Characteristics of 4H-SiC and diamond detectors for direct fast neutron detection

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Abstract

Nuclear fusion research is regarded as a key direction for the development of future clean energy, and the precise detection of high-energy neutrons in high-temperature (up to 300°C) environments is particularly important to advance the technological realization of fusion reactors. 4H-SiC and diamond are ideal candidate materials for direct fast neutron detection in such conditions due to their high carbon content and wide-band gap properties. Device structure has great influence on the detection performance and high temperature performance of the detector. In this study, the detection performance of three kinds of detectors based on 4H-SiC and diamond (SiC-SBD, SiC-MSM and Diamond-MSM) under high temperature conditions was investigated, and the influence of device structure and semiconductor material on the high temperature performance was analyzed. The performance of these detectors was evaluated by comparing leakage current, energy resolution, and thermal stability. The results demonstrate that SBD devices exhibit relative better detection accuracy at temperatures below 150°C, but their performance significantly deteriorates as the temperature continue increases, while SiC-MSM shows superior high-temperature stability than SiC-SBD; additionally, Diamond-MSM achieved the best thermal stability over all the test temperature range. At 25℃-350℃, the leakage current of Diamond-MSM remains below 5 nA, while the energy resolution remains below 2.5%@5486 keV. In addition, Diamond-MSM also exhibits the best fast neutron response and excellent counting linearity. This work indicates the great potential of Diamond-MSM device for high-temperature detection applications in nuclear fusion research especially for high-temperature environments.

Full Text

Fast Neutron Detection Characteristics of 4H-SiC and Diamond Detectors for Direct Detection

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Abstract

Nuclear fusion research represents a critical pathway toward future clean energy, and precise detection of high-energy neutrons in high-temperature environments (up to 300°C) is essential for advancing fusion reactor technology. Due to their high carbon content and wide bandgap properties, 4H-SiC and diamond are ideal candidate materials for direct fast neutron detection under such extreme conditions. Device structure significantly influences both detection performance and high-temperature operation. This study investigates the detection performance of three detector types based on 4H-SiC and diamond (SiC-SBD, SiC-MSM, and Diamond-MSM) under elevated temperatures, analyzing how device architecture and semiconductor material affect high-temperature behavior. Performance evaluation focused on leakage current, energy resolution, and thermal stability. The results demonstrate that SBD devices exhibit relatively superior detection accuracy below 150°C, but their performance degrades substantially at higher temperatures. SiC-MSM shows better high-temperature thermal stability compared to SiC-SBD, while Diamond-MSM achieves the best stability across the entire tested temperature range. From 25°C to 350°C, the leakage current of Diamond-MSM remains below 5 nA, with energy resolution staying under 2.5% at 5486 keV. Furthermore, Diamond-MSM demonstrates the best fast neutron response and excellent counting linearity. This work highlights

the great potential of Diamond-MSM devices for high-temperature detection applications in nuclear fusion research, particularly in demanding thermal environments.

Keywords: 4H-SiC, Diamond, Fast neutron detector, High temperature, Energy resolution

1 Introduction

Nuclear fusion research is widely regarded as a key direction for developing future clean energy, and accurate detection of high-energy neutrons is crucial for advancing fusion reactor technology [1]. The China Fusion Engineering Test Reactor (CFETR), as a critical experimental platform for studying and validating fusion reactor technologies, requires precise detection of 14.1 MeV fast neutrons produced by fusion reactions under harsh temperatures reaching up to 300°C to ensure successful experimental outcomes and deepen our understanding of fusion processes [2, 3].

Wide-bandgap semiconductor materials have emerged as an important option for fast neutron detection at high temperatures due to their excellent performance in extreme thermal environments [4-6]. Direct detection of high-energy neutrons through nuclear reactions between material elements and neutrons has proven effective for fast neutron detection. Carbon is particularly important for high-energy neutron detection because of its high cross-section with fast neutrons and the distinct energy characteristics of its reaction products [7]. Table 1 summarizes the main reaction types, cross-sections, and energy thresholds for carbon interacting with 14.1 MeV neutrons [8, 9], providing a theoretical foundation for efficient fast neutron detection. Both 4H-SiC and diamond, with their high carbon content and wide bandgap properties, are ideal materials for direct fast neutron detection in high-temperature environments [10, 11].

Recent years have seen growing research on 4H-SiC and diamond materials for fast neutron detection. In 2006, F. H. Ruddy developed a 4H-SiC-based fast neutron detector that achieved direct detection of 14.1 MeV fast neutrons [12]. In 2018, D. Rigamonti fabricated a single-crystal diamond detector grown by standard Chemical Vapor Deposition (sCVD) and demonstrated accurate fast neutron detection at room temperature [13]. Also in 2018, O. Obraztsova compared the response of 4H-SiC and sCVD diamond-based detectors to 14-MeV neutrons, with both detectors showing well-characterized energy spectra [14]. In 2016, D. Szalkai investigated 4H-SiC semiconductor detectors under 14 MeV fast neutron irradiation at high temperatures (up to 500°C), revealing that thermal noise increased and counting rate decreased with temperature [15]. Despite this progress, research on carbon-based semiconductor detectors for fast neutron detection in high-temperature environments remains limited.

Detector structure design plays a crucial role in determining performance, particularly regarding leakage current, energy resolution, and thermal stability. The Metal-Semiconductor-Metal (MSM) structure is widely considered a classic design for diamond-based devices, primarily due to the challenges associated with P-type and N-type doping in diamond [16]. These doping processes are difficult to control in terms of concentration and efficiency, making PN junction implementation challenging. Additionally, metal-semiconductor contacts in diamond are difficult to optimize, resulting in contact issues for Schottky Barrier Diodes (SBD), while heterojunction structures are also problematic due to lattice mismatch and stress issues. Consequently, the MSM structure remains the preferred choice for diamond-based devices because of its simplicity and ease of fabrication. In contrast, 4H-SiC devices can be fabricated in various structures, including SBD, PN, PIN, MOS (Metal-Oxide-Semiconductor), and MSM [17]. Among these configurations, the SBD structure is particularly favored for its high energy resolution and fast response time [18]. In 2020, K. C. Mandal developed a Ni/4H-SiC SBD detector and reported an optimal energy resolution of 0.29% at 5486 keV [19]. However, systematic comparisons and in-depth studies on which device structures and materials can achieve high-performance fast neutron detection at high temperatures are still lacking.

In this work, we designed and fabricated 4H-SiC detectors (with SBD and MSM structures) and a diamond detector (with MSM structure). The influence of device structure and material on detector performance was characterized by comparing critical parameters including leakage current, energy resolution, and thermal stability across three device groups under varying temperature conditions. Additionally, we explored their feasibility for direct detection of 14.1 MeV neutrons.

2.1 Calculation Methods

The I-V characteristics of Schottky diodes can be explained by the thermionic emission model. A straight-line fit to the ln(I)–V plot was used to determine the Schottky barrier height Φb (in volts) and ideality factor n according to Eq. (1):

$$I = AA^{*}T^{2}\exp\left(-\frac{q\Phi_b}{kT}\right)\exp\left(\frac{qV}{nkT}\right)\left[1-\exp\left(-\frac{qV}{kT}\right)\right]$$

where A is the device area, A* is the effective Richardson constant (146 $A \cdot cm^{-2} \cdot K^{-2}$ for 4H-SiC), k is Boltzmann' s constant, T is absolute temperature, q is the elementary electron charge, and Vd is the applied reverse bias voltage.

The I-V characteristics of MSM devices can be explained by the following equation:

$$I = I_0 \exp\left(\frac{qV}{nkT}\right)\left[1 - \exp\left(-\frac{qV}{kT}\right)\right]$$

where Eg is the bandgap width of the semiconductor.

For the SBD junction, the width of the depletion region can be estimated using:

$$W_d = \sqrt{\frac{2\varepsilon_s\varepsilon_0(V_{bi} - V)}{qN_{eff}}}$$

where Wd is the depletion region width, s is the semiconductor' s relative dielectric constant, 0 is vacuum permittivity, and Neff is the doping concentration.

The drift-diffusion model was applied to explain charge collection efficiency (CCE) as a function of applied bias [10]:

$$\text{CCE} = \frac{1}{E_\alpha}\int_0^L \frac{dE}{dx}\exp\left(-\frac{x}{L_d}\right)dx$$

where Ld is the minority carrier diffusion length, Eα is the alpha particle energy, dE/dx is the energy loss rate, and L is the range.

The total number of nuclear reactions Rt can be calculated by:

$$R_t = \Sigma\phi V_{det}$$

where Σ is the macroscopic cross-section, ϕ is the neutron fluence, and Vdet is the detector' s effective volume.

The theoretical detection efficiency   of neutron detectors based on 4H-SiC or diamond as a function of semiconductor plate thickness Lm can be expressed in terms of interaction probability [23]:

$$\eta = 1 - \exp\left(-\frac{L_m}{\lambda}\right)$$

where λ, defined as $1/\Sigma$, represents the neutron mean free path.

The range and energy deposition of α particles in 4H-SiC and diamond materials were calculated using the Stopping and Range of Ions in Matter (SRIM-2013) program [24].

2.2 Device Design and Fabrication

From the ENDF/B-VIII.1 nuclear database, 12C and 28Si have total reaction cross-sections of 1.32 b and 1.89 b, respectively, for 14.1 MeV neutrons [25]. The density of 4H-SiC is 3.2 g/cm^3, with atomic densities of both Si and C elements at 4.81$\times10^{22}$ cm^{-3}. The macroscopic cross-section for 4H-SiC with 14.1 MeV neutrons is 1.54$\times10^{-1}$ cm^{-1}, yielding a mean free path of 6.48 cm. Diamond density is 3.5 g/cm^3 with a carbon nucleus density of 1.76$\times10^{23}$ cm^{-3}. The macroscopic cross-section for diamond with 14.1 MeV neutrons is 2.32$\times10^{-1}$ cm^{-1}, corresponding to a mean free path of 4.30 cm.

Based on Eq. (6), the ideal detection efficiency for 14.1 MeV neutrons as a function of 4H-SiC and diamond plate thickness was calculated, as shown in Fig. 1 [Figure 1: see original paper]. For both semiconductor plates, detection efficiency increases approximately linearly over the thickness range of 0-1000 m. Therefore, to maximize detection efficiency, the semiconductor plate thickness should be as large as possible while reducing doping concentration to improve charge collection efficiency. In this work, the calculated detection efficiencies for detectors with 80- m-thick 4H-SiC and 500- m-thick diamond plates are 0.12% and 1.17%, respectively.

The 4H-SiC detector was fabricated on a 350- m-thick 4H-SiC n+ substrate, on which an 80- m-thick n-type epitaxial layer with low nitrogen doping concentration (~7.1$\times10^{13}$ cm^{-3}) was grown as the sensitive region. After substrate cleaning using the standard Radio Corporation of America (RCA) procedure, Ti/Al/Ti/Au (30/30/30/30 nm) films were deposited on the bottom side of the 4H-SiC substrate via magnetron sputtering. These films were annealed at 500°C for 3 minutes in nitrogen (N_2) atmosphere to form ohmic contacts. The Schottky electrode was prepared by depositing Ni/Au (30/30 nm) films on the 4H-SiC epitaxial layer. For the SiC-MSM detector, Ti/Au (30/30 nm) films were deposited on the 4H-SiC epitaxial layer and annealed at 400°C in N_2 environment for 30 minutes.

The diamond detector was fabricated at Xidian University. Single-crystal diamond material was grown by microwave plasma chemical vapor deposition (MPCVD), with detailed processing methods described in reference [26]. The diamond sample was soaked in H_2SO_4 for 30 minutes to remove amorphous carbon and organic contaminants, followed by ultrasonic cleaning in acetone, alcohol, and deionized water for 15 minutes each at 60 W power. Using electron beam evaporation with a metal mask, 150-nm-thick Au electrodes (3.6$\times$3.6 *mm^{2}) were deposited on both hydrogen-terminated surfaces. Oxygen-terminated surfaces were formed for isolation. These device fabrication processe* *electrode regions were described in our previous work* [27, 28]. *Subsequently*, 200 *nm-thick Si{3}N{4}*$ was deposited on both surfaces for passivation using plasma-enhanced chemical vapor deposition (PECVD) at 350°C. Photolithography and inductively coupled plasma (ICP) etching were used to form electrical connection pads. The device was then packaged in a TO-254 ceramic package using conductive silver paste (bottom surface) and silicon-aluminum wire (top surface), completing the Diamond-MSM detector fabrication. Schematic diagrams of the three detectors are illustrated in Fig. 2 [Figure 2: see original paper].

2.3 Detector Characterization

The basic electrical properties of the detectors were characterized through current-voltage (I-V) measurements. As shown in Fig. 3 [Figure 3: see original paper], the neutron test system employed in this study consists of the detector, a deuterium-tritium (D-T) neutron source, charge-sensitive preamplifiers, multi-channel digital analyzers, and a personal computer running COMPASS software [10]. Neutron tests were conducted using the High Intensity Deuterium-Tritium Fusion Neutron Generator (HINEG), which generates D+ ions via an Electron Cyclotron Resonance (ECR) ion source. D-T fusion neutrons are produced by bombarding a rotating tritium target with accelerated ions, yielding a neutron output of 2.0×10^{10} n/s [29]. Detector signals were amplified using a multichannel charge-sensitive preamplifier (CSA), with data acquisition and analysis performed using COMPASS software for online operational control and data storage.

3.1 Electrical Characterization

Fig. 4 Figure 4: see original paper shows the forward I-V characteristics of the SiC-SBD detector at 25°C under dark conditions. Using the thermionic emission model, the barrier height Φb and ideality factor n were calculated as 1.47 eV and 1.15, respectively. The reverse I-V characteristics at different temperatures are shown in Fig. 4(b). At -200 V, the dark currents are 3.21 nA, 52.4 nA, 0.45 A, and 5.35 A at 25°C, 100°C, 150°C, and 200°C, respectively—representing an approximately 1600-fold increase from 25°C to 200°C. As shown in Eq. (1), SBD leakage current is strongly temperature-dependent. At elevated temperatures, increased thermal excitation of intrinsic carriers leads to higher leakage currents, degrading energy resolution and overall detector reliability [30]. In 2024, Norbert Gál reported a Ni/4H-SiC SBD detector with 1 pA leakage current at room temperature that increased 10,000-fold to 10 nA at 500°C [31].

The dark current I-V characteristics of SiC-MSM detectors were measured at various temperatures, as shown in Fig. 5 [Figure 5: see original paper]. As expected, dark currents increased with temperature. At 200 V, the currents were 0.57 nA, 0.76 nA, 1.17 nA, 1.45 nA, 2.60 nA, 8.59 nA, 16.14 nA, and 91.75 nA at 25°C, 50°C, 100°C, 150°C, 200°C, 250°C, 300°C, and 350°C, respectively. The leakage current increased approximately 4.5-fold from 25°C to 200°C and about 161-fold from 25°C to 350°C. Compared with SiC-MSM, SiC-SBD shows much more dramatic leakage current variation with temperature, indicating significant differences in internal physical mechanisms and structural responses to thermal elevation. These results demonstrate completely different temperature-dependent leakage characteristics between SiC-SBD and SiC-MSM, providing important guidance for device selection in different thermal environments. For high-temperature applications, SiC-MSM offers advantages over SiC-SBD due to superior temperature stability and lower leakage current.

The dark current I-V characteristics of Diamond-MSM devices were measured at various temperatures, as shown in Fig. 6 [Figure 6: see original paper]. At 200 V, the dark currents were 0.88 nA, 0.84 nA, 0.92 nA, 2.28 nA, 2.21 nA, 2.83 nA, 3.55 nA, and 4.01 nA at 25°C, 50°C, 100°C, 150°C, 200°C, 250°C, 300°C, and 350°C, respectively. Thanks to diamond' s larger bandgap, the leakage current increased only 4.5-fold from 0.88 nA at 25°C to 4.01 nA at 350°C. In contrast to SiC-MSM, Diamond-MSM dark currents also rise with temperature, but at a much lower rate. This occurs because 4H-SiC' s bandgap is relatively narrow compared to diamond, meaning more electrons can be thermally excited from the valence to conduction band at elevated temperatures, contributing more significantly to dark current. With minimal dark current growth, excellent high-temperature stability, and high thermal conductivity enabling effective heat dissipation, Diamond-MSM is better suited for high-temperature environments than SiC-MSM.

3.2 Alpha Response

Based on SRIM calculations, the ranges of 5486 keV alpha particles in 4H-SiC and diamond are 19 m and 15 m, respectively, with the difference primarily due to diamond' s higher density. Fig. 7 [Figure 7: see original paper] shows the final Bragg ionization distributions for both materials, with corresponding dE/dx data used for subsequent CCE fitting calculations.

Fig. 8 Figure 8: see original paper shows the variation of CCE and energy resolution with bias voltage for the SiC-SBD detector under alpha particle irradiation at room temperature. The experimental CCE data as a function of reverse bias voltage fit well with the theoretical curve calculated from Eq. (4) using Ld = 13.5 m. The overall CCE, particularly at lower biases, results from the interplay between majority carrier (electron) drift and minority carrier diffusion. As voltage increased, CCE reached saturation and energy resolution achieved its optimal state, reaching 0.61% at -70 V bias. Fig. 8(b) presents the corresponding pulse height spectrum, clearly showing all three primary alpha emission peaks (α_1, α_2, and α_3) at 5486, 5443, and 5388 keV. The peak intensity ratio of α_1:α_2:α_3 is 85.23:12.67:0.94, consistent with the branching ratio from the ^{241}Am source (86:12.5:1). These results demonstrate excellent energy resolution and charge collection performance for SiC-SBD at room temperature.

Fig. 9 Figure 9: see original paper shows the variation of CCE and energy resolution with bias voltage for the SiC-MSM detector at room temperature. Notably, alpha particle signals are detectable even at zero bias voltage, attributable to different diffusion lengths of electrons and holes. At zero bias, though no external field is applied, charge carriers generated by alpha particles can still diffuse and be collected, albeit with low efficiency. When bias is applied, the electric field causes controllable drift of charge carriers, improving collection efficiency and resulting in increased peak height in the alpha particle spectrum. The peak shifts to higher channels with increasing bias voltage, indicating improved detector performance, better energy resolution, and more efficient charge collection.

It is important to note fundamental differences in how MSM and SBD devices respond to applied bias. In MSM devices, bias voltage creates an electric field that sweeps charge carriers toward electrodes, facilitating signal generation and more efficient collection. In contrast, bias voltage in SBD devices widens the depletion region, altering charge collection dynamics and producing different effects on performance. This distinction in bias response is crucial for understanding the balance between signal sensitivity and resolution. Fig. 9(b) presents the pulse height spectrum of the SiC-MSM device at 200 V bias, showing 1.21% energy resolution. The alpha spectral lines from ^{241}Am at 5.486, 5.443, and 5.388 MeV overlap severely, producing a broad spectrum attributed to electronic noise, imperfect charge collection, and the detector' s natural resolution limit. The FWHM at 200 V is 66.4 keV, significantly worse than that observed in the SiC-SBD detector at -70 V, with SiC-MSM' s energy resolution approximately twice that of SiC-SBD, indicating a clear performance deficit.

Fig. 10 Figure 10: see original paper shows the variation of CCE and energy resolution with bias for Diamond-MSM at room temperature. At zero bias, no alpha particle spectrum was obtained, as signals were lost in the detector bulk due to the lack of an electric field to collect charge carriers. To obtain meaningful data, bias voltages above 30 V were applied. At higher biases, CCE increased with voltage, indicating that stronger electric fields help collect more charge carriers from incident alpha particles. Energy resolution also improved with bias voltage, reaching its optimal value at 200 V—a common trend where higher bias provides better charge separation and collection, leading to clearer peak detection. The pulse height spectrum at 200 V bias, shown in Fig. 10(b), corresponds to 0.97% energy resolution, suggesting effective discrimination between different alpha particle energies with minimal uncertainty. These results emphasize the importance of bias voltage in optimizing Diamond-MSM detector performance.

Fig. 11 Figure 11: see original paper shows pulse height spectra for SiC-SBD detecting 5.48 MeV ^{241}Am alpha particles at different temperatures under -70 V bias. As temperature increases, spectra broaden and peak heights decrease, indicating signal clarity loss. Fig. 11(b) presents energy resolution and peak position variation from 50°C to 200°C. Comparing Fig. 11(b) with Fig. 4(b) reveals that energy resolution trends with temperature mirror leakage current trends. As temperature rises, increased leakage current leads to higher thermal noise, degrading energy resolution. At 200°C, SiC-SBD energy resolution is 5.1%, a noticeable decline from lower-temperature performance. Increased leakage current and thermal noise interfere with signal distinction, broadening spectral peaks and making precise energy measurement difficult. This performance degradation limits SiC-SBD's utility for accurate alpha particle detection at elevated temperatures, rendering it unreliable above 200°C. These results emphasize the importance of temperature control for SiC-SBD operation.

Pulse height spectra for SiC-MSM detecting 5.48 MeV ^{241}Am at different temperatures are shown in Fig. 12 Figure 12: see original paper, with energy resolution and peak position versus temperature presented in Fig. 12(b) from 50°C to 350°C. Energy resolution is optimal at 120°C for two reasons. First, leakage current at 120°C is only 0.76 nA, minimally impacting spectral broadening and enabling precise measurement. Second, temperature effects reduce the average ionization energy of 4H-SiC, explaining the peak position improvement from 50°C to 250°C. This ionization energy reduction produces more electron-hole pairs, decreases statistical fluctuation-induced broadening, and improves energy resolution. However, beyond 250°C (specifically at 270°C and 300°C), operating voltage was reduced to 170 V and 150 V respectively to stabilize the baseline, causing peak intensity drops due to lower applied bias. Despite these challenges, SiC-MSM demonstrates higher thermal stability than SiC-SBD, with better-controlled leakage current across a broader temperature range, making it more reliable for high-temperature applications.

Pulse height spectra for Diamond-MSM at different temperatures are shown in Fig. 13 Figure 13: see original paper, with energy resolution FWHM and peak positions versus temperature presented in Fig. 13(b) from 50°C to 350°C. Energy resolution is optimal at 200°C, remaining consistently below 2.5% from 50°C to 300°C, indicating excellent thermal stability. Notably, even at 350°C, Diamond-MSM does not require voltage reduction for stable operation. Compared to 4H-SiC devices, Diamond-MSM demonstrates superior thermal stability and energy resolution. While SiC-based detectors show significant leakage current increase and resolution deterioration with temperature (especially above 150°C for SiC-SBD and above 300°C for SiC-MSM), Diamond-MSM maintains stable performance with energy resolution below 2.5% across a wider temperature range (up to 350°C), reflecting robust thermal management. This consistent performance suggests Diamond-MSM detectors are more reliable for high-temperature applications where thermal stability is critical, highlighting their advantages over 4H-SiC detectors in demanding environments.

3.3 Fast Neutron Response

Based on HINEG measurements, pulse height spectra for SiC-SBD under 14.1-MeV neutrons are shown in Fig. 14 Figure 14: see original paper. Testing was performed at 25°C with approximately 75 cm between the neutron source and detector. Spectra were calibrated using the 12C(n,α_0)9Be reaction correlation peak at 8.3 MeV. Below 4 MeV, the SiC detector response is dominated by elastic and inelastic neutron scattering on 12C and 28Si nuclei. At higher energies, contributions from 12C(n,α_1)9Be charged products (6.72 MeV total energy) are overshadowed by the 12C(n,n')3α continuum. The strongest spectral peak appears at 8.3 MeV with 2.6% energy resolution, attributed to the 12C(n,α_0)9Be reaction at the 12C ground state. A secondary peak at 11.4 MeV, associated with the same reaction channel in 28Si, is observed but less intense because the (n,α) reaction in 28Si produces 25Mg at excited levels, with multiple excitation levels identified in Fig. 14(a).

For 14.1 MeV neutrons, the 12C(n,α_0)9Be reaction cross-section is 62.3 mb, with a 4H-SiC macroscopic cross-section of 3.0$×10^{-3}$ cm^{-1}. At a neutron flux of 2.78$×10^{8}$ cm^{-2}, Eq. (5) calculates 6665 total reactions, exceeding the actual 12C(n,α_0)9Be count of 6189. This discrepancy arises because 8.3 MeV alpha particles (range 36.6 m in 4H-SiC) escape the detector' s 80- m-thick sensitive volume. With neutron source strength varied between 2.5$×10^{10}$ n/s, 1.5$×10^{10}$ n/s, 5.0$×10^{9}$ n/s, and 2.0$×10^{9}$ n/s, Fig. 14(b) shows the relationship between detector counting rate and neutron source strength. The linear fitting curve yields an R^2 value of 0.99984, demonstrating excellent linearity between counting rate and neutron source intensity.

Pulse height spectra for SiC-MSM under 14.1-MeV neutrons are shown in Fig. 15 Figure 15: see original paper. Testing was performed at 25°C with approximately 80 cm between source and detector. The energy spectrum is generally consistent with SiC-SBD (Fig. 14(a)) but exhibits worse energy resolution (4.9% at 8.3 MeV), consistent with previous alpha response results. At a neutron flux of 1.24$×10^{9}$ cm^{-2}, the calculated total reaction number is 4769, higher than the actual 12C(n,α_0)9Be count of 4474. With source strength set to 1.7$×10^{10}$ n/s, 1.0$×10^{10}$ n/s, 5.6$×10^{9}$ n/s, and 2.1$×10^{9}$ n/s, Fig. 15(b) shows the counting rate versus source strength relationship. The linear fitting curve yields $R^2 = 0.99888$, indicating good linearity between counting rate and neutron source intensity.

Pulse height spectra for Diamond-MSM under 14.1-MeV neutrons are shown in Fig. 16 Figure 16: see original paper. Testing was performed at 25°C with approximately 36 cm between source and detector. Below 4 MeV, elastic and inelastic neutron scattering on 12C nuclei dominates the Diamond-MSM response. At higher energies, a well-defined peak from the 12C(n,α_0)9Be reaction is clearly visible with 2.6% energy resolution at 8.3 MeV. Unlike SiC detectors, diamond shows no peaks from neutron reactions with 28Si nuclei in the 7-12 MeV range. The diamond macroscopic cross-section for 12C(n,α_0)9Be is 1.1$×10^{-2}$ cm^{-1}. At a neutron flux of 4.13$×10^{8}$ cm^{-2}, Eq. (5) calculates 29,278 total reactions, closely matching the observed 12C(n,α_0)9Be count of 29,131. For equivalent neutron flux and detection area, the diamond counting rate for the 12C(n,α_0)9Be peak is 24.6 times higher than in 4H-SiC, attributed to diamond' s higher carbon atomic density and thicker sensitive region. With source strength varied between 1.0×10^{10} n/s, 5.7×10^{9} n/s, 3.0×10^{9} n/s, and 1.2×10^{9} n/s, Fig. 16(b) shows the Diamond-MSM counting rate versus source strength relationship. The linear fitting curve yields $R^2 = 0.99921$, indicating highly linear count rate response to neutron source intensity.

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4 Conclusion

This study systematically compared the performance of 4H-SiC, SiC-MSM, and Diamond-MSM detectors under high-temperature and radiation environments, focusing on I-V characteristics, alpha particle response, energy resolution, and fast neutron detection capabilities. Our results provide critical insights into the stability and performance of these semiconductor materials under extreme conditions.

I-V characteristics evaluated at elevated temperatures revealed significant temperature dependence for SiC-SBD reverse leakage current: 3.21 nA at 25°C increasing to 5.35 A at 200°C, indicating high leakage and poor thermal stability. In contrast, SiC-MSM showed better thermal stability, with leakage current increasing from 0.57 nA at 25°C to 91.75 nA at 350°C—a much slower rise. Diamond-MSM exhibited the least leakage current variation, remaining below 1 nA at 25°C and under 5 nA even at 350°C, demonstrating excellent high-temperature stability. These results highlight that MSM structures offer superior thermal stability compared to SBD, and that Diamond-MSM shows less high-temperature dark current degradation than SiC counterparts.

For alpha particle response, SiC-SBD achieved 0.61% energy resolution at 5486 keV at room temperature, while SiC-MSM and Diamond-MSM achieved 1.21% and 0.97%, respectively. In high-temperature environments, SiC-SBD is suitable up to 150°C, SiC-MSM up to 300°C, and Diamond-MSM up to 350°C and beyond. Diamond-MSM demonstrates excellent stability under high-temperature conditions compared to SiC devices.

For fast neutron response, all three detectors show good linearity and high counting rates. Diamond's high carbon atomic density provides the best neutron detection sensitivity. Energy resolutions at 8.3 MeV are 2.6% for SiC-SBD, 4.9% for SiC-MSM, and 2.6% for Diamond-MSM.

In summary, SiC-SBD devices offer precise detection advantages in low-temperature environments, while both SiC-MSM and Diamond-MSM devices can meet the high-temperature operating requirements of CFETR.

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Note: Figure translations are in progress. See original paper for figures.