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From Silicon to Wide Bandgap Semiconductors: Exploration of Compound Semiconductors in High Frequency and High Power Devices

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Abstract. As electronic systems become more demanding in terms of power density, thermal stability, and operating frequency, the performance limitations of traditional silicon-based semiconductors become increasingly apparent. The superior electrical and thermal properties of compound semiconductors like gallium nitride (GaN) and silicon carbide (SiC) have led to their classification as wide-bandgap (WBG) materials, attracting significant attention for their potential to meet the demands of next-generation devices. This study begins by comparing the key physical properties of typical semiconductor materials, including Si, GaAs, GaN and SiC. Then, the advantages of compound semiconductors in high-frequency and high-power applications are studied through representative scenarios such as 5G RF power amplifiers, electric vehicle (EV) power modules, and photovoltaic inverters. This study uses a qualitative approach, integrating insights from recent academic literature and industry case studies. The research show that GaN and SiC have significant advantages in terms of energy efficiency and thermal management, making them strong candidates to replace silicon in advanced electronic systems. GaN is particularly well-suited for high-frequency and RF applications, whereas SiC excels in high-voltage and power conversion scenarios. Their complementary nature also provides opportunities for heterogeneous integration. This paper concludes that the future development of compound semiconductors will focus on advancing ultra-wide bandgap materials and achieving heterogeneous integration for superior performance, while the main challenges lie in reducing manufacturing costs, improving material quality, and enhancing long-term device reliability.

Keywords: Compound semiconductor, Gallium nitride, Silicon carbide, High power devices, Wide bandgap materials

1. Introduction

Silicon (Si) has dominated semiconductors for decades due to its cost-effectiveness and established manufacturing infrastructure. However, its inherent limitations in breakdown fields and thermal conductivity restrict its performance in high-frequency and high-power applications [1,2]. Consequently, wide-bandgap (WBG) semiconductors like gallium nitride (GaN) and silicon carbide

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(SiC) have emerged as promising alternatives, offering superior breakdown voltage, thermal stability, and switching performance [3-5]. These materials are crucial for next-generation power electronics and RF systems, especially with the rapid development of technologies like 5G, electric vehicles, and renewable energy systems, which expose the limitations of silicon-based semiconductors [4,5].

This study explores the potential and challenges of compound semiconductors across three core analytical layers:

First, material level: How do GaN and SiC's physical properties, such as bandgap, thermal conductivity, and breakdown field strength, compare to traditional semiconductors like Si and GaAs?

Second, device level: What is the performance of GaN and SiC devices under high-frequency (e.g., RF power amplifiers) and high-power (e.g., EV inverter modules) conditions?

Third, system and industry level: What are the current manufacturing, cost, and reliability challenges for deploying GaN and SiC devices? How can future developments like heterogeneous integration, advanced packaging, or ultra-wide-bandgap materials address these challenges and enable wider commercialization?

This paper uses a qualitative research approach, including literature comparative analysis and case studies, to systematically review relevant publications and compare the properties of various semiconductor materials [1,2]. This study compares gallium nitride and silicon carbide, revealing their performance benefits, application suitability, and technical hurdles in advancing efficient, reliable power electronics, while also highlighting emerging trends like GaN-on-SiC integration and ultra-wide-bandgap materials (e.g., Ga_2O_3, diamond) that may shape the future of semiconductor innovation [6,7].

2. Comparative analysis of properties of semiconductor materials

2.1. Key physical and electrical parameters

Semiconductor properties are predominantly determined by intrinsic physical parameters, including band gap, breakdown field, thermal conductivity, electron mobility, and saturation velocity. This section presents a comparative analysis of Si, GaAs, GaN, and SiC based on these key metrics. Silicon has a medium band gap (1.1 eV) and performs well at low to medium power, but is limited at high pressure or high temperature conditions. Gallium arsenide has high electron mobility, but it has problems of mechanical brittleness and high cost. In contrast, GaN and SiC, wide bandgap semiconductors with band gaps of approximately 3.4 eV and 3.3 eV, respectively, exhibit superior breakdown fields (>3 MV/cm) and exceptional thermal stability, rendering them highly suitable for demanding environments. GaN's high electron saturation speed (~2.5 × 10^7cm/s) supports faster switching, while SiC excels in low on-resistance and thermal conductivity, enhancing power density and heat dissipation [2,3,5].

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Table 1: Key physical and thermal parameters of representative semiconductormaterials [2,3,5]

Property	Si	GaAs	GaN	SiC
Bandgap (eV)	1.1	1.42	~3.4	~3.3
Breakdown Field (MV/cm)	~0.3	~0.4	~3.3	~3.0
Thermal Conductivity (W/cm·K)	1.5	0.46	~1.3	~4.9
Electron Mobility ($cm^2/V·s$)	1400	8500	~1500	~900
Saturation Velocity (cm/s)	$1×10^7$	$2×10^7$	$2.5×10^7$	$2×10^7$

Table 1 summarizes the fundamental physical and electrical characteristics of typical semiconductor materials, highlighting the superiority of GaN and SiC in high-voltage and high-temperature applications.

2.2. Advantages in harsh operating conditions

In high-stress scenarios such as power conversion and RF electronics, GaN and SiC are superior to Si due to their strong thermal and electrical properties. GaN's switching speed facilitates RF and microwave devices, while SiC's mechanical strength and high voltage capacity are suitable for industrial and automotive power systems. While silicon remains cost-effective, WBG materials offer significant long-term system-level gains in performance and reliability [1,6].

3. Device-level performance in high-frequency and high-power scenarios

3.1. GaN for RF and microwave applications

Gallium nitride-based high electron mobility transistors (HEMTs) have revolutionized high-frequency electronics. These devices provide high gain, power density (> 10w /mm) and efficiency (>70%) in 5G RF amplifiers, radar and satellite systems [3]. Gallium nitride's high breakdown voltage and heat resistance reduce cooling requirements for a compact, efficient design.

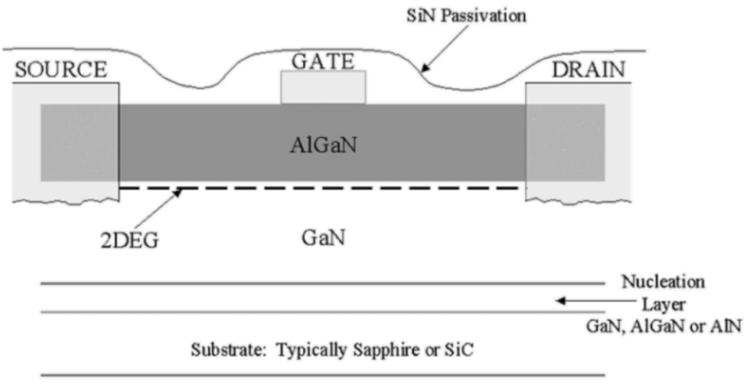


Figure 1: Basic HEMT structure [3]

Figure 1 illustrates the cross-sectional structure of a GaN HEMT, which enables high breakdown voltage and high-frequency operation.

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3.2. SiC in power conversion applications

SiC MOSFETs and Schottky diodes are widely used in electric vehicle inverters, renewable energy systems and industrial motor drives. High breakdown voltage, low switching loss and excellent thermal conductivity make the system efficient, compact and reliable. In electric vehicles, silicon carbide inverters improve energy efficiency and extend driving range. The thermal robustness of SiC ensures long-term reliability at higher operating temperatures [2,8].

Figure 2 illustrates two typical structures of SiC MOSFETs: (a) planar structure and (b) trench structure. Compared to planar designs, trench MOSFETs offer higher channel density and lower on-resistance by utilizing vertical conduction paths, making them more suitable for high-current, low-loss applications.[2]

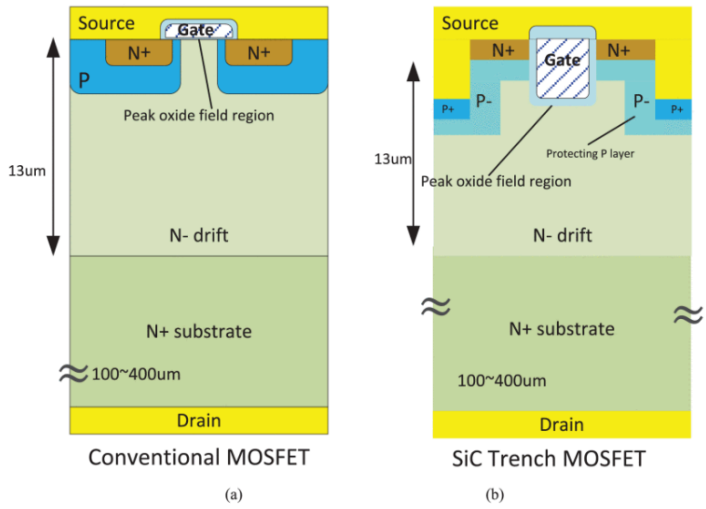


Figure 2: Two typical SiC MOSFET structures: (a) planar and (b) trench. Epi thickness is typical of a 1200-V device [2]

4. Engineering challenges and future opportunities

4.1. Manufacturing and cost barriers

Despite the performance advantages, cost remains a key barrier. GaN often requires heteroepitaxial growth on mismatched substrates, such as sapphire or Si, resulting in a high defect density. GaN-on-Si technology reduces costs, but introduces thermal mismatch problems. SiC wafer processing technology is mature, but due to the material hardness and slow growth rate, the cost is high. Defects such as micropipe defects affect the yield and reliability of the device [4,8].

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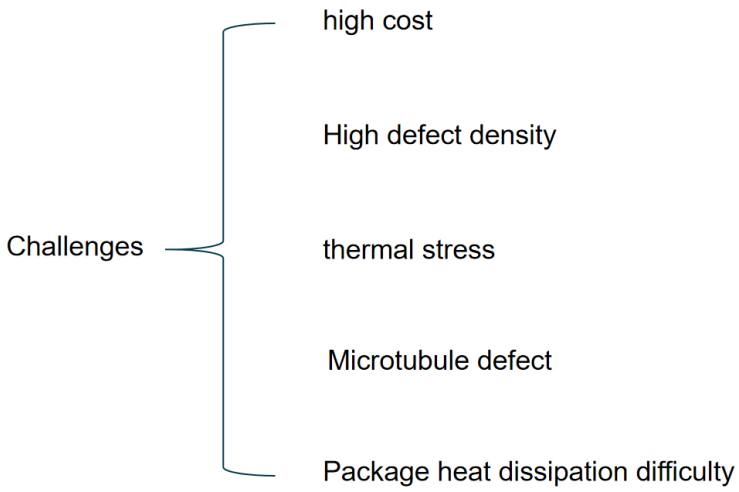


Figure 3: Key manufacturing and packaging challenges in GaN and SiC device deployment

Figure 3 highlights the main technological bottlenecks limiting the large-scale adoption of compound semiconductors.

4.2. Reliability, packaging, and thermal management

Under high stress conditions, equipment reliability is still a concern. GaN is susceptible to dynamic R_{on} degradation and capture effects. SiC, while more thermally stable, requires advanced packaging for optimal heat dissipation. Emerging solutions include silver sintering, double-sided cooling and new thermal interface materials. Automotive and aerospace applications further require powerful gate drivers and protection circuits [4].

4.3. Future trends beyond GaN and SiC

The research is being extended to ultra-wide bandgap (UWBG) materials, such as gallium oxide (Ga_2O_3) and diamond, which offer higher breakdown fields and thermal conductivity. Heterogeneous integration strategies (for example, GaN-on-SiC) can combine material advantages. As manufacturing technology advances, these approaches are expected to redefine the performance standards for power and RF electronics [6,7].

5. Conclusion

In this paper, the transition from traditional Si to wide bandgap compound semiconductors is discussed, with emphasis on GaN and SiC in high frequency and high power electronic systems. Through multi-scale comparative analysis, the study highlights the superior performance of GaN and SiC in terms of breakdown voltage, thermal conductivity and switching efficiency. GaN shows clear advantages in RF and microwave applications, while SiC is well suited for high-voltage power conversion scenarios such as electric vehicles and renewable energy systems.

Despite their potential, widespread deployment of GaN and SiC is still limited by high manufacturing costs, substrate compatibility issues, and reliability issues under extreme conditions. GaN-on-Si is subject to thermal mismatch and defect density, while SiC machining remains expensive and prone to defects.

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This study relies on literature analysis and lacks empirical verification and real-time reliability test. Future research should address long-term device aging behavior and explore scalable, cost-effective manufacturing methods.

In addition, ultra-wide bandgap materials (e.g., Ga_2O_3, diamond) and heterogeneous integrations (e.g., GaN-on-SiC) represent promising directions for future exploration. Continued advances in materials engineering, packaging, and thermal management are critical to unlocking the full potential of WBG semiconductors in next-generation power electronics. These developments will ultimately enable the next generation of power electronics for autonomous systems, aerospace platforms, and ultra-efficient energy networks.

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