Wide-Bandgap Semiconductors for Radiation Detection

Subjects: Physics, Condensed Matter
Contributor: Ivana Capan

An overview of wide-bandgap (WBG) semiconductors for radiation detection applications is given. The recent advancements in the fabrication of high-quality wafers have enabled remarkable WBG semiconductor device applications. The most common 4H-SiC, GaN, and β-Ga_2O_3 devices used for radiation detection are described.

Keywords: wide-bandgap semiconductors ; radiation ; detectors

1. Introduction

The need for reliable and efficient radiation detectors for particle physics, space technologies, nuclear power plants, medicine, and homeland security applications is growing rapidly. The requirements set for radiation detectors are complex, from exceptional efficiency and energy resolution to extreme radiation tolerance. Among numerous candidates, semiconductor radiation detectors offer plenty of advantages due to their exceptional material properties. For many decades, Si-based radiation detectors have been the champions in the radiation detection arena [1]. However, Si-based devices are reaching the limit of their performance, and it is dubious that significant improvements will follow in the years to come. Due to the wider bandgap (compared to Si 1.12 eV, for example) and the recent astonishing progress in material fabrication, wide-bandgap (WBG) semiconductors are becoming a new driving force for radiation detection.

The list of the most scrutinized WBG semiconductors includes, but is not limited to, silicon carbide (SiC), gallium nitride (GaN), gallium arsenide (GaAs), cadmium telluride (CdTe), and gallium oxide (Ga_2O_3). Attention will primarily be focused on the selected materials, namely, SiC, GaN, and Ga_2O_3—more precisely, 4H-SiC and β-Ga_2O_3. The reasoning is the following, the 4H polytype is the preferred material among the best-known SiC polytypes (2C-, 3C-, 4H-, and 6H-SiC) for electronic components due to the high and isotropic mobility of charge carriers [2][3].

Figure 1 shows several areas where WBG semiconductors are used. Due to the material properties, WBG semiconductors are dominantly used for applications in power electronics [4][5][6]. However, the number of new applications is continuously increasing, and WBG semiconductors are becoming the material of special interest for quantum technology [7][8][9], gas sensing [10], and radiation detection [11][12][13][14][15][16].

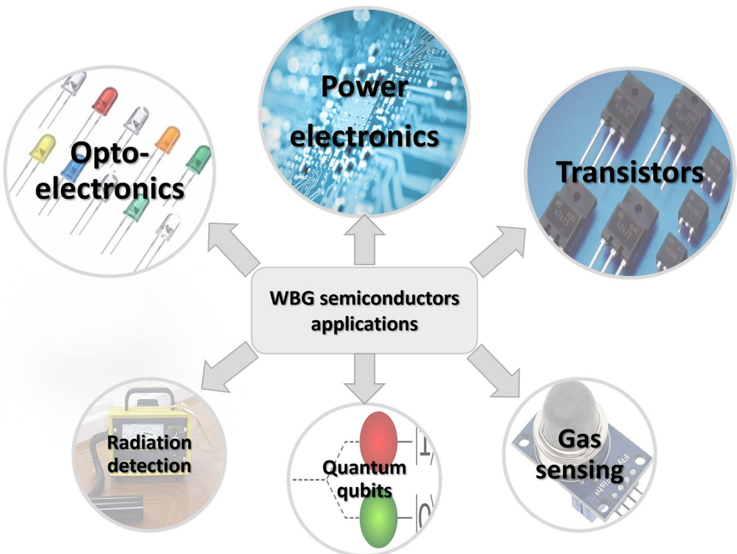

Figure 1. Diagram representing areas for the WBG semiconductor devices applications.

2. 4H-SiC

Research on SiC dates back to the end of the 19th century when SiC was recognized as a material for an abrasive powder and refractory bricks [4]. In the 1950s, the SiC potential was again recognized, this time for high-temperature electronic devices [4]. Despite certain efforts through the decades that followed, research on SiC began to flourish by the end of the 20th century. The progress in the fabrication of high-quality 4H-SiC wafers has enabled remarkable 4H-SiC-based device applications: power electronics [5][6], quantum sensing [7][8][9], and radiation detection [11][12][13][14][15][16]. This has influenced the significant increase in the market value. The SiC device market, valued at around USD 2 billion in 2023, is projected to increase from USD 11 billion to USD 14 billion in 2030 [17].

There is a whole variety of 4H-SiC-based devices that are currently being used as radiation detectors. The most common are PiN diodes [18], metal-oxide-semiconductor (MOS) structures [19][20], and Schottky barrier diodes (SBDs) [13][14][15]. Even though the SBD is one of the simplest devices, it has many advantages, and it has been chosen as the preferred structure in many studies [21]. **Figure 2**a shows a scheme of a typical n-type 4H-SiC SBD. In lots of reported studies, Ni is a preferred material for Schottky and Ohmic contacts for the n-type SBDs. However, it should be noted that other metals are also being used. Osvald et al. [22] have recently reported on Ni/Au Schottky contacts and Chen et al. [23] on the possible benefits of Mo Schottky contacts. Lees et al. [24] have made additional changes and used semi-transparent Cr/Ni Schottky contacts. Semi-transparent Schottky contacts could improve the efficiency for the detection of low-energy X-rays, compared to conventional Schottky contacts. More detailed information about the key parameters of 4H-SiC SBDs, such as the epitaxial layer thickness and Schottky contact area, could be found elsewhere [21]. De Napoli [25] and Coutinho et al. [3] have provided extensive overviews of crystal growth, material properties, and characterization techniques, with a dedicated focus on SiC radiation detection applications.

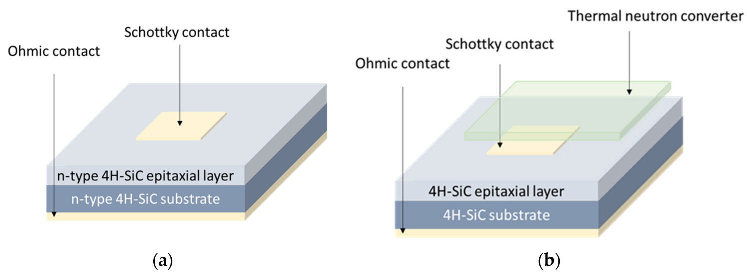

Figure 2. (**a**) A scheme of the typical n-type 4H-SiC SBD used for radiation detection and (**b**) a scheme of 4H-SiC SBD with the additional thermal neutron converter placed above the Schottky contact. The converter is used for thermal neutron detection and is usually placed a few mm above the Schottky contact.

2.1. Radiation Response to Alpha Particles and Neutrons

Almost all research on the radiation response starts with laboratory tests using alpha particles from ^{241}Am source. 4H-SiC-based devices are not an exception. The early and yet still significant work in the area of 4H-SiC radiation response to alpha particles was conducted by Ruddy et al. [12]. SBDs were fabricated on nitrogen-doped (1×10^{14} cm^{-3}) 4H-SiC epitaxial layers, 100 µm thick. Schottky contacts Au/Pt/Ti were deposited by electron beam evaporation. Using the various alpha emitters such as ^{148}Gd, ^{238}Pu, ^{225}Ac, ^{221}Fr, ^{217}At, and ^{213}Po in the 3.18–8.38 MeV energy range, an excellent energy resolution was achieved. Through the years, progress in energy resolution and efficiency has been reported by many authors [26][27][28][29]. Chaudhuri et al. [29] achieved an excellent energy resolution of 0.29% at the full width at half maximum (FWHM) for 5.48 MeV alpha particles using a 20 µm thick 4H-SiC epitaxial layer. The Schottky contact was Ni/Au, while the Schottky contacts were 2.9 mm or 3.9 mm in diameter. Additionally, the same group has applied 4H-SiC-based MOS structures and compared them to 4H-SiC SBDs. They have reported the highest energy resolution ever measured on SiC-based MOS detectors: 0.42% for 5.48 MeV alpha particles [19].

While most of the radiation tests are performed at room temperature (RT), Bernat et al. [30] have recently investigated the 4H-SiC SBDs radiation response to alpha particles at elevated temperatures in a vacuum. They have used n-type 4H-SiC SBDs with a 25 µm thick 4H-SiC epitaxial layer and an active area of 25 mm^2. **Figure 3** shows the response to alpha particles (^{241}Am source with a characteristic alpha particle maximum of 5.48 MeV) measured at different temperatures (200–390 K) in a cryostat under a vacuum (<0.1 mbar) [31]. As seen in **Figure 3**, the peak maximum is shifted on the x-scale as the radiation temperature increases. The estimated energy resolution was 2.5% and did not change with the temperature.

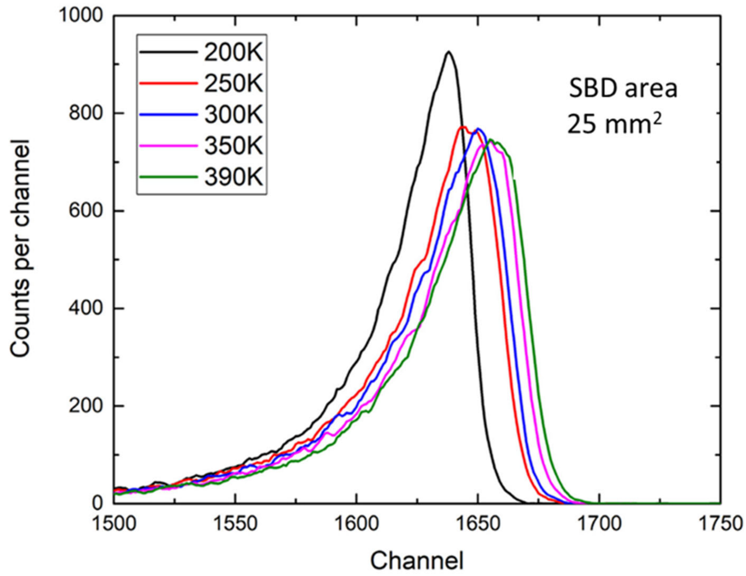

Figure 3. Radiation response of 4H-SiC SBDs (active area of 25 mm^2) to alpha particles (^{241}Am source) in a vacuum at different temperatures.

Due to their specific material properties, WBG semiconductors are suitable for radiation harsh environments, such as the International Thermonuclear Experimental Reactor (ITER) [30]. The significant advantage of SiC lies in the fact that SiC can detect and distinguish both thermal and fast neutrons. The detection of thermal and fast neutrons by SiC-based devices differs, as thermal neutrons could not be directly detected. Thermal neutron presence is obtained from the detection of ionizing neutron reaction products, such as alpha particles and tritons. In contrast, fast neutrons could be directly detected due to the elastic scattering of fast neutrons with Si or C atoms, or indirectly using polyethylene-based converters. Possible neutron-induced reactions with Si and C that could participate in the 4H-SiC detector response are $^{12}C(n,n)^{12}C$ and $^{28}Si(n,n)^{28}Si$ [32]. The probability of this scattering increases as the detector's active layer thickness increases. Currently, the highest layer thickness is 250 µm as reported by Kleppinger et al. [14]. SBDs with Ni as a Schottky contact were fabricated on 250 µm thick epitaxial layers. An energy resolution of 0.5% FWHM using a ^{241}Am source was achieved. Unfortunately, radiation response to fast neutrons has not been measured. Very thick (>300 µm) high-quality 4H-SiC epitaxial layers used for fast neutron detection have not yet been reported. It is reasonable to expect that further advances will be made with an increase in the thicknesses of high-quality epitaxial layers.

The prospect of detecting 14 MeV fast neutrons by 4H-SiC detectors was demonstrated by F.H. Ruddy et al. [33]. Fast neutron response measurements were reported for radiation detectors based on large-volume 4H-SiC SiC pin diodes. Several reaction peaks associated with 14 MeV neutron reactions with the silicon and carbon nuclides in the pin diode were observed. Another work also worth mentioning is that by Flamming et al. [16], who measured the radiation response to fast neutrons using the 100 µm thick 4H-SiC SBD with and without polyethylene converters. Fission neutrons were simulated by using a 2.5 MeV deuterium-deuterium (D-D) neutron generator. As anticipated, better results are achieved using the polyethylene converters.

Hitherto, 4H-SiC SBDs have mostly been used for thermal neutron detection. As already said, they cannot be directly measured; therefore, effective thermal neutron converters are needed. The requirement for such converters is that they are rich in isotopes with a large cross-section for neutrons with energy in the range of k_BT at RT (k_B is the Boltzmann constant). The frequently used converters are ^6Li and ^{10}B [34]. **Figure 2**b shows a typical set-up for thermal neutron detection using the 4H-SiC SBD with the thermal neutron converter placed just above the Schottky contact (a few mm above). The converter has been horizontally shifted in **Figure 2**b, for clarity.

The best-reported efficiencies for thermal neutron detection using the 4H-SiC devices are between 4 and 5% [35][36][37]. Recently, Bernat et al. [30] have reported on the effects of large-area 4H-SiC SBDs on the radiation response to thermal neutrons. Two different diode areas were compared: 1 mm^2 and 25 mm^2. SBDs were fabricated using a 25 µm thick 4H-SiC epitaxial layer and Ni as a Schottky contact. An efficiency of 5.02% with the use of a 26.54 µm thick ^6LiF thermal neutron converter layer is reported (**Figure 4**). Additionally, they have shown that with the increase in the SBD active area, the detector could register thermal neutrons with a nuclear reactor power as low as 1 kW.

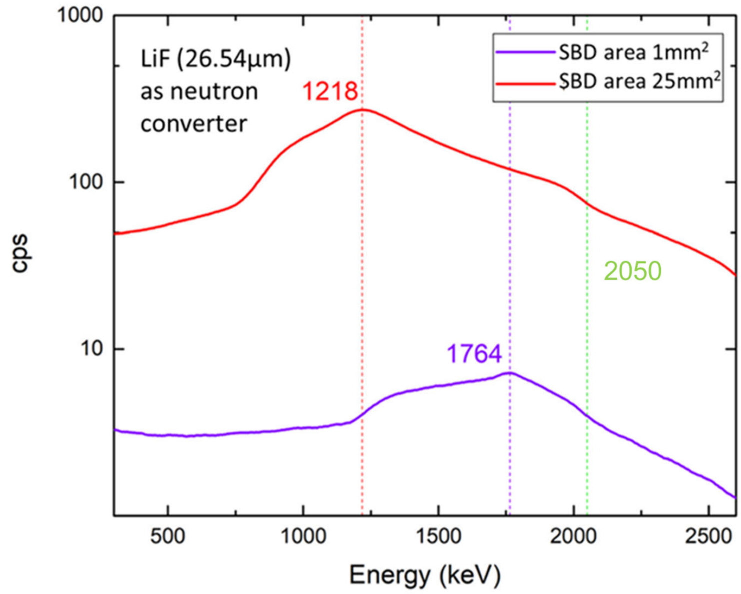

Figure 4. Radiation response of two 4H-SiC SBDs with different active areas (1 mm^2 and 25 mm^2). The 26.54 μm thick ^{6}LiF thermal neutron converter layer was placed above the SBDs, as already described in the text.

Contrary to the alpha particles and neutrons, the low-energy X-ray and γ-ray detection by 4H-SiC devices has not yet reached the same level of efficiency. However, several attempts have been made, and they should be noted. Puglisi et al. [38] studied 4H-SiC microstrip detectors for soft X-ray (<20 keV) detection. They achieved an energy resolution of about 700 and 1300 eV FWHM for 1 mm^2 and 10 mm^2 detectors measured at RT, respectively. Mandal et al. [39] have achieved an FWHM of 1.2 keV at 59.6 keV using the 50 μm thick 4H-SiC SBDs. Moreover, using the same SBDs, they were able to detect low-energy X-rays in the energy range of 13.93–26.20 eV. Lees et al. [24] have used a slightly different SBD structure. They have reduced the thickness of the Schottky contact (Ni/Ti was used), from a typical 50–100 nm down to 18 nm, and prepared so-called semi-transparent SBD. Different X-ray sources were used: ^{55}Fe and ^{109}Cd. With 4H-SiC SBD, an energy resolution of 1.47 keV FWHM at 22 keV at RT was reported. Lioliou et al. [40] fabricated photon-counting detectors for X-ray and gamma-ray spectroscopy using the 35 μm thick 4H-SiC SBDs with Mo as a Schottky contact. An energy resolution of 1.67 keV FWHM at 5.9 keV and 1.6 keV FWHM at 59.54 keV was achieved.

As demonstrated in different studies on X-ray detection, energy resolution can be increased by additional modifications on the Schottky contacts (thickness, area, and metal) for 4H-SiC SBDs.

References

1. Akimov, Y.K. Silicon radiation detectors (Review). Instrum. Exp. Tech. 2007, 50, 1–28.
2. Kimoto, T.; Cooper, J.A. Fundamentals of Silicon Carbide Technology: Growth, Characterization, Devices, and Applications; John Wiley & Sons Singapore Pte. Ltd.: Hoboken, NJ, USA, 2014.
3. 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.
4. Matsunami, H. Fundamental research on semiconductor SiC and its applications to power electronics. Proc. Jpn. Acad. Ser. B Phys. Biol. Sci. 2020, 96, 235–254.
5. Hedayati, R.; Lanni, L.; Rodriguez, S.; Malm, B.G.; Rusu, A.; Zetterling, C.M. A monolithic, 500 °C operational amplifier in 4H-SiC bipolar technology. IEEE Electron. Device Lett. 2014, 35, 693–695.
6. Ryu, S.-H.; Krishnaswami, S.; Hull, B.; Heath, B.; Das, M.; Richmond, J.; Fatima, H.; Zhang, J.; Agarwal, A.; Palmour, J.; et al. High Speed Switching Devices in 4H-SiC—Performance and Reliability. In Proceedings of the 2005 IEEE International Semiconductor Device Research Symposium, Bethesda, MD, USA, 7–9 December 2005; pp. 162–163.
7. Wang, J.; Zhou, Y.; Zhang, X.; Liu, F.; Li, Y.; Li, K.; Liu, Z.; Wang, G.; Gao, W. Efficient Generation of an Array of Single Silicon-Vacancy Defects in Silicon Carbide. Phys. Rev. Appl. 2017, 7, 064021.
8. Widmann, M.; Lee, S.Y.; Rendler, T.; Son, N.T.; Fedder, H.; Paik, S.; Yang, L.P.; Zhao, N.; Yang, S.; Booker, I.; et al. Coherent control of single spins in silicon carbide at room temperature. Nat. Mater. 2015, 14, 164–168.
9. Fuchs, F.; Stender, B.; Trupke, M.; Simin, D.; Pflaum, J.; Dyakonov, V.; Astakhov, G.V. Engineering near-infrared single-photon emitters with optically active spins in ultrapure silicon carbide. Nat. Commun. 2015, 6, 7578.

10. Zhai, H.; Wu, Z.; Fang, Z. Recent progress of Ga2O3-based gas sensors. Ceram. Int. 2022, 48, 24213–24233.
11. 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. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip. 2020, 972, 164122.
12. 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.
13. Zaťko, B.; Hrubčín, L.; Šagátová, A.; Osvald, J.; Boháček, P.; Kováčová, E.; Halahovets, Y.; Rozov, S.V.; Sandukovskij, V.G. Study of Schottky barrier detectors based on a high quality 4H-SiC epitaxial layer with different thickness. Appl. Surf. Sci. 2021, 536, 147801.
14. 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. Appl. Phys. 2021, 129, 244501.
15. 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, 10.
16. Flammang, R.W.; Seidel, J.G.; Ruddy, F.H. Fast neutron detection with silicon carbide semiconductor radiation detectors. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip. 2007, 579, 177–179.
17. New Silicon Carbide Prospects Emerge as Market Adapts to EV Expansion. Available online: https://www.mckinsey.com/industries/semiconductors/our-insights/new-silicon-carbide-prospects-emerge-as-market-adapts-to-ev-expansion (accessed on 7 February 2024).
18. 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. Sens. Actuators A Phys. 2022, 333, 113241.
19. Chaudhuri, S.K.; Karadavut, O.; Kleppinger, J.W.; Mandal, K.C. High-resolution radiation detection using Ni/SiO2/n-4H-SiC vertical metal-oxide-semiconductor capacitor. J. Appl. Phys. 2021, 130, 074501.
20. Karadavut, O.; Chaudhuri, S.K.; Kleppinger, J.W.; Nag, R.; Mandal, K.C. Enhancement of radiation detection performance with reduction of EH6/7 deep levels in n-type 4H–SiC through thermal oxidation. Appl. Phys. Lett. 2022, 121, 012103.
21. Capan, I. 4H-SiC Schottky Barrier Diodes as Radiation Detectors: A Review. Electronics 2022, 11, 532.
22. Osvald, J.; Hrubčín, L.; Zaťko, B. Temperature dependence of electrical behaviour of inhomogeneous Ni/Au/4H–SiC Schottky diodes. Mater. Sci. Semicond. Process. 2022, 140, 106413.
23. 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 Electron. 2021, 185, 108152.
24. 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. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip. 2007, 578, 226–234.
25. De Napoli, M. SiC detectors: A review on the use of silicon carbide as radiation detection material. Front. Phys. 2022, 10, 898833.
26. 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. In Proceedings of the IEEE Nuclear Science Symposium and Medical Imaging Conference, Seoul, Republic of Korea, 27 October–2 November 2013; pp. 1–6.
27. 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.
28. Zat'ko, B.; Dubecký, F.; Šagátová, A.; Sedlačová, K.; Ryć, L. High resolution alpha particle detectors based on 4H-SiC epitaxial layer. J. Instrum. 2015, 10, C04009.
29. Chaudhuri, S.K.; Zavalla, K.J.; Mandal, K.C. High resolution alpha particle detection using 4H–SiC epitaxial layers: Fabrication, characterization, and noise analysis. Nucl. Instrum. Meth. Phys. Res. A 2013, 728, 97.
30. Bernat, R.; Knežević, T.; Radulović, V.; Snoj, L.; Makino, T.; Ohshima, T.; Capan, I. Radiation Response of Large-Area 4H-SiC Schottky Barrier Diodes. Materials 2023, 16, 2202.
31. Krasilnikov, V.; Bertalot, L.; Barnsley, R.; Walsh, M. Neutron Detector Needs for ITER. Fusion Sci. Technol. 2017, 71, 196–200.
32. Obraztsova, O.; Ottaviani, L.; Klix, A.; Döring, T.; Palais, O.; Lyoussi, A. Comparison between Silicon-Carbide and diamond for fast neutron detection at room temperature. EPJ Web Conf. 2018, 170, 08006.

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 Trans. Nucl. Sci. 2006, 53, 1666–1670.
34. McGregor, D.S.; Hammig, M.D.; Yang, Y.H.; Gersch, H.K.; Klann, R.T. Design considerations for thin film coated semiconductor thermal neutron detectors—I: Basics regarding alpha particle emitting neutron reactive films. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip. 2003, 500, 272–308.
35. 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.
36. 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.
37. 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.
38. Puglisi, D.; Bertuccio, G. Silicon Carbide Microstrip Radiation Detectors. Micromachines 2019, 10, 835.
39. 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 Trans. Nucl. Sci. 2013, 60, 2888–2893.
40. 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, 1027, 166330.