Dean&Francis
ISSN 2959-6157

The comparison between the WBG semiconductors

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Abstract:

Silicon carbide (SiC) MOSFETs and gallium nitride (GaN) HEMTs, as representative wide-bandgap (WBG) power devices, are accelerating the shift beyond conventional silicon technology by enabling higher efficiency, higher power density, and operation at elevated switching frequencies. This paper provides a comparative assessment of SiC MOSFETs and GaN HEMTs using a set of core performance metrics that are most relevant to practical converter design, including thermal robustness, short-circuit tolerance, switching speed, and the resulting implications for efficiency and reliability. Drawing on published research and experimental reports from 2022–2024, the study shows that SiC MOSFETs offer clear advantages in high-temperature stability and short-circuit ruggedness, making them a strong candidate for harsh, high-power operating conditions. In contrast, GaN HEMTs demonstrate superior high-frequency switching capability, supporting compact passive components and high-density converter layouts, but they typically encounter greater reliability challenges under severe electrical and thermal stress. Therefore, device selection should be driven by application requirements: SiC is generally preferable for high-power, high-temperature, and reliability-critical systems, whereas GaN is more suitable for high-frequency, compact, and fast-dynamics power conversion.

Keywords: Wide bandgap semiconductor; SiC MOSFET; GaN HEMT; power electronics; reliability; switching performance.

1. Introduction

In power conversion systems, continuous efforts are made to improve efficiency, increase power density, and enhance thermal performance. This has led to the widespread adoption of Wide Bandgap (WBG) semiconductors. Due to their larger bandgaps compared to silicon, SiC and GaN enable devices to operate at higher switching frequencies, voltages, and temperatures [1]. The GaN HEMT and the SiC MOSFET are two major WBG power devices. Although both are WBGs, their material properties and device structures lead to significantly different performance characteristics. This paper compares these two device types across multiple critical aspects, including device structure, primary applications, switching characteristics, control methods, temperature behavior, reliability, and short-circuit withstand capability, based on the latest research published between 2022 and 2024.

2. Comparative Performance Analysis

2.1 Device Structure and Key Application

2.1.1 SiC MOSFET Structure and Applications

The SiC MOSFET commonly employs a Vertical Double Diffused Metal Oxide Semiconductor (VDMOS) structure. Currently it flows vertically from the source to the drain through a channel at the surface. This vertical design enables high breakdown voltage and low specific on-resistance. Advanced trench gate structures in modern SiC MOSFETs further reduce specific on-resistance (Rsp), with values below 2.2 mΩ·cm² for 1200V devices [2]. Enhanced gate oxide reliability, achieved through improved oxidation and annealing processes, allows for stable operation at high electric fields [3]. SiC MOSFETs are predominantly used in high-voltage and high-temperature applications such as electric vehicle traction inverters, onboard chargers, industrial motor drives, and renewable energy systems like solar and wind power converters.

2.1.2 GaN HEMT Structure and Applications

The GaN HEMT is fundamentally a lateral device. Its operation relies on a two-dimensional electron gas (2DEG) channel formed at the AlGaN/GaN heterojunction interface. This channel provides extremely low on-resistance and high electron mobility, enabling very fast switching. Advances in GaN-on-Si technology have achieved breakdown voltages up to 900V with specific on-resistance under 1.5 mΩ·cm² [4]. The use of carbon-doped buffer layers and advanced field plate designs mitigates dynamic R_DS(on) degradation [5]. p-GaN gate technology is the primary solution for enhancement-mode operation, offering stable threshold voltage [6]. Owing to its superior high-frequency performance and lateral structure, GaN HEMTs are ideal for high-power-density applications, including wireless power transfer, laptop adapters, data center server power supplies (e.g., 48V conversion), and fast chargers for mobile devices [3, 5].

2.2 Switching Characteristics and Control Methods

2.2.1 Comprehensive Switching Performance Analysis

Switching speed is a major differentiator. GaN HEMTs generally exhibit superior switching performance compared to SiC MOSFETs. They have significantly lower gate charge (Q_g) and output capacitance (C_oss), and their inherent reverse conduction mechanism results in virtually no reverse recovery charge (Q_rr). For instance, 650V GaN HEMTs can achieve switching times below 10ns, enabling MHz-range operation in LLC converters with high efficiency [7]. In totem-pole PFC circuits, they can operate at 300-500kHz without Q_rr-related losses [8]. SiC MOSFETs, while faster than silicon IGBTs, are slower than GaN HEMTs. Contemporary 1200V SiC MOSFETs are suitable for 100-500 kHz applications, with switching times typically between 15-25ns [9]. Their body diode exhibits a small but non-negligible Q_rr, which contributes to switching losses in hard-switching topologies, limiting their maximum practical frequency to several hundred kHz.

2.2.2 Methods of Advanced Control

The gate driving and control requirements for these devices also differ.

SiC MOSFETs typically require a higher gate drive voltage (e.g., +15V to +20V for turn-on, and 0V to -5V for turn-off) to ensure full enhancement and prevent dv/dt-induced turn-on. Modern gate driver ICs integrate features like desaturation detection, active Miller clamps, and soft-turn-off circuits [10]. Adaptive gate driving strategies can further reduce switching losses [11].

GaN HEMTs have a lower threshold voltage and a narrow gate-source voltage margin (typically around +6V), making them sensitive to overvoltage and requiring precise, low-inductance gate loops. Monolithically integrated GaN ICs, which combine the driver and HEMT, minimize parasitic inductance for clean, high-speed switching [12]. Dedicated gate drivers are essential for optimal performance at multi-MHz frequencies [13].

2.3 Temperature Characteristics

WBG semiconductors exhibit a stronger temperature dependence than silicon, yet maintain superior high-temperature performance.

SiC MOSFETs: Channel carrier mobility decreases with temperature, increasing on-resistance. However, their temperature coefficient remains favorable compared to silicon. Modern devices maintain good switching and conduction performance at junction temperatures exceeding 175°C, suitable for automotive and industrial applications [14].

GaN HEMTs: The 2DEG channel exhibits low negative temperature dependence for static on-resistance. However, the degradation of dynamic on-resistance after high-volt-

ISSN 2959-6157

age switching can be significantly exacerbated at elevated temperatures, posing thermal management and circuit design challenges [15].

2.4 Reliability

Reliability encompasses failure mechanisms and long-term operational stability.

SiC MOSFET Reliability: Primary concerns include threshold voltage (Vth) shift and gate oxide integrity under high-field stress. Advances in interface passivation techniques have substantially improved gate oxide reliability and Vth stability, extending device lifetime [16].

GaN HEMT Reliability: Challenges for GaN-on-Si devices include current collapse (dynamic RDS(on) degradation) and trap-related effects. The absence of a high-quality native oxide in structures like p-GaN gates can lead to gate leakage and dynamic behavior issues during reverse conduction. Ongoing research focuses on epitaxial growth optimization, advanced field plate design, and cascode structures to enhance robustness [17].

2.5 Short Circuit Withstanding Capacity

The ability to withstand short-circuit faults is critical for safety-sensitive applications like motor drives.

SiC MOSFETs typically have a short-circuit withstand time (SCWT) of 3-5 µs. Their vertical structure and good thermal conductivity aid in heat dissipation during a fault, though fast protection circuits are still required [18].

GaN HEMTs generally have a much shorter SCWT, often less than 1 µs. Their lateral structure and high-power density lead to rapid temperature rise during a short circuit, necessitating the development of novel, ultra-fast protection schemes for high-power applications.

3. Conclusion

The comparison underscores the complementary strengths of SiC and GaN technologies. SiC, with its robust vertical structure, offers established reliability, excellent high-temperature and high-power capability, and moderate short-circuit ruggedness, making it the preferred choice for electric vehicles and industrial drives. Conversely, GaN technology, leveraging its lateral HEMT design and 2DEG channel, achieves unparalleled switching speed and efficiency, enabling ultra-compact power adapters and data center power supplies. However, it requires careful management of dynamic effects and has limited intrinsic short-circuit capability. Continued advancements in materials science, packaging, and driver integration will further push the performance boundaries of both technologies, expanding their respective and potentially overlapping application fields.

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