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Beyond silicon: technological development and applications of SiC and GaN wide-bandgap semiconductors

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Abstract. Semiconductors play a crucial role in electronic engineering, with both fields mutually reinforcing each other to drive technological progress. In modern electronic engineering, semiconductor materials serve as indispensable foundational materials. In recent years, the continuous expansion of semiconductor materials' application scope in electronic engineering has significantly enhanced the technological level of semiconductor material preparation. Conversely, the rapid evolution of electronic engineering has increased performance demands for semiconductor materials, leading to swift iterations in their development. This paper focuses on commercially available GaN and SiC power transistors, highlighting the characteristic advantages of these two new materials through qualitative analysis based on relevant literature. It introduces the application of Silicon Carbide (SiC) in Tesla and explains the function of Gallium Nitride (GaN) in 5G communications. The findings reveal that these two materials have created new breakthroughs and possibilities for scientific and technological development. However, their practical applications are limited due to the generally cumbersome preparation processes and high requirements for experimental conditions.

Keywords: SiC, GaN, MOSFETs, 5G

1. Introduction

As the cornerstone of the modern electronics industry, semiconductor technology has undergone a developmental trajectory since the mid-20th century, progressing from first-generation semiconductors such as germanium (Ge) and silicon (Si) to second-generation semiconductors like Gallium Arsenide (GaAs) and Indium Phosphide (InP). It has now entered the era of third-generation semiconductors, typified by wide-bandgap semiconductors such as silicon carbide (SiC) and Gallium Nitride (GaN). Each transformative innovation in semiconductor materials has significantly propelled the advancement of the electronic engineering field, giving rise to a series of technological and product revolutions of landmark significance.

Advanced semiconductor materials such as SiC and GaN, by virtue of their unique physical properties, exhibit remarkable advantages over traditional semiconductor materials in aspects including wide bandgap, high electron mobility, and high thermal conductivity, thereby bringing new development opportunities to the electronic engineering field. Against the backdrop of increasingly severe energy constraints and the continuous elevation of performance requirements for electronic products, the application of advanced semiconductor materials is of critical importance for enhancing the efficiency of electronic systems, reducing their volume, and improving their reliability. As such, these materials have become a pivotal force driving the sustained progress of electronic engineering technologies.

In this context, SiC and GaN emerge as standout materials. Their superior characteristics—higher breakdown voltage, lower on-resistance, and higher thermal conductivity—compared to traditional silicon (Si) enable excellent performance in high-power and high-frequency applications. These materials are used to manufacture power electronic devices that often outperform existing silicon-based semiconductors. SiC and GaN are particularly effective for high-voltage switches in power converters (both DC-AC inverters and DC-DC converters). Notably, they are among the most mature and industrialised: several commercial devices with several commercial devices currently available and adopted across various applications [1].

This paper introduces SiC and GaN transistors that have currently been commercialized, providing a detailed analysis of the characteristics of devices based on these materials. Additionally, it presents the current commercial applications of semiconductor materials, offering theoretical support for readers intending to carry out more in-depth research and discussion on such semiconductor materials.

2. Advantages

The device structures and materials (Si/GaN/SiC) used in semiconductor devices differ, leading to variations in applicable power capacity and operating frequency bands. Historically, silicon (Si) has dominated this field. However, due to market demands for high-frequency operation and high power, GaN and SiC have gained attention. Compared with Si, GaN and SiC feature wider bandgaps, offering superior advantages in voltage resistance, thermal conductivity, and electron mobility. These properties enable them to perform effectively in high-temperature, high-current, high-voltage, and high-frequency environments [3]. Table 1 reports the relevant physical properties of these semiconductors and their comparisons with silicon

Table 1. Main material properties for mature and promising, research-grade, semiconductors for power electronics [2]

Properties	Si	4H - SiC	GaAs	GaN
Crystal Structure	Diamond	Hexagonal	Zincblende	Hexagonal
Energy Gap: Eg(eV)	1.1	3.26	1.43	3.5
Electron Mobility: μ_n(cm^2/Vs)	1400	900	8500	1250
Hole Mobility: μ_p(cm^2/Vs)	500	100	400	200
Breakdown Field: $E_{((B))}$(V/cm)×10^5	0.3	3	0.4	3
Thermal Conductivity (W/cm·°C)	1.5	4.9	0.5	1.3
Saturation Drift Velocity: V_s(cm/s)×10^7	1	2.7	2	2.7
Relative Dielectric Constant: ε_r	11.8	9.7	12.8	9.5
p.n Control	○	○	×	△
Thermal Oxide	○	○	×	×

2.1. SiC

SiC is a compound semiconductor material composed of Si and carbon (C). Its dielectric breakdown field strength is 10 times that of Si, and its bandgap is three times larger. Additionally, during device fabrication, it allows for controlled p-type and n-type doping within a wide range, making it a power device material that surpasses the limitations of Si.

Owing to its 10× higher dielectric breakdown field strength than Si, SiC enables the fabrication of high-voltage power devices (600 V to several thousand volts) with drift layers of higher impurity concentration and thinner thickness compared to Si devices. The drift layer's impedance is the primary determinant of the impedance of high-voltage power devices. As a result, high-voltage devices with very low on-resistance per unit area may be made utilizing SiC. The drift layer impedance per unit area of SiC can theoretically be lowered to 1/300th of that of Si for devices with the same voltage rating.

In Si-based materials, to address the increase in on-resistance associated with higher voltage ratings, minority carrier devices such as Insulated Gate Bipolar Transistors (IGBTs) are commonly used. However, these suffer from significant switching losses, and the resulting heat generation limits the high-frequency operation of IGBTs. In contrast, SiC can achieve high voltage and low impedance in MOSFETs without requiring conductivity modulation. Moreover, MOSFETs inherently do not generate tail currents. Therefore, replacing IGBTs with SiC-MOSFETs can significantly reduce switching losses and enable miniaturization of heat dissipation components [4]. These characteristics collectively enable the simultaneous realization of "high voltage resistance," "low on-resistance," and "high frequency operation."

2.2. GaN

GaN is a compound semiconductor material composed of gallium (Ga) and nitrogen (N). Compared with the physical properties of Si, GaN exhibits more superior physical characteristics in high-temperature operation, high-speed operation, maximum operating voltage, and low power consumption. Additionally, GaN has a wider bandgap than Si, earning it the designation of "wide-bandgap semiconductor." The wider the bandgap, the higher the achievable voltage resistance. Transistors using this GaN material are referred to as "GaN HEMTs (High Electron Mobility Transistors)."

Compared with the currently dominant semiconductor material Si, GaN HEMTs feature lower conduction losses (low on-resistance) and excellent high-speed switching performance, capable of meeting market demands for improved power conversion efficiency and miniaturization [5, 6]. At the same time, the industry's commercial path is the low-cost AlGaN/GaN HFET produced on Si with a lateral structure [6]. GaN HEMTs have found increasingly widespread applications in the high-frequency range with moderate voltage ratings.

3. Current applications

3.1. SiC MOSFETs on Tesla

Tesla has used SiC devices as core components of traction inverters in its electric vehicles since 2017. The high efficiency and power density of SiC devices give them significant advantages in electric vehicle motor drive systems [4]. For example, SiC MOSFETs are employed as high-frequency switching elements in the traction inverter of the Tesla Model 3 [1]. Because of the capacitance connection between the base plate and Direct Bonded Copper (DBC), parasitic capacitors are present, as shown in Figure 1. The gate-drain parasitic capacitor CGD and the gate-source parasitic capacitor CGS make up the input capacitance Ciss of a SiC MOSFET. The SiC MOSFET's ON/OFF switching state is established based on the gate-source voltage VGS and the threshold voltage Vth. When the drain-source current iDS passes through the MOSFET and the gate-source voltage VGS is increased to the threshold voltage Vth, the power device is activated. Conversely, the power apparatus is turned off and the drain source-voltage VDS is blocked when the input capacitor is depleted and the gate-source voltage VGS falls to a threshold voltage Vth [7, 8]. The high efficiency and low-loss characteristics of SiC devices also give Tesla's electric vehicles significant advantages in acceleration performance and driving range. For example, the Tesla Model S Plaid, which employs SiC devices, achieves a 0-60 mph acceleration time of just 2.1 seconds, far exceeding traditional silicon-based electric vehicles [9]. Additionally, the high reliability of SiC devices enables them to perform excellently under the complex operating conditions of electric vehicles, such as frequent starts/stops and high-speed driving.

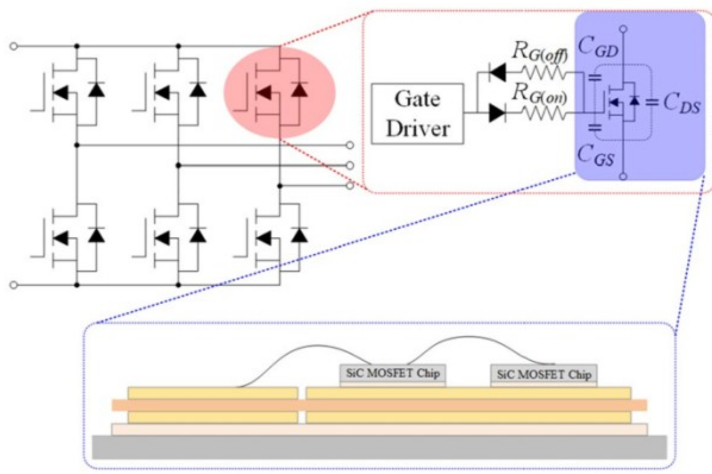

Figure 1. SiC MOSFET schematic [7]

3.2. GaN on 5G

The rapid development of fifth-generation communication networks presents several issues for gallium nitride power amplifiers [11]. In order to enable numerous transmit and receive routes in Multi-Input Multi-Output (MIMO) setups, 5G architecture calls for an Analog Front-End (AFE). The subarray Active Phased Array Antenna (APAA) block diagram for large-scale MIMO is displayed in Figure 2. The Radio Frequency (RF) front-end module is made up of switches, low-noise amplifiers (LNAs), and Power Amplifiers (PAs), as illustrated in Figure 2. It is well known that the performance of RF PAs typically dominates the overall Transmitter (TX) performance, as their Power-Added Efficiency (PAE) determines the power consumption and heat dissipation of the entire TX. To enhance the user experience and enable massive MIMO antennas at centimeter-wave/millimeter-wave frequencies, 5G systems will require more PAs integrated into RF Front-End Modules (FEMs), making the design of 5G PAs more critical than that of 4G PAs. This has led to a growing demand for FEMs and PAs in 5G communications [10, 12]. These amplifiers are important in increasing signal strength and quality hence increasing efficiency of communication over large distance and tough path. Gallium Nitride (GaN) has a melting point as high as 1,700°C [13]. Its high chemical stability, combined with a wide bandgap of 3.4 eV, endows it with excellent radiation resistance, enabling it to maintain signal accuracy and stability even under external interference [14]. Meanwhile, its outstanding Figure of Merit (FOM) grants GaN devices the characteristics of high frequency, high power density, and high efficiency, thus making it a key material in 5G communication systems [15].

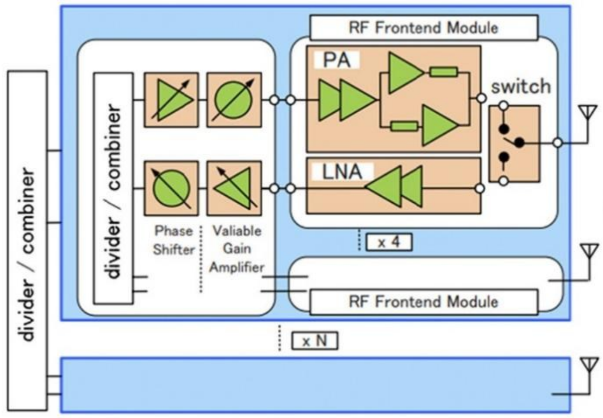

Figure 2. Block diagram of a sub-array APAA massive MIMO [10]

4. Perspectives on future development and challenges

Despite early recognition of SiC and GaN's benefits over conventional Si materials by the academic and industrial sectors, their uses were constrained for years by issues with manufacturing equipment, prices, and procedures, failing to threaten the dominance of Si-based devices. However, with the emergence of new markets like 5G and automotive industries, the irreplaceable advantages of SiC/GaN have accelerated the R&D and application of related products. With advancements in preparation technologies, SiC and GaN devices and modules have become cost-effective alternatives. Driven by growing demand and declining costs, the era of SiC/GaN has arrived. However, people must also confront a series of challenges simultaneously.

The most critical challenge is enhancing the safety of these devices. Although SiC and GaN power devices exhibit superior performance characteristics compared to traditional Si-based devices, for example, the crystal structure of silicon carbide is more prone to defects than silicon, which can affect device reliability and performance. Meanwhile, they are more susceptible to issues such as high-temperature operation, gate oxide breakdown, and current collapse [5]. Therefore, current research efforts should focus on optimizing SiC and GaN power devices to improve operational accuracy and reliability.

Another challenge is reducing the cost of these devices. Currently, SiC and GaN power devices are more expensive than traditional Si-based devices, limiting their applications in certain areas [1]. Therefore, further research is needed to optimize the manufacturing process to reduce production costs while maintaining their superior performance characteristics.

Additionally, expanding the application scope of new semiconductor materials poses another challenge. For instance, leveraging SiC's high thermal conductivity, stable operation at high temperatures, and radiation resistance for aerospace rocket capsule coatings; or exploring whether GaN materials could be used in the development of 6G after 5G has matured, among other possibilities.

In conclusion, with proper support and collaboration, SiC and GaN power devices have the potential to revolutionize the power electronics industry and serve as a vanguard leading the way toward a more sustainable and efficient energy future.

5. Conclusion

This paper systematically explores third-generation semiconductor materials represented by SiC and GaN. Through quantitative comparisons with current mainstream Si-based devices across key performance dimensions—such as breakdown voltage, thermal conductivity, electron mobility, and power loss—it deeply analyzes their technological adaptability in frontier fields like new energy vehicles and 5G communications. The goal is to construct a panoramic analytical framework for the future technological roadmap of semiconductor materials.

The introduction of new semiconductor materials has successfully achieved efficiency improvements and volume reduction in motor drive systems, as well as effectively reduced base station energy consumption and expanded signal coverage. However, challenges persist, including complex manufacturing processes, high costs, lagging theoretical research, and device failures in extreme environments. Undeniably, they still exhibit broad market potential and a trend to drive future technological advancements.

While this paper discusses the workflow of SiC MOSFETs in the traction inverter of the Tesla Model 3, it lacks a quantitative analysis of how parameters such as voltage and current influence this process. Additionally, in 5G FEMs, a simulation model has not been established for the impact of nonlinear distortion in GaN PAs on the Bit Error Rate (BER) of MIMO systems. Therefore, this paper looks forward to gaining further insights into specific approaches for experimentally demonstrating how new semiconductor materials affect device-specific parameters to optimize overall processes and macroscopically reshape the future of the power electronics industry.

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