Comparison of High Voltage Device Based on Si and SiC

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Abstract. High voltage devices play a crucial role in various power electronic applications. Silicon (Si) has been the dominant material for such devices, but silicon carbide (SiC) is emerging as a promising alternative due to its superior properties. The objective of this study is to comprehensively compare high voltage devices based on Si and SiC. This study will focus on their different characteristics and performances in individual environments. Based on the analysis, we have observed that SiC devices exhibit superior performance in several key aspects. Notably, SiC devices demonstrate lower power losses attributed to reduced line and switching losses. These findings underline the immense potential of SiC as the preferred material for high voltage applications. The research outcomes offer valuable insights into the performance disparities between silicon-based and SiC-based high voltage devices. This knowledge is crucial for guiding future advancements in the field of power electronics, enabling the development of more efficient and reliable high voltage systems. By embracing SiC devices, one can enhance power transmission, improve energy efficiency, and advance sustainable energy solutions.

Keywords: High voltage devices, SiC, Si, efficiency.

1. Introduction

Contemporarily, the demand for high-voltage devices has been steadily increasing across various fields. These devices play a crucial role in energy conversion, power transmission, electric vehicles, and industrial automation. As the world's energy needs continue to grow, the development of high-voltage devices aims to provide efficient and reliable power transmission and control solutions. Over the past few decades, significant progress has been made in the research of materials and structures for high-voltage devices, driven by the need for higher power densities, improved efficiency, and enhanced reliability.

One area of notable advancement is in bipolar silicon carbide (SiC) solid-state high-voltage device technology. Previous study introduces the advantages of silicon carbide materials in high-voltage devices compared to silicon materials, including higher breakdown field strength, carrier saturation speed, and thermal conductivity [1]. Silicon carbide offers higher breakdown field strength, carrier saturation speed, and thermal conductivity compared to silicon. These characteristics enable SiC-based high-voltage devices to achieve high blocking voltage, low conduction resistance, high switching frequency, high efficiency, good high-temperature performance, and radiation resistance. The utilization of SiC materials has opened up new possibilities for high-voltage power applications. Other study emphasizes the widespread application of high-voltage power VDMOSFET (Vertical Double-Diffused Metal-Oxide-Semiconductor Field-Effect Transistor) devices based on silicon carbide in electronic power systems [2]. The article also sheds light on existing large-scale production lines, indicating the increasing commercial viability of SiC-based high-voltage devices. Another study provides insights into the application of high-voltage power device technology in power systems [3]. It discusses the main types, characteristics, and application scenarios of high-voltage power devices, while also proposing potential future research directions. This highlights the ongoing efforts to explore new technologies and optimize the performance of high-voltage devices in various practical applications.

Silicon (Si) and silicon carbide (SiC) are commonly used materials for high-voltage power semiconductor devices. Si materials have a long history of successful implementation in the medium-pressure range, finding applications in various devices such as voltage motor drivers and grid-connected converters. However, as the demand for more efficient power conversion and higher voltage capabilities continues to rise, SiC materials have emerged as promising alternatives. SiC is a wide bandgap semiconductor material that exhibits excellent electrical properties. Consequently, it is appropriate for high-voltage power applications. With the increasing integration of renewable energy sources into the power grid, the need for advanced power converters that can handle high voltages and deliver higher efficiencies becomes more critical. SiC-based high-voltage devices offer the potential to meet these demands and enable the development of more efficient and sustainable power systems. While significant progress has been made in the field of high-voltage devices, there are still challenges that need to be addressed. These include minimizing high-voltage device losses, improving temperature stability to ensure reliable operation under various conditions, and advancing packaging technologies to enhance device performance and longevity. Continued research and innovation are essential for overcoming these challenges and further advancing the field of high-voltage devices. Previous study will cover various aspects related to high-voltage devices [4, 5]. It will provide basic descriptions of high-voltage devices, discuss silicon (Si) high-voltage devices and silicon carbide (SiC) high-voltage devices, compare the characteristics of Si and SiC devices, highlight the limitations and future outlooks for high-voltage devices, and conclude with key findings. By exploring these topics, readers will gain a comprehensive understanding of the current state and future prospects of high-voltage devices, paving the way for advancements in power transmission, energy efficiency, and sustainable electrical systems.

2. Basic Descriptions of High Voltage Device

The high voltage device refers to the device whose voltage exceeds 35 kV ac. According to one group of researchers [6], Four categories that can be used to group the high voltage device structure -power thyristors, MOSFETs, IGBTs, and MOS-gated thyristors. Silicon or silicon carbide is able to be used to create the devices. The detailed structure introduction will be shown below. The power thyristor structures have the ability to block high voltage when the positive and negative bias is supplied. When the device is operated at the first quadrant, it can be brought into on-state by applying a modest current to the gate terminal. These capabilities mentioned above are more suitable for the AC power supply device and the DC power supply like electric trains etc. [6]. The only one in the structure which can handle the high voltage is the first quadrant.

As for MOS-gated thyristors which usually have three basic structures-DMOS-MCT, DMOS-BRT, and D-MOS EST that all have the ability to turn-off. The detailed information about MOSFET will be introduced in the following passage. Although the silicon power MOSFET is very good, the silicon carbide one has more advantages compared with the former one. It achieves the superior switching behavior of unipolar devices while still achieving a low specific on-resistance for the drift area. According to a book named “Advanced HighVoltage Power Device Concepts,” [6] the difference between them is that they use different bases-the inversion-mode MOSFET uses P-base while the accumulation-mode MOSFET uses N-base.

The IGBT function with Si, SiC, or GaN insulation satisfies the requirement- with high breakdown voltage, low forward voltage drop, and the capacity for quick switching according to one group of researchers [7]. As for the capacitances of the power device. The capacitance of the power device is inverse to the thickness of the voltage blocking layer according to a group of researchers’ experiment [7]. They have proposed two traditional ways to measure both the capacitance and the voltage dependence of the capacitance between the terminals of the power devices- finite-element device simulation and validate it using circuit modeling or testing or experimentally defining the capacitances [7]. The methods have some drawbacks. The former one needs precise device structure, dimension, and process information. The latter one’s terminal capacitance of high-voltage power

devices cannot be measured commercially. The composition of the capacitive component in a power device is examined by a group of researchers using a VDMOSFET and a planar gate device arrangement [7]. The terminal capacitance of VDMOSFET will be illustrated in the following. The capacitance components that exist in the MOSFET are incorporated into the terminal capacitances Cgs, Cgd, and Cds which can be measured by measurement circuits.

3. Si Application in Specific High Voltage Devices

Silicon has been used in semiconductors since the early developments of solid-state science, and is still researched and applied in modern high voltage devices, primarily in transistors like MOSFETs [8]. Two types of Si based devices will be introduced in this section: transistors and high energy Li batteries. MOSFETs are a type of fundamental and important transistor. These devices primarily operate as unipolar transistors, relying on the potential difference applied to their gates to control the flow of current in the component. This unipolar behavior simplifies their operation and makes them suitable for various applications. One significant advantage of Si MOSFETs is their fast switching capability. They can rapidly switch from an off-state to an on-state and vice versa, making them crucial in high-frequency circuits such as power amplifiers and switching regulators. Other study points out that this feature prohibited tail currents and reverse recovery [9]. Tail currents are small, undesired currents that flow even when the device is supposed to be turned off. Engineers continually work to minimize tail currents to improve energy efficiency. Additionally, Si MOSFETs do not suffer from the reverse recovery time limitation seen in some other semiconductor devices like diodes. This is the time it takes for excess charge carriers to be removed or neutralized so that the device can effectively block reverse current. Hence, making them suitable for applications that require fast switching without the delays associated with reverse recovery.

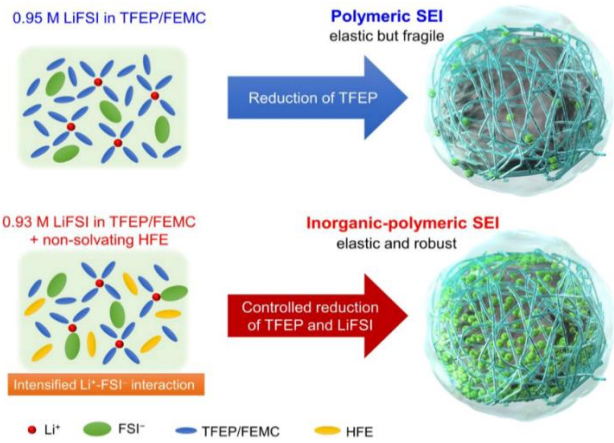


Figure 1. Safe electrolyte design for Si-base anodes

Silicon offers a significantly higher theoretical capacity compared to graphite, making it an attractive candidate for increasing the energy density of batteries. Si can store up to ten times more lithium ions, which translates to longer-lasting and higher-capacity batteries. This characteristic is vital for applications like electric vehicles and grid energy storage, where extended battery life and increased energy storage capacity are highly desirable. However, Si anodes face several challenges that researchers and engineers are actively addressing. The most prominent issue is the dramatic volume expansion and contraction of silicon during lithiation and delithiation processes. This repeated expansion and contraction can lead to mechanical stress, electrode cracking, and ultimately, reduced cycle life. Another problem is that a solid electrolyte interface (SEI) would form on the Si surface, which can hinder ion transport and degrade the anode's performance. Researchers are working on SEI stabilization techniques to enhance the overall stability of Si anodes. To mitigate this problem, Ref. [10] designs a new method in producing an elastic and robust SEI as shown in Fig. 1. This method allows the voltage that was high for batteries to operate on to be reduced to around 0.2V compared to Li/Li+ whilst producing a very high energy density of around 590 $Whkg^{-1}$.

4. High Voltage Device Based on SiC and Applications

According to previous study [11], the substance SiC has excellent chemical and physical qualities, such as the strong chemical link between Si and C that gives it high hardness and excellent thermal conductivity. Based on Ref. [12], due to its broad bandgap, SiC can operate at temperatures up to 1000°C. The intrinsic carrier density of SiC is shown at Fig. 2 indicating that the intrinsic density is inverse to the temperature [13].

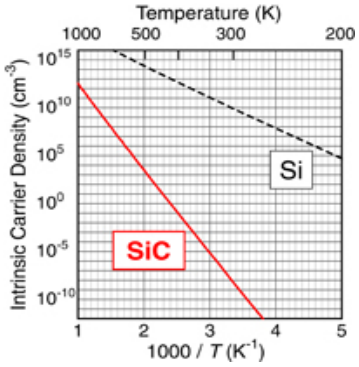


Figure 2. Arrhenius plot of the intrinsic carrier density for SiC and Si

The large diameter of SiC single crystal is 150nm. Having electron and hole impact ionization efficient at 960 cm^{-1} and 2.4×10^4 cm^{-1} at 2.5 MV cm^{-1} based on the paper [8], due to the influence of the distinct conduction band structure brought about by zone folding along SiC, the electric field strength may be much stronger than anticipated. The SiC has many applications and is widely used now. High voltage SiC power semiconductor device is an example. The typical one includes diodes, MOSFET, IGBT, BJT, thyristor, and JFET. Nowadays, SiC MOSFETs are widely applied and will be discussed in the following passage. Based on the previous study, the SiC MOSFETs have static behavior and dynamic behavior that makes SiC material have better properties compared with other materials like Si [13]. According to the results, the dynamic behavior of MOSFETs can be proved by the following experiment. The short circuit waveforms of the 3.3kV 14 and 26um MOSFETs with conditions restricted to VD=1800V and VGS=15V are investigated by one group of researchers. In their experiment, the 14um pitch cannot meet the industry requirement standard-10us. The conditions were controlled at 125℃, 3600V, and 40A. During the experiment, different values of dV/dt were changed. Though there is a big oscillation, all the required INOM level is turned-off by the MOSFETs. The MOSFETs indicate short circuit capability with 5μs and current excess 600A. Assuming the equal current through each ship, each MOSFET takes exceed 150A, which is a very great achievement. The HTRB of SiC MOSFETs and high voltage ruggedness are responsible for the fantastic performance of SiC MOSFETs. The former one is able to be tested with a sample size of n=80pcs pf 90/1.2kV SiC MOSFETs with area of 0.2 cm^2 [14]. As a consequence of the test, the maximum change in threshold voltage was just 1.6% and the maximum change in Drain-Source leakage is 5% after 1000hr HTRB stress during the test. As for the high ruggedness of SiC MOSFETs, the large termination area is required in typical 1.2kV SiC MOSFETs, the 20-40% overall area is belonging to the termination area. Based on the results, avoiding channel leakage, which increases with Drain Bias and can have additional impacts when the device is under avalanche conditions, will help the device have a positive temperature coefficient of breakdown voltage, and they were tested through an experiment. During the experiment, 1.2kV/53mOhm and 1.2kV/25mOhm devices were tested under TO247 style discrete packages and die sizes of A=0.1cm^2 and A=0.2cm^2 to measure the UIS waveforms. Following avalanche test was conducted by researchers on SiC MOSFETs under different current conditions. The scholar indicates that only 25Ohm/90A/1.2kV SiC MOSFETs achieved avalanche ruggedness. The SiC diodes are another application. The traditional SiC diodes use SBDs while many diodes use JBSs. The difference is that a depletion zone produced at the interface between the P+-wells and the N- drift layer is capable of blocking the Schottky interface conduction current

[15]. The heavy-ion experimental result for SiC JBS degradation and SEB by a group of researchers is shown in Fig. 3.

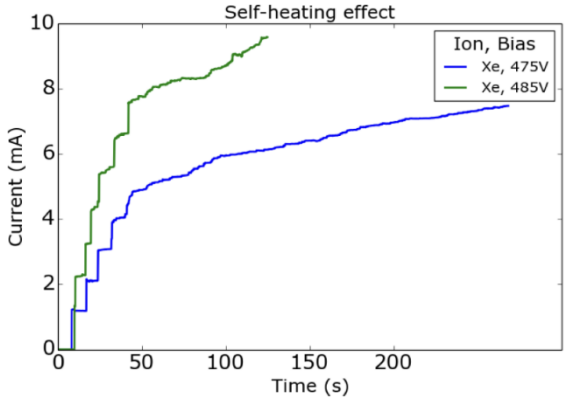


Figure 3. Measured diode current vs. time during heavy-ion irradiation for two diodes, showing discrete increases in leakage current with individual heavy ions, with self- heating effect. Xenon flux was 68, Neon was 5.7 to 6.1 ions/cm2/sec

In the Fig. 3, leakage current with individual heavy ions increases, as seen by the drain leakage current degradation at a low ion flow. The relationship between the drain current and time is then conducted [15]. The result shows that the significant rise of current can be more than five order degrees. The relationship between the reverse current and voltage after ion fluence is also investigated. According to the Fig. 4, all fluences have rapid increase in leakage at voltage less than 200V and at voltage above 200V, there is a more gradual rise of leakage. However, there is no voltage greater than 1100V. The threshold boundaries for leakage degradation and SEB as functions of bias and LET are finally determined by the researchers. The graph also illustrates that the SiC diode curve illustrates the nonlinear relationship on LET. To examine the cumulative impact of leakage current, a group of researchers subjected one device to 300V of Xe ion bias, and finally suggested that the breakdown voltage of diode greater than 1100V while no other evidence of latent damage was seen.

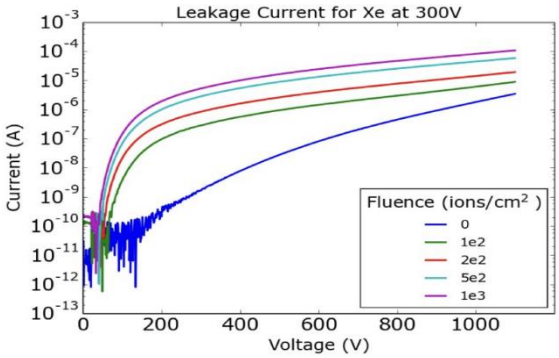


Figure 4. Leakage current vs. voltage for diodes irradiated with Xe ions while biased at 300V at various fluences

5. Comparison between Si and SiC High Voltage Devices

SiC materials possess unique characteristics that differentiate them from Si materials. Firstly, SiC materials have a wider energy gap. This wider energy gap allows SiC devices to operate effectively at higher temperatures, making them suitable for high-temperature environments. The higher breakdown field strength of SiC enables these devices to handle higher voltage levels, making them ideal for high-voltage applications. Additionally, the superior thermal conductivity of SiC allows for efficient heat dissipation, which is crucial in high-power applications. According to Fig. 5, SiC chips have a fraction of the area of Si chips. This translates to higher power density in SiC power modules, and heat dissipation capability of SiC power modules are significantly prominent. Furthermore, SiC

materials exhibit higher carrier velocity saturation than Si materials. This property determines the maximum speed at which charge carriers can move through the material. The higher carrier velocity saturation of SiC contributes to the overall performance enhancement of SiC devices, making them highly desirable for various high-voltage applications. In summary, these characteristics enable SiC devices to provide higher voltage and power density, perform better in high-temperature environments, and achieve faster switching speeds. These advantages make SiC devices increasingly attractive for a wide range of high-voltage applications, including power electronics, electric vehicles, and renewable energy systems.



Figure 5. General view of high voltage SiC and Si chips (a) Si IGBT and SiC MOSFET (b) Si FRD and SiC SBD

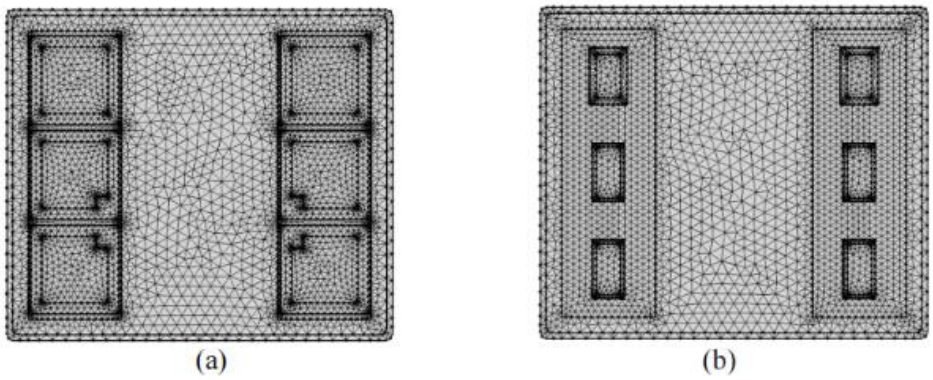


Figure 6. Geometric models assembly (a) Si IGBT module(b) SiC MOSFET module

We discuss the comparison of packaging structures between SiC MOSFET and Si IGBT power modules. Other scholars utilized COMSOL Multiphysics, to conduct three dimensional thermal simulations of SiC MOSFET and Si IGBT modules. The purpose was to analyze the variations in thermal performance between the two. The geometric models used for the simulations are illustrated in Fig. 6 [16]. It examines the thermal resistance characteristics of these modules under similar packaging configurations. The findings reveal that, when considering the same packaging structure, SiC MOSFET modules exhibit a higher thermal resistance compared to Si IGBT modules. However, SiC modules offer the advantage of higher power density. Hence, SiC devices can deliver increased power output within packages of the same size, but it also leads to the generation of more heat.

The higher thermal resistance in SiC MOSFET modules may be attributed to factors such as the unique material properties of SiC, the design of the packaging structure, and the interfaces between different components. Despite the higher thermal resistance, SiC modules still hold a significant advantage in terms of power density. This characteristic makes them highly desirable for applications where maximizing power output within limited space constraints is crucial, such as in electric vehicles, renewable energy systems, and high-performance industrial equipment. Efficient thermal management techniques and advanced packaging designs are essential for ensuring optimal performance and reliability of SiC modules while effectively managing the generated heat. According to the Ref. [17], one can know that SiC devices exhibit better performance in high-power and high-temperature applications because they have wider energy gaps, higher thermal conductivity, and so on. However, despite the many advantages of SiC devices, they are still in a less commonly used

stage in certain specific applications. This may be due to manufacturing and cost challenges, as well as the need for more time and effort in the adoption of SiC technology. Si is still widely used as a material, while SiC is still in a less commonly used stage in certain specific applications. With the development of technology, SiC is expected to replace Si as the best choice for high-power and high-temperature applications at some point in the future.

6. Limitations and Prospects

Si devices commonly have lower breakdown voltages compared to SiC devices, restricting them from better stability and area of employment. Other scholars pointed out that the band gap of Si is 1.1eV, this leads to devices unable to withstand higher voltages [16]. In contrast, SiC devices have a larger band gap of 3.3eV. This is more advantageous for SiC devices to withstand voltage spikes and provide better insulation. This physical property also leads to poor scalability of Si devices. Furthermore, Si devices have a lower critical electric field compared to SiC, as they possess a lower critical electric field (or avalanche breakdown field). As a result, Si devices are more susceptible to breakdown at higher voltages at lower electric field strengths.

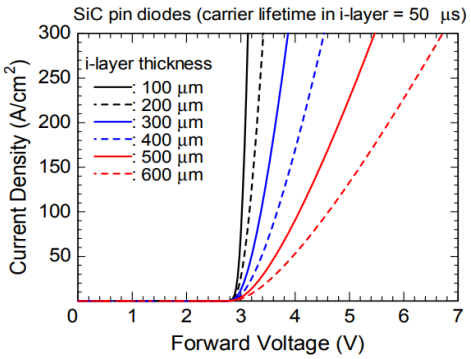


Figure 7. The forward voltage changes as thickness varies

SiC devices also have limitations, one of such is when employed in pin diodes. The thickness of their intrinsic layer (i-layer) can affect the performance on its forward voltage drop. In fact, there is a large voltage drop when this thickness value increases to 600μm [17]. The results as shown in Fig. 7. High voltage drop can result in poor voltage regulation. This can lead to under-voltage conditions, hence disrupting the proper operation of connected devices. Additionally, voltage drop causes a certain amount of the electrical energy to be dissipated as thermal energy in the conductors. Hence, this energy loss makes the system less efficient. The future outlook for Si is promising with ongoing research and mass application in electrical devices. The trend of miniaturization and integration in Si devices is closely tied to Moore's Law. This law predicts that the number of transistors on a chip will double every two years as the cost of each transistor continues to decrease. In the 1980s, the size of MOSFETs using Si was around 500 nanometers, through years of development recently this value has decreased to 3 nanometers. As Si devices become smaller, more Si components can be packed onto a single chip. This integration has profound implications for the size, weight, and power consumption of electronic devices. SiC high-voltage devices offer several advantages also making the devices to have significant potential. Such strengths include higher breakdown voltage, lower on-resistance, faster switching speeds, and exceptional temperature performance. These attributes make SiC devices ideal for high-voltage applications such as electric vehicles, renewable energy systems, and electronic components. Examples are Schottky diodes and MOSFETs [18, 19].

7. Conclusion

To sum up, as the demand for energy-efficient solutions and compact power electronics grows, SiC devices are expected to play a pivotal role in addressing these needs. Furthermore, research and development efforts are focused on improving SiC device manufacturing processes, reducing costs,

and increasing their availability in the market. As SiC high-voltage technology matures and becomes more accessible, it is likely to succeed traditional Si devices in many applications, ushering in an era of higher efficiency, reduced energy consumption, and enhanced performance.

Author Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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