Analysis of the Principle and Applications for High Voltage Device Based on SiC

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Abstract. The field of high-voltage electronics is rapidly evolving, with a particular focus on materials and devices that can withstand high voltages and temperatures while maintaining reliable performance. Silicon Carbide (SiC) is one such material that has been gaining significant attention due to its unique physical and chemical properties. This study will delve into the principle and applications of high-voltage devices based on SiC, exploring its potential for use in a range of power electronic systems. This paper will first explore the principle of SiC high-voltage devices, including a detailed analysis of the physical and chemical processes involved in their operation. Subsequently, this study will discuss the current state-of-the-art in SiC device fabrication and characterize the resulting devices based on their performance metrics. This will be followed by a discussion on the potential applications of SiC high-voltage devices in power electronics and beyond. Finally, this study will address the current limitations in SiC device research and development and explore possible future research directions that may lead to improved performance and reliability of SiC devices. By delving into the principle and applications of high-voltage devices based on SiC, this paper aims to provide a comprehensive understanding of the material’s unique properties and its potential for use in a range of power electronic systems. The analysis of current limitations and prospects will aid in identifying areas for future research and development efforts, leading to the advancement of SiC high-voltage devices for even more demanding applications.

Keywords: Silicon Carbide (SiC); high-voltage devices; physical and chemical properties; application areas.

1. Introduction

Silicon carbide (SiC) has attracted much interest due to its corrosion resistance, large band gap, high mechanical strength, low density, high hardness, high thermal conductivity, and low thermal expansion coefficient [1]. In this background introduction, this part will explore the principles and applications of SiC-based high-voltage devices, summarize the current research progress in this field, and discuss the motivation for this paper.

High-voltage devices are essential for a wide range of semiconductor applications that require operation under high electric fields. These devices enable the control and manipulation of large amounts of electrical power, thereby playing a crucial role in areas such as power conversion, electric vehicles, railways, aviation, and military electronics. The performance of high-voltage devices is typically limited by the intrinsic properties of the semiconductor materials used [2]. Silicon carbide (SiC), as a wide bandgap semiconductor, offers the advantage to overcome the physical limitations of silicon. Wide band-gap semiconductor silicon carbide (SiC) high-power MOSFET can greatly reduce the energy consumption of the electric power system [3]. Therefore, the search for novel materials with improved high-voltage characteristics has been a topic of interest in recent years.

Silicon carbide (SiC) power devices are playing a major role in the power electronics technology due to its superior material properties compared to Silicon (Si). The photovoltaic (PV) inverter is a major component in the solar energy conversion system whose performance relies on the efficient design of power electronics. In order to obtain maximum power from the solar panels, the power loss in the energy conversion system must be minimized by proper selection of semiconductor devices and thereby minimizing the number of power electronic components used. The necessity to reduce the overall switch mass and volume have led to the development of advanced high-power, high-temperature semiconductor materials such as SiC [4].

Silicon Carbide (SiC) is a promising wide bandgap semiconductor material with exceptional physical and chemical properties that make it suitable for high-voltage device applications. Silicon carbide (SiC) power devices are playing a major role in the power electronics technology due to its superior material properties compared to Silicon (Si) [5]. SiC has been the focus of extensive research in recent years due to its high breakdown field, high thermal conductivity, and excellent stability at high temperatures. The high breakdown field of SiC enables the design of devices with higher voltage ratings compared to silicon devices, while maintaining a smaller device footprint. Additionally, SiC's high thermal conductivity allows for efficient heat dissipation, enabling higher power density and increased device reliability.

Researchers have been developing various SiC-based high-voltage devices, including diodes, transistors, and thyristors, with improved performance compared to their silicon counterparts. SiC diodes have shown reduced recovery time and lower forward voltage drop under high current conditions, making them suitable for high-power applications. SiC transistors have demonstrated higher gain and faster switching speeds compared to silicon transistors, enabling more efficient power conversion. SiC thyristors have also shown improved performance with regard to voltage blocking ability and thermal stability.

The development of SiC-based high-voltage devices has the potential to revolutionize power electronic systems by enabling improved performance, higher reliability, and extended operating temperatures. However, there are still several challenges associated with the fabrication and characterization of these devices that need to be addressed. This study aims to provide a comprehensive review of the principles and applications of SiC-based high-voltage devices, summarize the current research progress in this field, and identify potential areas for future research. It is hoped that this review will serve as a resource for researchers and practitioners interested in exploring the potential of SiC for high-voltage device applications.

2. Basic Descriptions of SiC

Silicon Carbide (SiC) is a wide bandgap semiconductor material with unique physical and chemical properties that make it an attractive candidate for use in high-voltage devices. This section will provide a basic description of the fundamental properties of SiC and its potential applications in high-voltage devices Also it will discuss what advantages does it have over silicon. Silicon Carbide is a crystalline compound consisting of silicon and carbon atoms. It exists in various polytypes, the most used being 4H-SiC and 6H-SiC for high-voltage device applications. SiC has a cubic crystal structure and is a superhard material, with a hardness similar to diamond. It has a high melting point and is chemically inert, exhibiting excellent stability under high temperatures and harsh environments.

One of the key features of SiC is its wide bandgap energy, which refers to the energy difference between the top of the valence band and the bottom of the conduction band. SiC has a bandgap energy wider than that of silicon, which allows for higher breakdown voltages.Band gap width is an important characteristic of SiC, which refers to the energy difference between the top of the valence band and the bottom of the conduction band. SiC has a larger bandgap than silicon, which allows it to withstand higher breakdown voltages and greater energy. Additionally, SiC has a high electron saturation velocity and low intrinsic carrier concentration, which make it suitable for high-speed and high-temperature applications.

The high breakdown field and high saturation velocity of SiC result in devices with improved performance compared to silicon devices. SiC devices can operate at higher temperatures, allowing for smaller cooling systems to be used, thereby reducing the overall system footprint and cost. Additionally, SiC devices offer lower losses and higher switching frequencies, resulting in more efficient power electronic systems.SiC devices are typically fabricated using epitaxial growth techniques, such as chemical vapor deposition (CVD) or physical vapor deposition (PVD). The fabrication process involves the deposition of SiC layers on silicon or sapphire substrates, followed by the implantation of dopants to control the electrical properties of the device. SiC devices typically operate at higher voltages and temperatures compared to silicon devices, while exhibiting lower losses and higher switching frequencies.

The application areas for SiC high-voltage devices include power conversion, electric vehicles, railways, aviation, and military electronics. Before SiC, commercial MOSFETs existed only in Si, because a sufficient electronic passivation of dangled bonds at the semiconductor surface could only be achieved by thermally grown SiO2 as the gate dielectric [6]. SiC MOSFETs have demonstrated that, in addition to drastically reduced switching losses, they can also offer low conduction losses for voltage ratings up to 10kV [7]. SiC diodes, MOSFETs, and thyristors have been developed for use in power conversion systems, where they offer improved efficiency and reduced losses compared to silicon-based devices. In electric vehicles, SiC MOSFETs have been demonstrated to enable more efficient motor drives with lower switching losses, enabling increased vehicle range with a given battery size. In aviation and military electronics, SiC devices offer improved performance at high temperatures, enabling more reliable systems in extreme environments.

Despite the advantages of SiC high-voltage devices, there are currently some limitations in their development. The manufacturing process is complex and expensive compared to silicon-based devices, due to the difficulty in growing thick SiC films with low defect densities. Additionally, there is a lack of standardized test methods and reliability data for SiC devices, which makes it difficult to predict their performance and long-term reliability in field applications. In conclusion, SiC's unique combination of physical and chemical properties makes it an attractive material for use in high-voltage devices. The development of SiC-based high-voltage devices promises to enable more efficient and reliable power electronic systems for a wide range of applications. However, further research is required to address the current limitations in their performance and manufacturing process, and to ensure their long-term reliability in field conditions.

3. Principle

Silicon Carbide (SiC) is a ceramic material that has unique physical and chemical properties that make it extremely suitable for use in high-voltage devices.The principles behind SiC's ability to withstand high voltages are outlined in this section. SiC's hardness, chemical inertness, and high-temperature stability are a result of its strong covalent bonding between silicon and carbon atoms. The material's cubic crystal structure also contributes to its stability, providing excellent mechanical strength and resistance to mechanical stress at high temperatures (seen from Fig. 1).

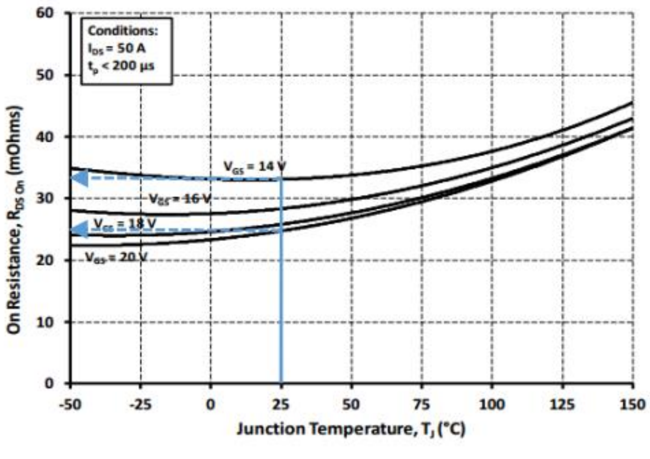

Fig. 1 On-Resistance vs. Temperature for Various Gate Voltage.

One of the key properties of SiC that makes it suitable for high-voltage devices is its wide bandgap energy. As one saw in the last section, the bandgap energy refers to the difference in energy between the top of the valence band and the bottom of the conduction band. SiC's bandgap is wider than that of silicon, which means that it can withstand higher electric fields without undergoing electron avalanche and breakdown.The high breakdown field of SiC is due to its high critical electric field, which is the maximum electric field that can be applied to a material without causing breakdown. The high critical electric field of SiC is a result of its strong covalent bonding, which allows the material to withstand high electric fields without undergoing electron avalanche.

SiC's high electron saturation velocity and low intrinsic carrier concentration also contribute to its high-voltage performance. The electron saturation velocity is the maximum velocity that electrons can travel in a material without undergoing collisions. In SiC, the electron saturation velocity is higher than that of silicon, which allows electrons to travel at higher velocities and switch at higher frequencies. The low intrinsic carrier concentration of SiC means that there are fewer free charge carriers in the material to cause conduction at low temperatures. This allows SiC devices to be operated at higher temperatures with lower leakage currents, which improves their high-voltage performance. In summary, the unique combination of physical and chemical properties exhibited by SiC results in its ability to withstand high voltages.Silicon Carbide (SiC) Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFETs) are gradually replacing traditional silicon-based devices such as IGBTs in high-voltage, high-frequency, high-temperature applications due to their higher breakdown filed strength, lower switching losses, better thermal stability and thermal conductivity [8]. Wide bandgap (WBG) power semiconductor devices that are based on Silicon Carbide (SiC) and Gallium Nitride (GaN), enable the improved performance of power electronic converters in a range applications. These devices can operate at higher switching frequencies, higher junction temperatures, higher breakdown voltages for the same blocking length, and therefore can deliver higher power density as compared to Silicon (Si) based power devices. Hence, WBG power semiconductor devices have gained considerable interest and are projected to displace Silicon power devices that are prevalent in the market today [9].

4. Devices and Facilities

AS a ceramic material with unique physical and chemical properties SiC extremely suitable for use in high-voltage devices (seen from Fig. 2). SiC's hardness, chemical inertness, and high-temperature stability are a result of its strong covalent bonding between silicon and carbon atoms. The material's cubic crystal structure also contributes to its stability, providing excellent mechanical strength and resistance to mechanical stress at high temperatures.

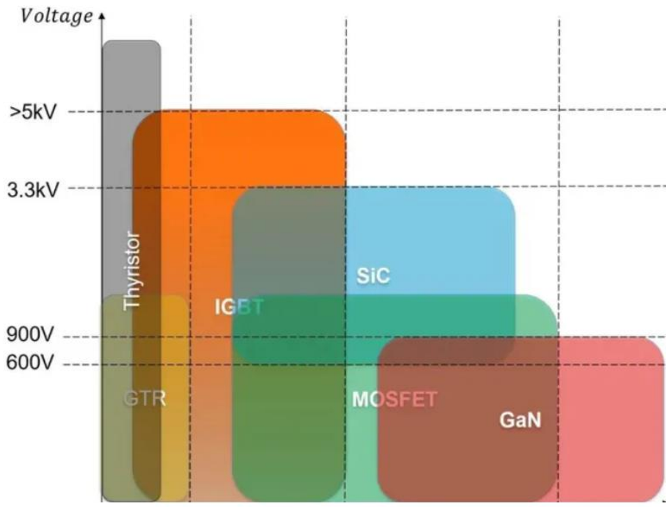

Fig. 2 Common voltage limits and common switching frequency ranges for commercial devices

SiC high-voltage devices are typically fabricated using epitaxial growth techniques, such as chemical vapor deposition (CVD) or physical vapor deposition (PVD). The fabrication process involves the deposition of SiC layers on silicon or sapphire substrates, followed by the implantation of dopants to control the electrical properties of the device. SiC devices typically operate at higher voltages and temperatures compared to silicon devices, while exhibiting lower losses and higher switching frequencies. The combination of electrophoretic deposition and polymer infiltration and pyrolysis has proven to be an effective way to produce SiC-matrix material with limited porosity and sufficient thermal conductivity [10]. Over the last few decades, new device designs and fabrication techniques have been explored to expand the applicability of SiC-based power devices [11]. SiC high-voltage devices are typically fabricated using epitaxial growth techniques, such as chemical vapor deposition (CVD) or physical vapor deposition (PVD). The CVD process involves the deposition of SiC layers on silicon or sapphire substrates using reactant gases such as silane and propane in a high-temperature furnace. The PVD process involves the deposition of SiC layers using a sputtering or evaporation technique. After the deposition of the SiC layer, the device is doped with impurities to control its electrical properties. Common dopants include aluminum, boron, and phosphorus, which are introduced into the SiC lattice using ion implantation or diffusion techniques.

SiC devices are typically packaged in hermetically sealed enclosures to protect them from environmental conditions and ensure reliable operation. The packaging process involves the attachment of the SiC chip to a metal header using a solder or adhesive, and the sealing of the package with a metal or ceramic lid. The package must provide mechanical support and electrical connections to the chip, while maintaining hermeticity to ensure reliable operation. SiC devices are typically characterized using test equipment such as voltage meters, current meters, and oscilloscopes. Common performance metrics include breakdown voltage, leakage current, forward voltage drop, and switching time. The breakdown voltage is the maximum voltage that can be applied to the device without causing avalanche breakdown. Leakage current is the amount of current that flows through the device when it is in the OFF state. Forward voltage drop is the voltage drop across the device when it is in the ON state. Switching time is the time required for the device to transition between the ON and OFF states. In conclusion, SiC’s unique combination of physical and chemical properties makes it an attractive material for use in high-voltage devices. The devices and facilities used in the fabrication and characterization of SiC high-voltage devices ensure their reliable operation at high voltages and temperatures while exhibiting low losses and high switching frequencies.

5. Applications

This part will provide a basic description of the fundamental properties of SiC and its potential applications in high-voltage devices. SiC is as a crystalline compound consisting of silicon and carbon atoms. It exists in various polytypes, the most commonly used being 4H-SiC and 6H-SiC for high-voltage device applications. SiC has a cubic crystal structure and is a superhard material, with a hardness similar to diamond. It has a high melting point and is chemically inert, exhibiting excellent stability under high temperatures and harsh environments. One of the key features of SiC is its wide bandgap energy, which refers to the energy difference between the top of the valence band and the bottom of the conduction band. SiC has a bandgap energy wider than that of silicon, which allows for higher breakdown voltages and larger energy barriers. Additionally, SiC has a high electron saturation velocity and low intrinsic carrier concentration, which make it suitable for high-speed and high-temperature applications [12].

SiC devices are typically used in applications where high voltages and temperatures are encountered, such as power conversion, electric vehicles, railways, aviation, and military electronics. SiC diodes, MOSFETs, and thyristors have been developed for use in power conversion systems, ilicon carbide have higher electric breakdown voltage, and thus fewer devices are required in series to withstand the output voltage which improved efficiency and reduced losses compared to silicon-based devices. 12In electric vehicles, SiC MOSFETs have been demonstrated to enable more efficient motor drives with lower switching losses, enabling increased vehicle range with a given battery size. In aviation and military electronics. In order to improve the efficiency, reliability and maintainability of the aircraft, the aerospace world has found in progressive electrification that reduces or removes the hydraulic, mechanical and pneumatic power systems. Power devices are widely applied in power system, while conventional Si power devices have reached the theoretical limitation. Admittedly, many advantages, such as high breakdown electric field strength, high saturated electron drift velocity and high thermal conductivity can be seen from SiC semiconductor material, and SiC power electronic devices made of which can have the ability to adapt to high voltage, high power, high frequency, high temperature and other harsh environment [13]. SiC devices are also being used in high-power RF applications such as radar and microwave systems. The high breakdown field and high saturation velocity of SiC result in transistors with improved performance compared to silicon devices. Additionally, SiC's wide bandgap allows it to operate at higher frequencies and higher power levels, making it suitable for use in high-power RF amplifiers.

Due to the difficulty in growing thick SiC films with low defect densities. Additionally, there is a lack of standardized test methods and reliability data for SiC devices, which makes it difficult to predict their performance and long-term reliability in field applications. In conclusion, the unique combination of physical and chemical properties exhibited by SiC result in its ability to withstand high voltages. The material's hardness, chemical inertness, high-temperature stability, wide bandgap energy, high breakdown field, high electron saturation velocity, and low intrinsic carrier concentration all contribute to SiC's suitability for use in high-voltage devices. The various applications discussed in this part demonstrate the versatility and widespread use of SiC devices in power electronics and beyond.

6. Limitations and Prospects

As a ceramic material with unique physical and chemical properties, Silicon Carbide is an attractive candidate for use in high-voltage devices. SiC's hardness, chemical inertness, and high-temperature stability are a result of its strong covalent bonding between silicon and carbon atoms. The material's cubic crystal structure also contributes to its stability, providing excellent mechanical strength and resistance to mechanical stress at high temperatures. SiC's high breakdown field and high saturation velocity make it suitable for high-voltage devices, but there are currently some limitations in its research and development. The most significant limitation is the difficulty in growing thick SiC films with low defect densities. Defects in the films can lead to electrical breakdown and poor reliability of the devices. Additionally, there is a lack of standardized test methods and reliability data for SiC devices, which makes it difficult to predict their performance and long-term reliability in field applications. Another limitation is the high cost of manufacturing SiC devices compared to silicon-based devices. The fabrication process for SiC devices involves complex deposition techniques, such as chemical vapor deposition (CVD) or physical vapor deposition (PVD), and requires high temperatures and specialized equipment, leading to high production costs.

Despite these limitations, SiC devices have potential for future research and development. SiC's wide bandgap energy and high breakdown field make it attractive for use in high-power RF applications such as radar and microwave systems. Additionally, SiC's high temperature stability and chemical inertness make it suitable for use in extreme environments, such as in space or underwater, where traditional silicon devices may fail. Future research in SiC may focus on developing more efficient growth techniques for thick SiC films with low defect densities. Improving the quality of the films will increase the reliability and performance of SiC devices. Additionally, research on more standardized test methods and reliability data will help predict the performance of SiC devices under various operating conditions. Overall, the future outlook for SiC research is promising.The unique combination of physical and chemical properties exhibited by SiC will continue to make it an attractive material for use in high-voltage devices and other applications where traditional silicon devices are challenged.

7. Conclusion

To sum up, this study presents an overview of the principles behind Silicon Carbide's (SiC) ability to withstand high voltages and its use in high-voltage devices. The unique physical and chemical properties of SiC, including its hardness, chemical inertness, and high-temperature stability, contribute to its suitability for use in high-voltage devices. SiC devices are currently being used in a variety of applications, including power conversion, electric vehicles, railways, aviation, and military electronics, where they offer improved efficiency and reduced losses compared to silicon-based devices. However, there are currently some limitations in the research and development of SiC high-voltage devices, including the difficulty in growing thick SiC films with low defect densities and the lack of standardized test methods and reliability data. Nonetheless, the outlook for SiC research is promising, as it has the potential to be used in high-power RF applications and extreme environments where traditional silicon devices may fail. The development of more efficient growth techniques for SiC films, standardized test methods, and reliability data will be important future research directions to improve the performance and reliability of SiC devices.

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