Chapter 8

# 4H-SiC Radiation Detectors: Properties and Detection Mechanisms

**Cihan, Öner**[1]

**Abstract**

4H-SiC radiation detectors possess characteristics that make them suitable, for a range of critical applications. This chapter presents an overview of these detectors, including their material properties, manufacturing processes and application in different situation and environments. 4H-SiC polytype stand out compared to conventional materials used for radiation detection, especially in radiation-harsh and very high temperature environments due to its superior physical, electrical, optical, and thermal properties. With its wide bandgap, high radiation resistance and efficient charge transport mechanisms, 4H-SiC detectors are highly capable of accurately measuring different types of incident radiation. 4H-SiC Schottky Barrier Diodes (SBD) especially show great detection capability in detecting alpha particles but also show great promise in Thermal Neutron detection, and X-ray and Gamma ray detection. These detectors excel in areas such as spectral response, energy resolution, stability and reliability. As a result, 4H-SiC is slowly becoming a sought-out material in nuclear radiation detection, X-ray and gamma ray imaging, as well as medical imaging applications. Whether it is safeguarding against threats or enhancing industrial quality control or healthcare practices; 4H-SiC radiation detectors have the ability in tackling complex challenges, across various applications and environments which makes this semiconductor polytype a real candidate to take over conventional ionizing radiation detector materials place in various detection applications in the future.

## 1. Introduction

### 1.1. Importance of Radiation Detection

Reliable Radiation detection holds great importance in an era that is defined by the impact and presence of radiation. The ability to detect and

1 Dr. Öğr. Üyesi, Nevşehir Hacı Bektaş Veli Üniversitesi, cihanoner@nevsehir.edu.tr, https://orcid.org/0000-0003-4967-9598

https://doi.org/10.58830/ozgur.pub250.c1207

measure radiation emission is crucial across several fields such as science, industry, medicine and security. Radiation possesses both many advantages and potential hazards. Its applications are diverse from using ionizing radiation for imaging to generating energy in reactors. However effective harnessing of ionizing radiation requires an understanding of its characteristics and optimal dosage. To be able to achieve this level of understanding, radiation detection occupies a pivotal position. Radiation detectors enable monitoring and measurement of radiation emissions. The ability to detect radiation levels becomes paramount in situations where minimizing the radiation exposure is vital, such as medical procedures, industrial facilities or emergencies. Nonetheless the significance of radiation detection extends beyond measurement; it is used in exploring the mysteries of the universe through cosmic ray examination. Moreover, it acts as an instrument, in driving the development of groundbreaking materials through conducting particle physics experiments. Additionally, it plays a part in safeguarding security by aiding in the detection of unauthorized radioactive substances.

### 1.2. Overview of 4H-SiC Material and Its Properties

Wide bandgap semiconductors possess superior electrical, physical and optoelectronic properties which makes them the perfect candidate for both high power, high temperature and high frequency applications. Among wide bandgap semiconductors, Silicon Carbide (SiC) stands out as a material known for its exceptional electrical, thermal and mechanical properties such as high radiation hardness, high thermal conductivity, high breakdown electric field, and high saturation electron drift velocity [1]. This chapter focuses on 4H-SiC, which is a polytype of silicon carbide with a hexagonal crystal structure. The unique arrangement of atoms gives rise to characteristics that collectively enhance its suitability for radiation detection.

One notable feature of 4H-SiC is its bandgap, which determines the threshold energy required for electron-hole pair creation. This characteristic not only provides resilience against ionizing radiation, it also allows the material to function effectively at elevated temperatures making it well suited for use in extreme conditions. 4H-SiC has very high radiation hardness which can be contributed to its high threshold displacement energy (22-35 eV) [2-3].

Furthermore, it's worth mentioning that 4H-SiC exhibits remarkable electron mobility [4], enabling charge transport within the material. This feature is important in speeding up the process of generating signals in radiation detectors ensuring accurate measurements. Moreover, its high thermal conductivity resulting effective heat dissipation is also important in high energy applications [5]. Typical SiC thermal conductivity is higher than copper thermal conductivity and more than 3 times of Si thermal conductivity.

One important aspect of 4H-SiC is its capability to incorporate impurities, which greatly affect its electrical properties. Intentionally introducing impurities to modify the conductivity of the material makes it adaptable for diverse detection requirements. It's ability to withstand ionizing radiation makes it a reliable choice for long term use in environments, with high levels of radiation exposure.

### 1.3. Motivation for Using 4H-SiC in Radiation Detection

A major concern in radiation detection is finding materials that can efficiently detect radiation while enduring prolonged exposure to ionizing radiation. This necessitates a material that can maintain its performance and structural integrity under these conditions.

4H-SiC is particularly well suited for radiation detection due to its resistance to radiation, which originates from its crystal structure and wide energy bandgap. This makes it highly suitable for radiation detection in environments where resilience is crucial.

Additionally, the high thermal conductivity of 4H-SiC provides key advantages. It effectively dissipates energy generated during radiation detection processes ensuring consistent measurements even in high energy environments. This thermal robustness aligns with the demands of modern applications, ranging from nuclear reactors to particle physics experiments.

In fields such as nuclear science, medical imaging and homeland security there is a growing demand for reliable and efficient radiation detectors. As a result, the appealing characteristics of 4H-SiC keeps gaining attention. Its high potential to function effectively in challenging environments and withstand damage caused by ionizing radiation make it an ideal choice, for applications that prioritize precision, stability and durability.

## 2. 4H-SiC Material Properties

### 2.1. Crystal Structure

The unique properties that make 4H-SiC a suitable material for radiation detection can be largely attributed to its crystal structure and the growth methods.

The 4H-SiC polytype has a hexagonal crystal structure with an ordered arrangement of silicon and carbon atoms as shown in Fig 1. In the figure silicon is represented by the large atoms while carbon is represented by small atoms. Four carbon atoms and four silicon atoms are found in a 4H-SiC unit cell. The crystal structure is an AB-type covalent bond where each silicon atom is surrounded by four carbon atoms [6]. This lattice structure plays a role in establishing the materials exceptional characteristics. Amongst all other polytypes of SiC, 4H-SiC stand out with its largest bandgap, highest electron and hole mobility. The hexagonal configuration allows for efficient charge transport and rapid signal formation, which are vital for its effectiveness in radiation detection.

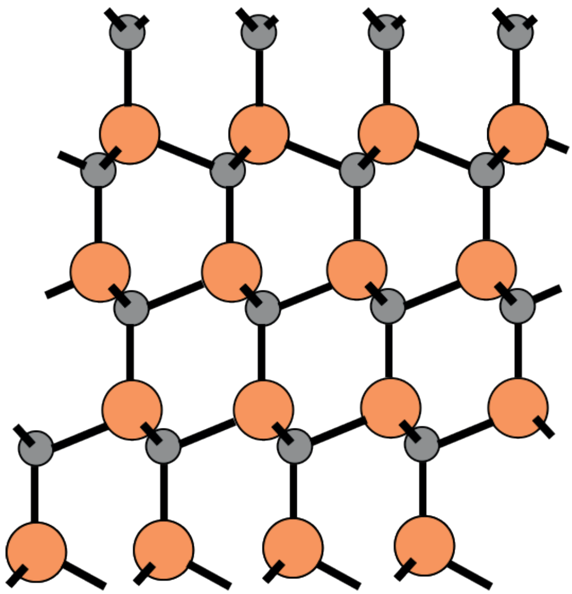

***Fig. 1. Crystal structure of 4H-SiC [6]***

**2.2. Electrical Properties**

One crucial aspect of the properties of 4H-SiC is its energy bandgap (3.26 eV at 300K) [7-8]. This represents the energy required for electrons to move from the valence band to the conduction band. The wide bandgap characteristic makes 4H-SiC well suited in high temperature and high radiation environments. Furthermore, it plays an important role in determining the energy needed for electron-hole pair generation when exposed to ionizing radiation.

Electron mobility and charge transport are characteristics that refer to how electrons move within the material in response to an electric field. This facilitates rapid charge transport, which is crucial, for generating timely signal formation in radiation detectors. High electron mobility helps mitigate radiation induced charge trapping.

By introducing controlled impurities into the crystal lattice, the electrical conductivity of 4H-SiC can be controlled. This process known as doping allows for customizing how the material responds to types and energy ranges of radiation. N-type doping involves adding excess electrons while p-type doping involves adding excess holes. The most common dopants used for n-type 4H-SiC are nitrogen and phosphorous while it is aluminum for p-type 4H-SiC [9-10]. This ability to manipulate carrier concentration greatly enhances the adaptability of the material, in radiation detection applications.

The high breakdown voltage of 4H-SiC is due to the intrinsic material properties, the point at which the material's resistivity breaks down under an applied electric field [11]. This property is crucial for maintaining detector efficiency under radiation exposure. Additionally, it's worth mentioning that 4H-SiC has the capability, for avalanche gain, where a single electron-hole pair triggers the generation of additional pairs. This effect enhances detector sensitivity especially while low energy radiation detection.

## 2.3. Optical Properties

The wide energy bandgap of 4H-SiC not only influences its electrical behavior but also dictates its interaction with light. When higher energy photons (with wavelengths shorter than the bandgap) encounter the material they are absorbed, they cause valence electrons to transition to the conduction band. This absorption phenomenon is why 4H-SiC appears transparent across infrared wavelengths [12].

The transparency of 4H-SiC in both visible and infrared region allows incoming radiation to penetrate its surface and interact with the crystal lattice. This property plays an important role in radiation detection scenarios as it enables absorption of radiation energy and converting it into detectable signals. The detectors sensitivity depends on the quantum efficiency, which's the ratio of the generated electron-hole pairs to incident photons.

As 4H-SiC has indirect bandgap, a change in momentum is needed on top of the incoming photon energy. This change in momentum require interaction with a phonon or lattice vibrations. This results in the need of extra energy to be able to separate the electron-hole pairs. This means if the energy of the incoming radiation is higher than the bandgap energy, the probability of the separation of an electron-hole pair increase. For this reason, as the energy of the incoming radiation increases, 4H-SiC absorption coefficient increases as well.

### 2.4. Thermal Properties

The remarkable thermal conductivity of 4H-SiC is a factor in its performance. The materials efficient heat conduction capability is particularly important in radiation detection applications those involving high energy interactions. Its high thermal conductivity allows for dissipation of heat generated during radiation detection processes ensuring stability and accuracy of measurements.

In high temperature and radiation environments, the compatibility of a material's thermal expansion coefficient with that of the surrounding components is crucial. The low thermal expansion coefficient of 4H-SiC enables compatibility, with a range of substrates and encapsulating materials [13]. This characteristic guarantees structural integrity and measurement accuracy when exposed to varying thermal conditions.

When heat is produced during the detection process, such as when ionizing radiation is absorbed it is important for the material to have the ability to dissipate heat uniformly. The high thermal conductivity of 4H-SiC ensures the dispersion of generated heat throughout the material evenly thus reducing the occurrence of localized temperature spikes that could potentially cause distortions in measurements.

4H-SiC's thermal robustness extends to its resistance against radiation-induced thermal effects. Its ability to maintain structural integrity and thermal properties even under ionizing radiation exposure reinforces its suitability for radiation detection in challenging environments. 4H-SiC serves as a reliable substrate that can be used for prolonged periods due to its resilience to heat and resistance against radiation. While materials such as CdTe and CdZnTe cannot operate precisely at elevated temperatures, 4H-SiC strive as a remarkable option with excellent thermal abilities it possesses.

### 2.5 Radiation Hardness

Radiation-rich environments pose the risk of inducing defects in materials, which can degrade their performance over time. 4H-SiC has exceptional crystalline structure and inherent resistance to radiation-induced damage that increase its defect tolerance. The ability to maintain its structural integrity even under prolonged radiation exposure contributes to the stability of the detectors.

When ionizing radiation interacts with a material, localized charge traps can be created. This results in effecting the mobility of charge carriers. However, the material properties of 4H-SiC including its wide bandgap and high electron mobility help mitigate the effects of charge trapping caused by ionizing radiation. This results in more consistent and accurate radiation measurements.

The thermal and optical properties of materials can deteriorate due to radiation exposure, affecting their behavior in detection scenarios. 4H-SiC's optical transparency and thermal resilience however ensures that its response to radiation remains stable. This is crucial for maintaining measurements and consistent performance over a period of time.

The combination of radiation resistance and ability to withstand temperatures and harsh environments of 4H-SiC makes it an ideal material for radiation detection. In fact, 4H-SiCs impressive resistance to radiation allows it to perform well in demanding settings, like nuclear facilities, space exploration and medical imaging. Materials such as Si and Ge shows limited performance because of their lack of radiation hardness and their need for cryogenic cooling during operation.

## 3. Radiation Detection Mechanisms in 4H-SiC

### 3.1. Ionization

The complex interaction, between radiation and material leads to the process of ionization, which forms the foundation for radiation detection in 4H-SiC. When high energy radiation passes through the crystal lattice of 4H-SiC, it transfers energy to the material by displacing electrons from their atomic orbits. This process, known as ionization, leads to electron-hole pair generation. The promotion of electrons to the conduction band generates positively charged holes within the valence band. The existence of these charge carriers forms the basis for detecting mechanisms.

Once generated, the electron-hole pairs experience an electric field that drives their movement towards the respective electrodes within the detector. Negatively charged electrons move towards the positively biased electrode while positively charged holes move towards negatively biased electrode as shown in Fig. 2. This is referred as charge carrier drift which leads to the separation of charges, results in formation of an electrical signal.

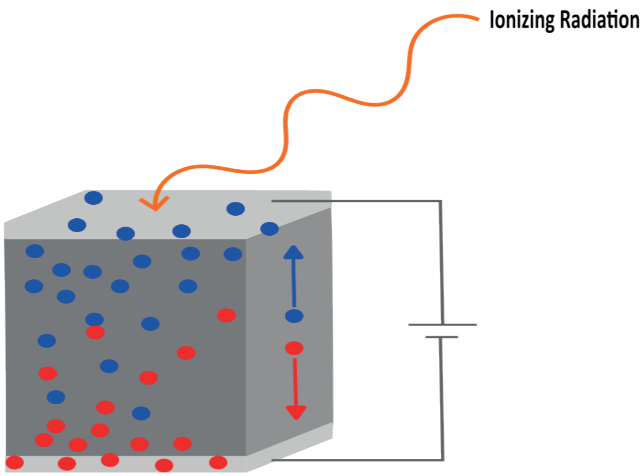


*Fig. 2. Ionizing process on Semiconductor Radiation Detectors [14]*

When charges become separated and accumulate at the respective electrodes it leads to the creation of an electrical signal that is directly proportional to the energy of the incoming radiation. Electrons are represented by blue dots while holes are represented by red. This generated signal forms the basis for detecting radiation. The intensity of the signal indicates how much energy has been transferred by the incident radiation, enabling quantification of the ionizing radiation energy.

The ionization mechanism, intrinsic to 4H-SiC's wide bandgap and electron mobility, plays an important role in achieving accurate and efficient radiation detection. The rapid generation and transportation of charge carriers ensures that the electrical signal accurately reflects the energy of the incident radiation. As a result, precise measurements can be obtained.

### 3.2. Charge Collection

When ionization events occur as mentioned above, electron-hole pairs are generated within 4H-SiC, causing charge carriers to move under the guidance of an electric field. Electrons, being negatively charged are attracted to positive biased electrodes. Conversely positively charged holes migrate towards negative biased electrodes. The speed at which these carriers move through the crystal lattice depends on their mobility and the electric field.

Determining how far a charge carrier travels before it reaches an electrode (known as drift length) is a crucial factor. If recombination occurs prematurely before reaching an electrode due to short drift length, this leads to signal loss. Drift length optimization is crucial to maximize the number of generated charge carriers actively involved in the electrical signal thereby increasing the sensitivity of the detector.

Effective charge collection maximizes detector efficiency, enabling the detector to accurately capture a broad range of radiation energies. During charge collection, interactions with defects and impurities in the material can alter the trajectory of charge carriers. Trapped charges can negatively impact signal quality leading to reduced energy resolution. However careful management of material doping and defect engineering can mitigate these effects ensuring successful transport of charge carriers towards the electrodes.

Deep level defects that could be present in the 4H-SiC crystal may hamper charge collection process. These defects may lead to trapping of charge carriers which results in recombination of the carriers with the opposite charged carriers in the end. Also, the trapped charge carriers end up de-trapped, in which case these charge carriers cannot be added to the timely charge collection. In both cases, deep level defects may end up effecting the 4H-SiC detectors performance.

### 3.3. Signal Formation

When ionization events occur, charge carriers generated by these events migrate towards the respective electrodes accumulating in the vicinity of these electrodes. The accumulation of these charge carriers creates an electric field within the material influencing the trajectories of following charge carriers. The accumulation of charge carriers near the electrodes leads to a modification in voltage distribution across the detector. Once a critical threshold is reached, this voltage distribution becomes disrupted which results a change in voltage known as a voltage pulse.

The voltage pulse, arising from the accumulation of charge carriers, carries information about the energy of the incident radiation. To ensure accurate measurement, electronic circuitry is used to amplify these voltage pulses. Fig. 3 shows the schematic of generic radiation detector testing setup in a nutshell. The amplified signal is then read out and processed, providing a quantifiable measure of the radiation energy.

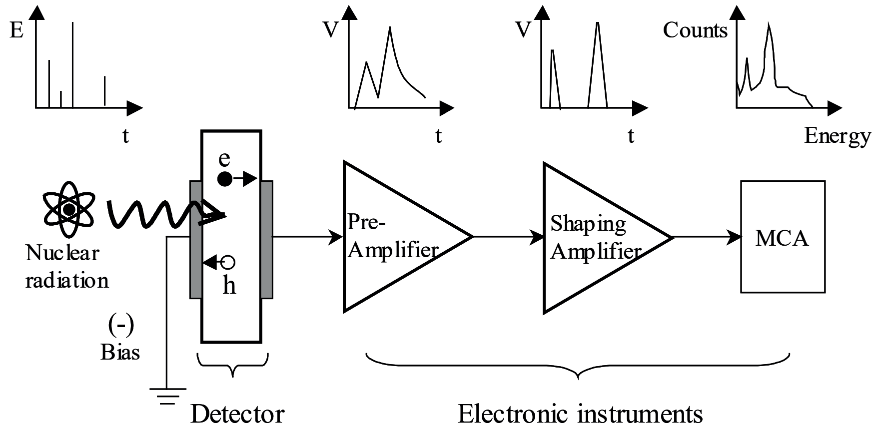


*Fig. 3. Schematic of a generic radiation detection setup [15]*

The amplitude of the voltage pulse corresponds to the energy deposited by the incident radiation. Calibrating the relationship between pulse amplitude and radiation energy enables energy spectroscopy – the identification and quantification of different radiation energies. This spectroscopic capability is pivotal in discerning various types of ionizing radiation.

By examining both the amplitude and shape of the voltage pulse, valuable information about the radiation type and its interaction within the detector can be deduced. Analyzing pulse patterns entails observing how the voltage pulse progresses over time.

## 4. Fabrication of 4H-SiC Radiation Detectors

### 4.1. Device Design and Layout

The successful creation of a working device, in the field of 4H-SiC radiation detectors rely heavily on the arrangement and design of its components. The performance characteristics of a radiation detector are significantly influenced by the geometric configuration of the radiation detector. Factors such as the size, shape and arrangement of the zone where ionization and charge collection occur influence factors such as energy resolution, efficiency, and spatial uniformity. Designing an optimal active area geometry aligns the detector's response with the targeted radiation scenarios.

The positioning and configuration of electrodes within the active area dictates how electric fields are distributed, which then controls the migration of charge carriers. Designing electrodes involves consideration for the voltage biasing schemes that play a role in determining the direction, in which charge carriers drift. Optimizing the electrode structure can enhance charge collection efficiency as well as spatial uniformity.

In Fig. 4 the cross-sectional representation of generic 4H-SiC SBD design can be seen. The front Schottky contact that is deposited on top of the epitaxial layer acts as the detector window. Through this window the ionizing radiation is captured. Epitaxial layer is the active region of the detector where the ionizing radiation is deposited. With sufficient reverse bias the depletion width is extended to the active region and forms a fully depleted area where the charge carriers that are created by the ionizing radiation can be collected. The buffer layer is used to mitigate the propagation of the defects from the substrate to the epilayer. It also helps preventing the generation of defects induced by stress.

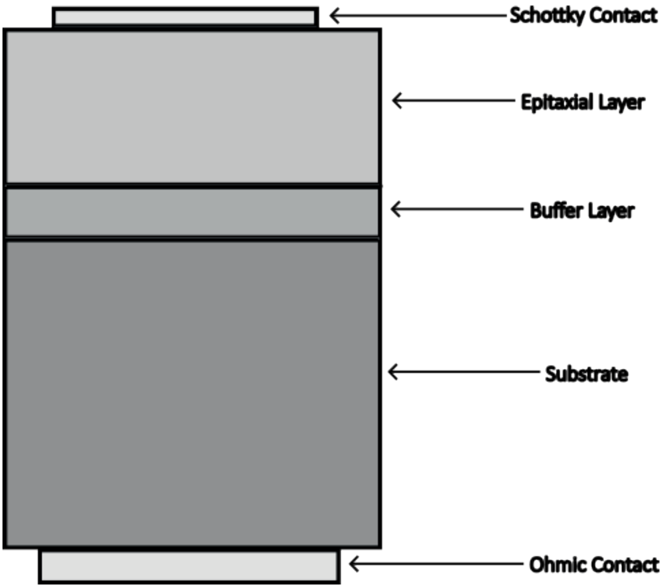


*Fig. 4. Cross-sectional representation of 4H-SiC SBD*

To mitigate edge effects effectively guard rings are often placed around the active area [16-17]. The interactions, between charge carriers and the edges of the detector, known as edge effects can cause issues. These effects have the potential to distort measurements and energy resolution. To address this, careful design and placement of guard rings are essential in minimizing these effects and ensuring accurate detection of radiation.

The performance of a detector is influenced by factors such as material quality and crystal orientation. Material defects can impact charge carrier mobility and trap effects, affecting signal formation and collection. Therefore, selecting high quality materials and optimizing crystal orientation are crucial for aligning the detectors response with desired radiation characteristics.

### 4.2. Growth Methods

The fabrication process involves an interplay, between growth methods that significantly influence its overall quality and inherent properties. One widely employed technique is sublimation, where SiC powder is controllably evaporated in a vacuum or inert gas environment [18]. This method allows high quality SiC layers to be grown in the temperature range of 1600-2100 Celsius. Fig. 5. shows the schematic of a system used for sublimation epitaxy growth.

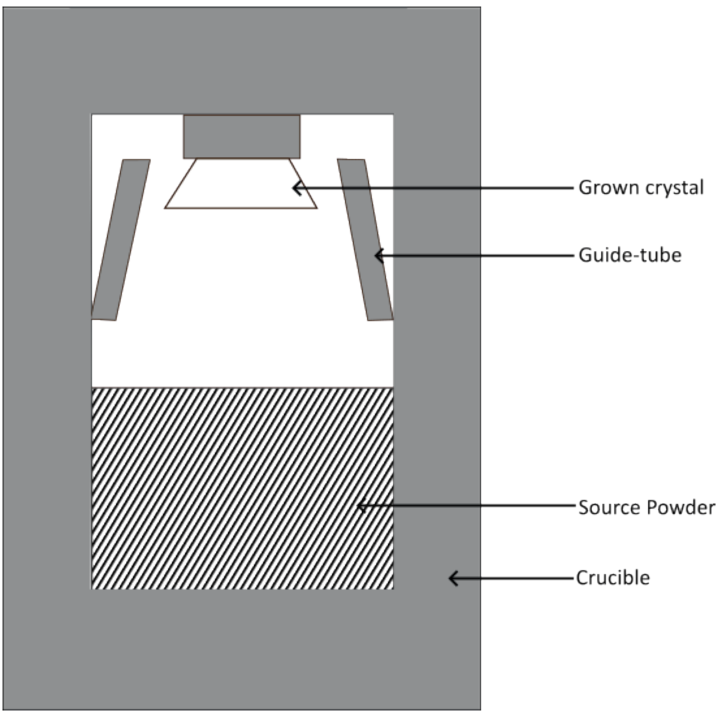


*Fig. 5. Schematic design of a generic sublimation system [19]*

Another method is Chemical Vapor Deposition (CVD) which employs a precursor gas to deposit silicon carbide (SiC) onto a substrate [20]. This technique ensures precise control over the crystal structure. Epilayers grown by this method offers high crystallinity. Compared to bulk growth techniques, CVD method also brings high reproducibility to the table. Dichlorosilane ($SiH_2Cl_2$, DCS) and propane ($C_3H_8$) gases are generically used as precursor gasses with hydrogen (~ 6 SLM) as the carrier gas. Growth temperatures less than 1600 Celsius are adequate to grow high quality epitaxial layers in this method. Fig. 6. shows the schematic of a generic CVD setup.

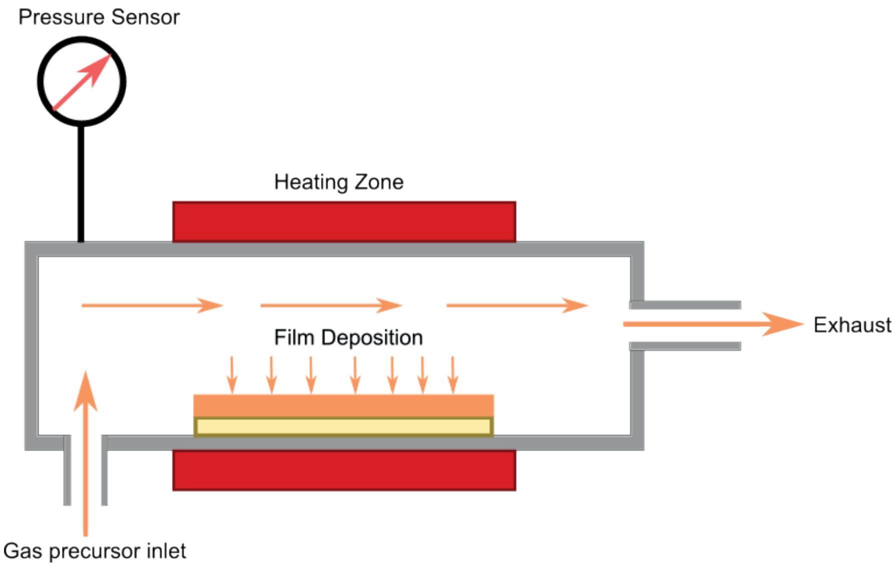


*Fig. 6. Schematic of a Chemical Vapor Deposition System [21]*

Low doping is preferred for radiation detection applications. 4H-SiC epitaxial layers that is grown using above mentioned techniques usually has doping levels range from $10^{13}$ $cm^{-3}$ to $10^{14}$ $cm^{-3}$ to achieve high level detection performance.

### 4.3. Ohmic and Schottky Contacts

Establishing electrical connections plays an important role, in the complex process of creating radiation detectors.

Ohmic contacts form low-resistance interfaces between metal electrodes and semiconductor materials. To achieve ohmic behavior, it is necessary to manipulate the interface enabling tunneling of charge carriers between the metal and semiconductor. This continuous movement of charge carriers within the region is vital for accurate radiation measurements by effectively collecting and extracting charges. Non-rectifying ohmic metal-semiconductor junctions are represented in Fig. 7.

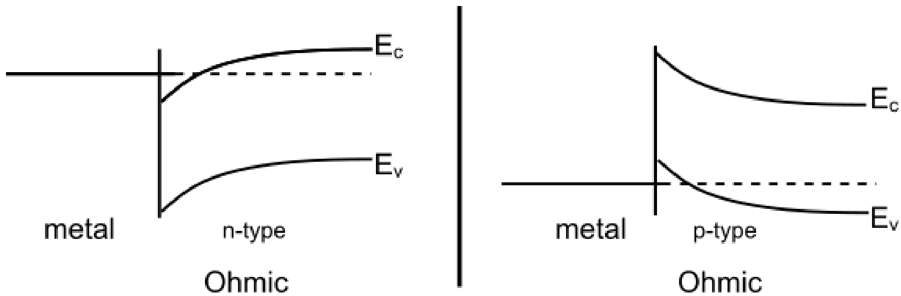


*Fig. 7. Non-rectifying Ohmic junctions*

On the other hand, Schottky contacts refer to a rectifying junction formed between a metal and a semiconductor. The presence of a built-in electric field at the junction eases the extraction of the majority carriers (electrons in n-type material and holes in p-type material) while restricting the flow of minority carriers. Schottky contacts are particularly useful for applications where fast charge extraction and low leakage current are desired. Representation of rectifying Schottky junctions is shown in Fig. 8.

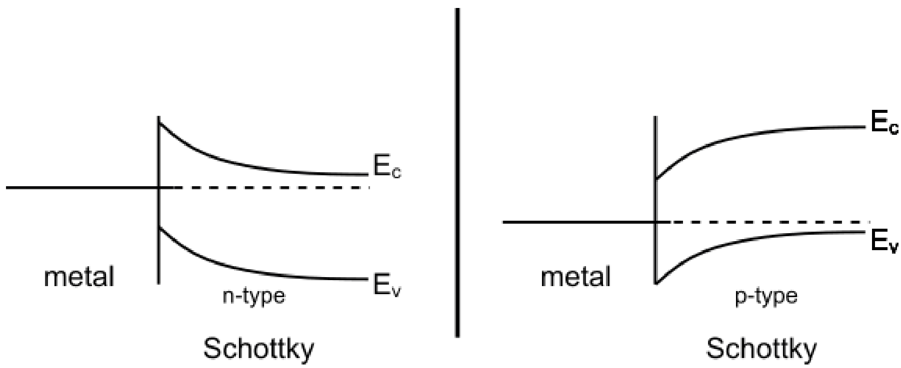


*Fig. 8. Rectifying Schottky Junctions*

In Schottky contacts the ease of charge carrier extraction depends on the height of energy barrier at the metal-semiconductor junction, commonly referred to as Schottky barrier height. Manipulating barrier height, in engineering applications directly affects the efficiency of charge collection and the detector's response to different radiation energies. The alignment of the metal's Fermi level with the semiconductor's energy bands is crucial for achieving desirable electronic behavior.

In Schottky barrier detectors, a depletion region that is free of charge carriers occurs at the metal-semiconductor interface. This depletion region is created at the semiconductor side of the junction. The depletion region can be controlled by the doping process during growth as well as the applied bias during operation. The Schottky barrier detectors operates under reverse bias, as the applied reverse bias increases the depletion region width.

Choosing the metal for contacts plays a critical role. Metals with suitable work functions and compatibility with 4H-SiC are selected to achieve desired electrical properties. Also, the right combination of semiconductor and metal affect the Schottky barrier height which in return directly change the effectiveness of the detector. Usually, high work function metals such as Nickel is paired with 4H-SiC to form a high barrier Schottky detector.

To maximize charge extraction efficiency, it's essential to reduce contact resistance—the resistance encountered by charge carriers as they traverse the metal-semiconductor interface. Signal loss and degraded detector performance can be the result of high contact resistance. Optimizing contact geometry, metal choice, and post-processing steps mitigates contact resistance effects.

### 4.4. Passivation

In the field of 4H-SiC radiation detectors, the process of passivation plays a crucial role, in ensuring their durability and effectiveness. 4H-SiC material surface can be impaired by dangling bonds and defects that trap charge carriers, crippling their mobility and collection efficiency. Surface states can introduce distortions in measurements and compromise energy resolution. Passivation techniques aim to counteract or minimize the influence of these surface states thereby improving detector stability.

To achieve passivation, dielectric layers are commonly used to deposit the detectors surface. These layers act as insulating barriers providing protection for the 4H-SiC material against ambient influences while simultaneously reducing the density of surface states. The choice of materials, such as silicon dioxide (SiO2) or silicon nitride (Si3N4) is based on their compatibility with 4H-SiC and their effectiveness in reducing surface traps [22-23].

Surface passivation techniques serve multiple purposes, insulating the detector and modifying the energy band alignment between semiconductor-dielectric interface. Passivation layers can reduce the density of interface states, enhance charge carrier mobility, and improve charge collection efficiency by adjusting the band alignment. After the deposition of the passivation layer, annealing techniques are often used to enhance material properties at the interface. Annealing encourages chemical reactions that repair defects and improve the uniformity and quality of the passivation layer.

Effective passivation enhances detector performance by reducing signal distortion, improving energy resolution, and stabilizing device characteristics over time. The mitigation of surface states and the protection from environmental influences extend the detector's operational lifetime, making it well-suited for prolonged usage in demanding environments.

## 5. Performance of 4H-SiC Radiation Detectors

### 5.1. Spectral Response

The spectral response of a radiation detector is intricately linked to the material's bandgap. Bandgap refers to the energy difference between the valence and conduction bands. When incident radiation carries energy levels beyond this bandgap it can promote charge carriers to the conduction band resulting in a measurable signal. The absorption coefficient, which is specific to each material determines how efficiently radiation is absorbed within the detector.

The bandgap influences the detector's energy threshold – the minimum energy of incident radiation that can generate a detectable signal. Detectors with wide bandgap are more sensitive to higher-energy radiation while those with low bandgap can detect lower-energy radiation. The energy threshold defines the detector's minimum detectable energy.

The performance of a detection system can be evaluated based on its response, which exhibits peaks and plateaus in the energy spectrum. Each of these features corresponds to interactions between the radiation and the detector. Sensitivity refers to the detector's ability to accurately measure radiation intensity. Energy resolution, on the other hand, gauges the detector's ability to differentiate between close energy levels. Improved sensitivity and enhanced energy resolution enable finer identification of radiation sources.

The shape of spectral response peaks in detectors is influenced by factors such as charge carrier mobility and interaction processes. Wider peaks indicate that charge carriers possess a broader range of energies whereas sharper peaks suggest efficient energy deposition and charge collection. Optimizing the material's charge carrier mobility enhances peak shape and resolution. Doping the material can influence the spectral response. Doped regions can create energy levels within the bandgap, resulting in additional interactions and distinctive spectral features. By manipulating the profile, detectors can be tailored to specific radiation sources and applications.

4H-SiC SBD show excellent spectral response particularly to alpha particles. 4H-SiC detectors slowly started getting interest in its spectral response to X-rays and Gamma radiation recently but it has not yet been matured on this area. Spectral response of 4H-SiC SBD to Neutron radiation shows high promise. Especially direct detection of fast neutrons is possible in these detectors due to elastic scattering processes. For high efficiency devices, thicker epitaxial layers hence larger active area is required.

### 5.2. Energy Resolution

Energy resolution refers to a measurement systems capability to accurately distinguish and resolve energy levels within a given spectrum or range. It is expressed as the full-width at half-maximum (FWHM) of the observed peak in the energy spectrum corresponding to a specific radiation energy. A narrower FWHM value signifies better energy resolution enabling finer discrimination of radiation sources. The following equation can be used to calculate the energy resolution of the detectors:

$$\%\, Energy\ Resolution = \frac{FWHM\ (keV)}{Incident\, Energy\ (keV)} * 100\% \tag{1}$$

where the centroid of the energy peak is used as the Incident Energy. Several factors contribute to the energy resolution of a radiation detector. These include intrinsic factors like charge carrier mobility, energy loss mechanisms and statistical fluctuations in charge collection, within the material. The extrinsic factors include elements such as the design of the detector, electrodes configuration and the complexities involved in signal formation.

An energy resolution levels of 4H-SiC SBD reach the levels of 0.29% FMHW for 5.48 MeV alpha particles nowadays [24]. While for Thermal Neutron detection the highest reached resolution is at the levels of 2.24% [25]. Best performing detectors for X-ray spectroscopy achieved an energy resolution of 1.47 keV FWHM at 22 keV [26]. The spectral response of 4H-SiC SBD to gamma rays shows promise with an energy resolution of 2.1% for 59.6 keV gamma rays [27].

The signal to noise ratio (SNR) is very important in determining the accuracy of energy measurement. Noise, which refers to fluctuations in the measured signal has the potential to distort spectral peaks and degrade resolution. Improving SNR and energy resolution is often achieved through optimizing detector electronics and utilizing signal processing techniques that aim to maximize the signal while minimizing noise.

Efficient charge collection ensures that a significant portion of the charge carriers generated by incident radiation contributes to the measured signal. Inadequate charge collection can lead to signal loss, broadening of energy peaks and degraded resolution. Maintaining resolution depends on optimizing charge collection pathways while minimization of charge trapping. Charge collection efficiency is the ratio of the energy deposited in the detector ($E_v$) to the actual energy emitted by the radiation source ($E_0$) given by:

$$CCE_{experimental} = E_v/E_0. \tag{2}$$

Detector electronics which include preamplifiers and analog-to-digital converters, influence the translation of charge carriers into measurable electrical signals. Calibration plays an essential role in establishing the relationship between signal amplitude and radiation energy by mapping detector responses to known energy levels.

### 5.3. Stability and Reliability

Detectors made of 4H-SiC are specially designed to withstand temperature variations, fluctuations in humidity and exposure to radiation sources without compromising their sensitivity, energy resolution, or detection efficiency. The stability of these detectors heavily depends on the intrinsic material properties of 4H-SiC. These properties that contribute to the material's resilience in extreme environments include high thermal conductivity, wide energy bandgap and radiation hardness. These properties enable the detector to withstand the rigors of prolonged usage in radiation-intensive scenarios.

Stability is closely linked to minimizing surface effects such as charge trapping or radiation induced defects. As already mentioned, passivation techniques are employed to safeguard the detectors surface from environmental influences, reducing the impact of surface states and ensuring consistent performance over time.

Reliability comprises the ability of 4H-SiC detectors to consistently deliver accurate measurements in demanding environments. These detectors find applications in nuclear plants, space exploration and demanding research scenarios where reliability is crucial, for safety and data integrity. Reliability assessment involves subjecting the system to mechanical stress, thermal cycling and radiation exposure. Mechanical and thermal stress can affect the detector's physical integrity, leading to signal distortion or even failure. Robust packaging and encapsulation techniques ensure that the detector withstands these challenges.

## 6. Applications of 4H-SiC Radiation Detectors

### 6.1. Nuclear Radiation Detection

The goal of nuclear radiation detection is to identify and measure the radiation released during nuclear decay processes. Radioactive nuclei undergo alpha, beta or gamma decay, releasing characteristic radiation that can be accurately measured using radiation detectors. 4H-SiC detectors exhibit high performance in capturing and characterizing these emitted radiations.

4H-SiC detectors exhibit remarkable sensitivity to alpha particles – helium nuclei emitted during alpha decay [15,24]. Wide bandgap and high atomic number of 4H-SiC makes the material effective at stopping and measuring alpha particles. This capability enables accurate alpha spectroscopy, which is crucial in detecting and quantifying alpha-emitting isotopes.

Furthermore, detectors made from 4H-SiC also demonstrate performance, in detecting beta and gamma radiations. Beta particles, which are high speed electrons or positrons interact with the material resulting in generated charge carriers that contribute to measurable signal. On the other hand, gamma rays interact through Compton scattering or photoelectric absorption resulting in energy deposition and signal creation. These detectors have the ability to accurately measure the energy distribution of gamma rays emitted by radioactive sources. Their energy resolution allows for accurate identification and quantification of isotopes, supporting applications in nuclear medicine and environmental monitoring [27].

Apart, from alpha, beta and gamma radiation 4H-SiC detectors can be specially designed to detect neutrons [25]. Neutrons are particles that require contact with the nuclei of the detector material for detection. The high atomic content of 4H-SiC, silicon and carbon allow for neutron interactions through mechanisms such as elastic scattering and nuclear reactions.

The use of 4H-SiC radiation detectors is widespread In the field of nuclear safeguard and security, 4H-SiC radiation detectors attracted a lot of interest as they are heavily relied on ensuring safe handling and transportation of radioactive materials. Their ability to discriminate between different radiation types aids in identifying potential threats or illicit materials in various environments, including ports and border crossings. In terms of security screening, enhancing screening processes at airports, border crossings and important infrastructure sites brings the need of detectors with excellent response capabilities. These devices are primarily designed to detect and analyze X-rays and gamma rays emitted by objects, like luggage, cargo and vehicles. In this area 4H-SiC material brings so many positive attributes to the table as mentioned above.

### 6.2. X-ray and Gamma-ray Imaging

The use of 4H-SiC detectors holds importance in the future of radiography. These detectors offer high energy resolution and detection efficiency enabling accurate differentiation of X-ray intensities [27]. This capability enables generating detailed images that are essential for diagnosing fractures, tumors and other medical conditions.

In industrial settings, 4H-SiC detectors enable non-destructive testing of materials and components. They have the ability to detect X-rays and gamma rays passing through objects, revealing internal structures, defects, and structural anomalies. Having this capability is crucial for ensuring quality control across industries such as aerospace and manufacturing.

4H-SiC detectors exhibit outstanding energy resolution and detection efficiency resulting in high quality images with enhanced precision and accuracy when deployed in X-ray and gamma ray imaging. Their ability to capture fine variations in radiation intensity allows for detailed visual representations and facilitates comprehensive analysis. The versatility and innovation of 4H-SiC detectors enable them to be customized for a wide range of imaging setups, including both handheld devices and extensive medical imaging systems. Their versatility and adaptability make them a good candidate for them to become invaluable tools in diverse imaging applications in the future.

### 6.3. Medical Imaging

In the field of healthcare, where accurate visualization's crucial, for diagnosis and treatments the need for reliable detector materials such as 4H-SiC has become essential. Especially in conventional X-ray imaging and computed tomography (CT) scans, the properties that 4H-SiC hold is sought after. Their ability to resolve subtle differences in X-ray intensities allows for the reconstruction of complex three-dimensional structures leading to improved accuracy, in medical diagnoses and treatment planning. The high energy resolution provided by these detectors enables accurate quantification of positron annihilation events allowing for the generation of three-dimensional images that would provide insights, into metabolic activity and disease progression. The exceptional energy resolution and sensitivity of 4H-SiC detectors enable high resolution imaging that would reveal the intricate anatomical details.

## 7. Conclusions

Schottky barrier contact structures with nickel (Ni) have been fabricated on 20 $\mu$m thick 4H-SiC epitaxial layer. Different contact structures with varying work functions of the metals and higher thickness of the epitaxial layers could be studied to optimize detector performance with reduced leakage current and improved energy resolution. In 4H-SiC epitaxial layer, the electron mobility is significantly higher than hole mobility. To compensate poor hole transport properties, specialized detector structures such as multi-pixel with small pixel size, Frisch grid, co-planar, and drift detectors could be fabricated and performance evaluation could be compared to the planar detectors studied in this dissertation.

Future efforts on 4H-SiC epilayer detectors could be carried out to lowering detector capacitance without reducing the active size of the detectors. In-detailed electronic noise analysis may reveal the possibility of achieving better performance with enhanced energy resolution by lowering the detector capacitance. This will reveal the white series noise due to the total input capacitance which may have substantial effects on detector performance. Improvement on 4H-SiC energy resolution and reduced leakage current is achieved by $Si_3N_4$ passivation in this work. $SiO_2$ and Si-O-N passivation could be studied to optimize detector performance further. For both 4H-SiC detector performance studies, defect delineating KOH etching may reveal the nature and type of various crystallographic defects and the results may be correlated to observe the impact of shallow and deep lying point and/or extended defects in the active region

## References


[1] M. De Napoli, "SiC detectors: A review on the use of silicon carbide as radiation detection material," *Frontiers in Physics*, vol. 10, Oct. 2022, doi: 10.3389/fphy.2022.898833.

[2] G. Lucas and L. Pizzagalli, "Comparison of threshold displacement energies in β-SiC determined by classical potentials and ab initio calculations," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 229, no. 3–4, pp. 359–366, Apr. 2005, doi: 10.1016/j.nimb.2004.12.119.

[3] K. C. Mandal, R. M. Krishna, P. G. Muzykov, S. Das, and T. S. Sudarshan, "Characterization of Semi-Insulating 4H Silicon Carbide for Radiation Detectors," *IEEE Transactions on Nuclear Science*, vol. 58, no. 4, pp. 1992–1999, Aug. 2011, doi: 10.1109/tns.2011.2152857.

[4] C. G. Rodrigues, "Electron Mobility in Bulk n-Doped SiC-Polytypes 3C-SiC, 4H-SiC, and 6H-SiC: A Comparison," *Semiconductors*, vol. 55, no. 7, pp. 625–632, Jul. 2021, doi: 10.1134/s1063782621070150.

[5] R. Wei *et al.*, "Thermal conductivity of 4H-SiC single crystals," *Journal of Applied Physics*, vol. 113, no. 5, Feb. 2013, doi: 10.1063/1.4790134.

[6] X. Wang *et al.*, "Density functional theory calculation of the properties of carbon vacancy defects in silicon carbide," *Nanotechnology and Precision Engineering*, vol. 3, no. 4, pp. 211–217, Dec. 2020, doi: 10.1016/j.npe.2020.11.002.

[7] G. L. Zhao and D. Bagayoko, "Electronic structure and charge transfer in 3C- and 4H-SiC," *New Journal of Physics*, vol. 2, pp. 16–16, Jul. 2000, doi: 10.1088/1367-2630/2/1/316.

[8] H. Morkoç, S. Strite, G. B. Gao, M. E. Lin, B. Sverdlov, and M. Burns, "Large-band-gap SiC, III-V nitride, and II-VI ZnSe-based semiconductor device technologies," *Journal of Applied Physics*, vol. 76, no. 3, pp. 1363–1398, Aug. 1994, doi: 10.1063/1.358463.

[9] K. C. Mandal, J. W. Kleppinger, and S. K. Chaudhuri, "Advances in High-Resolution Radiation Detection Using 4H-SiC Epitaxial Layer Devices," *Micromachines*, vol. 11, no. 3, p. 254, Feb. 2020, doi: 10.3390/mi11030254.

[10] K. Eto, H. Suo, T. Kato, and H. Okumura, "Growth of P-type 4H–SiC single crystals by physical vapor transport using aluminum and nitrogen co-doping," *Journal of Crystal Growth*, vol. 470, pp. 154–158, Jul. 2017, doi: 10.1016/j.jcrysgro.2017.04.025.

[11] T. Kim and K. Kim, "High Breakdown Voltage and Low On-Resistance 4H-SiC UMOSFET with Source-Trench Optimization," *ECS Journal of Solid State Science and Technology*, vol. 8, no. 8, pp. Q147–Q152, 2019, doi: 10.1149/2.0091908jss.

[12] R. Ahuja *et al.*, "Optical properties of 4H–SiC," *Journal of Applied Physics*, vol. 91, no. 4, pp. 2099–2103, Feb. 2002, doi: 10.1063/1.1429766.

[13] Z. Li and R. C. Bradt, "Thermal expansion of the hexagonal (4H) polytype of SiC," *Journal of Applied Physics*, vol. 60, no. 2, pp. 612–614, Jul. 1986, doi: 10.1063/1.337456.

[14] [1]H. Hu, G. Niu, Z. Zheng, L. Xu, L. Liu, and J. Tang, "Perovskite semiconductors for ionizing radiation detection," *EcoMat*, vol. 4, no. 6, Jul. 2022, doi: 10.1002/eom2.12258.

[15] Oner, C. (2018). *High Resolution Radiation Detectors Based On 4H-SiC N-Type Epitaxial Layers And Pixilated CdZnTe Single Crystal Devices.* (Doctoral dissertation). Retrieved from https://scholarcommons.sc.edu/etd/4907

[16] F. H. Ruddy, J. G. Seidel, Haoqian Chen, A. R. Dulloo, and Sei-Hyung Ryu, "High-resolution alpha-particle spectrometry using 4H silicon carbide semiconductor detectors," *IEEE Transactions on Nuclear Science*, vol. 53, no. 3, pp. 1713–1718, Jun. 2006, doi: 10.1109/tns.2006.875155.

[17] C. Feng-Ping, Z. Yu-Ming, L. Hong-Liang, Z. Yi-Men, and H. Jian-Hua, "Study of 4H-SiC junction barrier Schottky diode using field guard ring termination," *Chinese Physics B*, vol. 19, no. 9, p. 097107, Sep. 2010, doi: 10.1088/1674-1056/19/9/097107.

[18] M. Syväjärvi *et al.*, "Growth of 6H and 4H–SiC by sublimation epitaxy," *Journal of Crystal Growth*, vol. 197, no. 1–2, pp. 155–162, Feb. 1999, doi: 10.1016/s0022-0248(98)00890-2.

[19] S. Nishizawa, "Numerical modeling of SiC single crystal growth-sublimation and hot-wall epitaxy," *Journal of Crystal Growth*, vol. 311, no. 3, pp. 871–874, Jan. 2009, doi: 10.1016/j.jcrysgro.2008.09.105.

[20] D. Crippa *et al.*, "New Achievements on CVD Based Methods for SiC Epitaxial Growth," *Materials Science Forum*, vol. 483–485, pp. 67–72, May 2005, doi: 10.4028/www.scientific.net/msf.483-485.67.

[21] Q. Zhang, D. Sando, and V. Nagarajan, "Chemical route derived bismuth ferrite thin films and nanomaterials," *Journal of Materials Chemistry C*, vol. 4, no. 19, pp. 4092–4124, 2016, doi: 10.1039/c6tc00243a.

[22] Y. Ichikawa, M. Ichimura, T. Kimoto, and M. Kato, "Passivation of Surface Recombination at the Si-Face of 4H-SiC by Acidic Solutions," *ECS Journal of Solid State Science and Technology*, vol. 7, no. 8, pp. Q127–Q130, 2018, doi: 10.1149/2.0031808jss.

[23] M. Sochacki, R. Lukasiewicz, W. Rzodkiewicz, A. Werbowy, J. Szmidt, and E. Staryga, "Silicon dioxide and silicon nitride as a passivation and edge termination for 4H-SiC Schottky diodes," *Diamond and Related Materials*, vol. 14, no. 3–7, pp. 1138–1141, Mar. 2005, doi: 10.1016/j.diamond.2004.12.020.

[24] S. K. Chaudhuri, K. J. Zavalla, and K. C. Mandal, "High resolution alpha particle detection using 4H–SiC epitaxial layers: Fabrication, characterization, and noise analysis," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 728, pp. 97–101, Nov. 2013, doi: 10.1016/j.nima.2013.06.076.

[25] R. Bernat *et al.*, "4H-SiC Schottky Barrier Diodes for Efficient Thermal Neutron Detection," *Materials*, vol. 14, no. 17, p. 5105, Sep. 2021, doi: 10.3390/ma14175105.

[26] J. E. Lees *et al.*, "Semi-transparent SiC Schottky diodes for X-ray spectroscopy," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 578, no. 1, pp. 226–234, Jul. 2007, doi: 10.1016/j.nima.2007.05.172.

[27] K. C. Mandal, P. G. Muzykov, S. K. Chaudhuri, and J. R. Terry, "Low Energy X-Ray and γ-Ray Detectors Fabricated on n-Type 4H-SiC Epitaxial Layer," *IEEE Transactions on Nuclear Science*, vol. 60, no. 4, pp. 2888–2893, Aug. 2013, doi: 10.1109/tns.2013.2273673.