Semi-insulating GaAs detectors with HDPE layer for detection of fast neutrons from D–T nuclear reaction

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Bulk semi-insulating (SI) GaAs detectors optimized for fast-neutron detection were examined using mono-energetic neutrons. The detectors have an active area of 7.36 mm² defined by a multi-pixel structure of a AuZn Schottky contact allowing a relatively high breakdown voltage (300 V) sufficient for full depletion of the detector structure. The Schottky contact is covered by a HDPE (high density polyethylene) conversion layer, where neutrons transfer their kinetic energy to hydrogen atoms through elastic nuclear collisions. The detectors were exposed to mono-energetic neutrons generated by a deuterium (D)–tritium (T) nuclear reaction at a Van de Graaff accelerator.

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Neutrons reached a kinetic energy of 16.8 MeV when deuterons were accelerated by 1 MV potential. The influence of the HDPE layer thickness on the detection efficiency of the fast neutrons was studied. The thickness of the conversion layer varied from 50 μm to 1300 μm . The increase of the HDPE layer thickness led to a higher detection efficiency due to higher conversion efficiency of the HDPE layer. The effect of the active detector thickness modified by the detector reverse bias voltage on the detection efficiency was also evaluated. By increasing the detector reverse voltage, the detector active volume expands to the depth and also to the sides, slightly increasing the neutron detection efficiency.

Keywords: Solid-state detectors; GaAs; HDPE; detection efficiency; fast neutrons.

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1. Introduction

Detectors of fast neutrons find applications in many areas such as nuclear medicine, nuclear power engineering, high-energy physics, materials science, and astrophysics. Applications have recently been extended to petrology, archaeology, mining, geology, and security, thanks to neutron imaging, high-speed tomography, or neutron resonance imaging techniques. Semiconductor based detectors with a neutron conversion layer present a very promising solution of fast neutron detectors, exhibiting compactness, small dimensions and high spatial resolution. Recent processing methods for silicon and gallium arsenide allow realization of moderate- to high-efficiency neutron detectors.¹ Conversion layers for fast neutrons are attached to the detector in contact planar geometry and are usually based on polyethylene (PE)^{2,3,4} and high density polyethylene (HDPE),^{5,6,7} but also on fast plastic scintillator.⁸

We have optimized our bulk semi-insulating (SI) GaAs detectors for fast-neutron detection by a multi-pixel structure of a Schottky contact.⁷ Neutrons are converted by (n,p) elastic nuclear collisions in an HDPE layer covering the Schottky contact. In our previous research described in Ref. 7, detectors were tested using a ²³⁹Pu-Be source of fast neutrons with a continuous spectrum up to 12 MeV and mean energy of about 4 MeV. The maximum obtained experimental detection efficiency was 0.113% with a 500 μm thick HDPE layer at a 100 V reverse voltage. However, the ²³⁹Pu-Be neutron source is also a source of gamma-rays, which might have affected the results.

In this paper we have examined SI GaAs detectors with a different type of neutron source to study their detection properties. The detectors were exposed to mono-energetic neutrons with higher kinetic energy (16.8 MeV) generated by a deuterium (D)–tritium (T) nuclear reaction at a Van de Graaff (VDG) accelerator. The detection properties were evaluated considering two parameters: the thickness of the HDPE conversion layer (varying from 50 μm to 1300 μm) and the thickness of the active detector volume (varying from 60 up to 234 μm) modified by the detector reverse voltage (50 to 300 V).

2. Detector Structure

The neutron detectors were prepared from a bulk LEC (Liquid Encapsulated Czochralski) SI GaAs substrate made at CMK Ltd (Slovakia). The resistivity of GaAs is about $1.1 \times 10^8 \Omega\text{cm}$, and the Hall mobility is $5280 \text{ cm}^2/\text{Vs}$ at room temperature. The wafer was polished from both sides to a thickness of $270 \mu\text{m}$. The Schottky electrode was evaporated onto the topside using 120 nm thick AuZn metallization. Its multi-pixel structure was created by a system of 8×3 large pixels ($400 \mu\text{m} \times 400 \mu\text{m}$) connected with 7×2 small pixels ($200 \mu\text{m} \times 200 \mu\text{m}$), as seen in Fig. 1, covering an area of 7.36 mm^2 . A rectangular quasi-ohmic metal electrode was formed by evaporating a eutectic AuGeNi alloy (120 nm) on the back side of the substrate.

The Schottky contact was covered by an HDPE conversion layer, where neutrons transfer their kinetic energy to protons in the hydrogen atoms through elastic nuclear collisions, as depicted in Fig. 2. The HDPE layer of 50 , 650 or $1300 \mu\text{m}$ thickness was fixed at the surface of the Schottky metallization by a dielectric polypropylene (PP) based glue (about $2 \mu\text{l}$) diluted with toluene (10% solution), minimizing the prospective roughness of the detector or HDPE layer and preventing any air gap formation. Moreover, the insulating nature of the PP glue decreases the detector reverse current by a few nA.⁷

Fig. 1. Photograph of the multi-pixel structure of the detector Schottky contact.

Fig. 2. Cross-section view of the SI GaAs detector with HDPE conversion layer for neutrons fixed by PP glue.

3. Experiment

The measurements were performed at the Van de Graaff Laboratory of the Institute of Experimental and Applied Physics at the Czech Technical University in Prague. Fast neutrons were produced by bombarding a tritium target with deuterons accelerated by the VDG accelerator to 1 MeV kinetic energy. The kinetic energy of the produced fast neutrons was 16.755 MeV at 0 degree angle,⁹ and their flux on the sample was about 2.5×10^6 n/cm²s. The distance between the detector and the neutron source was about 3 cm. The detector tested was connected to a spectrometric chain based on InSpector2000 readout electronics. The fast neutrons transfer their energy to hydrogen nuclei in HDPE by elastic scattering. The SI GaAs detector detects the recoil protons,⁵ and the HDPE layer is directly sensitive to the fast neutrons.^{10,11} As the protons are slowed down in the detector volume, electron-hole pairs are created. The high electric field between the detector electrodes separates the generated charges, and the pulse corresponding to proton energy can be measured at the output of the detector (see Fig. 2). The measured pulse-height spectra showing the influence of the HDPE thickness on the detection of neutrons are shown in Fig. 3. The effect of the active detector thickness determined by the applied reverse voltage can be seen in Fig. 4. The first steeply decreasing part of the spectra (up to channel 30) corresponds to the preamplifier and detector noise, and the second part (channels 30 up to 300) represents the neutron detection.

Fig. 3. Spectra of fast neutrons measured by SI GaAs detectors coated by an HDPE conversion layer of various thicknesses at a reverse voltage of 200 V.

Fig. 4. Spectra of fast neutrons measured by SI GaAs detectors coated by a 650 μm thick HDPE conversion layer at different reverse voltages.

4. Results and Discussion

Two parameters were observed in our experiments: the neutron conversion layer thickness and the reverse voltage applied to the SI GaAs detector. The influence of these two parameters on the detection efficiency of neutrons was studied.

4.1. Conversion layer thickness effect

The HDPE conversion layer acts as a recoil proton source, and its thickness is an important parameter. We used HDPE layers of various thicknesses (50, 650 and 1300 μm) and compared the results with a bare detector. The conversion efficiency of the HDPE conversion layer is determined by two phenomena. The first is the number of neutrons recoiling the protons, which increases with the growing layer thickness. The second is the projected range of recoiled protons in the layer. The projected range of protons in HDPE increases with the proton energy, as is seen in Fig. 5. The maximum energy of recoiled protons in our experiment was 16.755 MeV, which means the maximum projected range is ~ 3 mm according to SRIM calculations.¹² If the conversion layer thickness exceeds the projected range of protons, some of them are absorbed in the layer and will not reach the active detector volume. The theoretical optimum thickness of the conversion layer can be determined by the Monte Carlo radiation transport computer code MCNPX.¹³ As shown in Ref. 14, the optimum values of the HDPE thickness, reaching the highest conversion efficiency, are shorter than the proton ranges in the layer calculated using the SRIM programme.¹² The neutron conversion efficiency is expressed as a ratio of the number of recoiled secondary particles (protons) and the number of neutrons impinging on the detector surface. The conversion efficiency of the HDPE reactive layer steeply increases with its thickness up to an optimum value of about 1.9 mm for 16.5 MeV neutrons, followed by a milder decrease. Because the thickness of

our HDPE layers ranges from 50 μm up to 1300 μm , the neutron conversion efficiency increases with growing thickness, leading to a higher neutron detection efficiency of the SI GaAs detector, as shown in Fig. 6. A similar tendency with the conversion layer thickness was observed in Ref. 5, where the GaAs detector was coated by 125 and 875 μm thick HDPE layers, detecting 14 MeV neutrons.

The neutron detection efficiency ε can be expressed as:

$$\varepsilon (\%) = \frac{N}{F \times A \times t} \times 100, \quad (1)$$

where N is the number of counts above the valley, F is the neutron flux (neutrons/ cm^2s) on the sample, A is the detector area in cm^2 and t is the exposure time in seconds. The investigated SI GaAs detectors were exposed to fast neutrons delivered by the VDG accelerator. The average neutron flux on the sample was 2.5×10^6 n/ cm^2s during irradiation, varying from 2.3×10^6 n/ cm^2s when using the SI GaAs detector with a 1300 μm HDPE layer up to 2.7×10^6 n/ cm^2s when the SI GaAs detector with a 650 μm HDPE layer was tested.

Fig. 5. Projected range of hydrogen nuclei recoiled by fast neutrons in the conversion layer (HDPE) vs. in detector material (GaAs) according to SRIM calculations.¹²

Fig. 6. Neutron detection efficiency of the SI GaAs detector coated by an HDPE neutron conversion layer as a function of the HDPE layer thickness for various reverse voltages applied.

4.2. Active detector thickness effect

The knowledge of the electric field distribution across GaAs detectors is of major interest for their optimization. To improve the performance of the detector, a high and as extended electric field as possible is required. In this way we prevent trapping and can utilize nearly the whole detector as an active effective volume of detection. In Ref. 15 it was proved that for reverse voltages higher than 20 V, the active layer thickness of the SI GaAs detector linearly increased with the voltage applied (see Table 1). By increasing the reverse voltage, we deepen the active detector volume, and a larger portion of the charge generated by slowing-down the protons is registered. It will be manifested by an increased number of counts in higher channels. At lower reverse voltage, the active detector volume is thinner, but the recoiled protons are registered alike. However, the smaller part of generated charge is collected. The pulse corresponding to the proton energy measured at the output of the detector is lower, thus registered in lower channels. We can follow this tendency in the spectra that were shown in Fig. 4.

Table 1. Thickness of the active volume of the SI GaAs detector as a function of the applied reverse voltage according to Ref. 15.

Reverse voltage (V)	Active thickness (μm)
50	59
100	94
150	129
200	164
250	199
300	234

Fig. 7. Neutron detection efficiency of the SI GaAs detector coated by variously thick HDPE layers as a function of the reverse voltage applied.

The count rate above the valley representing the detected protons should be constant and independent of the applied reverse voltage. Thus also the neutron detection efficiency should not change with voltage applied. However, our measurements showed a slight increase of detection efficiency with voltage at thicker HDPEs, which was most probably caused by the extending electric field. According to our previous results,¹⁶ the active volume of the SI GaAs detector expands not only to its depth but also to the sides, behind the Schottky contact edges. The multi-pixel structure of our Schottky contact will multiply this effect. This was the probable reason for the slight increase in neutron detection efficiency with increasing reverse voltage, observable with detectors with thicker HDPE layers (650 and 1300 μm) that exhibit a higher neutron conversion efficiency.

In our experiment, the maximum neutron detection efficiency of 0.243 % was obtained by the detector with a 1300 μm thick HDPE layer at 300 V, which is in good agreement with other research groups dealing with semiconductor neutron detectors. In Ref. 4, the authors obtained a neutron detection efficiency of 0.13 % using an epitaxial GaAs detector with a polyethylene converter exposed to an $^{241}\text{AmBe}$ neutron source (4.08 MeV mean neutron energy). Another group (Ref. 2) reached an intrinsic detection efficiency of 7.6×10^{-4} using an $^{241}\text{AmBe}$ source and 2.5×10^{-4} with ^{252}Cf (2.2 MeV mean neutron energy) utilizing a semiconductor alpha detector with a polyethylene conversion layer. Research with a Medipix2-based silicon device coated by 1300 μm of polyethylene showed a mean efficiency of 0.18 % for 14 MeV neutrons from a VDG (Ref. 3) and a neutron detection efficiency of about 0.09 % for 4 MeV neutrons from an $^{241}\text{AmBe}$ source.¹⁷ We have obtained an experimental detection efficiency of 0.113 %, using the optimal thickness of HDPE layer (500 μm) for an $^{241}\text{AmBe}$ neutron source in our previous research described in Ref. 7. The detection efficiency could be affected by the detector and readout electronic noise, which superposed with signal from low energy protons.

5. Conclusions

The response of SI GaAs detectors to mono-energetic fast neutrons (16.8 MeV) from the D–T nuclear reaction has been experimentally studied. First, the thickness of the HDPE neutron conversion layer and its influence on the neutron detection efficiency was the objective of the research. The HDPE thickness varied from 50 to 1300 μm . In this range, we observed an increasing neutron detection efficiency with greater HDPE thickness as the neutron conversion efficiency of the layer was also increasing. Second, the effect of active detector thickness modified by the detector reverse voltage was evaluated. By increasing the detector reverse voltage, the detector active volume expands to the depth of the GaAs substrate and also behind the edges of the blocking Schottky detector contact. The greater detector volume slightly increases the overall neutron detection efficiency in the case of thicker HDPE layers.

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