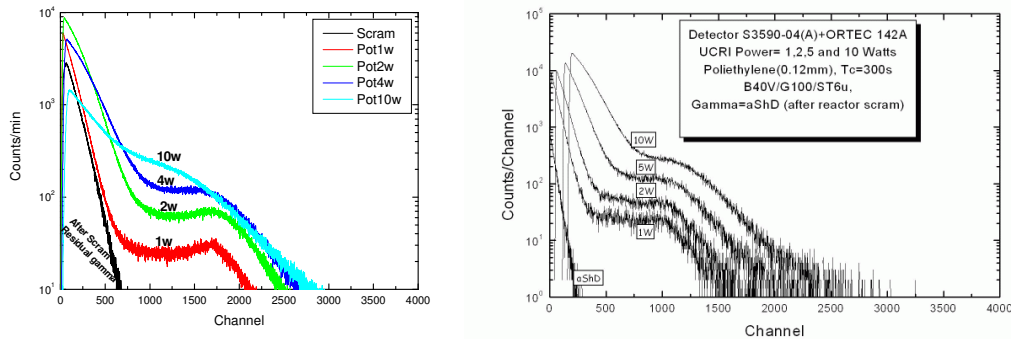


Figure 10. Response of TMF-1 SSB (left) and S3590-04 PIN photodiode (right,) to fast neutron in the IPEN-MB01 reactor for 1, 2, 4 and 10 watts thermal power.

5. CONCLUSIONS

The response, as a neutron detector of a silicon surface barrier TMF-1, ORTEC (BA-040-200-300) and the silicon photodiodes types S3590-04 and S1223-01, from Hamamatsu, together with a multi-channel analyzer Maestro configuration (ORTEC instrumentation) were investigated in an AmBe field (CENF Laboratory) and in the neutron environment of the IEA-R1 (Neutronography facility) and IPEN/MB-01 reactors (in-core hall experiments), at the CNEN/IPEN-SP facility.

The results showed that the SSB (TMF-1) detector has an overall better response than the S3590-04 detector. The TMF-1 detector could also be used as a power monitor-controller for the IPEN/MB-01 reactor, through a complete new design. Using these types of semiconductors (SSB and Photodiode), a spectrometer system may be developed. This spectrometer could be employed for assessing the neutron spectra in various radiation fields to be used, for example, in radiation biological cultures (BNCT application), to study the radiation damage in electronics devices or in shielding calculation for radiation protection and for teaching purposes. In the future, the detectors will be a) modeled, through Monte Carlo codes, to predict more accurately the response and to estimate the efficiency, b) compared with LiF TLD600 or TLD700 for absorbed dose measurements and foil activation techniques, for characterizing the neutrons beam, c) compared (data) with ISO 8529-2 recommended neutron energy distribution, in the case of AmBe source d) submitted (data) to uncertainties analysis, d) tested for saturation effect of the proton pulse height, in order to estimate the effective thickness of the detector depletion layer, e) improved (response) through analytical corrections (photodiodes) and applicability (maybe) in microdosimetry.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. Roberto Franjdlich and Dr. Walter Ricci from the IEA-R1 reactor, the reactor operation staff, radiation protection supervisors and technicians, Dr. Ulisses Bitelli, head of the IPEN/MB-01 reactor, operation staff, senior operator Physicist

Rogério Jerez and Radiological Protection technicians and, also, Dr. Reynaldo Pugliese and Dr. Marcos Pereira, for the support in the Neutronography facility.

REFERENCES

1. A. B. Rosenfeld, D. Cutajar, M. L. F. Lerch, G. Takacs, I.M. Cornelius, M. Yudelev and M. Zaider. "Miniature semiconductor detectors for in vivo dosimetry", *Radiation Protection Dosimetry*, **Vol. 120**, No. 1-4, pp. 48-55 (1986).
2. Hamamatsu photonics, *Technical Information*. "Si photodiodes and Charge Sensitive Amplifiers for Scintillation Counting and high Energy Physics" (1997)
3. Y. Eisen, G. Engler, E. Ovadia and Y. Shamai, Z. Baum and Y. Levi "A small size neutron and gamma dosemeter with a single silicon Surface Barrier Detector", *Radiation protection Dosimetry*, **Vol 15**, N° 1, pp.15-30 (1986).
4. W. G. Alberts, J. M. Bordy, J. L. Chartier, R. Jahr, H. Klein, M. Luszik-Bhadra, F. Posny, H. Schuhmacher and B. R. L., "Neutron Dosimetry", *Radioprotection (Revue de la Societe francaise de Radioprotection)*, **Vol. 31**, No 1, pp. 37-65 (1996).
5. S. Agosteo, P. G. Fallica, A. Fazzi and A. Póla "Feasibility study of a solid State microdosimeter". *Applied Radiation and Isotopes*, **Vol. 63**, pp. 529-535 (2005).
6. P. B. Rodrigues, M. A. Sanches and F. V. Tomoe, *Applied Radiation Isotopes*, **48(9)**, pp1215 (1997).
7. A. S. Tanarro, "Instrumentação Nuclear", *Servicio y Publicaciones de la Junta de Energia Nuclear (JEN)*, Madrid (1970).
8. J. C. Vareille, B. Barelaud, J. Barthe, J. M. Bordy, G. Curzio, F. D'Errico, J. L. Decossas, F. Fernandes-Moren, T. Lahaye, E. Luguera, O. Seupsonidis, F. Savvidis and M. Zamani-Valassiadou, "Advanced detectors for active neutron dosimeter", *Radiation Protection Dosimetry*, **Vol 70**, 1-4, pp. 79- (1997).
9. T. Madi, F. Shiriashi, M. M. Hamada and C. H. Mesquita, "Development of neutron detector using the surface barrier sensor with polyethylene (n,p) and B (n, γ) converter", *Nuclear Instruments and Methods in Physics Research*, **A458**, pp. 441-447 (2001).
10. M. A. S. Pereira, "Radiografia com partículas alfa induzida por nêutrons", *Tese de Doutorado, Instituto de Pesquisas Energéticas e Nucleares*, Universidade de São Paulo, Brasil (2007).
11. U. Bitelli, M. Alves and P. R. P. Coelho, "Mapeamento do fluxo de nêutrons térmicos no canal de irradiação #8 do reator IEA-R1", *VII ENFIR*, Atibaia-SP, Brasil (1991).
12. C. H. Mesquita, T. Madi and M. M. Hamada, "Development of neutron detector using the PIN photodiode with polyethylene (n,p) converter", *IEEE Transactions on Nuclear Science*, **Vol. 50**, N4, August (2003).
13. M. Farahmand, "A novel Tissue-Equivalent Proportional Counter Based on a Gas Electron Multiplier", *Doctorate Thesis, Interfaculty Reactor Institute (IRI), Delft University of Technology*, IRAN (2004).
14. Y. Takami, F. Shiriashi, H. Murakami, M. Sieminski and N. Iwasa, *IEEE Transactions on Nuclear Science*, **NS-36**, pp.181 (1989).
15. J. R. Lamarsh, "Introduction to nuclear reactor theory", 2nd Edition, Addison-Wesley, MA, USA (1972).
16. ORTEC INCORPORATED, "Instruction Manual-Surface barrier Detector", Oak Ridge, Tennessee, USA (1966).