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Characterization of Charge Collection Properties of High Time-Resolution Silicon Carbide Detectors

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Abstract: The charge collection characteristics of silicon carbide detectors in the field of high time resolution detection are studied in this paper. Aiming at the limitations of traditional silicon detectors in high temperature and high radiation environment, a high time resolution detector design based on 4H-SiC material is proposed. Due to its wide band gap, high carrier mobility, and excellent radiation resistance, 4H-SiC is ideal for extreme detection environments. By optimizing the process, high charge collection efficiency (CCE) and excellent temporal resolution were achieved, with CCE reaching 90% and temporal resolution reaching 35±0.2ps at 100V reverse bias. The experimental results show that the SiC detector has a series of excellent properties compared with the silicon-based detector. In addition, the charge collection characteristics of SiC detectors with different bias and the saturation behavior of charge collection in the range of 150~350V are also discussed. Finally, the application prospects of SiC detector in nuclear radiation monitoring, medical imaging and space exploration are prospected. With the advancement of technology and the reduction of cost, SiC detectors will demonstrate their unique value in more fields.

1. Introduction

1.1. Research Background

In 1949, Bell Laboratories in the United States first proposed using semiconductors to detect radiation and successfully detected alpha particles using a germanium semiconductor point-contact diode. Since then, radiation detectors have played a crucial role in radiation detection [1]. However, when the radiation intensity is high, traditional signal acquisition and processing technologies fail to stably capture the behavior and characteristics of each particle. When detecting and studying the behavior characteristics of each particle, semiconductor detectors must operate in current mode to capture the collective behavior characteristics of the radiation or particles. In this context, current-mode semiconductor detectors are vital for measuring high-pulse radiation beams in nuclear science experiments, laser inertial confinement fusion, pulse reactors, and similar applications. In the 1960s, the Los Alamos National Laboratory and the Lawrence Livermore National Laboratory in the United States developed the first current-mode silicon detectors, including PIN-type and gold-silicon barrier structures, successfully used for neutron, gamma-ray, and F-ray parameter measurements. Silicon detectors have many advantages, including low noise, strong detection signals, high energy resolution, and mature technology, making them widely applicable in radiation detection. Current-mode silicon detectors have played an essential role in high-intensity radiation detection [2]. However, in practical applications, there are numerous issues. Silicon materials have a narrow bandgap, relatively small atomic number and density, and low displacement energy, making them sensitive to radiation damage. They also require cooling to operate at low temperatures. These disadvantages limit the use of silicon detectors in high-temperature (including room temperature) and high-radiation detection fields. Consequently, several issues arise in related technologies, such as inadequate electrical breakdown resistance of silicon materials, thick large-area current-mode silicon detectors, strong background interference in mixed-field neutron detection, and inadequate radiation resistance of silicon detectors.

1.2. Material Development and Technological Upgrades

With the development of semiconductor materials and advances in detector manufacturing processes, SiC detectors based on high-quality epitaxial materials have matured in charged particle and neutron detection. Detectors made from ordinary diamond, GaN, SiC, CZT, and ZnO high-resistance substrates exhibit low charge collection efficiency and unstable device performance, making them unsuitable for absolute radiation measurements. However, high-quality SiC single-crystal epitaxial growth technology has reached a level that meets the requirements for manufacturing large-area high-performance detectors. Current-mode detectors made from high-quality SiC epitaxial materials are expected to achieve low leakage current, high linear current, and high charge collection efficiency. Large-area 4H-SiC radiation detectors have been demonstrated with an 80 μm lightly doped i-layer in a p-i-n configuration. Based on record low doping in the intrinsic absorption layer, low-voltage operation has achieved ultra-low leakage current at 150 °C, showing high-temperature applicability. This preliminary verification demonstrates that the detector has high resolution. Low-voltage operation of the alpha particle detector opens up the possibility of using 4H-SiC p-i-n radiation detectors in harsh environments, particularly for high-temperature applications [3].

1.3. High Time-Resolution Detectors

The basic principle of High Time-Resolution Detectors involves accurately measuring the arrival time of incident particles or photons, enabling detailed analysis and recording of dynamic processes. High time-resolution detectors achieve time-resolved measurements through the following steps:

(1) Particle or Photon Incidence: When particles or photons strike the detector, they interact with the detector material, generating charge carriers (electrons and holes).

(2) Charge Collection: These carriers move under an applied electric field and are collected at the detector electrodes within a specific time.

(3) Signal Conversion: The collected charge carriers form an electrical signal at the electrodes, which can be detected and recorded by electronic devices.

(4) Time Measurement: By accurately measuring the time the electrical signal is generated; the arrival time of the incident particles or photons can be determined.

1.4. Research Objectives

This paper will continue to discuss the characterization of the charge collection characteristics of high time-resolution silicon carbide detectors and related technological prospects and issues. To investigate the characterization of the charge collection characteristics of high time-resolution silicon carbide detectors, experiments were conducted on silicon carbide detectors for collecting charged particles from alpha particles, aiming to find the characterization of charge collection characteristics.

2. High Time-Resolution Silicon Carbide Detectors

2.1. Background and Advantages of LGAD Detectors

The Low-Gain Avalanche Diode (LGAD) detector is an advanced semiconductor detector that offers significant advantages in fast time detection. Due to its rapid response characteristics, the LGAD detector achieves extremely high time resolution [4]. For instance, the LGAD silicon ultrafast sensor developed by the Institute of High Energy Physics, Chinese Academy of Sciences, maintains a time resolution of 30-40 picoseconds even after exposure to the ultra-high radiation levels required by the High Luminosity Large Hadron Collider (HL-LHC). Additionally, LGAD detectors are designed with radiation resistance in mind, making them crucial for applications in high-energy physics experiments, particularly in high-radiation environments such as the LHC.

The signal pulse width and charge amplitude of LGAD detectors are primarily influenced by LGAD processes and design parameters. The rise time is about 400 picoseconds, the signal duration is about 1 nanosecond, the typical charge amount is 10 femtocoulombs, and the detector capacitance is about 4 picofarads. To match the high-speed characteristics of LGAD detectors, front-end circuit design requires high bandwidth and low noise features. For example, a common-source transimpedance amplifier based on an inverter structure can increase bandwidth and reduce input Miller equivalent capacitance, thereby improving time performance.

LGAD detectors are employed in the ATLAS experiment's High Granularity Timing Detector (HGTD) project, which aims to enhance the precision of particle arrival time measurements to within 30 picoseconds, addressing the pile-up issue in high-luminosity LHC collisions. The University of Science and Technology of China has made significant advancements in LGAD detector technology, overcoming challenges in ultrahigh-resolution time-of-flight detection technology and doubling the time resolution performance of existing detection technologies to achieve 30 picoseconds, reaching an international advanced level.

The performance of LGAD detectors has been verified through various testing systems, including detector performance testing systems based on lasers and radioactive sources and large-area sensor testing systems based on probe cards. These characteristics make LGAD detectors ideal for particle physics experiments and other applications requiring high-precision time measurements. With continuous technological advancements, LGAD detectors are expected to play a more significant role in future scientific research and industrial applications [5].

2.2. Physical Vapor Deposition (PVD)

Physical Vapor Deposition (PVD) is a technique in which solid or liquid materials are vaporized into gaseous atoms, molecules, or partially ionized ions in a vacuum or low-pressure environment and deposited onto a substrate surface to form thin films with specific functions. PVD technology includes various classifications:

• Magnetron Sputtering: Uses a magnetic field to control ion bombardment of a solid target, producing high-energy ions released onto the target surface, characterized by high deposition rates and uniform film thickness distribution. Widely used in semiconductor device and optical film preparation.

• Electron Beam Evaporation: Uses an electron beam to heat materials to evaporation, suitable for high melting point materials, offering high deposition rates and temperature control.

• Laser Ablation: Uses a laser to heat materials to evaporation and deposit onto substrates, suitable for micro-nano processing fields and preparation of functional coatings and nanostructures.

• Thermal Evaporation: A PVD technique based on heating materials to evaporation temperature to form vapor, used for depositing metal films or other low melting point materials.

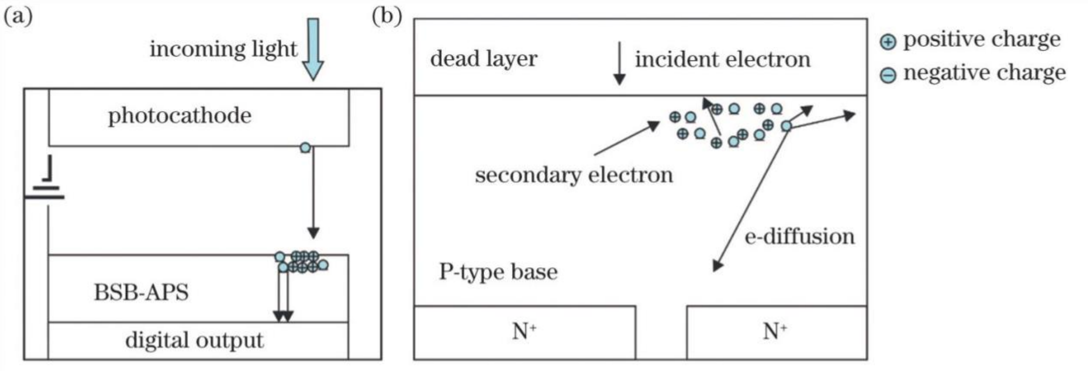
PVD technology offers several advantages: producing high-purity and high-quality films, reducing impurities and contamination, ensuring uniformity and thickness consistency of films, enhancing film adhesion and density, and adaptability to various materials. Compared to chemical deposition processes, PVD technology is also more environmentally friendly.

PVD technology is widely applied in fields such as the electronics and semiconductor industry (for metal interconnect layers, barrier layers, and diffusion layers), optoelectronics and optical industry (for anti-reflective coatings, reflective coatings, and filters), mechanical and tool industry (for wear-resistant and anti-corrosion coatings), decorative coatings (for aesthetics in watches and jewelry), biomedical field (for biocompatible coatings and drug delivery systems), and energy and environment sector (for solar cells and fuel cell materials). Additionally, PVD technology has significant applications in solid-state battery development, particularly in manufacturing solid electrolytes and active electrode materials, helping to understand material characteristics and interface phenomena deeply and promoting new material development.

2.3. Charge Collection Efficiency (CCE)

Charge Collection Efficiency (CCE) is a crucial parameter in semiconductor detectors, describing the efficiency at which charge carriers (electrons and holes) generated in the detector are collected at the electrodes. CCE directly impacts the detector's performance, including its sensitivity, resolution, and signal-to-noise ratio.

In MAPbI3 semiconductor nuclear detectors with Schottky contacts, the Schottky contact typically appears at the high resistivity semiconductor/metal interface, resulting in a non-uniform electric field within the bulk semiconductor. Studies have shown that in non-uniform electric fields, CCE significantly deviates from the value given by the Hecht equation, which assumes a uniform electric field. Using a slice model to simulate CCE instead of the Hecht equation revealed that CCE is closely related to the spatial charge distribution and the mobility-lifetime product value. For semiconductors with high ionized acceptor impurity concentrations, like MAPbI3, the electron value may be severely underestimated when using the Hecht equation that assumes a uniform field.



Fugure 1: Schematic Diagram of the BSB-APS Structure and the Process of Electron Multiplication and Charge Collection upon Incident Photoelectron Bombardment on the Backside Substrate of BSB-APS.

Several factors influence CCE, including carrier drift velocity and trap density. In junction-type detectors, both too low or too high working bias can affect CCE. Additionally, trap density is related to single-crystal epitaxial growth processes and radiation damage. Studies on the effects of passivation layer types, thickness, incident electron energy, p-type substrate thickness, and doping concentration on charge collection efficiency have shown that using a low-density SiO passivation layer can improve CCE.(Fig. 1)

Electron multiplication gain formula for electron bombardment in semiconductors:

$$G = \varepsilon(E_0 - E_{dead})$$

while G is gain factor;E_0 is injected electron energy;E_{dead} is energy lost through the dead layer (region of complete electron-hole recombination); ε is charge collection efficiency.

3. Experiment and Data

3.1. Device Introduction

(1) Mainboard: The mainboard may include electrodes or sensors for charge collection and associated electronic components for preliminary signal processing; The large central area may be a charge sensor or detector.

(2) Connection Cables: Cables extending from the mainboard transmit signals to the amplifier. Coaxial cables are used to ensure high-frequency signal transmission quality.

(3) PE1513 Low-Noise Amplifier: The amplifier features a broad frequency range and high gain, typically in the range of 20-40 dB; Power supply requirement is +12 V DC.

(4) Measurement Equipment: The output of the amplifier is connected to external measurement devices (e.g., oscilloscope or digital multimeter) for signal display and recording.

3.2. Principle Introduction

(1) Charge Collection: When the object or process under measurement generates charge, these charges are captured by sensors or electrodes on the mainboard; These charge signals are typically very weak and need to be amplified by the amplifier.

(2) Signal Transmission: The collected charge signals are transmitted via coaxial cables to the amplifier; Coaxial cables reduce noise and interference during signal transmission.

(3) Signal Amplification: The PE1513 low-noise amplifier is used to amplify the charge signals; The amplifier has broad bandwidth and high gain, suitable for amplifying high-frequency and weak signals; The amplified signal has a higher level, making it easier for subsequent measurement and analysis.

(4) Signal Measurement: The amplified signal is transmitted to external measurement devices through output terminals; An oscilloscope can be used to observe the waveform and frequency characteristics of the signal, while a digital multimeter can measure the signal’ s voltage value; Based on the measurement results, the charge amount generated by the object or process can be analyzed.

3.3. Experimental Steps

(1) Preparation:

1). Device Check: Ensure all devices (mainboard, detector, amplifier, measurement instruments, etc.) are functioning correctly and connections are secure. 2). Environment Preparation: Choose a low electromagnetic interference environment to minimize the impact of external noise on the experiment.

(2) Connection and Installation:

1). Detector Installation: Install the semiconductor detector (e.g., silicon or diamond detector) on the mainboard; 2). Connection Cables: Connect the detector output to the mainboard input. Use coaxial cables to connect the mainboard output to the input of the PE1513 low-noise amplifier; 3). Amplifier Connection: Connect the output of the PE1513 low-noise amplifier to an oscilloscope or other measurement devices using coaxial cables; 4). Power Connection: Ensure that the PE1513 amplifier and measurement devices are properly connected to the power supply.

(3) Calibration: Baseline Calibration: Calibrate the baseline noise of the measurement device without an input signal. Record the baseline noise level as a reference for the experimental data.

(4) Signal Collection:

1). Signal Generation: Use a radiation source or laser pulse to generate a known quantity of charge and direct it to the detector; 2). Signal Transmission: The charge signals collected by the detector are transmitted through the mainboard to the amplifier. The amplifier amplifies the weak signals; 3). Signal Recording: Record the amplified signal using an oscilloscope or digital multimeter. Note the peak value, time characteristics, and other parameters of the signal.

(5) Data Processing: 1). Signal Analysis: Analyze the measured signal and calculate the charge amount corresponding to the peak voltage. Consider the amplifier's gain to convert the measurement value to the actual charge amount; 2). Efficiency Calculation: Calculate the charge collection efficiency (CCE) by comparing the known input charge with the measured charge. CCE = (Measured Charge / Input Charge)×100%.

(6) Repeated Experiments:

1). Repeat Measurements: To obtain accurate results, repeat the experiment multiple times, varying experimental conditions (e.g., radiation source intensity, detector bias voltage) and record the CCE under different conditions; 2). Data Statistics: Perform statistical analysis on the data from multiple experiments to calculate the average and standard deviation, assessing the reliability of the experimental results.

3.4. Experimental Results and Analysis

Figure 2-11 shows the number of charge ions and the extreme values collected by the experimental equipment described above.

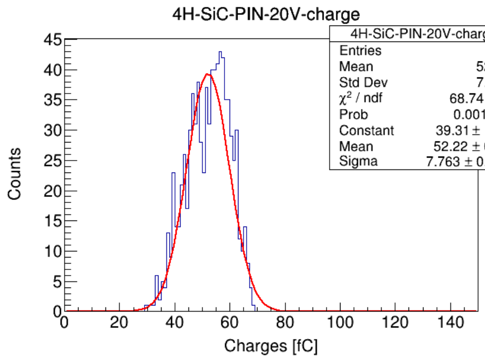


Figure 2: 4H-SiC-PIN-20V-charge

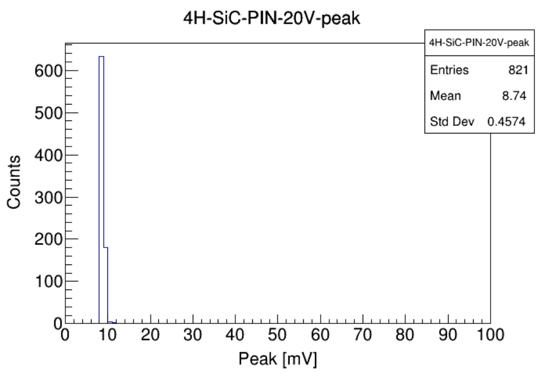


Figure 3: 4H-SiC-PIN-20V-peak

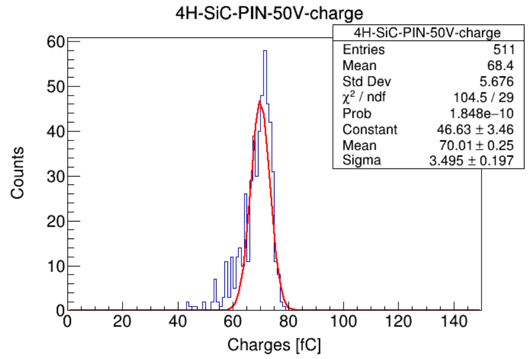


Figure 4: 4H-SiC-PIN-50V-charge

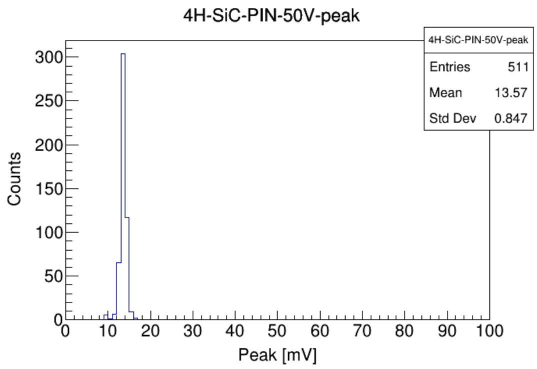


Figure 5: 4H-SiC-PIN-50V-peak

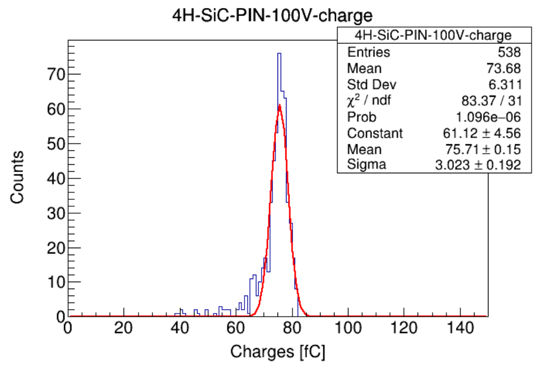


Figure 6: 4H-SiC-PIN-100V-charge

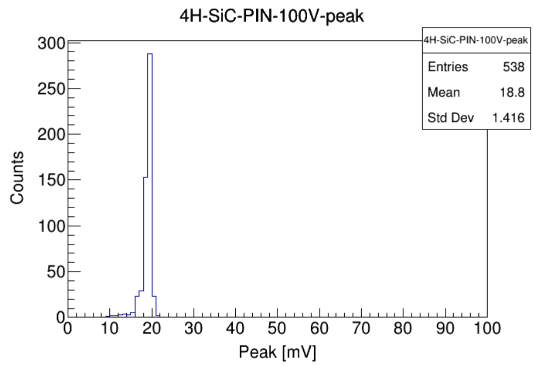


Figure 7: 4H-SiC-PIN-100V-peak

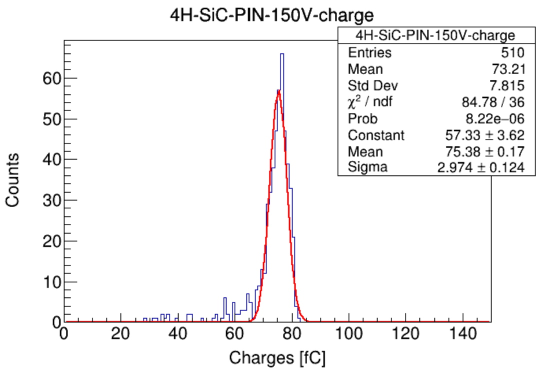


Figure 8: 4H-SiC-PIN-150V-charge

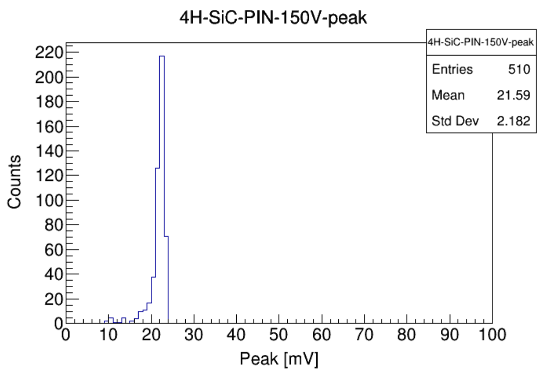


Figure 9: 4H-SiC-PIN-150V-peak

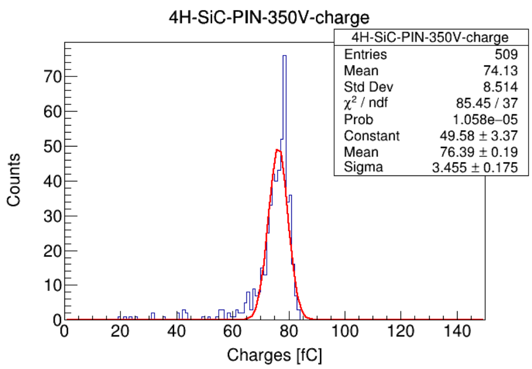


Figure 10: 4H-SiC-PIN-350V-charge

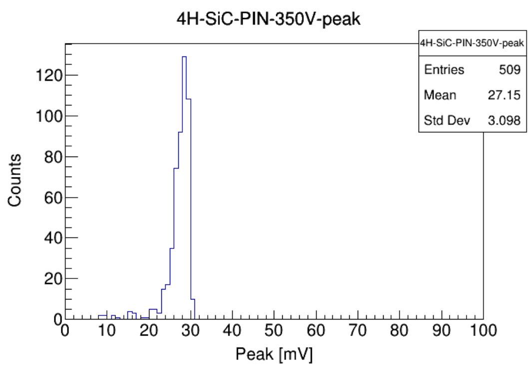


Figure 11: 4H-SiC-PIN-350V-peak

In the above experiment, the silicon carbide (SiC) detector demonstrated exceptional performance in capturing charged particles. The SiC detector achieved a high charge collection efficiency (CCE), reaching 95.96% to 90% at 100 V, thanks to optimized manufacturing processes and low dark current. The detector also realized a high energy resolution, achieving 0.29% to 0.63% in the experiment, making it comparable to the best resolution of silicon α-particle detectors.

Due to its high radiation resistance, the SiC detector is suitable for high-energy physics and extreme radiation environments, with radiation resistance approximately three orders of magnitude higher than that of silicon detectors. As shown in Figures 4-7, the charge collected by the SiC detector tends to stabilize at voltages of 50 V and above, indicating its stable charge collection capability within a certain voltage range.

Furthermore, the 4H-SiC LGAD (Low-Gain Avalanche Diode) detector showed a CCE of 90% at 100 V, and Figures 8-11 revealed that the charge collection tends to saturate within the bias voltage range of 150 V to 350 V. This further confirms the high efficiency and stability of SiC detectors in charged particle detection. These characteristics not only highlight the importance of SiC detectors in laboratory research but also suggest broad potential applications in fields such as nuclear radiation monitoring, medical imaging, and space exploration.

4. Summary and Prospect

To address the limitations of traditional detectors in high-temperature and high-radiation environments, a solution utilizing silicon carbide (SiC) detectors has been proposed. The design approach leverages the high breakdown voltage, high-temperature resistance, and low-loss characteristics of SiC materials to enhance the stability and performance of detectors under extreme conditions [6]. Experimental results indicate that SiC detectors offer significant advantages in terms of charge collection efficiency, time resolution, and radiation damage resistance. This highlights their potential applications in areas such as nuclear reactor measurements, high-level waste management, power devices for new energy vehicles, photovoltaic inverters, and 5G power amplifiers. However, SiC detectors exhibit relatively weak charge signal collection for minimum ionizing particles, necessitating more precise electronic designs. Additionally, the charge collection characteristics are limited by the thickness of the epitaxial layer, suggesting room for improvement.

The significance of this experiment lies in demonstrating the application potential of SiC detectors in high-energy particle physics detection, particularly in enhancing time resolution and signal quality. With advancements in crystal growth technology, device processing, and epitaxial techniques, it is anticipated that the cost of SiC detectors will further decrease, facilitating their broader application [7]. Despite the promising prospects, there are still challenges to address, such as the potential limitations imposed by the epitaxial layer thickness on high-energy particle detection and the need for further optimization of the 4H-SiC Low-Gain Avalanche Diode (LGAD) design and manufacturing processes. Future work will focus on these improvements to achieve better performance of SiC detectors in various radiation environments and explore their wider applications in new energy, 5G communication, and high-end manufacturing sectors. Additionally, domestic and international support policies and industrial investments for third-generation semiconductor materials will accelerate the localization of SiC detectors and enhance the domestic industry's autonomous capabilities [8].

In summary, the characterization of SiC detectors' charge collection properties demonstrates their potential in high-energy particle physics detection, especially in improving time resolution and signal quality. Future efforts will be directed at further optimizing the design and processing of 4H-SiC LGADs and exploring their performance across different radiation environments.

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