Detection of fast neutrons from D–T nuclear reaction using a 4H–SiC radiation detector

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The particle detector based on a high purity epitaxial layer of 4H–SiC exhibits promising properties in detection of various types of ionizing radiation. Due to the wide band gap of 4H–SiC semiconductor material, the detector can reliably operate at room and also elevated temperatures. In this work we focused on detection of fast neutrons generated the by D–T (deuterium–tritium) nuclear reaction. The epitaxial layer with a thickness of 105 μm was used as a detection part.

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A circular Schottky contact of a Au/Ni double layer was evaporated on both sides of the detector material. The detector structure was characterized by current-voltage and capacitance-voltage measurements, at first. The results show very low current density ($<0.1 \text{ nA/cm}^2$) at room temperature and good homogeneity of free carrier concentration in the investigated depth. The fabricated detectors were tested for detection of fast neutrons generated by the D-T reaction. The energies of detected fast neutrons varied from 16.0 MeV to 18.3 MeV according to the acceleration potential of deuterons, which increased from 600 kV up to 2 MV. Detection of fast neutrons in the SiC detector is caused by the elastic and inelastic scattering on the silicon or carbide component of the detector material. Another possibility that increases the detection efficiency is the use of a conversion layer. In our measurements, we glued a HDPE (high density polyethylene) conversion layer on the detector Schottky contact to transform fast neutrons to protons. Hydrogen atoms contained in the conversion layer have a high probability of interaction with neutrons through elastic scattering. Secondary generated protons flying to the detector can be easily detected. The detection properties of detectors with and without the HDPE conversion layer were compared.

Keywords: Solid-state detectors; SiC; fast neutrons.

1. Introduction

Silicon carbide (SiC) is a promising material for high-temperature electronics, high-frequency devices, and radiation-resistant electronics. The capability of SiC to function under extreme conditions can improve many systems and applications,¹ and SiC can also be used as a sensor of ionizing radiation.^{2,3,4} The 4H-SiC polytype is prospective due to its high breakdown voltage of about $2 \times 10^6 \text{ V/cm}$, electron mobility of about $900 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, and saturation drift velocity $2 \times 10^7 \text{ cm/s}$. The band gap energy of 4H-SiC is 3.26 eV at room temperature (RT).

Detectors based on the 4H-SiC epitaxial layer can attain high quality X-ray spectroscopic data at room as well as at increased temperatures. One of the best spectra of the ^{55}Fe radioisotope and the noise energy of 196 eV FWHM (Full Width at Half Maximum) at 300 K for the 5.9 keV photopeak were reported in Refs. 5 and 6. The detection efficiency is, however, limited primarily by a low thickness of the active region (around 100 μm) and by a low linear absorption coefficient, almost identical with silicon detectors. Very good radiation hardness was acquired in a study⁷ in which detectors were exposed to gamma radiation produced by ^{137}Cs with doses up to 5.5 MGy, and no significant deterioration in detection of α -particles emitted by ^{238}Pu radioisotope was observed. In addition, our previous work⁸ showed only a weak deterioration of the detected gamma spectrum from ^{241}Am after fast neutrons and gamma irradiation. Characterizations of the depletion region length of a 4H-SiC Schottky detector using a ^{90}Sr β -source have also been realized.⁹ A 100 % CCE (Charge Collection Efficiency) and fully depleted detector thickness was observed. Also in studies using α -particles, detectors achieve 100 % CCE, diffusion length of holes up to 13 μm , and energy resolution 0.38 % (FWHM) for an optimized detector in terms of material and contact thickness.¹⁰ SiC detectors can be utilized for detection of neutrons, using a converter layer of ^6LiF and ^{10}B for thermal neutrons, while HDPE (High Density Polyethylene) increases the detection efficiency of fast neutrons. In the case of thermal neutrons, the converter layer transforms neutrons to heavy charged particles (alpha, triton, etc.), which

are easily detected with high precision.¹¹ Since silicon and carbon are light atoms, the SiC detector is directly able to detect fast neutrons through elastic scattering of carbon and silicon ions and produce a measurable signal. The detection efficiency can be increased using an HDPE converter layer transforming fast neutrons to protons.¹²

In this paper, we have examined 4H-SiC detectors using a fast neutron source and studied their detection properties. The detectors were exposed to mono-energetic neutrons with different kinetic energy (from 16.0 MeV to 18.3 MeV) generated by deuterium-tritium (D-T) nuclear reactions at a Van de Graaff (VDG) accelerator. The detection properties of 4H-SiC detectors were evaluated considering the use of the HDPE conversion layer and the thickness of the active detector volume modified by the detector reverse voltage (100 to 400 V).

2. Preparation of Detector Structure

Several detector structures were prepared from a 105 μm thick nitrogen-doped 4H-SiC layer (with donor doping of about $1 \times 10^{14} \text{ cm}^{-3}$) grown by LPE (liquid phase epitaxy) on a fragment of a 3 inch 4H-SiC wafer (donor doping level $\sim 2 \times 10^{18} \text{ cm}^{-3}$, thickness 350 μm), by growing a 0.5 μm thick n^{++} -SiC buffer layer with donor concentration of $1 \times 10^{18} \text{ cm}^{-3}$. The radiation detector surfaces were prepared by evaporation of a double layer of Au-Ni/4H-SiC with a thickness of 80/40 nm on both sides of the wafer fragment using a high vacuum electron gun apparatus. The Schottky barrier contact with a diameter of 1.5 mm was formed on the epitaxial layer through a contact metal mask, while a full area contact was evaporated on the other side (substrate). Prior to evaporation, the sample was cleaned in boiling acetone and isopropyl alcohol, washed in deionized water, and dried by nitrogen flow. A schematic cross section of the detector is depicted in Fig. 1.

Fig. 1. Schematic cross-sectional view of the Schottky barrier 4H-SiC fast neutron detector.

3. Experiment and Discussion

At first, electrical characterization was performed, which included current-voltage and capacitance-voltage measurements. Then the detectors were utilized for detection of fast neutrons generated by the D–T nuclear reaction.

3.1. Electrical characterization of detector

The current–voltage characteristics for forward and reverse voltages were measured at RT, and the results are shown in Fig. 2. The detector diode has a high rectifying ratio. In the reverse direction, the sublinear saturation current region is followed by a superlinear shape over about 100 V due to superposition of the injection and leakage currents. The reverse current density at RT lays below 1×10^{-10} A/cm² at a bias of 100 V.

Fig. 2. Measured forward (circle symbols) and reverse (square symbols) current–voltage characteristics at RT.

A capacitance–voltage measurement was performed using an Agilent 4234A Precision LCR Meter operating at 1 MHz up to -40 V. In Fig. 3 (black line), $1/C^2$ is shown as a function of the reverse bias voltage. The dependence is almost linear indicating a very good homogeneity of the doping concentration in the measured range. The dashed curve shows the depletion width profile corresponding to the measured capacitance. The thickness of the space charge region is about $3 \mu\text{m}$ at zero bias voltage and about $18 \mu\text{m}$ at a bias of -40 V. The doping concentration calculated from the measurement was about $1.4 \times 10^{14} \text{ cm}^{-3}$, and it is in good agreement with the value reported by the producer of the epitaxial layer.

Fig. 3. Capacitance–voltage measurement and calculated corresponding width of the depletion region in 4H–SiC Schottky diode detector.

3.2. Fast neutron detection

Fast neutron detection was performed at the VDG Laboratory of the Institute of Experimental and Applied Physics at the Czech Technical University in Prague. Fast neutrons were generated by the D–T nuclear reaction in a tritium target bombarded by deuterons accelerated to kinetic energies from 0.6 MeV up to 2 MeV. The kinetic energy of the produced fast neutrons varied from 16.0 MeV for the lowest acceleration potential up to 18.3 MeV for the highest acceleration potential of 2 MV.¹³ The tested detector was connected to a spectrometric chain based on InSpector2000 readout electronics. Because silicon and carbon are light atoms, primary interactions will be $^{12}\text{C}(\text{n},\text{n}')^{12}\text{C}$ and $^{28}\text{Si}(\text{n},\text{n}')^{28}\text{Si}$ elastic and inelastic scattering. In the detected recoil spectrum, charged particles like alphas and protons will also be revealed if the energy of the fast neutrons is higher than the required threshold depicted in Table 1.

Table 1. Fast neutron reactions on SiC and the respective neutron thresholds.

Nuclear reaction	Neutron energy threshold in MeV
$^{28}\text{Si}(\text{n},\text{n}')^{28}\text{Si}$	0
$^{28}\text{Si}(\text{n},\text{n}')^{28}\text{Si}$ (first excited state)	1.843
$^{28}\text{Si}(\text{n},\alpha)^{25}\text{Mg}$	2.749
$^{28}\text{Si}(\text{n},\text{p})^{28}\text{Al}$	3.999
$^{12}\text{C}(\text{n},\text{n}')^{12}\text{C}$	0
$^{12}\text{C}(\text{n},\text{n}')^{12}\text{C}$ (first excited state)	4.809
$^{12}\text{C}(\text{n},\text{n}')^{12}\text{C}$ (second excited state)	8.292
$^{12}\text{C}(\text{n},\text{n}')^{12}\text{C}$ (third excited state)	11.158
$^{12}\text{C}(\text{n},\text{n}')^{12}\text{C}$ (fourth excited state)	13.769
$^{12}\text{C}(\text{n},\alpha)^9\text{Be}$	6.180
$^{12}\text{C}(\text{n},\text{n}')3\alpha$	7.886
$^{12}\text{C}(\text{n},\text{p})^{12}\text{B}$	13.643

The measured spectra of fast neutrons using the 4H-SiC detector are shown in Fig. 4. We used four different acceleration potentials of 0.6, 1.0, 1.5 and 2.0 MV, which correspond to fast neutron energies of 16.0, 16.8, 17.5 and 18.3 MeV, respectively. In each spectrum, several parts can be identified. In the lowest channels (below 50), there are mainly pulses corresponding to elastic recoils of fast neutrons on Si atoms. Next, elastic recoils follow on C atoms, which are lighter than Si, and neutrons can transfer to them several times more energy. Pulses in channels above 250 correspond primarily to nuclear reactions between neutrons and Si and C atoms. We were able to identify the following nuclear reactions in the measured spectra: $^{12}\text{C}(n,n')3\alpha$, $^{12}\text{C}(n,\alpha)^9\text{Be}$, $^{28}\text{Si}(n,\alpha)^{25}\text{Mg}$ and $^{12}\text{C}(n,p)^{12}\text{B}$. Monoenergetic peaks of alpha particles are shifted to higher channels with increasing neutron energy.

Fig. 4. Measured pulse height spectra of fast neutrons with the 4H-SiC detector. The energy of deuterons was 0.6, 1.0, 1.5 and 2.0 MeV and corresponding energy of neutrons was 16.0, 16.8, 17.5 and 18.3 MeV.

The detection efficiency can be increased by using the HDPE conversion layer, which should be glued on the Schottky contact of the detector. Optimal thickness of HDPE depends on the fast neutron energy. In our experiment we used 1.3 mm thick HDPE,

which is close to the optimal value of 1.6 mm. The comparison of spectra with and without the conversion layer is depicted in Fig. 5. The energy of fast neutrons was 16.0 MeV. The conversion layer transforms fast neutrons to recoil protons since it contains hydrogen atoms. Recoiled protons generate a measurable signal in the 4H-SiC detector. The energy of protons depends on the scattering angle and can reach up to 16.0 MeV in the case of straight collisions. Since the range of 16.0 MeV protons in SiC is several times longer than the active thickness of the detector, only part of the proton energy is passed to the detector. Therefore the signal from protons appeared in the lower part of the spectrum. Fig. 5 shows a comparison of the measured spectra with and without HDPE conversion layer. The increase of counts in channels between 20 and 210 is given by the detection of protons from the conversion layer. The remaining part of the spectrum is unchanged.

Fig. 5. Measured pulse height spectra of fast neutrons with and without HDPE conversion layer. The energy of fast neutrons was 16.0 MeV and the thickness of HDPE was 1.3 mm.

4. Conclusion

We prepared detectors based on a 4H-SiC epitaxial layer for detection of fast neutrons. At first, the electrical characterization (current-voltage and capacitance-voltage measurements) of a Schottky contact detector was performed to find an operational mode. We used the D-T nuclear reaction as a source of fast neutrons. The fast neutron energy ranged from 16.0 MeV up to 18.3 MeV depending on the accelerated energy of the deuterons. In the measured neutron spectra, elastic and inelastic scattering of neutrons on Si and C atoms was revealed as well as nuclear reactions that produce alpha particles and protons. The energy of alpha particles and protons is given by the energy of the fast neutrons. The HDPE conversion layer was used to increase the detection efficiency. When comparing the spectra with and without the conversion layer, the pulses from protons generated by the conversion layer are clearly seen. Because the range of protons

in SiC is longer than the active thickness of the detector, only part of the proton's energy is passed to the detector, and therefore the signal from protons appeared in the lower part of the measured spectrum.

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References

1. B. J. Baliga, *IEEE Trans. on Elect. Dev.* **43**, 1717 (1996).
2. F. Nava et al., *Meas. Sci. Technol.* **19**, 102001 (2008).
3. J. E. Lees et al., *JINST* **6**, C01032 (2001).
4. M. Bruzzi et al., *Diamonds and Related Materials* **12**, 1205 (2003).
5. G. Bertuccio et al., *NIM in Phys. Res. A* **522**, 413 (2004).
6. G. Bertuccio et al., *NIM in Phys. Res. A* **652**, 193 (2011).
7. F. H. Ruddy and J. G. Seidel, *NIM in Phys. Res. B* **263**, 163 (2007).
8. F. Dubecky et al., *JINST* **7**, P09005 (2012).
9. F. Moscatelli et al., *NIM in Phys. Res. A* **546**, 218 (2005).
10. K. J. Zavalla et al., *Proc. of SPIE Vol.* **8852**, 88520D 1 (2013).
11. A. Lo Giudice et al., *NIM in Phys. Res. A* **583**, 177 (2007).
12. R. W. Flammig et al., *NIM in Phys. Res. A* **579**, 177 (2007).
13. H. Liskien and A. Paulsen, *Nuclear Data Tables* **11**, 569 (1973).