Evaluation of Wide Bandgap (WBG) Devices as a Successor to Silicon Technology in Modern Power Conversion Systems

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***Abstract*—The transition from Silicon (Si) to wide bandgap (WBG) semiconductors is one of the most important developments in modern power electronics. Conventional Si MOSFETs, diodes, and IGBTs are mature, low-cost, and reliable, but their performance is increasingly limited by intrinsic material properties such as critical electric field, carrier transport, and maximum junction temperature. Silicon Carbide (SiC) and Gallium Nitride (GaN) overcome many of these limits through larger bandgap energy, higher breakdown field, and faster switching capability. This paper evaluates WBG devices as successors to Si technology by comparing material properties, device structures, figures of merit, loss mechanisms, thermal behavior, and system-level impact. The study shows that SiC is especially suited to medium- and high-voltage applications such as electric vehicle (EV) traction inverters, fast chargers, and renewable-energy converters, while GaN is attractive for high-frequency and compact power supplies up to the 650 V class. Important design challenges including gate driving, electromagnetic interference (EMI), reliability, packaging parasitics, and manufacturing cost are also discussed. The results indicate that WBG devices are not merely drop-in replacements for Si devices; they require converter-level redesign to fully realize efficiency, power density, and thermal-management benefits.**

***Index Terms*—Wide Bandgap (WBG), Silicon Carbide (SiC), Gallium Nitride (GaN), Power Electronics, Electric Vehicles, Thermal Management, Semiconductor Devices.**

I. INTRODUCTION

Power electronics is the enabling interface between electrical sources, storage systems, machines, and loads. In renewable-energy systems, it performs maximum power point tracking, dc–dc conversion, and grid synchronization. In electric vehicles, it controls traction motors, onboard charging, auxiliary supplies, and battery energy flow. In data centers and telecom power systems, it determines the efficiency and volume of power delivery stages. Because these systems operate continuously and often process kilowatts to megawatts of power, even small efficiency improvements can reduce thermal stress, cooling volume, and lifetime energy loss [12].

For several decades, Si has been the dominant semiconductor material for power devices. Its success is due to mature wafer processing, low defect density, stable oxide quality, and a vast manufacturing ecosystem. Si power MOSFETs are preferred at low voltage because of their ease of drive and low conduction loss, while Si IGBTs dominate many medium- and high-power converters because they combine high blocking voltage with acceptable conduction loss. However, the theoretical and practical limits of Si power devices have become increasingly restrictive. In high-voltage unipolar Si devices, the drift region must be thick and lightly doped, which increases on-resistance. In bipolar devices such as IGBTs, conductivity modulation reduces conduction loss, but stored charge produces turn-off tail current and limits switching frequency [1].

Wide bandgap semiconductors such as 4H-SiC and GaN address these limitations at the material level. Their larger bandgap reduces intrinsic carrier concentration and enables high-temperature operation. Their higher critical electric field allows thinner, more highly doped drift regions for the same blocking voltage. Their higher saturation velocity and lower switching charge enable faster transitions and smaller passive components. These advantages have been widely reported in surveys of WBG devices and converter applications [3], [5], [6].

The objective of this paper is to evaluate WBG devices as practical successors to Si technology in power conversion systems. The discussion is organized from material physics to system impact. Section II presents the semiconductor properties that determine blocking voltage, on-resistance, and thermal limits. Section III compares important figures of merit and loss mechanisms. Section IV discusses SiC and GaN device technologies. Section V evaluates system-level applications, and Section VI summarizes design challenges and future trends.

II. SEMICONDUCTOR MATERIAL PHYSICS

A. Bandgap Energy and Intrinsic Carrier Concentration

The bandgap energy E_g is the energy required to move an electron from the valence band to the conduction band. Si has a bandgap of approximately 1.12 eV at room temperature, while 4H-SiC and GaN have bandgaps of approximately 3.26

eV and 3.4 eV, respectively. The intrinsic carrier concentration n_i varies approximately as

$$n_i \propto T^{3/2} \exp\left(-\frac{E_g}{2kT}\right), \tag{1}$$

where T is absolute temperature and k is Boltzmann's constant. A larger E_g therefore strongly suppresses intrinsic carrier generation at elevated temperature. This is one reason WBG devices can maintain blocking capability and leakage performance at junction temperatures where Si devices become less favorable [4].

High-temperature capability is valuable at the system level, but it does not mean that WBG converters should always be operated at the highest possible temperature. Higher temperature still increases resistance, accelerates package fatigue, and may reduce long-term reliability. The practical benefit is that the designer has more thermal margin, which can be traded for higher power density, reduced cooling requirements, or improved overload capability.

B. Critical Breakdown Field and Drift Layer Design

The critical electric field E_c determines how much electric field a semiconductor can withstand before avalanche breakdown. For a one-sided abrupt junction, the drift-region width W_d and doping concentration N_d for a blocking voltage V_B can be approximated by

$$W_d = \frac{2V_B}{E_c}, \quad N_d = \frac{\epsilon_s E_c^2}{2qV_B}, \tag{2}$$

where ϵ_s is the semiconductor permittivity and q is the elementary charge. Since the critical field of SiC is roughly an order of magnitude higher than that of Si, a SiC device can block the same voltage using a much thinner and more heavily doped drift layer.

For an ideal unipolar device, the specific on-resistance of the drift region can be expressed as

$$R_{on,sp} = \frac{4V_B^2}{\epsilon_s \mu_n E_c^3}, \tag{3}$$

where μ_n is electron mobility. The cubic dependence on E_c shows why WBG materials offer a dramatic advantage in high-voltage unipolar switches. A high E_c allows WBG MOSFETs and high-electron-mobility transistors (HEMTs) to achieve blocking voltages that would require excessive resistance in Si unipolar devices [2], [3].

C. Thermal Conductivity and Heat Spreading

Thermal conductivity determines how efficiently heat is removed from the active junction region to the case, substrate, and heat sink. 4H-SiC has significantly higher thermal conductivity than Si and GaN, making it particularly attractive for high-power modules and high-temperature operation. GaN has excellent electronic properties, but lateral GaN-on-Si devices often face thermal spreading limitations because heat must flow through buffer layers and the Si substrate [6], [8]. Therefore, thermal design must consider not only the semiconductor material but also the device structure, substrate, package, and cooling path.

TABLE I
MATERIAL PROPERTY COMPARISON FOR POWER DEVICES

Parameter	**Symbol**	**Si**	**4H-SiC**	**GaN**
Bandgap (eV)	E_g	1.12	3.26	3.4
Breakdown field (MV/cm)	E_c	0.3	2.2–3.0	3.0–3.3
Electron mobility (cm^2/Vs)	μ_n	1400	900–1000	1200–1500
Saturation velocity (10^7 cm/s)	v_{sat}	1.0	2.0	2.5
Thermal cond. (W/cm·K)	λ	1.5	3.7–4.9	1.3–2.3

III. COMPARATIVE PERFORMANCE METRICS

A. Figures of Merit

Material and device performance can be compared using figures of merit (FOMs). The Baliga Figure of Merit (BFOM) emphasizes conduction performance in unipolar power devices and is proportional to

$$BFOM \propto \epsilon_s \mu_n E_c^3. \tag{4}$$

A higher BFOM indicates lower theoretical specific on-resistance for a given breakdown voltage. Since E_c is cubed, SiC and GaN obtain much higher BFOM values than Si even when their mobility is not always higher. This explains why WBG devices are especially attractive above several hundred volts, where the Si drift-region resistance becomes dominant.

The Johnson Figure of Merit (JFOM) considers high-frequency and high-voltage capability and is often related to the product of critical field and saturation velocity:

$$JFOM \propto E_c v_{sat}. \tag{5}$$

This figure highlights why GaN is compelling in fast-switching converters: its high electron velocity and lateral HEMT structure allow very low charge and high switching speed [7]. However, FOMs are not complete design rules. They do not include package inductance, gate-loop design, reliability, device capacitance nonlinearity, or the availability of normally-off structures. Practical converter performance depends on both the semiconductor and the surrounding power stage.

B. Conduction and Switching Losses

In a hard-switched converter, total semiconductor loss is often divided into conduction loss and switching loss:

$$P_{cond} = I_{rms}^2 R_{DS(on)} \tag{6}$$

for a MOSFET-like device, and

$$P_{sw} = (E_{on} + E_{off}) f_{sw}, \tag{7}$$

where E_{on} and E_{off} are turn-on and turn-off energy losses and f_{sw} is the switching frequency. In Si IGBTs, turn-off losses are strongly affected by minority-carrier tail current. In Si superjunction MOSFETs, output capacitance and reverse-recovery behavior of the body diode can become limiting factors. SiC MOSFETs reduce switching energy because they are majority-carrier devices and can be paired with SiC Schottky barrier diodes that have negligible reverse recovery. GaN HEMTs can switch even faster because they have very low gate charge and output charge, although their reverse conduction and dynamic on-resistance behavior require careful design [6], [7].

The ability to increase f_{sw} has an important converter-level effect. Inductor and capacitor values generally decrease as switching frequency increases. Therefore, WBG devices can reduce the size and weight of magnetic components and filters. However, higher switching frequency also increases core loss, winding loss, gate-drive loss, and EMI filter requirements. The optimum design is not simply the highest possible frequency, but the frequency at which semiconductor, magnetic, thermal, and EMI constraints are balanced.

C. Thermal Resistance and Power Density

The junction temperature of a power device can be approximated by

$$T_j = T_a + P_{loss} R_{\theta JA}, \tag{8}$$

where T_a is ambient temperature and $R_{\theta JA}$ is junction-to-ambient thermal resistance. WBG devices reduce P_{loss} and may also tolerate higher T_j, allowing smaller heat sinks or increased power throughput. In traction and renewable-energy systems, this benefit is especially important because cooling hardware contributes to cost, mass, and volume. Experimental comparisons of SiC MOSFET and Si IGBT traction systems have reported higher inverter efficiency and lower device temperature under comparable operating conditions [9].

IV. DEVICE-LEVEL TECHNOLOGIES

A. Silicon Carbide Devices

SiC technology is most mature in the 650 V to several-kilovolt range. Commercial products include SiC Schottky barrier diodes, MOSFETs, junction field-effect transistors, and power modules. The SiC Schottky diode was one of the earliest WBG devices widely adopted because it eliminates reverse-recovery charge, reducing switching loss in boost power-factor-correction circuits and inverter freewheel paths.

The SiC MOSFET is now the dominant SiC switch for many industrial and automotive converters. Compared with Si IGBTs, it has no tail current and can switch at much higher frequency. It also has a positive temperature coefficient of on-resistance, which helps current sharing when devices are paralleled. Nevertheless, SiC MOSFETs introduce design issues that are different from Si MOSFETs. The gate oxide and SiC/SiO$_2$ interface have historically been reliability concerns, and threshold-voltage stability, short-circuit withstand time, body-diode degradation, and avalanche ruggedness must be evaluated for each application [10]. Gate-drive voltage is also device-specific; many SiC MOSFETs require a relatively high positive gate voltage for low $R_{DS(on)}$ and sometimes a negative turn-off voltage to avoid false turn-on in bridge circuits.

B. Gallium Nitride Devices

Most commercial GaN power devices are lateral GaN-on-Si HEMTs. In these devices, a two-dimensional electron gas (2DEG) forms at the AlGaN/GaN heterointerface, creating a high-mobility channel. This structure provides low charge and very fast switching, which is ideal for compact adapters, telecom power supplies, server power stages, class-D amplifiers, and high-frequency dc–dc converters. The same material system has also been important in RF power electronics, which helped establish the high-frequency potential of GaN technology [11].

A key challenge for power GaN is normally-off operation. Native GaN HEMTs are often normally-on, which is undesirable for fail-safe power conversion. Commercial normally-off solutions include cascode structures, p-GaN gate HEMTs, and MIS-gate devices [6], [8]. GaN devices also have unique reliability and application issues such as dynamic $R_{DS(on)}$, trapping effects, gate overvoltage sensitivity, and reverse-conduction behavior. These characteristics do not prevent practical use, but they require careful gate-drive design, layout optimization, and validation under realistic switching conditions.

TABLE II
PRACTICAL DEVICE SELECTION TRENDS

Device	Strengths	Common Applications
Si MOSFET	Low cost, mature, easy gate drive at low voltage	Low-voltage dc–dc converters, synchronous rectifiers
Si IGBT	High current, high voltage, low cost per ampere	Motor drives, industrial inverters, legacy traction systems
SiC MOSFET	High voltage, low switching loss, strong thermal performance	EV traction, fast chargers, PV inverters, solid-state transformers
GaN HEMT	Very low charge, high frequency, compact layout potential	Adapters, telecom supplies, server power, high-frequency dc–dc stages

V. SYSTEM-LEVEL IMPACT AND APPLICATIONS

A. Electric Vehicle Traction Inverters

The traction inverter is one of the highest-value applications for SiC. A vehicle inverter must operate efficiently over a wide speed-torque map, not only at rated power. Si IGBTs can be efficient at high current, but their switching losses and tail current reduce performance at higher switching frequencies. SiC MOSFETs reduce turn-off loss and often improve light-load efficiency, which is important because vehicles spend much of their drive cycle away from peak torque.

In a comparative EV traction study, SiC MOSFET inverters showed increased efficiency and reduced thermal stress compared with Si IGBT systems [9]. The practical benefits include longer driving range, reduced heat-sink size, higher dc-link voltage compatibility, and improved motor current quality if the switching frequency is increased. For 800 V battery platforms, the voltage margin and efficiency of 1200 V SiC MOSFET modules are especially attractive. However, automotive adoption also requires cost reduction, high-volume module packaging, robust short-circuit protection, and qualification over thermal cycling and vibration.

B. Onboard Chargers and Fast Charging

Onboard chargers and dc fast chargers benefit from WBG devices because they require high efficiency over a wide load range and must be compact enough for vehicle integration or charging-station cabinets. In power-factor-correction stages, SiC diodes and MOSFETs reduce reverse-recovery and switching losses. In isolated dc–dc stages such as LLC resonant converters or dual-active bridges, SiC and GaN allow higher switching frequencies, smaller transformers, and improved soft-switching opportunities. GaN is particularly effective in lower-power, high-frequency chargers, while SiC is preferred when higher bus voltage, higher current, or stronger thermal margin is required.

C. Renewable Energy and Grid Interfaces

Photovoltaic inverters, wind converters, and battery energy storage systems are driven by efficiency and lifetime requirements. In PV string inverters, WBG devices reduce conduction and switching losses and can improve power density by shrinking filters and magnetic components. In grid-connected applications, higher switching frequency can also improve current control bandwidth and reduce harmonic distortion. However, faster voltage transitions increase common-mode noise and leakage current through parasitic capacitances, so EMI filters and grounding strategy must be redesigned rather than copied from Si converters.

D. Data Centers, Telecom, and Consumer Power

Data centers and telecom systems use large numbers of ac–dc and dc–dc converters, so small efficiency gains produce significant energy savings. GaN devices are well matched to these applications because many stages operate below 650 V and strongly value high frequency and small form factor. High-frequency GaN converters can reduce the size of magnetics and enable higher-density power shelves. In consumer electronics, GaN has already become common in compact laptop and phone chargers. These products demonstrate that WBG technology can be commercially successful when the system-level value of smaller size and higher efficiency compensates for higher device cost.

VI. DESIGN CHALLENGES

A. Gate Driving and Layout Parasitics

WBG devices switch faster than Si devices, which means that parasitic inductance and capacitance become more important. A small common-source inductance can produce significant gate-voltage disturbance during high di/dt switching. Similarly, power-loop inductance can cause overshoot and ringing during turn-off. The gate driver should be placed close to the switch, the power loop should be minimized, and Kelvin-source connections should be used where available. In high-power modules, laminated busbars and low-inductance packages are often required.

Fast switching also increases dv/dt and di/dt, which can cause EMI, false turn-on, bearing currents in motor drives, and stress on insulation systems. Designers may intentionally slow down switching with gate resistance, active gate control, snubbers, or optimized modulation. This demonstrates an important point: the best WBG converter is not the one with the fastest possible edge, but the one that uses fast switching only as far as the complete system can support it.

B. Reliability and Ruggedness

Reliability remains a major topic for WBG adoption. For SiC MOSFETs, important concerns include gate oxide quality, threshold-voltage drift, short-circuit withstand capability, avalanche operation, and body-diode bipolar degradation. For GaN HEMTs, reliability concerns include dynamic on-resistance, trapping, gate robustness, and thermal limitations of lateral structures [8], [10]. Since WBG devices often operate at higher electric field and faster switching speed than Si devices, reliability testing must reflect real converter stresses rather than only static datasheet conditions.

C. Manufacturing Cost and Packaging

Cost is a practical barrier to universal WBG replacement. Si wafers are large, inexpensive, and supported by extremely mature processing. SiC boule growth is slower and more difficult, and defect control remains more challenging than in Si. GaN-on-Si benefits from larger Si substrates, but high-voltage vertical GaN technology is still less mature than lateral GaN-on-Si power devices. Packaging is also critical because the semiconductor die may no longer be the main bottleneck. To exploit WBG performance, packages must provide low inductance, low thermal resistance, good isolation, and high reliability under thermal cycling.

VII. FUTURE OUTLOOK

The future of WBG power electronics will likely be application-specific rather than a single replacement of Si by one new material. Si will remain important in cost-sensitive low-voltage converters and in applications where its maturity is sufficient. SiC will continue to expand in EV traction, charging infrastructure, grid converters, railway traction, aerospace systems, and industrial drives. GaN will expand in high-frequency ac–dc adapters, telecom power, data centers, integrated power stages, and possibly higher-voltage applications as vertical GaN and advanced substrates mature.

Research directions include improved SiC gate oxides, trench and superjunction SiC structures, higher-quality GaN buffers, vertical GaN devices, monolithic GaN integration, double-sided cooling, embedded power modules, and active gate drivers. At the converter level, WBG adoption will push engineers toward co-design of semiconductor devices, packaging, magnetics, controls, and EMI filters. The value of WBG technology is therefore not only in replacing a switch, but in enabling new converter architectures that were unattractive or impossible with Si.

VIII. CONCLUSION

Wide bandgap devices provide a strong technical pathway beyond the practical limits of Si power semiconductors. The high critical electric field of SiC and GaN reduces drift-region resistance and enables high-voltage unipolar devices with lower conduction loss. Their fast switching capability reduces switching loss and allows higher converter frequency, which can shrink passive components and improve power density. SiC is the strongest candidate for high-voltage and high-power applications such as EV traction inverters, fast chargers, and renewable-energy interfaces. GaN is especially attractive for compact, high-frequency, lower- to medium-voltage converters such as consumer adapters, telecom supplies, and server power stages.

At the same time, WBG devices are not simple plug-in replacements for Si MOSFETs or IGBTs. Gate driving, PCB layout, EMI control, thermal design, protection, and reliability qualification must be reconsidered. The most successful WBG systems will be those that redesign the complete converter around the strengths and limits of the selected device. As manufacturing volume increases and packaging improves, WBG technology will become a central foundation for high-efficiency, high-density power conversion.

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