

Experimental analysis of Schottky-barrier 4H-SiC-detector-response to fast neutrons: comparison with Si and diamond detectors

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Abstract— The response of 4H-SiC detectors to 17 MeV neutrons was experimentally analysed using detectors composed solely of carbon or silicon. The detectors were tested using three different neutron energies (14.5 MeV, 15 MeV and 17 MeV) at two different facilities with T(d,n) neutron generators, the Van de Graaff laboratory at IEAP CTU in Prague and at the DANAIDES facility at CEA research center in Cadarache. The calibration via interactions on ²⁸Si nuclei, the (n, α) nuclear reaction to ground and excited states of ²⁵Mg, was made. The standard deviation of experimental values measured by Si detector from prepared calibration curve, was of 0.073 MeV, which represents the uncertainty of less than 1% in this energy range (≈ 10 MeV). The experiment showed that the pulse height defect affects the measured spectra the way that the peak energies from the C interactions are shifted by about 0.5 MeV to higher values when the calibration from the Si interactions is used.

Keywords — 4H-SiC detector, Si detector, diamond detector, fast-neutron spectroscopy.

I. INTRODUCTION

THE 4H-polytype SiC remains promising semiconductor material for detector preparation. Its wide bandgap of 3.23 eV at room temperature [1] determines the operability of the prepared detectors even at relatively high temperatures up to several hundred degrees Celsius [2]. The high breakdown voltage of 4 MV/cm enables high drift velocity of radiation-generated charge carriers, ensuring fast detector response. Moreover, 4H-SiC stands out in a relatively high atomic displacement energy (20–35 eV) compared with other semiconductor materials, making it very promising in terms of

resistance against radiation damage. The exceptional thermal and radiation resistance of SiC as a detector material implies its application for today's nuclear reactors, or in other radiation and thermally harsh technologies. Nuclear reactors are characterized by neutron radiation fields, for the registration of which the 4H-SiC detectors could be suitable. The 4H-SiC detectors were studied for registration of fast neutrons in the energy range of 1 to 18.3 MeV [3–7]. In [3,6] the 4H-SiC detector response to 14 MeV neutrons was also compared to diamond detectors. In this paper we have prepared single pad Schottky-type detectors based on 4H-SiC epitaxial material dedicated to registration of fast neutrons. Their response to 17 MeV neutrons was compared and analysed with both the silicon and the diamond detectors.

II. EXPERIMENT

The SiC detector structures, characterized in [7], were fabricated from an 80 μm thick nitrogen-doped 4H-SiC epitaxial layer (with a donor doping level ≈ 7×10¹³ cm⁻³) on 4-inch 4H-SiC wafer. Detector was created by Schottky electrode of 3 mm in diameter (Table I) and opposite full area ohmic contact. For comparison, the silicon and carbon detectors were prepared at the Institute of Electrical Engineering SAS in Bratislava as well (Table I). The Schottky barrier type Si detector was prepared from 380 μm thick substrate by a 5×5 mm² square electrode as it is described in [8] and the carbon detector was manufactured from 500 μm thick high quality monocrystalline diamond substrate as used for detector preparation in [9] but this time with Au circle electrode of 3.5 mm diameter evaporated on both sides of the substrate. The three main types of detectors are illustrated in Fig. 1.

TABLE I
DETECTOR PARAMETERS

Material and Type	Area	Active Thickness
4H-SiC Schottky	Ø 3 mm	80 µm
C – monocrystalline diamond	Ø 3.5 mm	500 µm
Si Schottky	5×5 mm ²	380 µm

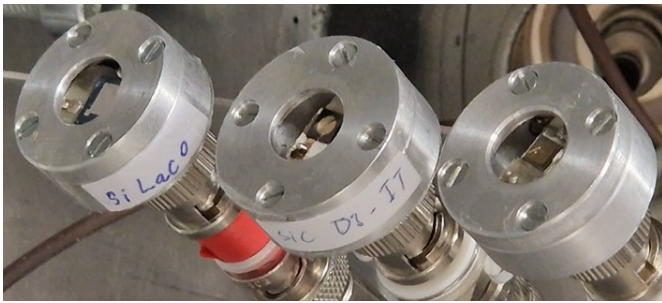
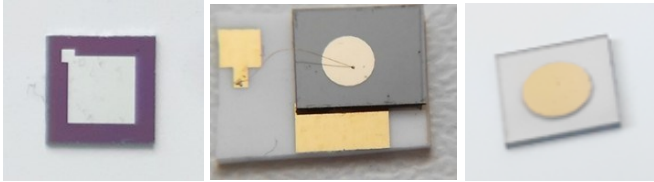


Fig. 1. Photographs of manufactured detectors from left to right: Si, SiC and diamond as bare detectors in the top row and encapsulated with BNC connection in bottom row.

Each tested detector was connected to spectrometric chain consisting of a charge sensitive preamplifier and a digital multi-channel analyser CAEN Hexagon with a high voltage source for detector, connected to the computer. Three detectors, one of each type, were placed around the neutron source in such geometry that each detector was exposed to neutrons of the same energy and flux. As a source of fast neutrons, the T(d,n) generators at two different facilities were used. The 14.5 MeV neutrons impinged detectors at DANAIDES facility at CEA Cadarache and the 15 and 17 MeV neutrons were obtained at Van de Graaff (VdG) laboratory of IEAP CTU in Prague. The Fig. 2 and Fig. 3 show photographs of the arrangement of detectors connected to preamplifiers during experiments at DANAIDES and VdG facilities.

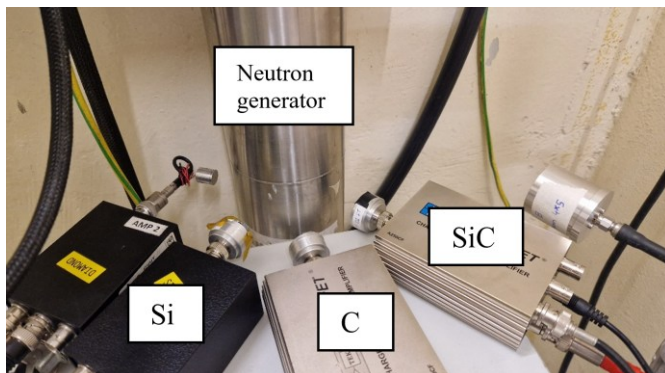


Fig. 2. Photograph of detector arrangement around neutron source at DANAIDES facility of CEA in Cadarache. Three evaluated detectors are labelled through their preamplifiers. The others were part of another experiment.

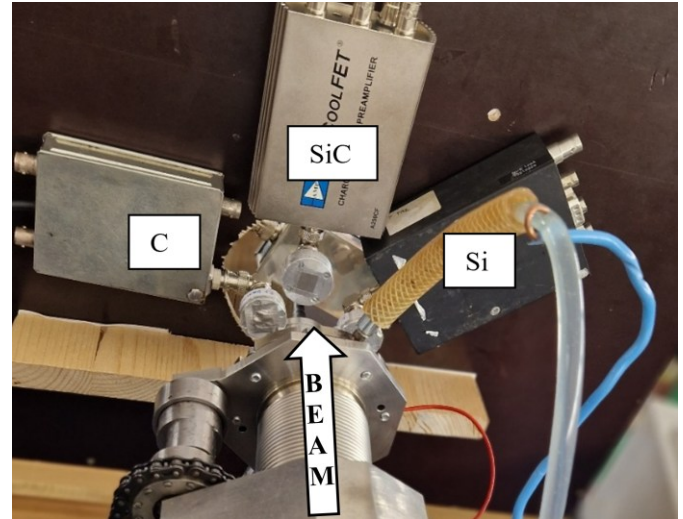


Fig. 3. Photograph of detector arrangement around the neutron source at VdG facility of IEAP CTU in Prague.

III. DISCUSSION

The SiC detectors register fast neutrons through scattering and nuclear reactions on Si and C nuclei, where it serves as a target and detection medium in one. The most relevant interactions of fast neutrons together with their Q-values from ENDF/B-VIII.1 [10] are listed in Table II. In the case of 17 MeV neutrons the energy released by interaction products, which detector registers in the spectrum, is shown in the right column of the table. In case of elastic scattering, the maximum energy transferred to the scattered nucleus is at a head on collision defined by:

$$T_{A,max} = \left\{ 1 - \left(\frac{A-1}{A+1} \right)^2 \right\} \times T_n, \quad (1)$$

with A as the mass number of the nucleus and T_n the energy of impinging neutron. Then, as a result of neutron scattering on Si or C nuclei, the nuclei gain at most, the following fraction of neutron's kinetic energy:

$$T_{Si,max} = 0.133 T_n, \quad (2)$$

$$T_{C,max} = 0.284 T_n, \quad (3)$$

which will be 2.26 and 4.83 MeV, respectively, for 17 MeV neutrons.

TABLE II
THE MOST PROBABLE INTERACTIONS OF NEUTRONS WITH SiC NUCLEI IN GROUND STATE WITH THEIR PRODUCTS' ENERGIES FOR 17 MEV INTERACTING NEUTRONS

Interaction	Q-value (MeV)	Products' energy (MeV)
$^{28}\text{Si}(n,\alpha)^{25}\text{Mg}$	-2.65	14.35
$^{12}\text{C}(n,\alpha)^9\text{Be}$	-5.702	11.298
$^{12}\text{C}(n,n')3\alpha$ edge	-7.367	9.633
Scattering edge for C	0	4.83
Scattering edge for Si	0	2.26

According to values in Table II all listed interactions of 17 MeV neutrons should be recognizable in measured spectra

except for the last one, scattering on Si, most of which cannot be distinguished from detector noise due to its low energy.

The aim of this paper is to experimentally break down the 17 MeV-neutron response in 4H-SiC detectors by resolving monoatomic spectral contributions using detectors composed solely of carbon or silicon. The (n, α) nuclear reaction on ²⁸Si has the highest energy yield for reaction products, so the peak will be the most right in the measured spectrum. Moreover, in this experimental case, the ²⁵Mg nucleus can be produced in one of 15 excited states, listed in Table III, which would be consistent with another 15 peaks towards left in the spectrum. This is why we analysed the spectra measured by Si detector first. Neutrons of chosen energies, 14.5, 15 and 17 MeV, irradiated the detectors separately. In measured spectra we assigned the corresponding energies (Table III) to the peaks from ²⁸Si(n, α) reaction to prepare the calibration curve.

TABLE III

REACTION ²⁸Si(n, α)²⁵Mg PRODUCTS' ENERGIES FOR 14.5, 15 AND 17 MEV NEUTRONS ENTERING THE REACTION. THE Q-VALUES ARE FROM ENDF/B-VIII.1 [10]

Label of ²⁵ Mg energy level	Q-value (MeV)	Products' energy (MeV) for 14.5 MeV	Products' energy (MeV) for 15 MeV	Products' energy (MeV) for 17 MeV
0	2.65	11.85	12.35	14.35
1	3.235	11.265	11.765	13.765
2	3.625	10.875	11.375	13.375
3	4.262	10.238	10.738	12.738
4	4.615	9.885	10.385	12.385
5	5.214	9.286	9.786	11.786
6	5.388	9.112	9.612	11.612
7	5.451	9.049	9.549	11.549
8	6.055	8.445	8.945	10.945
9	6.064	8.436	8.936	10.936
10	6.558	7.942	8.442	10.442
11	6.621	7.879	8.379	10.379
12	6.71	7.79	8.29	10.29
13	6.927	7.573	8.073	10.073
14	7.009	7.491	7.991	9.991
15	7.361	7.139	7.639	9.639

The raw spectra measured by Si detector irradiated with fast neutrons are shown in Fig. 4. The spectra were smoothed for better peak distinguishing by Savitzky-Golay method in OriginPro2022 program [11]. The result can be seen in Fig. 5 with counts for 17 MeV neutrons scaled 50 times to prevent the spectra overlapping. The numbers marked with an asterisk (*) represent the energy level of ²⁵Mg corresponding to a given peak. Some of the peak energies are so close together that the detector energy resolution is insufficient for distinguishing them. In this case, the overlapping peaks are labelled with a slash (/) as a divider. Labelled peaks in Fig. 5 were used to determine the calibration curve shown in Fig. 6. The chosen colour of each experimental point agrees with the colour of spectrum of its origin in Fig. 5. The R-Square of 0.99844 of the line fitted through experimental points confirms the correctness of the assignment of peaks to given energy states.

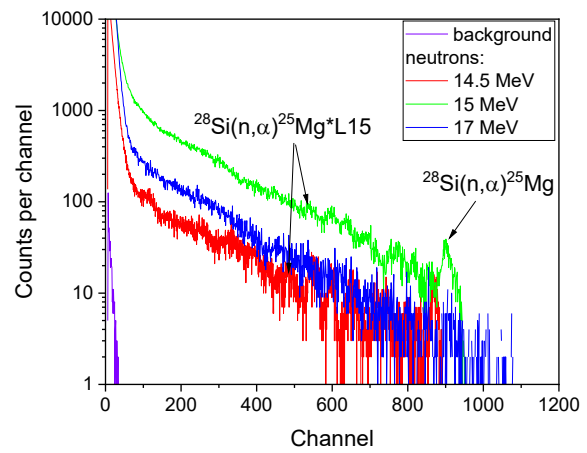


Fig. 4. The raw spectra measured by Si detector irradiated with 14.5, 15 and 17 MeV neutrons.

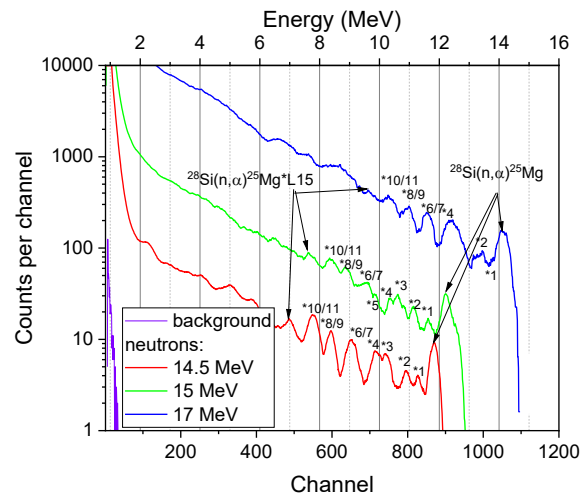


Fig. 5. The smoothed spectra measured by Si detector irradiated with 14.5, 15 and 17 MeV neutrons.

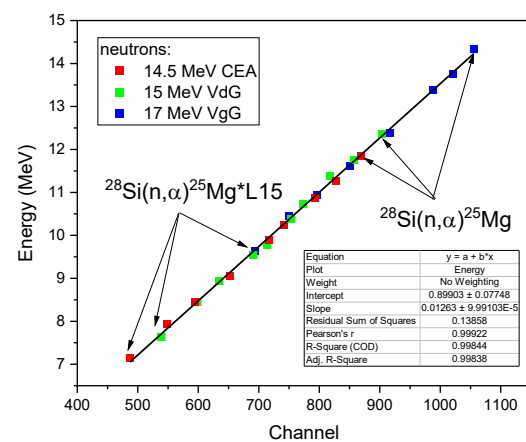


Fig. 6. The calibration curve for the Si detector.

Moreover, the dispersion of deviations of experimental values from the calibration curve (see Fig. 7) confirms their statistical origin and excludes systematic measurement error. The standard deviation of these values is of 0.073 MeV, which at measured energies around 11 MeV represents the uncertainty below 1%.

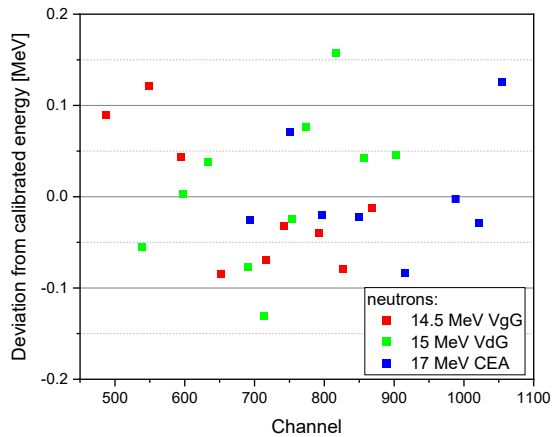


Fig. 7. The deviations of experimental values from the calibration curve measured by Si detector in Fig.6.

Fig. 8 represents the response of three different detectors with SiC, Si and diamond sensors, to 17 MeV neutrons. The calibration curve from Fig. 6 was used to obtain the red spectrum with the energy x-axis here and allowed to arrange the top energy axes in Fig. 5.

First the Si detector spectrum was displayed, then other two spectra were overlaid, first fitting the known peaks from (n, α) reaction on ^{28}Si (the SiC detector) and then the diamond detector spectrum according to (n, α) reaction on ^{12}C (Table II). Besides mentioned (n, α) reactions, the detectors containing carbon (blue and green spectrum) show the $^{12}\text{C}(n, n')3\alpha$ nuclear reaction with calculated edge at 9.63 MeV. The calculated values of mentioned peaks are written above them in Fig.8. However, one can observe, that the position of two peaks from carbon interaction is placed at higher energies on x-axis than the calculated value determines. This shift can be explained by the pulse height defect [12] of ions produced during nuclear reactions of neutrons with carbon and silicon nuclei in the detector. The pulse height defect, the charge deficit during charge collection, is more pronounced with ^{25}Mg ions from neutron interaction with ^{28}Si than in the case of ^9Be or ^4He ions from neutron interaction with ^{12}C . For detector calibration the peaks from neutron interaction with ^{28}Si were used, so it can be expected that the peaks from neutron interaction with ^{12}C will be overestimated in this calibration. We can see that the $^{12}\text{C}(n, \alpha)$ peak is at 11.8 MeV position, which is about 0.5 MeV more than calculated position (11.3 MeV). Also, the edge from $^{12}\text{C}(n, n')3\alpha$ reaction seems to appear higher than at 9.63 MeV. On the other hand, the peaks from ^{28}Si interactions fit exactly to their energy on x-axis. Similar effect was analysed in [3] with SiC and diamond detectors irradiated by 14 MeV neutrons.

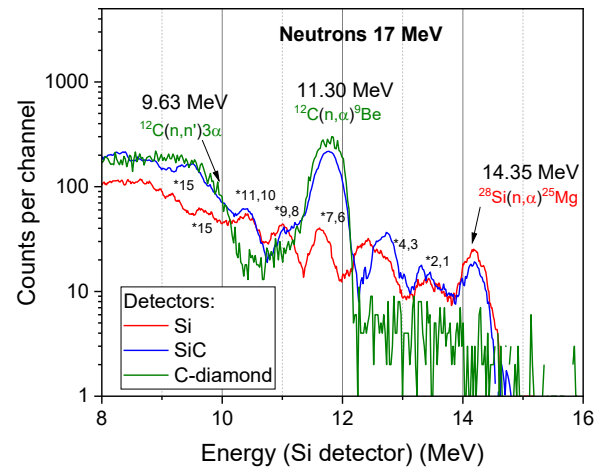


Fig. 8. The spectra measured using 4H-SiC (blue), Si (red) and diamond (green) detector when irradiated by 17 MeV neutrons.

Experimental comparison of Si-, SiC- and diamond-detector response to fast neutrons shows that when using the energy calibration from the interaction on Si, the difference in the peak positions from the interactions on carbon will be approximately 0.5 MeV, so the pulse height defect should be considered in this energy range in this height. Detailed peak energy-position determination including the pulse height defect effect can help in neutron spectrometry by semiconductor detectors, where via machine learning the neutron spectra can be reconstructed from the SiC detector response to neutrons [13].

IV. CONCLUSIONS

The 4H-SiC epitaxial Schottky barrier detector was studied as a detector of fast neutrons. The response of the SiC detector to 17 MeV neutrons was experimentally compared to the response of detectors based on solely silicon (Si detector) or solely carbon (chemical vapour deposited monocrystalline diamond detector). The Si detector was calibrated by three different neutron energies 14.5, 15 and 17 MeV provided by two different facilities. The results proved the correct determination of peaks from neutron interactions on Si and C nuclei at studied detectors and revealed the pulse height defect effect on measured spectra. The peaks from neutron interactions on carbon nuclei were shifted to higher energies by about 0.5 MeV with respect to the calibration from Si interactions. The study of this phenomenon in detail is the subject of our future research.

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