

Comparative Analysis of Sic and Gan: Third-Generation Semiconductor Materials

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Abstract. This article delves into a comprehensive comparative analysis of two prominent third-generation semiconductor materials, silicon carbide (SiC) and gallium nitride (GaN). It explores their foundational theories, practical applications, future prospects, and the hurdles they face in the realm of materials science. SiC is characterized by its impressive thermal conductivity and a wide bandgap, while GaN showcases remarkable electron mobility and high electron saturation velocity. Both materials have demonstrated outstanding capabilities in high-temperature, high-frequency, and high-power electronic devices, finding utility in power conversion, automotive systems, and optoelectronics. Looking forward, SiC and GaN hold tremendous potential in emerging fields such as new energy sources, advanced optoelectronic devices, and semiconductor packaging. Nevertheless, they encounter challenges, including manufacturing costs and the control of crystal defects. In conclusion, these third-generation semiconductors offer extensive possibilities across various domains, although overcoming significant challenges is essential for their widespread integration.

Keywords: Silicon Carbide (SiC), Gallium Nitride (GaN), Third-Generation Semiconductors, Applications and Challenges.

1. Introduction

In the field of materials science, the quest for alternatives to traditional silicon materials has been a constant pursuit of researchers. Silicon carbide (SiC) and gallium nitride (GaN) have emerged as two highly promising materials, showcasing significant potential in the fields of electronics, optoelectronics, and energy applications [1]. This paper aims to conduct a comparative study of these two materials, considering aspects such as fundamental theory, practical applications, future prospects, and challenges.

The paper will commence with an in-depth exploration of the fundamental theory behind silicon carbide and gallium nitride. Silicon carbide is a semiconductor material known for its high thermal conductivity and wide bandgap, while gallium nitride exhibits exceptional electron mobility and high electron saturation velocity. The paper will delve into their development history, crystal structures, band structures, and electronic properties to provide a better understanding of their performance in practical applications. The paper will also focus on the practical applications of silicon carbide and gallium nitride, where they have demonstrated excellent performance in high-temperature, high-frequency, and high-power electronic devices. A comparison of their performance and application prospects in these fields will be presented. The paper will subsequently explore the future developments of silicon carbide and gallium nitride. With advancements in technology, these materials may find broader applications in areas such as new energy sources, novel optoelectronic devices, and semiconductor packaging. The paper will investigate their potential advantages and challenges in these domains and provide insights into their future directions. Finally, the paper will discuss the challenges faced by silicon carbide and gallium nitride, including issues related to cost, fabrication techniques, crystal defects, and design optimization, which have limited their practical applications.

2. Basic Theory Analysis

2.1. Silicon Carbide (SiC)

Silicon carbide, or SiC, was first synthesized by Edward Goodrich Acheson in 1890. He achieved this by heating a mixture of graphite and quartz in an electric arc furnace, successfully synthesizing silicon carbide. In 1893, Henry Moissan also discovered silicon carbide mineral and synthesized it through various methods [2].

Initially, silicon carbide was not employed in electronic devices, but it was used as a material for the first radar detectors. In 1907, the first light-emitting diode (LED) was created using silicon carbide, and it was subsequently confirmed by Soviet scientists in 1923. It wasn't until the 1980s that silicon carbide gained attention in the field of electronics. Due to its outstanding electronic properties, such as high voltage and high-temperature capabilities, silicon carbide found applications in manufacturing power electronic devices like MOSFETs and diodes.

Silicon carbide exists in various crystalline forms, and different polymorphs exhibit different electrical and optical properties. These properties can be controlled and adjusted through different preparation methods and growth conditions to meet specific application requirements. The most common hexagonal crystal structures of silicon carbide, known as α -SiC, are 4H-SiC and 6H-SiC, which form at temperatures above 1700 degrees Celsius [3]. Below 1700 degrees Celsius, silicon carbide adopts the cubic zinc blende crystal structure, known as β -SiC. The structure of SiC is shown in figure 1.

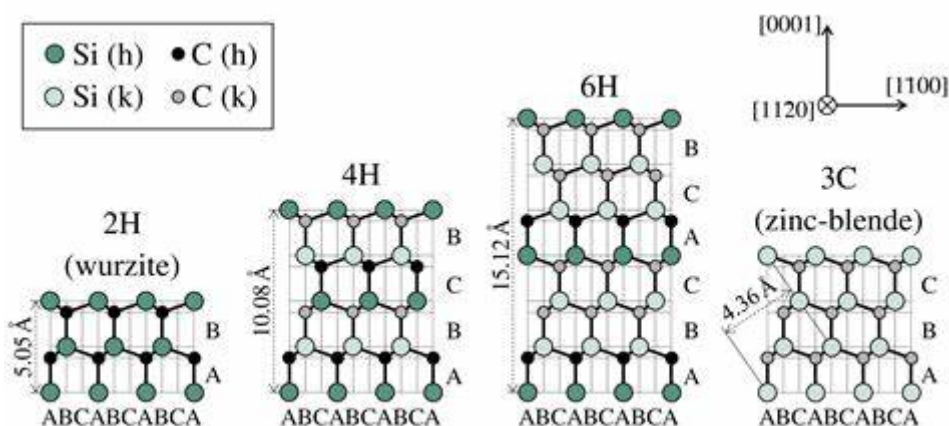


Fig. 1 The structure of SiC [3]

SiC boasts a robust electric field breakdown strength, higher current density, and high thermal conductivity. It can be doped with specific elements to create n-type or p-type semiconductors. For instance, doping with phosphorus introduces additional free electrons for conduction while forming covalent bonds, whereas doping with boron creates holes that serve as charge carriers. These are characteristics of the first type of superconductors [4]. Silicon carbide doped with aluminum (3C-SiC) and boron (3C-SiC and 6H-SiC) falls into the second type of superconductors.

Silicon carbide is highly temperature-resistant, making it suitable for high-temperature applications. It maintains its mechanical strength even at temperatures as high as 1400 degrees Celsius. Additionally, silicon carbide exhibits relatively high thermal conductivity, allowing for efficient heat transfer and enabling devices to operate at higher efficiency.

Its low coefficient of thermal expansion minimizes thermal expansion and contraction of materials, optimizing device performance in high-temperature environments. Silicon carbide possesses chemical inertness and corrosion resistance, making it suitable for applications in harsh environments.

2.2. Gallium Nitride (GaN)

The synthesis methods for gallium nitride were first proposed by Maruska and Tietjen in 1969, but it only gained widespread attention in the late 1980s. In the 1990s, gallium nitride started to find

extensive applications in the optoelectronic device field. The structure of gallium nitride is a hexagonal close-packed structure composed of gallium and nitrogen atoms. Each gallium atom is surrounded by four nitrogen atoms, while each nitrogen atom is surrounded by six gallium atoms. The crystal structure of gallium nitride can be adjusted by controlling growth conditions and introducing impurities to meet the requirements of different applications [5]. The structure of GaN is shown in figure 2.

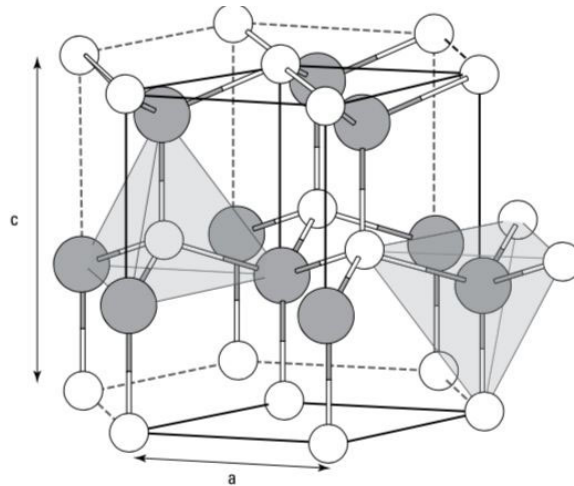


Fig. 2 The structure of GaN [5]

Gallium nitride possesses a wide bandgap, typically around 3.4 electron volts (eV). This allows gallium nitride to absorb high-energy light, making it widely used in optoelectronic devices.

Gallium nitride exhibits high electron mobility, indicating fast electron movement within the material. This advantage makes gallium nitride suitable for high-frequency and high-power applications. Gallium nitride also demonstrates good thermal stability, maintaining its electronic and optical properties in high-temperature environments. This potential is particularly valuable for high-temperature electronic devices and lighting applications. Gallium nitride boasts a high electron saturation velocity, meaning that electron speed does not continue to increase under high electric fields. These characteristic positions gallium nitride favorably in high-power applications, such as power amplifiers and converters [6]. The material also has a high electron concentration, implying a substantial number of free electrons within it. This characteristic gives gallium nitride an advantage in high-frequency and high-power applications, such as RF devices and power electronic devices. Gallium nitride possesses high mechanical strength and chemical stability, ensuring its reliability and stability in high-temperature and high-pressure environments, even when operating in harsh conditions. Gallium has high thermal conductivity, effectively dissipating heat to help devices maintain performance and unleash their full potential.

2.3. Comparison

Compared to materials like Si and GaAs, which have bandgaps of 1.12 eV and 1.43 eV, respectively, SiC and GaN have wider bandgaps of 3.2 eV and 3.4 eV. This wider bandgap allows them to have higher melting points, enabling them to withstand higher temperatures and better endure radiation damage, ultimately making them suitable for operation in harsher environments.

Both SiC and GaN exhibit improved thermal conductivity compared to GaAs and Si (from left to right, respectively: 4.9 W/(cm·K), 1.7 W/(cm·K), 0.46 W/(cm·K), and 1.5 W/(cm·K)). Enhanced thermal conductivity means that heat can be dissipated more efficiently, allowing devices to generate more heat in the same amount of time, thereby improving their overall performance [7].

Wide bandgap semiconductors have higher breakdown electric fields, which determine the maximum operating voltage, power, and power density of devices. At the same voltage, a higher breakdown electric field allows for higher doping levels, resulting in more compact device sizes. This

has multiple benefits, such as reducing parasitic resistance and enabling higher operating frequencies and voltages, ultimately leading to better device performance.

GaN and SiC have saturation electric field values of approximately 1.5×10^4 V/cm to 2.5×10^4 V/cm, significantly higher than GaAs and Si. The saturation electric field determines the saturation speed of charge carriers, thereby influencing the frequency performance. Wide bandgap semiconductors with low carrier mobility and high saturation electric fields result in higher knee voltage, leading to higher system frequencies [8].

One of the drawbacks of wide bandgap semiconductors is their lower carrier mobility, which increases device losses, parasitic resistance, and exacerbates temperature rise. This limitation is observed in SiC and GaN, restricting their use in p-type doping scenarios.

3. Analysis of application scenarios

3.1. Analysis of Silicon Carbide Applications

Silicon carbide (SiC) exhibits outstanding performance in power electronic devices, especially in high-temperature and high-voltage environments. SiC MOSFETs and SiC Schottky diodes are widely used, offering higher efficiency and smaller form factors. They feature low on-resistance, high switching speeds, and low switching losses, making them suitable for efficient power converters, inverters, and rectifiers. These devices find applications in high-frequency and high-temperature environments across various industrial sectors. For instance, companies like Maple Semiconductor offer such products.

SiC is also applied in power transmission and distribution systems. Due to its high voltage and high-temperature characteristics, SiC can reduce energy losses and enhance the efficiency and reliability of power systems. Products like Alpha Power Solutions ACD06PS065, with specifications of 6A 650V, can operate at high frequencies, resulting in faster operation [9]. They have zero forward/reverse recovery time, allowing immediate response and adjustment when the current direction changes, demonstrating excellent performance in terms of efficiency and accuracy. These devices are suitable for AC/DC converters, DC/DC converters, and uninterruptible power supplies (UPS).

Moreover, SiC is increasingly prevalent in the automotive industry. Its high-temperature resistance and high-power density make it an ideal choice for electric vehicles and hybrid vehicles, offering higher efficiency and longer driving ranges [10]. SiC is also becoming more common in electric vehicle charging stations. Its high-temperature capability and high-power density make it a critical component, enabling higher power output and improved efficiency.

3.2. Practical Applications of Gallium Nitride (GaN)

Power Electronic Devices: Gallium nitride (GaN) excels in power electronic devices, especially in high-frequency and high-power applications, where it offers higher efficiency and smaller form factors. For example, Dongke's high-performance AC-DC GaN power management chip, DK065G, detects the voltage (VDS) between the drain and source of power transistors. It turns on the power transistor when VDS reaches its minimum, reducing switching losses and improving electromagnetic interference [11]. This technology is suitable for a wide range of chargers and power adapters.

GaN also has significant potential in the automotive industry. For instance, Navitas has introduced the third generation GaNFast IC products, which enhance system parameter sensing in real-time, including current and temperature, by increasing integration levels. This technology can further improve energy efficiency by up to 10% and minimize the number of external components and system footprint. Navitas' GaNSense technology can quickly identify potentially hazardous system conditions and provide protection within 30 ns of detection, enhancing system reliability. This solution is suitable for designs in the power range of 2 kW to 20 kW.

Compared to motors that used to operate at a constant speed and output torque, modern technology requires variable speed drives (VSDs) in many applications. Integrated half-bridge power

components play a crucial role in many power conversion systems, and motor inverters are no exception. In motor inverter system design, integrated half-bridge power components are used for power factor correction (PFC) and the inverter stage. The design examples include a compact and efficient auxiliary power supply using active clamp flyback (ACF) quasi-resonant (QR) topology. Fully integrated GaN half-bridges support simpler designs compared to discrete methods and offer many advantages [12]. Motor inverters using GaNFast half-bridges provide compact and efficient power stages, significantly reducing cooling requirements. PFC, once again using GaNFast, achieves maximum efficiency and minimal external passive component count and footprint. Fully integrated GaN half-bridges have similar or better reliability compared to traditional silicon or GaN discrete designs while retaining superior performance. While concerns may arise about the robustness of new components compared to older, larger chips, GaN power switches can unlock their full performance potential only when well-protected. Integrated protection circuits with GaN micro-adjustments provide similar or better reliability compared to traditional silicon components while retaining superior performance.

4. Challenges and Prospects

4.1. Challenges in Third-Generation Semiconductor Materials

Third-generation semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN), hold immense potential in various fields like power electronics and optoelectronics. However, they face several challenges compared to traditional silicon materials:

The manufacturing cost of third-generation semiconductor materials is currently relatively high. This is primarily due to the need for high-temperature and high-vacuum environments during the manufacturing process, along with complex fabrication steps. Reducing manufacturing costs is a critical challenge to drive the commercialization of third-generation semiconductors.

Crystal quality and defect control are crucial issues for third-generation semiconductor materials. Since these materials have different characteristics and structures compared to traditional silicon, more research and optimization are required [13]. Crystal defects can affect device performance and reliability, making it important to improve crystal quality and defect control techniques.

Scaling up and integration of third-generation semiconductor materials also pose challenges. While some progress has been made, further technological development is needed to achieve large-scale production and integration.

Third-generation semiconductor materials have high thermal conductivity and low thermal resistance, making thermal management a challenge. Effective heat management is critical to ensure device performance and reliability, especially in high-power and high-temperature applications.

Device design and optimization for third-generation semiconductor materials are also challenging. Due to the different characteristics and processes of these materials, device structures and operation principles need to be redesigned and optimized to achieve higher performance and efficiency.

Standardization and reliability of third-generation semiconductor materials are challenges as well. Establishing uniform standards and testing methods is crucial for driving the commercialization of third-generation semiconductors.

4.2. Prospects

Third-generation semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN), offer numerous advantages and hold great promise in the future of the semiconductor industry. Here are some prospects for third-generation semiconductors:

Third-generation semiconductor materials have high voltage tolerance and low on-resistance, making them highly promising for high-power applications. For example, SiC and GaN devices can be used in electric vehicles, solar inverters, and industrial drives, improving energy conversion efficiency and reliability.

Third-generation semiconductor materials have high electron mobility and high-frequency characteristics, making them suitable for a wide range of high-frequency communication and radar systems. For instance, GaN devices can be used in 5G communication systems and high-frequency electronic devices, providing faster data transmission and higher bandwidth.

Third-generation semiconductor materials exhibit excellent high-temperature stability and corrosion resistance, making them potential candidates for high-temperature applications. For example, SiC devices can be used in high-temperature sensors, high-temperature electronic devices, and high-temperature power electronic systems, driving advancements in aerospace, energy, and industrial sectors [14].

Third-generation semiconductor materials also hold great promise in the field of optoelectronics. Due to their wide bandgap and high electron mobility, SiC and GaN can be used to manufacture high-power laser diodes, photodetectors, and optical fiber communication systems, advancing optical communication and storage technologies.

Third-generation semiconductor materials with low conduction and switching losses offer higher energy conversion efficiency. This makes them suitable for energy-efficient and environmentally friendly applications, such as energy conversion and lighting, reducing energy consumption and carbon emissions.

Third-generation semiconductor materials have important prospects in the field of new energy sources. For example, SiC and GaN devices can be used in solar power generation systems and wind energy conversion systems, improving energy conversion efficiency and the utilization of renewable energy sources.

These prospects indicate that third-generation semiconductor materials will drive technological innovations and applications in multiple fields. With ongoing technological advancements and in-depth research into these materials, third-generation semiconductors are expected to become a significant component of the future semiconductor industry.

5. Conclusion

This article has explored two highly regarded third-generation semiconductor materials, silicon carbide (SiC) and gallium nitride (GaN) and conducted a comparative study in the field of materials science, covering basic theory, practical applications, future prospects, and challenges. The following is a comprehensive analysis and conclusion regarding these two materials:

Firstly, silicon carbide is a semiconductor material with high thermal conductivity and a wide bandgap, while gallium nitride exhibits excellent electron mobility and high electron saturation velocity. Their development history, crystal structures, band structures, and electronic properties have been discussed in-depth in the basic theory analysis.

Secondly, silicon carbide and gallium nitride have demonstrated outstanding performance in practical applications, especially in high-temperature, high-frequency, and high-power electronic devices. Their low on-state resistance, high switching speed, and low switching losses make them suitable for efficient power converters, inverters, and rectifiers. Furthermore, they find extensive applications in power transmission, automotive, charging stations, and optoelectronics.

Additionally, the article has looked into the future prospects of silicon carbide and gallium nitride. These two materials hold great potential in areas such as new energy sources, advanced optoelectronic devices, and semiconductor packaging. Their high voltage tolerance, high electron mobility, high-frequency characteristics, and high-temperature stability are expected to drive technological innovations in these fields.

Lastly, the article has highlighted the challenges faced by silicon carbide and gallium nitride, including manufacturing costs, crystal quality and defect control, size scalability and integration, thermal management, device design, and standardization. Addressing these challenges will require ongoing research and technological advancements.

In conclusion, silicon carbide and gallium nitride, as third-generation semiconductor materials, show immense promise in various domains. Their exceptional performance and diverse application prospects will propel continuous advancements in semiconductor technology, leading to innovations in fields such as new energy sources, telecommunications, electric power, automotive, and photonics. However, overcoming the challenges ahead remains a crucial direction for future research and development to realize the widespread commercial applications of these materials.

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