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A Comparison of Silicon, Silicon Carbide, and Gallium Nitride for Power Semiconductor Devices

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Abstract. Power semiconductor devices are essential to modern power and electronic systems as they govern the switching, conversion, and delivery of electric power. Silicon has long been the dominant material in this field. However, the rapid growth of electric vehicles, renewable energy systems, fast chargers, and compact power supplies has created stronger demand for higher voltage capability, lower loss, faster switching, and better thermal stability. This paper compares three important materials used in power devices: silicon (Si), silicon carbide (SiC), and gallium nitride (GaN). The discussion focuses on material properties that directly affect device behavior, including bandgap, breakdown field, thermal conductivity, and carrier transport. The analysis shows that silicon still offers strong advantages in cost, manufacturing maturity, and broad industrial use. SiC is more suitable for high-voltage and high-temperature operation, while GaN is especially attractive for high-frequency and fast-switching applications. The main conclusion is that SiC and GaN are expanding rapidly because they overcome performance limits inherent to silicon. However, material selection in power electronics still depends strongly on the specific requirements of each application.

Keywords: power semiconductor devices, silicon carbide, gallium nitride, wide-bandgap semiconductors, power conversion

1. Introduction

Power semiconductor devices sit at the center of many power-electronic systems. They control how electrical energy is switched, converted, and delivered in motor drives, electric vehicles, renewable-energy converters, battery chargers, industrial power supplies, and consumer electronics. As these systems shrink and move toward higher power density, their power devices must tolerate more severe electrical and thermal stress [1].

Silicon has been the standard material for many decades. Its position comes from mature processing, a large supply chain, low cost, and long design experience. Silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) and insulated-gate bipolar transistors (IGBTs) are still widely used. Even so, silicon begins to face limits when the same device must block higher voltage, switch faster, or work at higher temperature.

These limits explain the growing attention given to wide-bandgap materials, especially silicon carbide (SiC) and gallium nitride (GaN). Both materials have wider bandgaps and much higher critical electric fields than silicon, so they can tolerate stronger electric fields before breakdown. This advantage can reduce loss under demanding operating conditions. The two materials, however, are useful in different ways. SiC is mainly valued for high-voltage and thermally demanding power conversion, while GaN is better known for fast switching and high-frequency operation [2].

This paper examines Si, SiC, and GaN as materials for power semiconductor devices. It compares the material parameters that control device behavior, connects those parameters with representative device structures, and then summarizes the main differences through a parameter table. The purpose is to show why SiC and GaN are being adopted in more systems while also explaining why silicon remains important in cost-sensitive and mature applications.

2. Key material properties

A small set of material properties has a large influence on power-device behavior. This section considers those properties first, then links them with common device structures, and finally places the main values side by side in a comparison table.

2.1. Bandgap and breakdown field

Bandgap is often introduced as a basic material parameter, but in power devices it quickly becomes a practical design limit. It influences carrier generation, temperature tolerance, and leakage behavior. Silicon has a bandgap of about 1.12 eV. By comparison, 4H-SiC is about 3.26 eV and GaN is about 3.4 eV. These wider bandgaps help lower the intrinsic carrier concentration and make SiC and GaN more stable in harsh operating conditions.

Breakdown field is the next parameter that directly connects material physics to device design. It describes the electric field a material can sustain before breakdown. Because silicon has a much lower breakdown field, a silicon power device usually needs a thicker drift region when it is designed for high-voltage blocking. That thicker region raises on-resistance and reduces efficiency. SiC and GaN can use thinner voltage-blocking regions because of their higher breakdown fields, which is one reason they are attractive for high-voltage devices.

2.2. Device structures, thermal conductivity, and carrier transport

Device structure must be considered together with material properties. In Figure 1, the Si and SiC examples are shown as MOSFET structures with source, drain, gate, and a channel controlled by the gate oxide. The GaN example is shown as a high-electron-mobility transistor (HEMT). These are simplified comparison drawings based on common layouts reported in Refs. [2, 3].

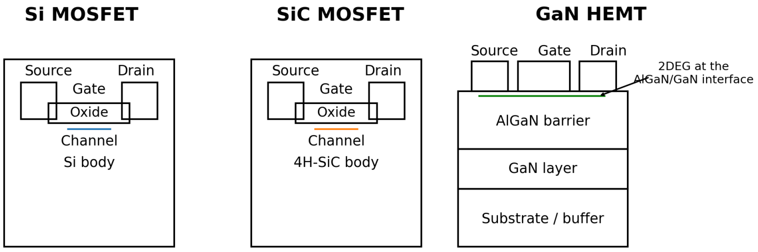

Figure 1. Simplified conceptual structures of a Si power MOSFET, a SiC power MOSFET, and a GaN HEMT

Figure 1 also points to an important difference in the GaN device. In the GaN HEMT, the AlGaN/GaN interface forms a high-density two-dimensional electron gas, which provides a fast current path. The Si and SiC MOSFETs instead use a more conventional gate-controlled channel together with a drift region for voltage blocking.

Thermal conductivity matters because power devices inevitably produce heat during conduction and switching. A material or package that removes heat more effectively can improve reliability. SiC is strong in this respect and is often chosen for high-power or high-temperature operation. Silicon has moderate thermal conductivity. GaN devices can perform very well, but their thermal behavior depends strongly on the substrate and package used to carry heat away from the active region.

Carrier transport is another part of the comparison. Higher electron mobility can lower conduction loss, while high saturation velocity supports fast switching. GaN is attractive because it combines a high critical field with strong transport behavior, which fits compact and high-frequency converter designs. Silicon remains useful in many established circuits, but SiC and GaN become more competitive when the design target shifts toward higher voltage, higher frequency, or higher power density.

2.3. Comparison of Si, SiC, and GaN

Table 1 gathers representative room-temperature values for bandgap, critical electric field, thermal conductivity, electron mobility, and typical strengths. The values should be read as approximate 300 K literature values rather than fixed constants for every device. Differences in polytype, crystal quality, substrate, and measurement conditions can shift the exact numbers, but the main trends are consistent across the cited sources [1-4].

Table 1. Representative room-temperature material properties of Si, 4H-SiC, and GaN for power devices

Material	Bandgap (eV)	Critical field(MV/cm)	Thermal conductivity(W/cm·K)	Representative electron mobility(cm²/V·s)	Typical strength
Si	1.12	0.3	1.5	~1400	Low cost; mature processing
4H-SiC	3.26	2.5-3.0	~3.7-4.9	~900	High voltage; high temperature
GaN	3.4	~3.0-3.5	1.3-2.3	~1500	High frequency; fast switching

Table 1 shows the basic trade-off clearly. Silicon is still very competitive where cost and manufacturing maturity are the main concerns. Its lower bandgap and breakdown field, however, make it less suitable for more demanding high-voltage operation. SiC is stronger in high-voltage and high-temperature settings because it combines a high breakdown field with excellent heat conduction. GaN offers a wide bandgap and strong carrier transport, so it is especially useful in high-frequency and efficient switching systems.

3. Device performance and trade-offs

The material trends discussed above become more useful once they are translated into device-level behavior. A wider bandgap or a larger breakdown field does not automatically make one material the best choice. Voltage rating, switching frequency, heat removal, packaging, cost, and process maturity all affect the final decision. This is why Si, SiC, and GaN are used in different parts of the power-electronics market.

3.1. Silicon: advantages and limitations

Silicon remains important because it is cheap, widely available, and supported by a very mature fabrication base. Silicon MOSFETs and insulated-gate bipolar transistors (IGBTs) are familiar devices with broad commercial use. They are still a good fit for many cost-sensitive products. The limitation is that silicon has a smaller bandgap and a lower critical electric field, so its performance becomes harder to improve in high-voltage or high-temperature designs.

3.2. SiC for high-voltage and high-temperature devices

SiC is better suited to situations where high voltage and high power are central requirements. Commercial SiC power devices already span approximately 600 V to 3.3 kV, and SiC MOSFETs are increasingly used in roles that were once served by silicon IGBTs. Its high breakdown capability and strong thermal performance make SiC a practical choice for traction inverters, industrial converters, and other systems exposed to high electrical and thermal stress [5].

3.3. GaN for high-frequency and fast-switching devices

GaN is most useful when fast switching, small size, and high power density are priorities. Studies of electric-vehicle fast charging show that GaN-based direct-current/direct-current (DC-DC) converters can offer high switching speed, good efficiency, and compact converter design. Some reported systems achieve efficiencies above 97% over a wide power range, supporting the use of GaN in fast chargers and other high-frequency conversion systems [6].

3.4. Efficiency, cost, and reliability

The main trade-off is that better material parameters by themselves do not guarantee a cheaper or more reliable system. A wide-bandgap device can reduce switching or conduction loss, but the final design still depends on gate driving, thermal layout, packaging, and long-term reliability. Silicon often remains the most economical option. SiC becomes more attractive when voltage and temperature demands are high. GaN becomes more attractive when frequency and power density dominate the design.

4. Applications

Applications make these material differences concrete. A parameter that looks ideal in a table may matter very differently in an electric vehicle, a charging station, a consumer adapter, or a server power supply.

4.1. Electric vehicles and power conversion

Electric vehicles and other high-power conversion systems need high efficiency, strong voltage blocking, and stable thermal performance. Ultra-fast charging systems often contain both alternating-current/direct-current (AC/DC) and direct-current/direct-current (DC/DC) conversion stages, and recent work also discusses solid-state-transformer-based architectures. In these systems, SiC is often preferred for high-voltage conversion stages, while GaN can be useful in stages that benefit from very fast switching. The material choice is therefore often different from one conversion stage to another [7].

4.2. Fast chargers and consumer electronics

At lower and medium voltage, compact power systems usually put more emphasis on high switching frequency and high power density. GaN can reduce passive-component size and support more integrated converter layouts in this range. One reported 48 V GaN power stage shows that monolithic integration can reduce the area needed for packaging and printed circuit boards. This helps explain why GaN is being considered for compact DC-DC converters and other size-sensitive power systems [8].

4.3. Why different applications need different materials

Different applications therefore push the material choice in different directions. Silicon remains useful where mature processing and low cost are most important. SiC is often selected when voltage, current, and heat are the main challenges. GaN is strongest when fast switching and compact converter size are the main goals. The suitable material is therefore chosen by balancing efficiency, voltage, frequency, thermal design, cost, and manufacturing maturity.

5. Conclusion

Taken together, the comparison of Si, SiC, and GaN suggests that power semiconductor development is moving away from reliance on a single material. Each material keeps a distinct role because its physical properties support a different set of device strengths. Silicon remains valuable because it is low cost, widely available, and supported by mature fabrication. It is still the practical choice in many established products. Its narrower bandgap and lower critical field, however, make it less competitive when high voltage and high temperature are the main design challenges.

SiC helps address these limits through stronger voltage-blocking capability and better heat conduction. These features make it well suited to traction inverters, industrial converters, and other high-power systems where efficiency and thermal control are central. GaN offers a different advantage. Its fast switches behavior and high power density can reduce the size of magnetic components and support compact converter layouts. This is why GaN is attractive in fast chargers, low- to mid-voltage DC-DC converters, and other high-frequency systems.

The main finding is that the growth of SiC and GaN should not be understood as a simple ending of silicon technology. It is better understood as a redistribution of roles across power-electronics applications. Device selection can no longer be made by looking at one material parameter alone. Voltage level, switching frequency, thermal conditions, packaging, cost, and manufacturing maturity must be considered together before a material choice is made.

This comparison also suggests that material properties only become meaningful when they are connected with device structure and application needs. SiC is gaining ground where high-power conversion and heat removal are difficult, while GaN is expanding in compact, high-frequency systems. Future improvements in reliability, integration, and cost reduction will likely strengthen both materials. At the same time, silicon will continue to serve many mainstream products. The future of power semiconductor devices is therefore more likely to be coexistence and specialization than complete replacement.

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