Compare gallium nitride, silicon carbide and monocrystalline silicon: application scenarios and research status

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Abstract. This paper conducts a comprehensive analysis of gallium nitride (GaN), silicon carbide (SiC), and silicon (Si) in the electronics and power industries, highlighting their current applications and future trends. GaN emerges as a front-runner for high-speed switching with its high-frequency, high-efficiency characteristics, and its superior electron mobility and voltage endurance are vital for miniaturized, high-performance electronics. In contrast, SiC's robustness at high temperatures, superior thermal conductivity, and exceptional breakdown field strength make it the material of choice for high-power, high-temperature electronics, playing a pivotal role in LED lighting, renewable energy systems, and power grid technologies. While Si lags behind in high-temperature and high-power performance, its cost-effectiveness and mature manufacturing keep it significant in the market. Furthermore, the paper addresses the technical challenges and innovative solutions in switch component applications for SiC and GaN, such as gate drive issues, breakdown mechanism optimization, and Si's ongoing advancements in microelectronics. By examining the strengths and weaknesses of each material, future research directions are pinpointed, including material synthesis, device design, and system integration advancements, aiming to enhance their application performance and efficiency in the electronics and power sector. In summary, GaN, SiC, and Si each bring unique advantages to electronics and power applications, indicating a future of more efficient, reliable, and eco-friendly technological innovations in power electronics.

Keywords: Gallium nitride semiconductor, Silicon carbide semiconductor, Single crystal silicon.

1. Introduction

The relentless march of technological innovation demands ever-greater power efficiency from contemporary electronic apparatuses. Silicon (Si), the quintessential semiconductor in power apparatuses, has encountered the zenith of its material capabilities in today's production, constrained by its intrinsic properties. In the quest for viable Si alternatives, gallium nitride (GaN) and silicon carbide (SiC) have emerged as the vanguards of the third-generation semiconductors, distinguished by their superlative electrical and optical properties, forging a commendable synergy between theoretical and empirical performance.

Si, lauded for its expansive research and commercial deployment, boasts a broad bandgap materiality. Its prodigious attributes, including formidable thermal conductivity, towering breakdown electric field robustness, and steadfast high-temperature stability, surmount the confines of Si, heralding the genesis of elite electronic devices. In realms demanding high voltage and enduring high temperature, SiC proves its mettle with heightened efficiency and dependability, notably in domains such as electric vehicular technology and sustainable energy matrices—where it markedly curtails energy dissipation and amplifies systemic longevity and efficacy. Nonetheless, SiC’s ascendancy in performance relative to Si is tempered by its onerous manufacturing expenditure and complex processing, curbing its ubiquitous application.

GaN, with its innate wide bandgap constitution, imparts it with exceptional electron agility, towering saturation drift rates, and commendable thermal transference, conferring distinct advantages in the fabrication of devices that operate at elevated frequencies, temperatures, and power. Moreover, GaN’s stellar optoelectronic traits unfurl expansive potential in sectors such as LED illumination and pioneer fresh horizons in avant-garde spheres like electronic power and switching. Yet, for all its vast potential, GaN’s intricate preparation intricacies, substantial costs, and ecological susceptibilities present formidable obstacles to its extensive deployment. Particularly, technical hurdles in material synthesis—like atomic dislocations, interface state density, and apparatus integration—necessitate rigorous scholarly pursuit to transcend. Therefore, an incisive dissection of the current investigative and applicative landscape of GaN and SiC not only marks a significant stride in their technological evolution but also fuels the innovation and progression within their respective disciplines.

These semiconductors demonstrate robust performance under elevated thermal, electrical, and kinetic conditions, boasting switching frequencies superior to their silicon-based counterparts. Such attributes earmark GaN and silicon SiC as the materials of choice for the avant-garde design of electronic apparatus [1]. Yet, despite their pronounced potential across myriad domains, they confront formidable barriers: intricate production processes, substantial fiscal demands, and acute environmental vulnerabilities impede their expansive deployment. Paramount among the technical hurdles are atomic misalignments, interface state density discrepancies, and the synthesis of cohesive device architectures, all of which mandate comprehensive scholarly inquiry. Ergo, an incisive discourse on the investigative and applicative dynamics of GaN and SiC substances is not merely instrumental in propelling semiconductor technology to new pinnacles but also catalyzes the innovation and evolution within adjunctive sectors. In summation, the semiconductors in discussion are endowed to function under conditions of elevated thermal, electrical, and kinetic stress, outstripping the transitory capabilities of their silicon counterparts. This manuscript endeavors to dissect and contrast the contemporary investigative stance and pervasive applicability of GaN, SiC, and Si, interrogating the primary quandaries they confront, and envisaging their developmental trajectory. Through an exhaustive analysis of their technological advancements and application potentialities, this treatise aspires to contribute seminal insights that propel the proliferation and sophistication of these pivotal semiconductor materials.

2. Comparison of material properties

SiC, as one of the commercially more advanced wide bandgap semiconductors, has been extensively studied due to its bandgap energy of approximately 3.3 electron volts (eV) — significantly higher than Si's 1.1 eV. This larger bandgap energy endows SiC-based power devices with numerous advantages, such as reduced conduction and switching losses, higher temperature tolerance, and improved efficiency. These exceptional characteristics make SiC devices particularly suitable for applications in electric vehicles, renewable energy systems, industrial motor drives, and aerospace [2]. On the other hand, GaN, as an emerging wide bandgap semiconductor material, has also attracted widespread attention in recent years. GaN exhibits a similar bandgap energy of about 3.4 eV to SiC, yet GaN-based power devices differ in performance characteristics, specifically demonstrating high breakdown voltage, fast switching speeds, and low on-resistance. These features make GaN devices especially suited for high-frequency operation applications, such as wireless power transfer, data centers, and radar systems [3].

Silicon plays an indispensable role in modern technology, particularly in its semiconductor properties, making it the ideal material for electronic devices and integrated circuits. In its pure state, Si is almost non-conductive, but doping it with small amounts of other elements (such as phosphorus or boron) can significantly alter its conductivity, thereby creating n-type or p-type semiconductors. Silicon-based semiconductor technology is the cornerstone of modern electronic devices, ranging from simple diodes to complex microprocessors and memory devices. The applications of silicon semiconductors are extensive, including computers, mobile phones, solar panels, and various sensors. In the solar energy industry, silicon is used to produce high-efficiency photovoltaic cells, one of the key technologies for converting solar energy into electrical energy. Additionally, the high thermal stability and excellent electronic properties of silicon enable its application in high-temperature environments (such as aerospace and military equipment), allowing future electronic devices to achieve higher performance and broader functionality. In summary, the semiconductor properties of silicon and its applications are the foundation of modern technological progress, playing a crucial role in driving the development of the information society and sustainable energy technologies.

The third-generation semiconductor material, GaN, possesses outstanding advantages such as wide band gap and high electron drift saturation speed, making it a hot topic in semiconductor material research due to its frequent applications in the microelectronics and optoelectronics fields [4]. Compared to the semiconductor materials used in electronic devices in the past, which were primarily silicon-based, gallium nitride semiconductor materials better meet the requirements of modern electronic device fabrication processes and performance aspects, such as high temperature resistance, high-frequency tolerance, and suitability for high power [5]. Figure 1 illustrates a comparative analysis of the fundamental physical properties of Si, SiC, and GaN, which are pivotal in semiconductor applications. SiC stands out with superior thermal conductivity and high electric field strength, indicating its robustness in high-power and high-temperature environments. GaN follows closely, with excellent electron velocity and a wide energy gap, making it ideal for high-frequency and high-efficiency applications. Si, while trailing in these advanced properties, showcases a lower melting point, suggesting easier handling and manufacturing benefits. These differences underscore the tailored application domains for each material: SiC for high-voltage power electronics, GaN for radio frequency and power electronics where high switching speeds are crucial, and Si for widespread electronics due to its well-established processing techniques and lower costs. Each material's profile in Figure 1 guides their respective roles in advancing semiconductor technology.

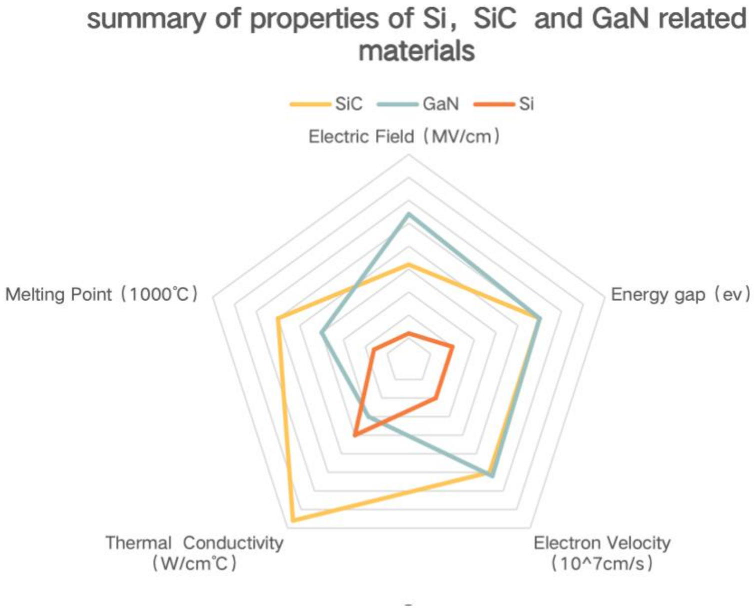

Figure 1. Summary of properties of Si, SiC and GaN related materials.

3. Industrialization status of semiconductors

The physical properties of GaN, SiC, and Si reveal distinct characteristics. GaN exhibits a higher breakdown voltage and lower specific on-resistance, making it exceptionally suitable for high-voltage and high-frequency applications, particularly in scenarios requiring high power density and efficient energy conversion, such as power transmission. Typically, GaN's voltage range extends up to 650 V, with some emerging devices reaching up to 1200 V. In contrast, SiC's voltage range starts at 650 V and goes beyond [2].

As shown in Figure 2, SiC's breakdown voltage is similar to that of GaN, but its specific on-resistance is lower, indicating higher efficiency in high-voltage applications. This makes SiC especially valuable in high-temperature electronic devices, offering improved energy management and the ability to withstand harsher operating conditions. In comparison, Si has a lower breakdown voltage and higher specific on-resistance, indicating its unsuitability for high-voltage applications but offering higher cost-effectiveness. Therefore, Si is more commonly used in low-voltage and large-scale integrated circuit applications, such as microprocessors and memory in computers and smartphones.

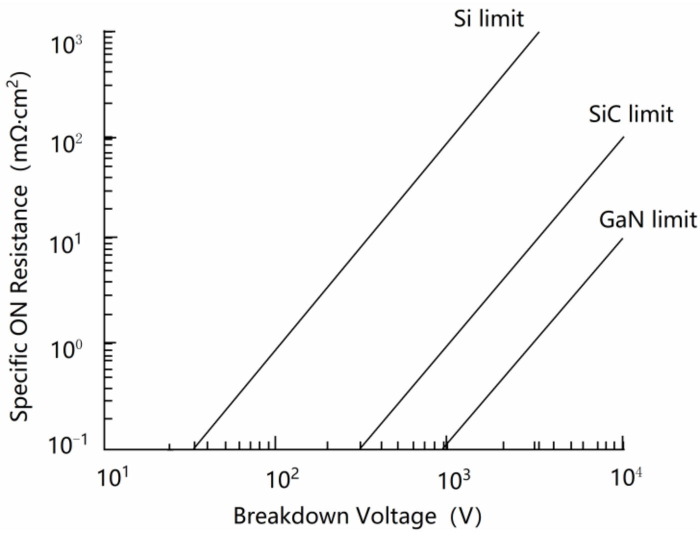

Figure 2. Comparative analysis of specific on resistance vs. breakdown voltage for Si, SiC, and GaN semiconductors.

3.1. Power electronic technology

The advancement of power electronics technology plays an indispensable role in the development of modern energy systems, directly influencing the effective conversion, distribution, and utilization of energy. In this process, high-voltage semiconductor devices play a pivotal role, serving not only as key enablers of technology but also as crucial factors in cost and efficiency optimization. For example, in the realm of electric vehicles, semiconductor components of a 50-kilowatt inverter account for 40% of the total material cost, highlighting the importance of high-performance semiconductor materials in enhancing energy efficiency and reducing costs [6].

Traditionally, Si has dominated the power electronics sector due to its widespread availability and mature technology platform. However, as the demand for higher energy efficiency, greater power density, and operation at higher voltages and currents grows, the physical limitations of silicon begin to emerge as a bottleneck to technological development [6]. This has prompted exploration into wide bandgap (WBG) semiconductor materials, which are considered key to surpassing the limitations of silicon due to their exceptional electrical and thermal performance [6].

Against this backdrop, 4H-silicon carbide (4H-SiC) and GaN, as representatives of wide bandgap semiconductor materials, have significantly transformed the design and application scope of power electronic devices [6]. SiC and GaN, offering higher voltage tolerance, lower conduction losses, and better thermal stability, have taken power electronic devices a significant step forward in terms of efficiency and performance.

According to Table 1, diodes made from different semiconductor materials exhibit varying levels of power losses under identical testing conditions. GaN diodes, with a 600V, 6A rating, and a reverse recovery time (trr) of 30ns, show losses of 2.98uJ at 25°C and slightly higher at 3.05uJ when the temperature is increased to 125°C. SiC diodes, rated at 600V, 10A with a faster trr of 10ns, demonstrate lower losses at 25°C with 2.6uJ, which marginally increase to 3.14uJ at 125°C. Silicon diodes, despite a comparable rating of 600V, 10A, suffer significantly higher losses of 45uJ at 25°C, doubling to 90uJ at 125°C, attributable to their much longer trr of 58ns.

In the realm of power electronics, these loss characteristics have profound implications. The lower losses at higher temperatures for GaN and SiC make them more efficient, particularly in applications where thermal management is crucial, like electric vehicle powertrains or renewable energy converters. Si, with its higher losses, may lead to increased energy dissipation as heat, requiring more robust cooling solutions which could increase the overall size and cost of the electronic system. The faster reverse recovery times of GaN and SiC are also beneficial in high-frequency switching applications, allowing for more compact and efficient designs. Thus, GaN and SiC diodes are generally preferred in advanced power electronics applications where efficiency and high-temperature performance are paramount.

Specifically, SiC materials have found widespread application in high-voltage domains such as electrical grid transmission and electric vehicle chargers. Their capability to operate at high temperatures, along with excellent voltage tolerance, makes them ideal for improving power efficiency and reducing system size. Furthermore, the application of SiC in solar inverters and electric vehicle traction inverters further demonstrates its value in enhancing system performance and reliability.

Meanwhile, GaN, with its outstanding high-frequency performance and high power density, has found applications in wireless power transmission, rapid charging technologies for mobile devices, and high-frequency power converters. GaN's low on-resistance and high switching speed offer unique advantages in the design of efficient and compact devices, especially in portable electronics and communication devices requiring lightweight and high-efficiency energy conversion. This year, Xiaomi launched a 65-watt GaN charger, which is half the size of a standard charger. This is widely regarded as a sign that the consumer-grade GaN mobile power supply market is beginning to flourish. At the same time, products such as low-power rapid charging USB power adapters and high-power adapters have also started to utilize GaN materials [7].

By introducing SiC and GaN, two wide bandgap semiconductor materials, power electronics technology can not only meet the current demands for high efficiency, high power density, and high reliability but also opens up new possibilities for the future development of energy systems. The application of these materials not only enhances the performance of devices but also provides a solid foundation for the continuous optimization and innovation of energy systems.

Table 1. Diode recovery loss.

Diode	Test Conditions	Losses
GaN 600V. 6A.trr 30ns Test conditions	25°C, 5A, 300 V 125°C, 5A, 300V di/dt 450A/us	2.98uJ 3.05uJ
SiC IDH1OSG60C 600V. 10A trr 10ns	25°C, 5A, 300 V 125°C, SA, 300V di/dt 450A/us	2.6uJ 3.14uJ
Si FEPFIOUP6OS 600V. 10A, trr 58ns	25°C. 5A. 300V 125°C, 5A, 300V di/dt 450A/us	45uJ 90uJ

3.2. Lighting industry LED lights

GaN, SiC, and Si are three semiconductor materials commonly used in the manufacturing of LED lamps, each possessing unique physical and chemical properties that allow them to exhibit distinct performance in various application scenarios.

GaN is a direct bandgap semiconductor with high thermal conductivity and electron mobility, which endows GaN-based LEDs with high efficiency and brightness. Additionally, GaN can operate stably across a wide temperature range, making it suitable for high-performance blue and ultraviolet LEDs. However, the cost of GaN materials is relatively high, and the manufacturing process is complex [8]. SiC, another wide bandgap semiconductor, outperforms single-crystal silicon in high-temperature, high-power, and high-frequency applications. The primary advantage of SiC-based LEDs lies in their ability to withstand higher voltages and currents, offering better thermal stability and energy efficiency. Similar to GaN, the high manufacturing cost of SiC limits its market proliferation [9]. In contrast, single-crystal silicon is one of the most commonly used semiconductor materials, characterized by its low cost and mature processing technology. Although Si-based LEDs may not match the efficiency and brightness of GaN and SiC-based LEDs, their low cost makes them more competitive in mass production. However, the narrower bandgap of Si makes it unsuitable for producing blue or ultraviolet LEDs [10].

In summary, gallium nitride, silicon carbide, and silicon each have their advantages and limitations in LED lamp applications, and the choice of material depends on specific performance requirements and cost considerations.

3.3. Power Switch Applications

In the transformative years spanning the late 1980s and early 1990s, both academia and industry commenced the acknowledgment of silicon carbide's prodigious potential in the engineering of high-performance power switches. Exhibiting an electric field strength at the point of breakdown of up to 300 V/μm—a staggering tenfold increase over silicon's modest 30 V/μm—SiC epitomizes the pinnacle of material resilience [11]. As delineated in Figure 2, this formidable property signifies that SiC is adept at withstanding voltages up to an impressive 10,000 V, even with an ON resistance maintained at 100 mΩ·cm^2. Beyond its extraordinary electrical prowess, SiC is proficient in the production of Schottky diodes, endowed with formidable barriers and lofty breakdown voltages.

Moreover, SiC's thermal conductivity, a remarkable 3.5 W/cm°C, dwarfs Si's 1.5 W/cm°C, thereby bolstering its heat dissipation capacity from the locus of the power switch and augmenting the thermal equilibrium and operational efficiency of the entire device. SiC Schottky diodes consistently perform under thermal loads far surpassing Si's threshold, positing SiC as the material par excellence for applications necessitating high thermal resistance. Concurrently, it is prudent to juxtapose SiC's capabilities with those of GaN. GaN, another exemplary wide bandgap semiconductor, excels beyond Si in applications requiring high frequency, efficiency, and thermal resilience, akin to SiC. While GaN rivals SiC in terms of electric field strength at breakdown, its unparalleled electron mobility may confer it with a distinct edge in certain high-frequency applications. Nonetheless, SiC maintains supremacy regarding high-temperature stability and thermal conductance, ideally suited to switching applications in the most demanding and unforgiving of environments.

4. Conclusion

Considering comprehensively, gallium nitride, silicon carbide, and silicon each occupy an important position in the preparation of electronic devices due to their outstanding physical and chemical characteristics. This paper provides a comprehensive analysis of the current research status and application scope of these three semiconductor materials, while comparing their performance advantages and existing shortcomings. GaN, with its high electron mobility and good thermal stability, demonstrates immense application potential in high-frequency, high-efficiency power conversion, and RF applications. GaN's low on-resistance and high breakdown voltage make it favored in miniaturized and high-performance electronic devices. However, the manufacturing costs and complex epitaxial growth processes of GaN limit its competitiveness in the market. In contrast, SiC, with its wide bandgap, high thermal conductivity, and high breakdown electric field strength, has significant advantages in high-temperature and high-power applications. The application of SiC in electric vehicles, power grids, and renewable energy systems has promoted its growth in the power electronics market. Nevertheless, the high cost and manufacturing difficulty of SiC devices remain major barriers to their widespread application. Silicon, as the cornerstone of the semiconductor industry, holds an unshakable position in the manufacture of large-scale integrated circuits due to its low cost and mature production process. However, Si's performance is constrained by its physical limits in high-temperature and high-power fields.

This paper also discusses the technical challenges and innovative solutions in switch device applications for these materials. For instance, the gate drive issues of SiC and GaN devices, optimization of breakdown mechanisms, and the continuous progress of Si in the microelectronics field are current research hotspots. Additionally, we point out future research directions, such as advances in material synthesis, device design, and system integration technologies, which will help further enhance the performance and efficiency of these materials in practical applications. In summary, GaN, SiC, and Si each have their strengths in the field of electronic power, and their comprehensive application prospects are broad. Future technological developments need to balance performance improvement and cost control to achieve more efficient, reliable, and environmentally friendly technological innovations in the power electronics field. With advancements in materials science and manufacturing technology, the roles of these three materials in future electronic and power applications are expected to become more defined, and their complementarity more pronounced. Meanwhile, research and applications of these materials will also promote our country's competitiveness in the global semiconductor materials field and accelerate the development pace of high-tech industries. Therefore, increasing research investment in gallium nitride, silicon carbide, and silicon semiconductor materials and exploring their potential in a broader range of applications is not only necessary for the development of electronic device fabrication technology but also an important component of the development of national strategic emerging industries.

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