 doi:10.20944/preprints202201.0290.v1

Review

4H-SiC Schottky Barrier Diodes as Radiation Detectors: A Review

Ivana Capan

Ruđer Boškovic Institute, Bijenička 54, 10 000 Zagreb, Croatia;
capan@irb.hr

Abstract: In this review paper, an overview of the application of n-type 4H-SiC Schottky barrier diodes (SBDs) as radiation detectors is given. We have chosen 4H-SiC SBDs among other semiconductor devices such as PiN diodes or metal-oxide-semiconductor (MOS) structures, as significant progress has been achieved in radiation detection applications of SBDs in the last decade. Here, we present the recent advances at all key stages in the application of 4H-SiC SBDs as radiation detectors, namely: SBDs fabrication, electrical characterization of SBDs, and their radiation response. Main achievements are highlighted, and main challenges are discussed.

Keywords: Schottky barrier diodes; 4H-SiC; radiation; detection

1. Introduction

Silicon carbide (SiC) is a wide band gap semiconductor that is used in numerous semiconductor devices, such as PiN diodes, MOSFET's, MEMS (Micro Electro-Mechanical Systems) and many others. This is due to the fact that SiC possesses a huge list of rather attractive properties such as: a wide band gap, large critical electric field, high thermal conductivity, high electron saturation velocity, chemical inertness, and radiation hardness [1].

Among all SiC polytypes, 4H is the most studied. It has the largest band gap of 3.23 eV. For comparison, some of the physical parameters for SiC polytypes are given in Table 1. Due to the high and isotropic mobility of charge carriers, the 4H polytype of SiC is preferred as a material for power electronics [1], bipolar devices [2] and quantum sensing [3]. Moreover, 4H-SiC has attracted considerable interest in recent years as a very promising material for radiation detection in harsh environments where detectors are exposed to high temperatures and high fluencies of radiation [1,4-5].

Table 1. Physical properties of SiC polytypes [1].

Polytype SiC	Energy band gap (eV)	Electron mobility ∣∣ / ⊥ to *c*-axis ($cm^2V^{-1}s^{-1}$)	Hole mobility ($cm^2V^{-1}s^{-1}$)	Electric field ∣∣ to c-axis (MV/cm)
4H	3.26	1200/1020	120	2.8
6H	3.02	100/450	100	3.0
3C	2.36	~1000/1000	100	1.4

Wide-spread applicability of 4H-SiC material for radiation detection was mostly hindered by trapping/recombination of charge carriers and compensation effects due to electrically active deep level defects. Recombination of charge carriers via as grown and/or

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 January 2022 doi:10.20944/preprints202201.0290.v1

radiation introduced electrically active deep level defects decreases the minority carrier lifetime and consequently the charge collection efficiency (CCE) of a detector.

Recent progress in the manufacturing of high-quality epitaxial 4H-SiC has enabled unprecedented detection properties of the 4H-SiC detectors for alpha-particles and neutrons as reported in numerous studies [5-10]. Moreover, promising results for the low energy gamma and X-ray detection have also been reported [11, 12].

A wide interest in using 4H-SiC for radiation detection applications has been driving the development of semiconductor devices such as 4H-SiC PiN diodes [16] or Metal-Oxide-Semiconductor (MOS) devices [13]. However, such devices will not be included in this review, as we will strictly focus on SBDs as one of the simplest and widely used radiation detectors. Moreover, we should keep in mind that other wide band gap materials like GaN [14], diamond [15] and Ga_2O_3 [16] are also being considered as useful materials for radiation detection applications. The comparison between different materials requires a separate research paper, and therefore it will not be addressed within this review paper.

The main aim of this review is to help graduate students and researchers who are at the initial stage of their research on radiation detection applications of 4H-SiC SBDs. This review will give them a practical overview of the main stages in the process of the application, starting from the SBDs fabrication up to measuring and analyzing detector response to various radiation sources (alpha particles, neutrons, gamma, and X-rays). It should be noted that each stage in the process deserves a dedicated research paper which would allow that all issues are comprehensively addressed. Here, we have tried to pinpoint only the key issues for each stage. Therefore, we highly recommend to our readers to look for more details in provided references and references therein.

2. 4H-SiC Schottky barrier diodes

SBDs are among the most fundamental structures, and yet the most interesting, for the realization of radiation detectors. A typical 4H-SiC SBD used for radiation detection is shown in Figure 1. Due to band alignment, a volume depleted of charge carriers is created at the semiconductor side of the junction, making the device very sensitive to the presence of electron-hole pairs generated upon exposure to ionizing radiation. The SBD is operated under reverse bias, which increases the potential drop across the semiconductor and increases the depletion region width. To limit the required operation voltage, the doping level of the substrate is usually two orders of magnitude higher than that of the epitaxial layer. Typical doping levels for the epitaxial layer are between 10^{12}–10^{14} cm^{-3}. Most examples to be presented in this review are based on n-type 4H-SiC SBDs with Ni as Schottky contact and we will refer to them simply as 4H-SiC SBDs through the text. Exceptions will be highlighted.

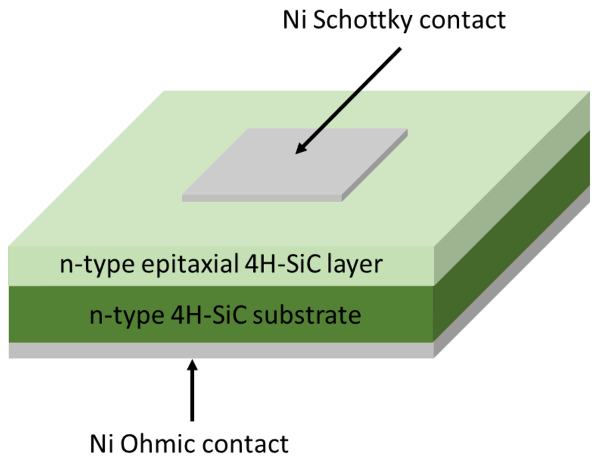


Figure 1. A scheme of the 4H-SiC SBD used for radiation detection.

2.1. Important parameters of 4H-SiC SBDs

Two important parameters for SBDs which are crucial for efficient radiation detection: 1) epitaxial layer thickness and 2) Schottky contact area.

As mentioned in the previous section, the significant progress in the manufacturing of high-quality epitaxial 4H-SiC layers has enabled its widespread application in radiation detection. Typically reported thicknesses of epitaxial 4H-SiC in SBDs used for radiation detection are in the range starting from a few µm up to 100 µm [5-11]. Radulovic et al. [4] have reported neutron radiation tests using the SBDs with 170 µm, while Kleppinger et al. [8] have recently reported the thickest 4H-SiC epitaxial layer (250 µm) used for radiation detection applications. Thicknesses up to 250 µm have the best reported quality, and they are almost free from electrically active defects. The most dominant defects, present in the as-grown 4H-SiC material are acceptor (=/0) and donor (++/0) states of the carbon vacancy (V_c), known as $Z_{1/2}$ and $EH_{6/7}$, respectively [8,17-18]. Electrically active defectswill be explained later in the text.

Another parameter important for radiation detection applications is the area of the Schottky contact. Schottky contact are usually fabricated by thermal evaporation of nickel (average thickness around 100 µm) through a mask with openings in different sizes. The most common reported values are varying from 1 mm^2 up to 20 mm^2 [4-11].

2.2. Electrical parameters of 4H-SiC SBDs and the impact of radiation

Upon SBD fabrication, the first step is to check electrical properties, and that includes temperature dependent current-voltage (I-V-T) and capacitance-voltage (C-V-T) measurements.

From these measurements we obtain crucial information on device properties and estimate parameters such as ideality factor, Schottky barrier height, series resistance, Richardson constant, free carrier concentration, and doping depth profile. The forward-biased I-V-T measurements usually give information on transport properties, ideality factor and Schottky barrier height [7-8]. As SBDs are operating under reverse voltage, we are also very interested in the reverse-biased I-V-T characteristic.

I-V and C-V measurements are usually performed before and after radiation tests. To obtain information about the quality of the fabricated SBDs, for example check the leakage current and estimate the physical parameters, measurements are performed before the radiation tests. As radiation can introduce damage into material, and affect the electrical properties of SBDs, for example increase the leakage current and lead to the charge carrier removal, measurements are also performed after radiation tests.

Figure 2 shows I-V measured at room temperature (RT) for the 4H-SiC SBD, before and after it was exposed to thermal neutron radiation tests [19]. SBD parameters are the following: 4H-SiC epi-layer thickness of 25 μm, and the SBD area of 9 mm². As seen in Figure 2. the leakage current is very low, and it was not affected by neutron radiation.

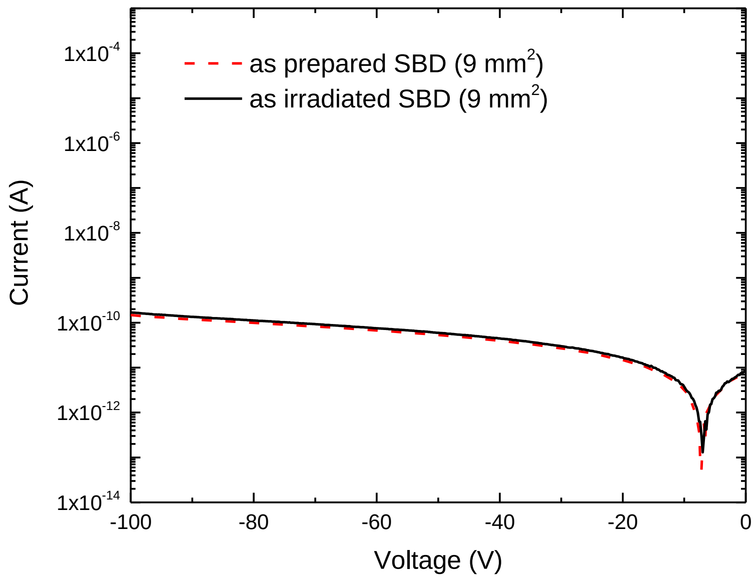


Figure 2. I-V measurement at RT of 4H-SiC SBD before and after the neutron radiation tests. Data adapted from Ref. [19].

Figure 3 shows high-frequency (1 MHz) C-V measurement at RT for 4H-SiC SBD before and after it was exposed to alpha particles radiation tests [9]. SBD parameters are: 4H-SiC epi-layer thickness of 25 μm, and SBD area of 1 mm². The C-V characteristic is unchanged upon radiation tests with alpha particles.

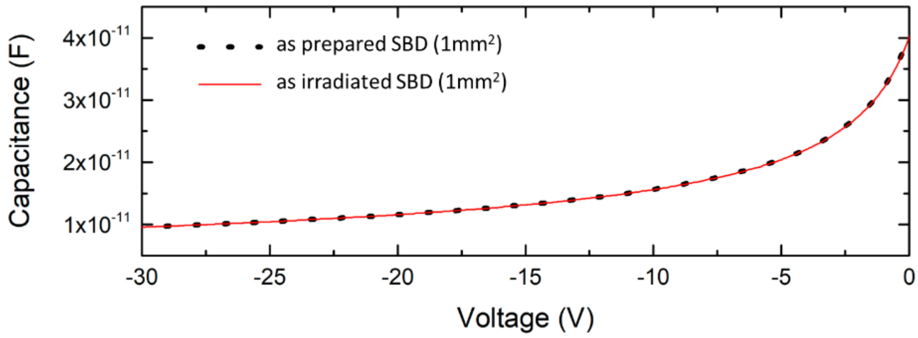


Figure 3. C-V measurements at RT of 4H-SiC SBD before and after the alpha particle radiation tests. Data adapted from Ref. [9].

Since alpha particles did not introduce any damage, neutron irradiation tests were also performed to study its impact on the C-V characteristics of SiC SBDs. Figure 4 shows the doping concentration profiles of the as prepared, and neutron-irradiated 4H-SiC SBDs (solid lines, left y axis) and the calculated vacancy concentration profile (dashed line, right y axis). SBD parameters are: 4H-SiC epi-layer thickness of 25 μm, and SBD area of 1 mm².

A slight decrease in the free carrier concentration is detected upon neutron radiation tests. This is due to the electrically active defects introduced by neutron radiation. The displacement damage introduced by neutron irradiation in the 4H-SiC SBD was simulated

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 January 2022 doi:10.20944/preprints202201.0290.v1

by FLUKA software [20]. Such simulations are an integral part of the electrical characterization of a SBD, before and after SBD was exposed to radiation, as they provide useful information on the concentration of introduced defects and their depth distribution. For example, the SRIM code is widely used for simulating depth profiles of displacement damage introduced by ions [21].

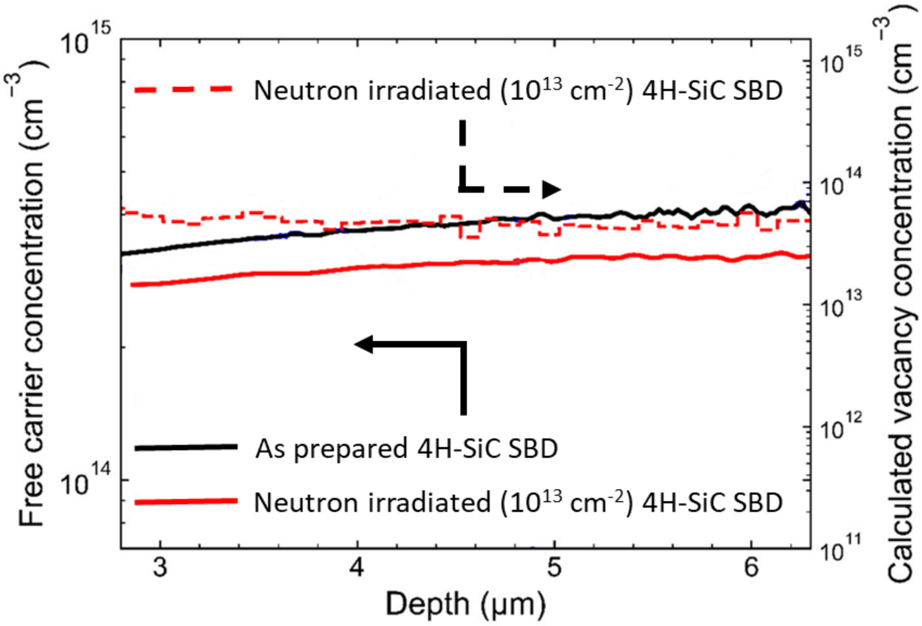


Figure 4. Free-carrier concentration profiles of as prepared and neutron-irradiated n-type 4H-SiC SBD (solid lines, left y-axis). The calculated vacancy concentration profile for neutrons using FLUKA software (red, dashed, right y-axis). The free carrier concentration profiles are obtained from the C–V measurements. Adapted from Ref [22].

2.3. Electrically active deep level defects in 4H-SiC SBDs

Another step in the electrical characterization of SBDs is to look for electrically active deep level defects in either as prepared and/or as irradiated SBDs. Electrically active deep level defects act as traps for charge carriers, and therefore influence electrical properties of SBDs and cause a deterioration of detector performance. These defects are mainly created during i) semiconductor material growth, ii) processing by ion implantation or iii) operation in a harsh ionizing radiation environment.

To obtain information about defects, deep level transient spectroscopy (DLTS) is mostly used. DLTS is a well-established technique, and it is the most sensitive method for measurements of electronic properties of deep level defects in semiconductors, it can detect deep level defects in concentration around 10^9 cm^3 [23]. It provides information regarding the activation energy for electron/hole emission, capture cross section and concentration/density of defects. These data are crucial for defining a “defect fingerprint”.

Electrically active defects in 4H-SiC material are ordinarily introduced during crystal growth. Figure 5 shows the DLTS spectrum for the as prepared 4H–SiC SBD. One peak with maximum at around 320 K is present. This peak known as $Z_{1/2}$ is assigned to (=/0) transition from the carbon vacancy (V_C) and has been extensively studied in the past decades [17-18, 22, 24]. It is usually present in the as prepared material in concentrations in the range of 10^{11}–10^{13} cm^{-3}. It is known as “lifetime killer” as its concentration can be increased either by irradiations or high-temperature annealing, which results with a reduction of carrier’s lifetime [22, 24]. In addition to $Z_{1/2}$, V_c introduce another deep level defect in n-type 4H-SiC. That defect, known as $EH_{6/7}$ is ascribed to (++/0) transitions from the V_c [8,18].

 doi:10.20944/preprints202201.0290.v1

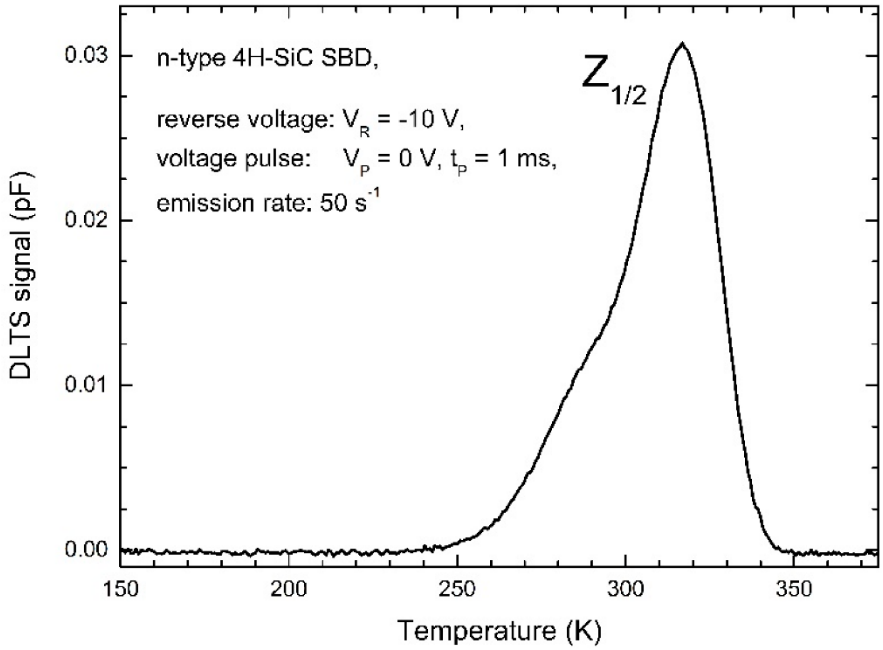


Figure 5. Typical DLTS spectrum for as prepared n-type 4H-SiC SBD. Data reproduced from Ref. [9].

In addition to $Z_{1/2}$ and $EH_{6/7}$, there is a whole group of electrically active defects in 4H-SiC introduced by protons, neutrons, electrons, ions etc. The most dominant defects are silicon vacancy (V_{Si}) [3], carbon interstitials (C_i) [25], and carbon antisite-carbon vacancy (CAV) complex [26]. More details on radiation induced defects could be found in above mentioned references and references within.

3. Radiation response of 4H-SiC SBDs

To efficiently test and analyze the radiation response of fabricated 4H-SiC SBDs, an electronic read-out system is needed. Although the systems can vary from each study, depending on the applications, the key elements are basically identical for all systems. Here, we briefly describe the electronic system consisting of a charge sensitive preamplifier, a shaping amplifier, a high voltage module, a power supply and a multichannel analyzer. A standalone battery-powered power supply is useful in minimizing the level of electronic noise. The block diagram of the electronic system is shown in Figure 6.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 January 2022 doi:10.20944/preprints202201.0290.v1

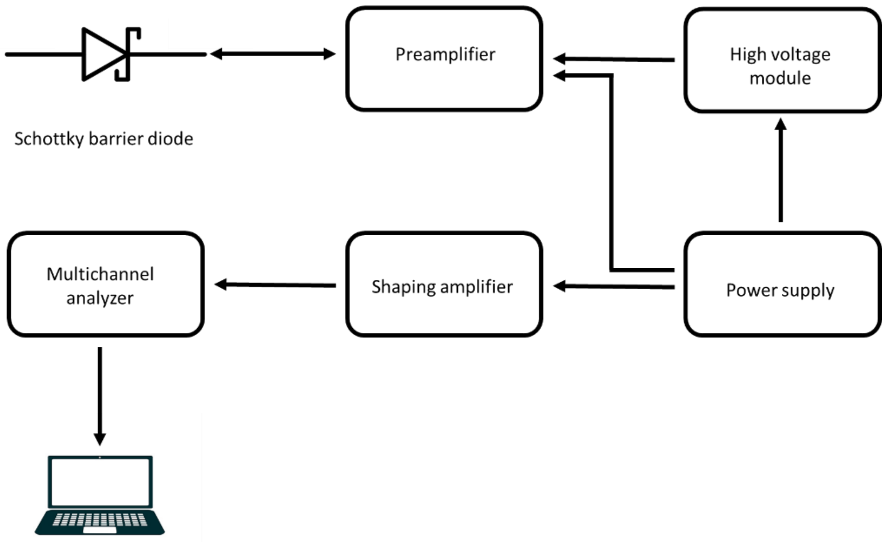
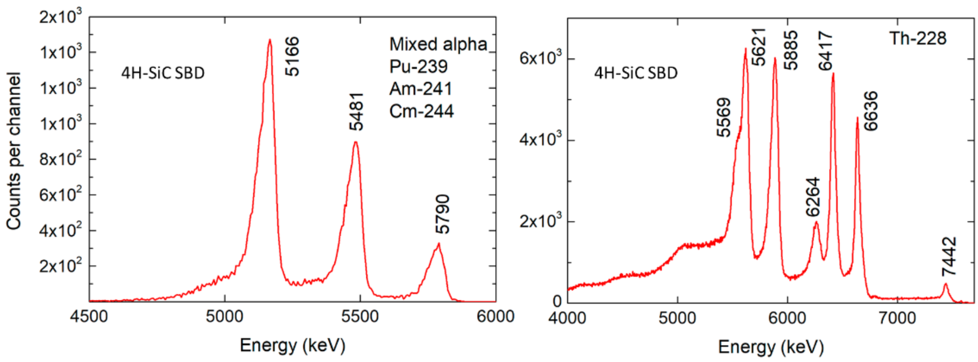


Figure 6. Block diagram of the basic detector system.

3.1. Response to alpha radiation

The vast majority of reported studies on radiation response of 4H-SiC SBD include radiation tests with alpha particles. The pioneering work in this area has been made by Ruddy et al. [6]. A linear energy response and excellent energy resolution were obtained for various alpha emitters in the 3.18 – 8.38 MeV energy range. Recent advances in energy resolution and efficiency have been reported by several groups [7-9, 27-29]. Zat'ko et al. [7] have used 4H-SiC SBDs with various epitaxial layer thicknesses ranging from 25 up to 70 μm and Schottky contacts with 2.0 or 3.0 in diameter. They have reported a high energy resolution below 20 keV in the full width at half maximum (FWHM) for 5.5 MeV alpha particles. Kleppinger et al. [8] have made additional progress by applying the thickest 4H-SiC epi-layer of 250 μm. The Schottky contacts were 2.9 or 3.9 mm in diameter. They have reported similar energy resolution of less than 0.5 % FWHM for 5.5 MeV alpha particles. Bernat et al. [9] have reported the charge collection efficiency (CCE) of fully depleted 4H-SiC SBDs for detection of alpha particles from the large area ^{241}Am source up to 100%. They have achieved energy resolution of 3% FWHM for 5486 keV.

Figure 7 shows a typical spectral response of a SBD to the mixed energy alpha particles [9]. SBD parameters are the following: 4H-SiC epi-layer thickness of 25 μm, and Schottky contact area of 4 mm^2.



(a) (b)

Figure 7. (a) Response of the 4H-SiC SBD to mixed alpha particle source (Pu-239, Am-241, Cm-244) and (b) response of the same 4H-SiC SBD to Th-228 alpha reference source. Data reproduced from Ref [9].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 January 2022 doi:10.20944/preprints202201.0290.v1

3.2. Response to neutron radiation

Since SiC material is suitable for radiation-hard environments the 4H-SiC SBDs have attracted a lot of interest for applications in nuclear science, homeland security, detection of spatial nuclear materials etc [4-5]. In the case of neutron detection, the 4H-SiC SBDs could be used for detection of thermal and fast neutrons. As thermal neutrons could not be directly detected by 4H-SiC, their presence is observed from the detection of ionizing neutron reaction products, such as alpha particles, tritons and others. Therefore, an efficient thermal neutron detection is achieved by using a converter layer rich in isotopes with large cross-section for neutrons with energy in the range of kBT at room temperature (with k_B representing the Boltzmann constant). The most used are ^{6}Li and ^{10}B converter layers [19].

Results on radiation response of 4H-SiC SBDs to thermal neutrons have been reported in numerous studies. The highest reported efficiency is about 5% [30-32]. Bernat et al. [19] have achieved the thermal neutron efficiency of 4.67% with ^{6}LiF converter layers. Lower efficiency (2.24 %) was achieved with ^{10}B4C converter layers.

Figure 8 shows the radiation response of the 4H-SiC SBD equiped with ^{6}LiF converter to the thermal neutron field. SBD parameteres are: 4H-SiC epitaxial layer thickness of 25 µm and Schottky contact area of 4mm^2. Two maxima are expected, one for alpha particles at 2050 keV and the other for tritons at 2730 keV (dashed lines, Figure 8). Those maxima are clearly visible in the measured radiation response.

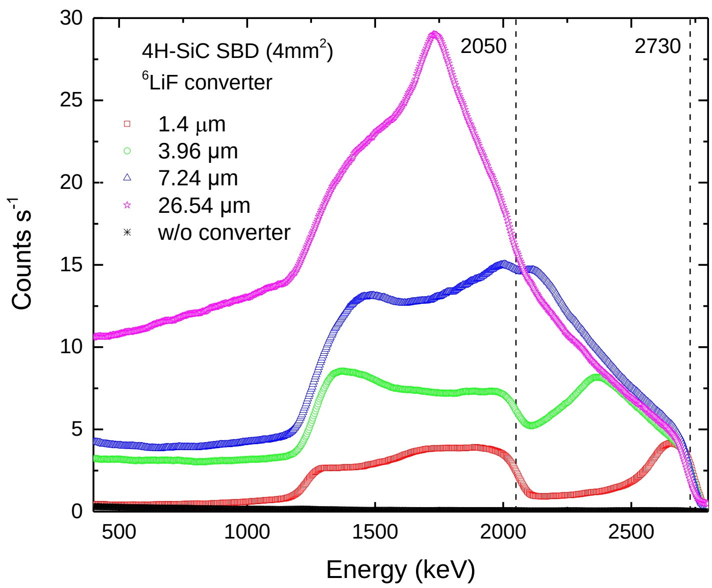


Figure 8. Radiation response of the 4H-SiC SBD equipped with ^{6}LiF thermal neutron converter layers with different thicknesses to the neutron field. Data adapted from Ref. [19].

Fast neutrons could be measured directly or with Polyethylene-based converters [5, 10, 33]. The first attempts have been made by Flamming et al. [11]. In this study, 2.5 MeV neutron response spectra were measured with and without polyethylene converters. The higher sensitivity is obtained with converters.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 January 2022 doi:10.20944/preprints202201.0290.v1

Although, detection of fast neutrons is possible due to the elastic scattering of fast neutrons with Si or C atoms, the probability of such event and therefore the efficiency of the detector increases as the epitaxial layer thickness increases too. The high-quality thick epitaxial layers (> 250 μm) used for radiation detection have not yet been reported. This has so far hindered the successful application of 4H-SiC for direct fast neutron detection. It is not unreasonable to expect that further advances will be made with thicknesses the increase of the thicknesses of the high-guality epitaxial layers.

3.3. Response to X-rays and gamma radiation

While 4H-SiC SBDs have proven themselves as efficient radiation detectors for alpha particles and thermal neutrons, radiation response to X-rays is unfairly less explored. Puglisi et al. [34] have studied 4H-SiC for soft X-ray (< 20 keV) detection and spectroscopy. They have used various 4H-SiC epitaxial layer thickness and Schottky contact areas, and achieved energy resolution of about 700 and 1300 eV FWHM for 1mm^2 and 10 mm^2 detectors measured at RT, respectively. Figure 9 shows the X-ray spectrum from a ^{241}Am source using a SiC detector in the energy range 0 to 28 keV [34].

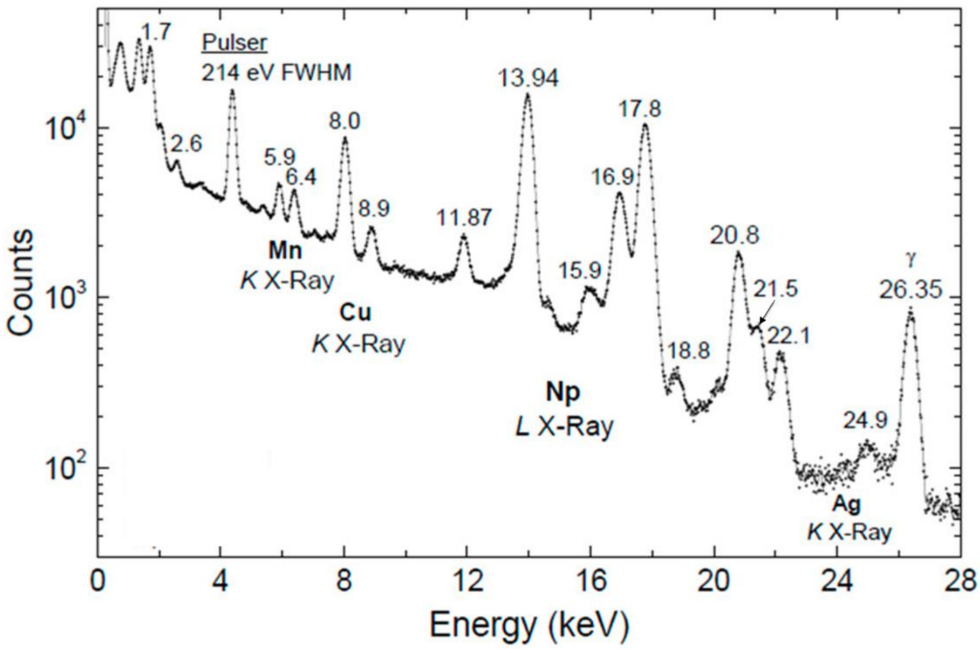


Figure 9. X-ray spectrum from a ^{241}Am source measured at RT using a SiC detector in the energy range 0 to 28 keV. Data taken from Ref. [34]

Significant progress regarding X-ray detection has been achieved by Lees et al. [11]. They have proposed a novel 4H-SiC SBD architecture, as shown in Figure 10. The semi-transparent 4H-SiC SBD has an ultra-thin Schottky contact, a gold annular overlayer and a gold corner-contact pad. It was shown that semi-transparent 4H-SiC SBDs exhibit higher efficiency for low energy (< 5keV) X-rays compared to conventional SBDs structure (as shown in Figure 1). They have achieved an energy resolution of about 1.47 keV FWHM at 22 keV measured at RT [11]. Figure 10 shows a schematic of the semi-transparent diode cross-section and schematic of the semi-transparent Schottky contact and a gold bond pad.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 January 2022 doi:10.20944/preprints202201.0290.v1

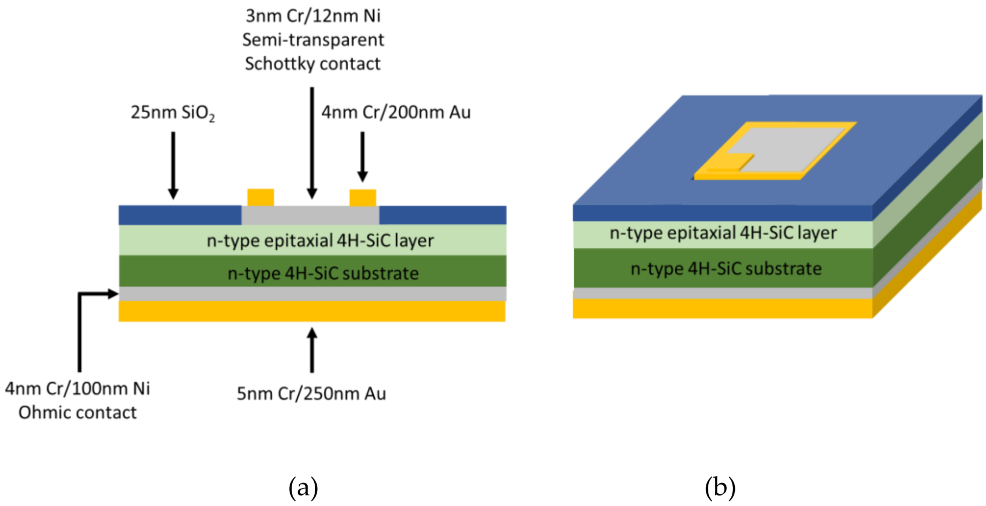


Figure 10. Semi-transparent Schottky diode. (a) cross-section of semi-transparent SBD, and (b) semi-transparent Schottky contact and a gold bond pad (top view). Adapted from Ref. [11].

The radiation response to gamma rays is by far the least explored. Among the first attempts to apply 4H-SiC SBDs is the work done by Mandal et al. [35]. SBD' used in their study included a 50 µm thick 4H-SiC epitaxial layer and Schottky contacts with a diameter of 3.2 mm. They have reported a 2.1 % energy resolution for 59.6 keV gamma rays. Figure 11 shows the radiation response to gamma radiation of three different 4H-SiC SBDs. SBD parameters were: 25 µm thick 4H-SiC epitaxial layer, and Schottky contact areas of 1, 4 and 9 mm². It has been observed that the sensitivity of the 4H-SiC SBD with the largest Schottky contact area is decreasing. Such behaviour was not observed for the radiation response of the 4H-SiC SBDs to alpha particles, for example.

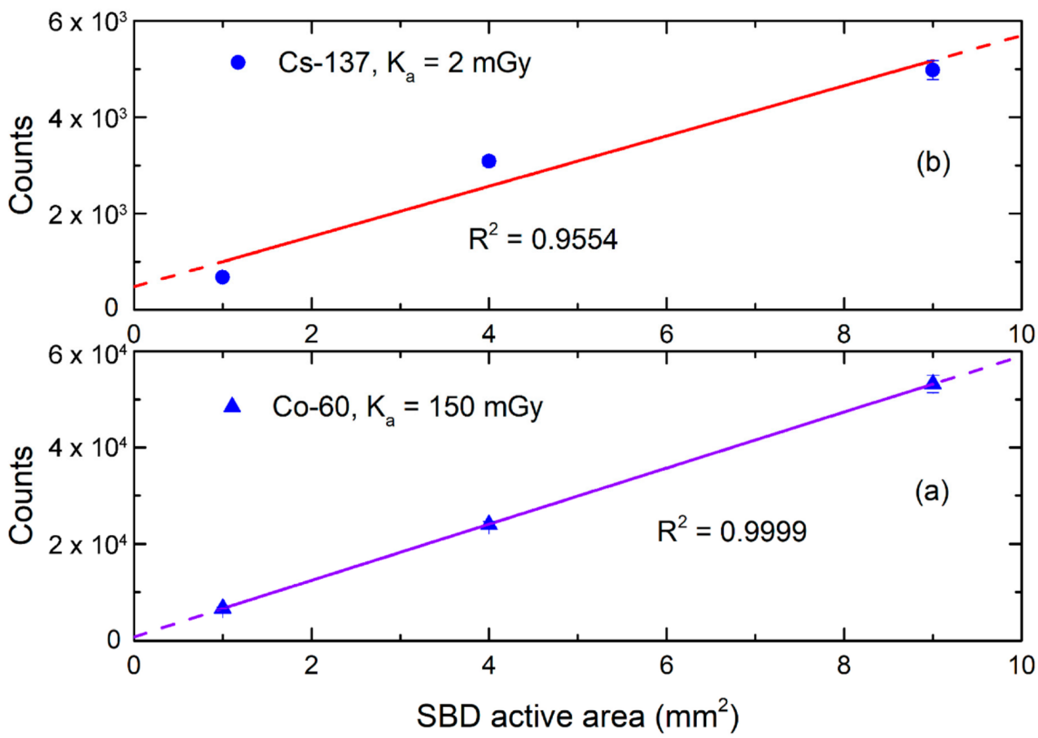


Figure 11. Response of three different 4H-SiC SBDs (1 mm^2, 4 mm^2 and 9 mm^2 areas) to gamma sources of Cs-137 (a) and Co-60 (b). The solid line shows linear fit for three 4H-SiC SBDs. Data reproduced from Ref [9].

With recent advances in using Mo as a Schottky contact [36], the Mo/4H-SiC SBDs have been investigated as photon counting detectors for X-ray and gamma-ray spectroscopy [37]. They have used SBDs with a 35 μm thick epitaxial layer, and achieved an energy resolution of 1.67 keV FWHM at 5.9 keV and 1.6 keV FWHM at 59.54 keV, all measured at RT. As seen from different studies on X-ray response measurements, energy resolution can be increased by making additional modifications on 4H-SiC SBDs structure, mainly in Schottky contacts.

4. Conclusion

The main idea behind this review is to provide a practical overview of the main stages in the application of 4H-SiC SBDs for radiation detection. That includes SBDs fabrication, electrical characterization of SBDs, and measuring the radiation response. The best results so far have been achieved for the detection of alpha particles and thermal neutrons. As the thicknesses of the high-guality 4H-SiC epitaxial layers are increasing, it is expected that advancement in direct fast neutron detection will be achieved shortly. Moreover, it is not unrealistic to expect additional progress with radiation detection of X-rays in the following years, too.

Funding: The present work was financially supported by the NATO Science for Peace and Security Programme, project no. G5674

Data Availability Statement: Data is contained within the article.

Acknowledgments: The author would like to thank Ivan Capan, Jasminka Popović, Robert Bernat, and Tihomir Knežević for useful comments on the manuscript.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Kimoto, T.; Cooper, J. A.; (2014). Fundamentals of Silicon Carbide Technology: Growth, Characterization, Devices, and Applications. John Wiley & Sons Singapore Pte. Ltd (2014), doi:10.1002/9781118313534
2. Yang, A,; Murata, K.; Miyazawa, T.; Tawara, T.; Tsuchida, H. Analysis of carrier lifetimes in N + B-doped n-type 4H-SiC epilayers. J. Appl. Phys. 2019, 126, 055103, https://doi.org/10.1063/1.5097718
3. Bathen, M.E.; Galeckas, A.; Müting, J.; Ayedh, H.M.; Grossner, U.; Coutinho, J.; Frodason, Y.K.; Vines, L. Electrical charge state identification and control for the silicon vacancy in 4H-SiC. NPJ Quantum Inf. 2019, 5, 111
4. Radulović, V.; Yamazaki, Y.; Pastuović, Ž.; Sarbutt, A.; Ambrožič, K.; Bernat, R.; Ereš, Z.; Coutinho, J.; Ohshima, T.; Capan, I.; et al. Silicon carbide neutron detector testing at the JSI TRIGA reactor for enhanced border and port security. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 2020, 972, 164122, doi:10.1016/j.nima.2020.164122.
5. Coutinho, J.; Torres, V.J.B.; Capan, I.; Brodar, T.; Ereš, Z.; Bernat, R.; Radulović, V. Silicon carbide diodes for neutron detection. Nucl. Inst. Methods Phys. Res. A 2020, 986, 164793.
6. Ruddy, F.H.; Seidel, J.G.; Chen, H.; Dulloo, A.R.; Ryu, S.H. High-resolution alpha-particle spectrometry using silicon carbide semiconductor detectors. IEEE Nucl. Sci. Symp. Conf. Rec. 2005, 3, 1231–1235.
7. Zat'ko, B.; Hrubčin, L.; Šagatova, A.; Osvald, J.; Bohaček, P.; et al. Study of Schottky barrier detectors based on a high quality

4H-SiC epitaxial layer with different thickness Appl. Surf. Sci. 2021, 536, 147801.

8. Kleppinger, J.W.; Chaudhuri, S.K.; Karadavut, O.F.; Mandal, K.C. Defect characterization and charge transport measurements in high-resolution Ni/n-4H-SiC Schottky barrier radiation detectors fabricated on 250 μm epitaxial layers. J. App. Phys. 2021, 129, 244501.

9. Bernat, R.; Capan, I.; Bakrač, L.; Brodar, T.; Makino, T.; Ohshima, T.; Pastuović, Ž.; Sarbutt, A. Response of 4h-sic detectors to ionizing particles. Crystals 2021, 11, 1–13, doi:10.3390/cryst11010010.

10. Flammang, R.W.; Seidel, J.G.; Ruddy, F.H. Fast neutron detection with silicon carbide semiconductor radiation detectors. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 2007, 579, 177–179, doi:10.1016/j.nima.2007.04.034.

11. Lees,J.E.; Bassford,D.J.; Fraser, G.W.; Horsfall,A.B.; Vassilevski, K.V.; Wright, N.G.; Owens,A. Semi-transparent SiC Schottky diodes for X-ray spectroscopy. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip 2007, 578, 226-234, doi:10.1016/j.nima.2007.05.172.

12. Puglisi, D.; Bertuccio, G. Silicon Carbide Microstrip Radiation Detectors. Micromachines 2019, 10, 835. https://doi.org/10.3390/mi10120835

13. Gao, R.L.; Du, X.; Ma, W.Y.; Sun, B.; Ruan,J.L.; Ouyang, X.; Li, H.; Chen, L.; Liu, L.Y.; Ouyang, X.P. Radiation tolerance analysis of 4H-SiC PIN diode detectors for neutron irradiation, Sensors and Actuators A: Physical. 2022, 333, 113241, https://doi.org/10.1016/j.sna.2021.113241

14. Grant, J.; Bates, B.; Cunningham, W.; Blue, A.; Melone, J.; McEwan, F.; Vaitkus, J.; Gaubas, E.; O'Shea,V. GaN as a radiation hard particle detector. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 2007, 576, 60-65, https://doi.org/10.1016/j.nima.2007.01.121

15. Kania, D.R.; Landstrass, M.I.; Plano, M.A.; Pan, L.S.; Han, S. Diamond radiation detectors. Diamond and Related Materials, 1993, 2, 1012-1019, https://doi.org/10.1016/0925-9635(93)90266-5

16. Chen, J.; Tang, H.; Li, Z.; Zhu, Z.; Gu,M.; Xu,J.; Ouyang, X.; Liu, B. Highly sensitive X-ray detector based on a β-Ga2O3:Fe single crystal. Opt. Express 2021, 29, 23292-23299, https://doi.org/10.1364/OE.435366

17. Capan, I.; Brodar, T.; Coutinho, J.; Ohshima, T.; Markevich, V.P.; Peaker, A.R. Acceptor levels of the carbon vacancy in $4H$-SiC: combining Laplace deep level transient spectroscopy with density functional modeling. 2018, 245701, doi:10.1063/1.5063773.

18. Pastuović, Z.; Siegele, R.; Capan, I.; Brodar, I.; Sato, S.; Ohshima, T. Deep level defects in 4H-SiC introduced by ion implantation: The role of single ion regime. J. Phys. Condens. Matter 2017, 29, 475701.

19. Bernat, R.; Bakrač, L.; Radulović, V.; Snoj, L.; Makino, T.; Ohshima, T.; Pastuović, Ž.; Capan, I. 4H-SiC Schottky Barrier Diodes for Efficient Thermal Neutron Detection. Materials 2021, 14, 5105. https://doi.org/10.3390/ma14175105

20. Battistoni, G.; Cerutti, F.; Fassò, A.; Ferrari, A.; Muraro, S.; Ranft, J.; Roesler, S.; Sala, P.R. The FLUKA code: Description and benchmarking. AIP Conf. Proc. 2007, 896, 31–49

21. Ziegler, J.F.; Ziegler, M.D.; Biersack, J.P. SRIM—The stopping and range of ions in matter (2010). Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms. 2010, 268, 1818–1823.

22. Capan, I.; Brodar, T.; Makino, T.; Radulovic, V.; Snoj, L. M-Center in Neutron-Irradiated 4H-SiC. Crystals 2021, 11, 1404. https://doi.org/10.3390/cryst11111404

23. Peaker, A.R.; Markevich, V.P.; Coutinho, J. Tutorial: Junction spectroscopy techniques and deep-level defects in semiconductors. J. Appl. Phys. 2018, 123, 161559.

24. Son, N.T.; Trinh, X.T.; Løvlie, L.S.; Svensson, B.G.; Kawahara, K.; Suda, J.; Kimoto, T.; Umeda, T.; Isoya, J.; Makino, T.; et al. Negative-U System of Carbon Vacancy in 4H-SiC. Phys. Rev. Lett. 2012, 109, 187603.

25. Capan, I.; Brodar, T.; Bernat, R.; Pastuović, Ž.; Makino, T.; Ohshima, T.; Gouveia, J.D.; Coutinho, J. M-center in 4H-SiC: Isothermal DLTS and first principles modeling studies. J. Appl. Phys. 2021, 130, 125703

26. Karsthof, R.; Bathen, M.E.; Galeckas, A.; Vines, L. Conversion pathways of primary defects by annealing in proton-irradiated

n-type 4H-SiC. Phys. Rev. B 2020, 102, 184111.

27. Mandal, K.C.; Chaudhuri, S.K.; Nguyen, K. An overview of application of 4H-SiC n-type epitaxial Schottky barrier detector for high resolution nuclear detection. IEEE Nuclear Science Symposium and Medical Imaging Conference, 2013, 1-6, doi: 10.1109/NSSMIC.2013.6829844.

28. Kleppinger, J.W.; Chaudhuri, S.K.; Karadavut, O.F.; Mandal, K.C. Role of deep levels and barrier height lowering in current-flow mechanism in 150 μm thick epitaxial n-type 4H–SiC Schottky barrier radiation detectors. Appl. Phys. Lett. 2021, 119, 063502

29. Zat'ko, B.; Dubecký, F.; Šagátová, A.; Sedlačová, K.; Ryć, L High resolution alpha particle detectors based on 4H-SiC epitaxial layer. Journal of Instrumentation, 2015, 10, C04009.

30. Giudice, A.L; Fasolo, F.; Durisi, E.; Manfredotti, C.; Vittone, E.; Fizzotti, F.; Zanini, A.; Rosi, G. Performances of 4H-SiC Schottky diodes as neutron detectors. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip. 2007, 583, 177–180.

31. Sedlačková, K.; Zat'ko, B.; Šagátová, A.; Nečas, V.; Boháček, P.; Sekáčová, M. Comparison of semi-insulating GaAs and 4H-SiC-based semiconductor detectors covered by LiF film for thermal neutron detection. Appl. Surf. Sci. 2018, 461, 242–248.

32. Uher, J.; Holý, T.; Jakůbek, J.; Lehmann, E.; Pospíšil, S.; Vacík, J. Performance of a pixel detector suited for slow neutrons. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip. 2005, 542, 283–287.

33. Ruddy, F.H.; Dulloo, A.R.; Seidel, J.G.; Das, M.K.; Ryu, S.H.; Agarwa, A.K. The fast neutron response of 4H silicon carbide semiconductor radiation detectors. IEEE Transactions on Nuclear Science 53, 2006, 1666-1670, l10.1109/TNS.2006.875151

34. Bertuccio, G.; Casiraghi, R. Study of Silicon Carbide for X-Ray Detection and Spectroscopy. IEEE Transaction on nuclear science 2003, 50, 175-185.

35. Mandal, K.C.; Muzykov, P.G.; Chadhuri, S.K.; Terry, J.R. Low Energy X-Ray and γ-Ray Detectors Fabricated on n-type 4H-SiC Epitaxial Layer. IEEE Transactions on nuclear science, 2013, 60, 2888-2893.

36. Chen, K.; Cao, F.; Yang, Z.; Li, x.; Yang, J.; Shi, D.; Wang, Y. Improved interface characteristics of Mo/4H-SiC schottky contact, Solid-State Electronics, 2021,185, 108152.

37. Lioliou,G.; Renz,A.B.; Shah, V.A.; Gammon, P.M.; Barnett,A.M. Mo/4H-SiC Schottky diodes for room temperature X-ray and γ-ray spectroscopy. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip. 2022, accepted manuscript, doi: 10.1016/j.nima.2022.166330