

# Detection of fast neutrons using 4H-SiC radiation detectors

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**Abstract**—The particle detector based on a low concentration 4H-SiC epitaxial layer shows promising properties for the detection of various types of ionizing radiation. The wide bandgap energy of the 4H-SiC semiconductor material (3.23 eV at room temperature) allows the detector to operate reliably at room temperature and at elevated temperatures up to several hundred degrees Celsius. The 80 μm thick 4H-SiC epitaxial layer grown on a 350 μm 4H-SiC substrate was used for detector preparation. The active area of the detector was defined by a 3 mm Schottky contact. The current-voltage measurement shows a reverse current of less than 30 pA up to 1000 V. Capacitance-voltage measurements show that the epitaxial layer is completely depleted at bias voltages above 250 V. The detector has been tested with neutrons of energies from 370 keV up to 14.9 MeV. Neutrons were produced by three nuclear reactions p-T, d-D and d-T. The measured spectra clearly identified the elastic and inelastic scattering at silicon and carbon atoms of detector material.

**Keywords** —4H-SiC detector, low concentration SiC epitaxial layer, fast neutron detection.

## I. INTRODUCTION

IN recent years, neutron detectors have become an essential part of many areas of science and research. These are currently: fundamental physics research, cosmology research, neutron imaging as a complementary technique to X-rays and magnetic resonance, small angle scattering for materials research, radiation safety and security, monitoring of transport, nuclear energetics, and others. Neutrons do not directly ionize the material they pass through, so their detection is most often possible through elastic collisions or nuclear reactions that produce secondary radiation (charged particles, photons, etc.).

A typical way of describing neutron detection methods is in terms of two broad categories of neutrons, namely of slow thermal neutrons and fast neutrons. Standard neutron detectors can be categorized as gaseous, semiconductor, scintillation and passive [1]. We have focused on semiconductor detectors, which have a number of advantages such as fast response, compact size and high operational stability. Since neutrons have no charge, a conversion layer is usually required for proper detection. The neutron-converting material can be incorporated into the detector as an external layer placed close to the detector. For the detection of thermal neutrons, the <sup>10</sup>B or <sup>6</sup>Li conversion layer is most commonly used because of its high cross section, and when the neutron is captured, it produces charged particles that are easy to detect. The most effective is <sup>3</sup>He, but due to its scarcity and very high price other alternatives are in demand. Fast neutrons can be detected by elastic scattering from light nuclei. Here we can use a High Density PolyEthylene (HDPE) layer, which contains hydrogen and converts neutrons into protons. Other possibilities are endoergic reactions, which are threshold processes. There is a minimum energy below which the reaction is energetically impossible.

We have many years of experience with 4H-SiC (silicon carbide) detectors and they also show good potential as neutron detectors. For thermal neutron detection, the conversion layer is required and 4H-SiC detectors show excellent performance [2-5]. In the case of fast neutrons, SiC detectors are capable of direct detection because they consist of light atoms such as silicon and carbon. Fast neutrons can be detected by means of the elastic scattering and threshold nuclear reactions. In our previous studies we detected fast neutrons from 16.0 MeV to 18.3 MeV with 4H-SiC detectors [6-8].

In this paper we have tested 4H-SiC detectors over a wide range of neutron energies from 370 keV to 14.90 MeV. Fast neutrons were produced by p-T (proton – tritium), d-D (deuterium – deuterium) and d-T (deuterium – tritium) reactions at the Van de Graaff (VdG) accelerator.

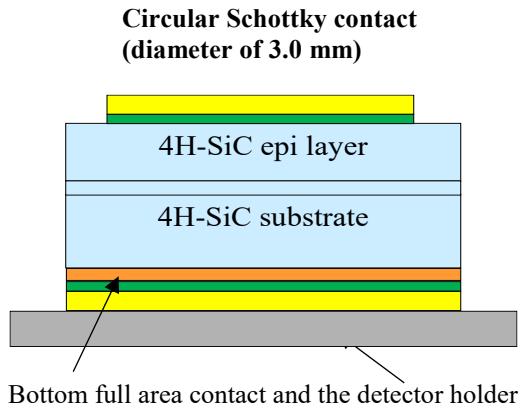


Fig. 1. The cross-section of fabricated 4H-SiC radiation detector.

## II. DETECTOR STRUCTURE

The detector structure has been fabricated from an 80  $\mu\text{m}$  thick nitrogen-doped 4H-SiC layer (with a donor doping level of about  $7 \times 10^{13} \text{ cm}^{-3}$ ) grown by liquid phase epitaxy (LPE) on a fragment of 4-inch 4H-SiC wafer (with donor doping level  $\sim 2 \times 10^{18} \text{ cm}^{-3}$ , thickness 350  $\mu\text{m}$ ) by growing a 0.5  $\mu\text{m}$  thick n++ 4H-SiC buffer layer with a donor concentration of  $1 \times 10^{18} \text{ cm}^{-3}$  between them. The radiation detectors were produced by evaporation of a double layer of Ni/Au with a thickness of 15/25 nm on the top side in a high vacuum chamber. The Schottky barrier contacts of Ni/Au with a diameter of 3.0 mm are formed through a metal contact mask, while a full area contact of Ti/Pt/Au (15/30/80 nm) was deposited on the other side (substrate). The cross-section of detector is in Fig. 1.

## III. EXPERIMENT AND DISCUSSION

First, the current-voltage characteristics of the 4H-SiC Schottky barrier detectors were measured at room temperature. The reverse current is below 30 pA up to 1000 V and the typical characteristic is shown in Fig. 2. The capacitance-voltage characteristic depicted in Fig. 3. was then measured to determine the full depletion reverse bias of the detector. The capacitance (blue curve) does not change with a reverse bias higher than 250V. The black curve shows the calculated depletion width using the following formula:

$$W_D = \frac{\varepsilon_r \varepsilon_0 S}{C_D} \quad (1)$$

where  $\varepsilon_r$  is the relative permittivity of 4H-SiC (9.66 [9]),  $\varepsilon_0$  is the permittivity of free space and  $C_D$  is the measured capacitance of the detector and  $S$  is the detector contact area.

The low concentration epitaxial layer of the detector is completely depleted at bias voltages above 250 V.

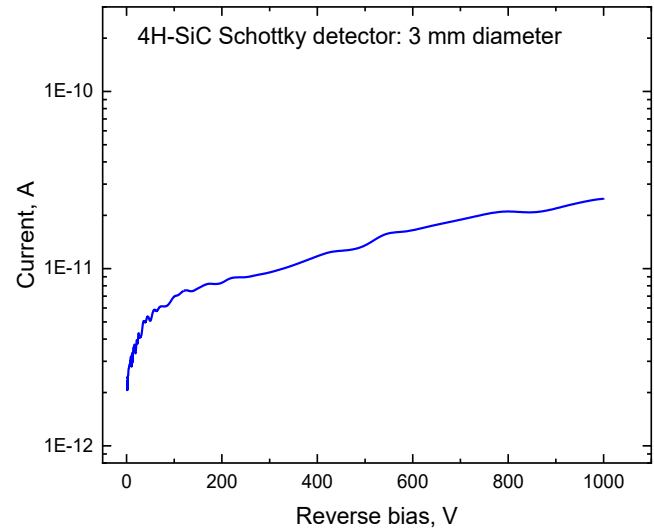


Fig. 2. The typical reverse current–voltage characteristic of 4H-SiC Schottky radiation detector.

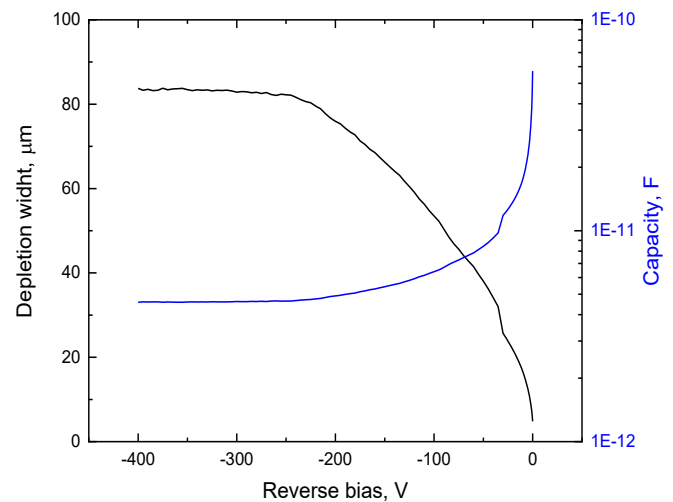


Fig. 3. The capacitance-voltage characteristic of 4H-SiC Schottky radiation detector and the calculated depletion width.

The fast neutron detection was performed at the Van de Graaff Laboratory of the Institute of Experimental and Applied Physics of the Czech Technical University in Prague. Three nuclear reactions were used to produce fast neutrons in a wide range of energies. The applicable nuclear reactions are as follows: p-T (proton-tritium), d-D (deuterium-deuterium) and d-T (deuterium-tritium). The detector has been tested with neutron energies from 370 keV up to 14.9 MeV. As mentioned above, the SiC detector is capable of detecting fast neutrons by elastic scattering in light atoms of the detector material  $^{12}\text{C}(n,n')^{12}\text{C}$  or  $^{28}\text{Si}(n,n')^{28}\text{Si}$  and the nuclear reactions presented in Table I [10]. There are two reactions on  $^{12}\text{C}$  and  $^{28}\text{Si}$  atoms that produce  $\alpha$ -particles and protons. The Q-value (released energy during reaction) is negative so its absolute

value represents the amount of energy that is absorbed during the nuclear reaction and reduced for the resulting products.

TABLE I  
NEUTRON REACTIONS ON SiC AND THE CORRESPONDING ENERGY THRESHOLDS.

Nuclear reaction	Branch	Q-value (MeV)
$^{12}\text{C}(n,n')^{12}\text{C}$	Ground state	0
$^{12}\text{C}(n,n')^{12}\text{C}$	First excited state	-4.4389
$^{12}\text{C}(n,\alpha)^9\text{Be}$	Ground state $\alpha_0$	-5.7012
	1 <sup>st</sup> excited state $\alpha_1$	-7.3859
	2 <sup>nd</sup> excited state $\alpha_1$	
$^{12}\text{C}(n,p)^{12}\text{B}$	Ground state $p_0$	-12.5865
	1 <sup>st</sup> excited state $p_1$	-13.5396
$^{28}\text{Si}(n,n')^{28}\text{Si}$	Ground state	0
$^{28}\text{Si}(n,n')^{28}\text{Si}$	First excited state	-1.779
$^{28}\text{Si}(n,\alpha)^{25}\text{Mg}$	Ground state $\alpha_0$	-2.6537
	1 <sup>st</sup> excited state $\alpha_1$	-3.2387
	2 <sup>nd</sup> excited state $\alpha_2$	-3.6284
	3 <sup>rd</sup> excited state $\alpha_3$	-4.2655
	4 <sup>th</sup> excited state $\alpha_4$	-4.6183
$^{28}\text{Si}(n,p)^{28}\text{Al}$	Ground state $p_0$	-3.8599
	1 <sup>st</sup> excited state $p_1$	-3.8905
	2 <sup>nd</sup> excited state $p_2$	-4.8323

The 4H-SiC Schottky barrier detector was connected to the spectrometric chain consisting of the charge sensitive preamplifier Amptek A250CF, the digital multi-channel analyzer CAEN Hexagon with a high voltage source providing the reverse bias to the detector and a personal computer. The detection spectra of fast neutrons of different energies are shown in Fig. 4. The most complex spectrum was obtained by detecting 14.9 MeV monoenergetic neutrons produced by the d-T reaction. In the detected spectrum, the elastic scattering of neutrons on Si and C atoms is clearly visible. The peaks from the main nuclear reactions were then identified. According to Table I, the peak corresponding to an energy of 9.19 MeV is produced by the nuclear reaction  $^{12}\text{C}(n,\alpha)^9\text{Be}$ . The second clearly visible peak corresponds to the nuclear reaction between neutrons and silicon,  $^{28}\text{Si}(n,\alpha)^{25}\text{Mg}$ . The energy of the peak is 12.27 MeV according to the input fast neutrons. Smaller peaks with lower energies represent higher excited states. In the case of the 3.5 MeV neutrons produced by the d-D reaction, the peak from the silicon reaction is identified with a corresponding energy of 846 keV. Neutrons with energies of 370 keV and 1.1 MeV were produced in the p-T reaction. As the neutron energy is below the nuclear reaction threshold, only elastic scattering occurs in their detection. The measurements presented demonstrate that the 4H-SiC detector is suitable for the detection of a wide range of fast neutrons.

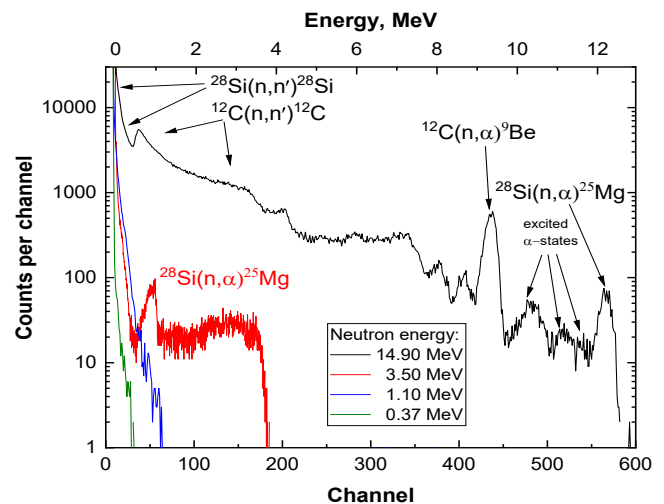


Fig. 4. The detected spectra of fast neutrons with different energies (370 keV, 1.1 MeV, 3.5 MeV and 14.9 MeV) using 4H-SiC detector.

#### IV. CONCLUSIONS

The 4H-SiC epitaxial Schottky barrier detector was fabricated and studied as a fast neutron detector. The thickness of the active layer was 80  $\mu\text{m}$ . Firstly, the electrical characterization (current–voltage and capacitance–voltage measurements) of a Schottky contact detector was carried out to find the optimum operating bias. The detector is fully depleted at a reverse bias greater than 250 V. The detector was then used for the detection of monoenergetic fast neutrons with energies from 0.37 MeV to 14.9 MeV produced by the three nuclear reactions (p-T, d-D, d-T). The measured neutron spectra revealed elastic and inelastic neutron scattering from Si and C atoms, as well as nuclear reactions that produce  $\alpha$ -particles. The results show that the 4H-SiC-based detectors are capable of detecting fast neutrons over a wide range of energies.

#### ACKNOWLEDGMENT

This work was partially supported by grants of the Slovak Research and Development Agency No. APVV-SK-CZ-21-0116, APVV-22-0382 and of the Scientific Grant Agency of the Ministry of Education of the Slovak Republic and the Slovak Academy of Sciences No. 2/0084/20. The measurements took place in the Van de Graaff accelerator laboratory supported by the LM2018108 grant of MEYS, Czech Republic.

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