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Performances of 4H-SiC Schottky diodes as neutron detectors

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Abstract

Large area 4H-SiC Schottky diodes equipped with a ^{6}LiF converter were tested as neutron detectors in the epithermal column realized for Boron Neutron Capture Therapy (BNCT) applications at the fast reactor TAPIRO (ENEA Casaccia Roma). The neutron spectra were assessed using the Monte Carlo code MCNP-4C. The performances of SiC detectors were evaluated with neutron fluences in the range of 10^{9}–$10^{13}\,cm^{-2}$ which is typical for BNCT. Spectra of alpha and tritium particles generated by $^{6}Li(n,\alpha)^{3}H$ reaction were collected at various neutron fluences and spectra obtained by interposing polyethylene moderators of different thickness. Only weak damaging effects primarily due to the alpha particles were observed; at neutron fluence of $10^{13}\,cm^{-2}$ the count rate decreased by $<0.3\%$. The experimental results were compared with the theoretical ones calculated using MCNP-4C and SRIM codes.

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Keywords: Radiation detector; Neutron detection; Boron neutron capture therapy; Epitaxial silicon carbide; Neutron beam monitoring; MCNP

1. Introduction

It is well known that 4H-SiC Schottky diodes can be used as neutron detectors via neutron-induced charged particles produced by converters like ^{6}LiF. The capabilities of such type of detectors to discriminate gamma from neutron signals were well established [1,2]. Moreover, the wide band gap makes SiC very suitable for high-temperature applications [2,3].

A possible use of 4H-SiC neutron detectors is the monitoring of neutron flux in Boron Neutron Capture Therapy (BNCT), where the total neutron fluence required for the treatment is around $10^{12}\,cm^{-2}$ [4]. In this field, the knowledge of the actual neutron flux and spectrum and the possibility of a priori simulation have an important role. In order to test the reliability of simulation methods and the capabilities of 4H-SiC detectors, the response to epithermal neutron fluxes realized for BNCT was studied [5]. Various neutron fluences and spectra obtained by interposing polyethylene moderators of different thickness were used and experimental results were compared with simulations by means of MCNP-4C and SRIM codes.

2. Experimental

4H-SiC detectors were made using a process described in a previous work [6]. 4H-SiC Schottky diodes, with large area Ni/Au electrodes (3 or 5 mm diameter), were realized by Alenia Marconi System JV (Rome) on 50 μm epitaxial layers, deposited by the Institute of Crystal Growth (IKZ, Berlin) on LMP n-type 4H-SiC wafers (purchased from CREE Res. Inc.). Circular ^{6}LiF converters, about 100 μm thick and with a diameter of 4.6 mm, were placed externally and close to the electrodes (the distance was smaller than 1 mm).

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SiC detectors were exposed to neutron fields in the epithermal column realized for BNCT applications at the fast reactor TAPIRO (ENEA Casaccia Roma). The neutron spectra, peaked at around 1 keV, were assessed using the Monte Carlo code MCNP-4B [7]. The performances of SiC detectors were evaluated with neutron fluences in the range of 10^9–$10^{13}\,cm^{-2}$. The ^{6}LiF converter exploits the nuclear reaction ^{6}Li(n,α)^{3}H which has a *Q*-value of 4.78 MeV. For incoming thermal neutrons, alpha and triton particles with energy of 2.05 and 2.73 MeV, respectively, are generated and detected by SiC detectors. Spectra of alpha and tritium particles, generated by ^{6}Li(n,α)^{3}H reaction, were collected at different applied bias voltages and at various neutron spectra obtained by interposing polyethylene moderators of thickness from 10 to 55 mm.

The experimental results were compared with the theoretical ones calculated using MCNP-4C and SRIM codes. Neutron fluence in ^{6}LiF was evaluated by means of MCNP-4C for each moderator thickness. Unfortunately, this code does not transport charged ions therefore, SRIM code and analytical calculations were necessary to complete the study.

All the data were calculated at the maximum reactor power, i.e. 5 kW and then normalized to 1 W, the value used during the experiment.

3. Results and discussion

The capabilities of these detectors to discriminate gamma rays from alpha and triton particles were already proved [6]; the gamma-ray signal contributes to the spectra only below 500 keV as experimentally observed using neutron reactor without ^{6}LiF converter or ^{60}Co source.

The spectra obtained using a 20 mm^2 area detector (sample M) at different applied bias voltages during neutron irradiation at 1 W reactor power (i.e. 2.3×10^5 neutrons cm^{-2} s^{-1}) are shown in Fig. 1. Changes in the spectrum shapes are due to the partial collection of charges. In fact, the maximum penetration range of 2.05 MeV alpha particles and 2.73 MeV triton particles in SiC are about 5 and 28 μm, respectively as underlined by SRIM calculations. Therefore, we can expect a total collection of the produced charges only if the active region is thicker than 28 μm. This condition is achieved at about −100 V applied bias, as highlighted from *C–V* measurements [6]. The flat shape of the spectra at full collection of the charges is due to the isotropic angular distribution of ions produced in ^{6}LiF and due to the converter thickness which is greater than particles range inside it. Therefore, alpha and triton particles hit the detector carrying all the energies from 0 to 2.05 and 2.73 MeV, respectively.

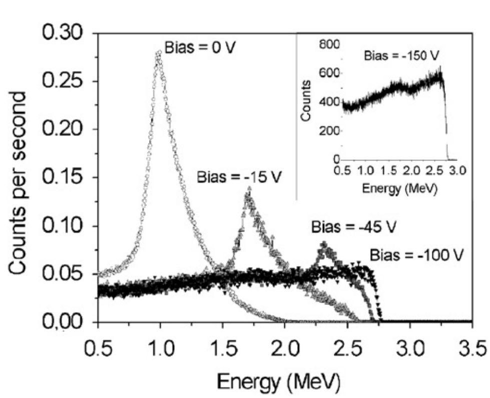

Fig. 1. Spectra obtained using a 20 mm^2 area detector (sample M) at different applied bias voltages during neutron irradiation (1 W reactor power). In the square is reported the spectrum obtained at full collection conditions (−150 V).

The spectrum obtained at full collection conditions (i.e. at −150 V) is shown in the inset of Fig. 1. The maximum energy is about 2.7 MeV as expected, but a shoulder is visible at about 1.8 MeV, which corresponds to the maximum energy released by alpha particles in the detector active region taking into account the energy loss in the Au + Ni electrode [8] and in the thin air layer between ^{6}LiF and the electrode.

The total measured counting rate as function of the moderator thickness is reported in Table 1. In order to avoid the contribution of gamma rays, only counts above 500 keV in the spectra were considered. The uncertainty was estimated averaging the spectra obtained in the same conditions.

Only weak damaging effects were observed, primarily due to the alpha particles that generate in SiC more vacancies/μm than triton particles [9]; spectra measured before and after irradiation at neutron fluences of $10^{13}\,cm^{-2}$ in full collection conditions ($V_{bias} < -100$ V) were very similar and the counting rate decreased to <0.3%. However, at low bias voltage, CCE spectra display a noticeable change in shape, as shown in Fig. 2 for a 7 mm^2 area detector (sample H). This effect can be ascribed to the dominant role of diffusion in charge collection mechanism which turns out to be much more sensitive than drift in reducing the minority carrier lifetimes due to trap level generated by ion irradiation [10].

As far as the simulations are concerned, the spectra of neutron flux and the ions production rate inside the ^{6}LiF converter, carried out with MCNP-4C code, are shown in Fig. 3. Spectra obtained without moderator are displayed

Table 1
Experimental counting rate (second column) and total particles generation rate in ^{6}LiF calculated using MCNP-4C (third column) as function of moderator thickness

Moderator thickness (mm)	Experimental counting rate (cps)	Total particle generation rate in ^{6}LiF (s^{-1})
0	134±5	360
10	188±6	992
16	214±6	1324
26	226±7	1490
39	208±6	1236
55	168±5	856

in Fig. 3a and b; in this case the neutron flux is related to the bare epithermal spectrum. The spectra obtained after 26 mm of moderator thickness, which corresponds to the highest ions production, are shown in Fig. 3c and d. It is possible to observe a neutron energy shift to lower energies as the moderator is interposed. This means that there is a greater probability (higher reaction cross-section) of neutron interaction in ^{6}LiF via the ^{6}Li(n,α)^{3}H reaction and a higher ion production rate. However, at the same time the overall neutron flux decreases, due to the neutron absorption and scattering within the moderator. This implies lower particles production by interposing moderator of increasing thickness. The total ion production rate is reported in Table 1 for each experimental configuration as calculated by MCNP-4C at 1 W reactor power; the calculated counting rate is higher than the experimental one due to geometrical effects and to the stopping particles in the ^{6}LiF converter. As shown in Fig. 4, these data are linearly correlated to the measured counting rate with a correlation coefficient of about 0.995. The fitting parameters calculated in Fig. 4 are used to compare the simulated alpha production with the experimental results. Normalized data are reported in Fig. 5 showing a fairly well fit that demonstrates the reliability of the Monte Carlo simulation.

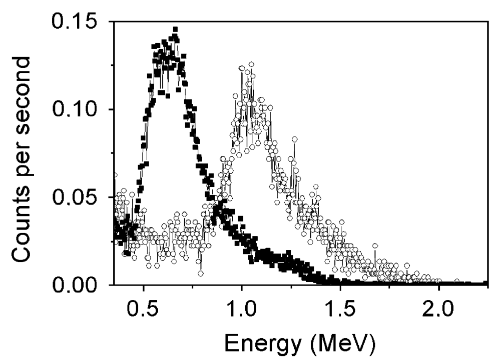

Fig. 2. Spectra measured using a 7 mm^2 area detector (sample H) at -1 V bias and at 1 W reactor power. The spectra were recorded before (open circles) and after (dark squares) a neutron fluence of 10^{13} cm^{-2}.

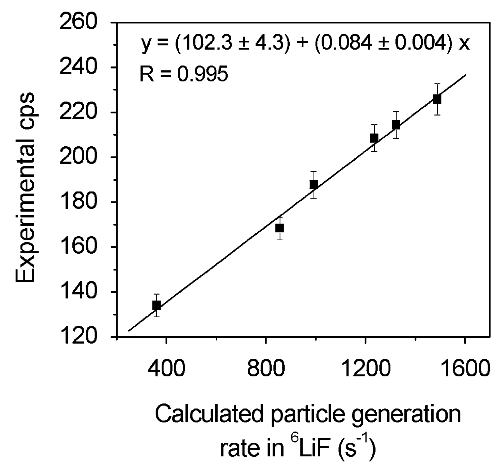

Fig. 4. Linear fit of measured counting rate as function of calculated values reported in Table 1.

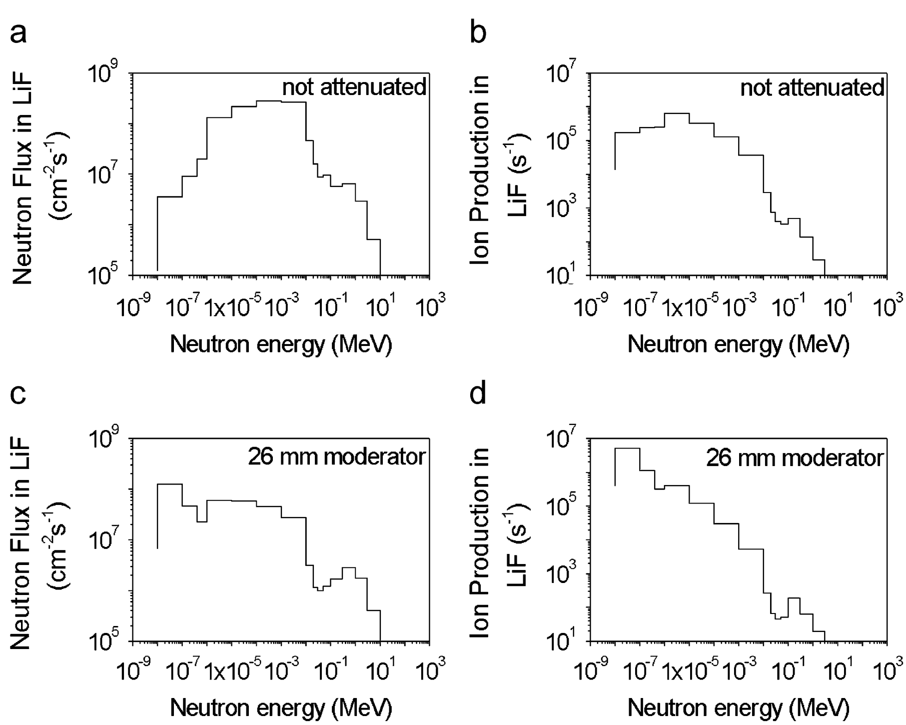

Fig. 3. Spectra of neutron flux and ions production rate inside the ^{6}LiF converter carried out with MCNP-4C code at 5 kW reactor power: (a) and (b) are the spectra due to the bare epithermal spectrum; (c) and (d) are the spectra after 26 mm polyethylene moderator.

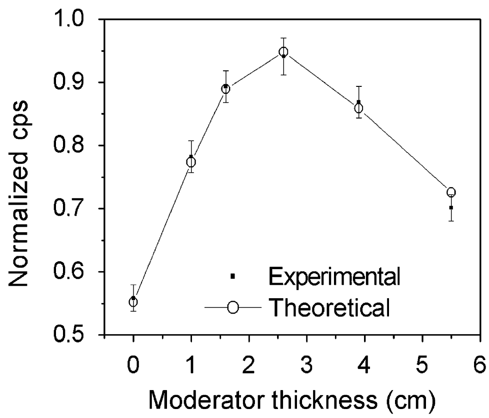

Fig. 5. Comparison between experimental data and calculated values as a function of moderator thickness.

4. Conclusions

In this paper, 4H-SiC detectors up to $20\,mm^2$ area and equipped with ^6LiF converters were characterized as epithermal neutron detectors in the fluence range of 10^9–$10^{13}\,cm^{-2}$. Alpha and triton particles from $^6Li(n,\alpha)^3H$ reaction were completely collected only for a polarization above $-60\,V$ where the depletion layer is thicker than the particles range in SiC. Only weak damaging effects, primarily due to alpha particles were observed at neutron fluence of our interest.

MCNP-4C and SRIM codes were used to assess the effects of polyethylene moderators interposed between source and detector on neutron spectra, particles generation rate in LiF, and SiC detector collection. The good agreement between experimental and calculated data demonstrates the reliability of the Monte Carlo simulation.

Acknowledgment

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