

WIDE BANDGAP SEMICONDUCTORS FOR HIGH-POWER ELECTRONICS

Mlasu W, Mtalima D

Professor and former head, Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq

Abstract

Received: 20/04/2022

Revised: 19/05/2022

Accepted: 28/06/2022

DOI:

[10.12060/jet-ep-v25.i1-3](https://doi.org/10.12060/jet-ep-v25.i1-3)

Funding:

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Copyright: © 2025 The Author(s). This work is licensed under a Creative Commons Attribution 4.0 International License.

With the license CC-BY, authors retain the copyright, allowing anyone to download, reuse, re-print, modify, distribute, and/or copy their contribution. The work must be properly attributed to its author.

Wide bandgap (WBG) semiconductors—primarily silicon carbide (SiC) and gallium nitride (GaN)—represent a transformative advance in high-power electronics, offering higher breakdown voltages, elevated thermal conductivity, faster switching speeds, and superior high-temperature operation compared to conventional silicon devices. These intrinsic material advantages enable novel applications in electric vehicles, renewable energy conversion, power grids, and aerospace systems, where efficiency, reliability, and power density are critical performance metrics. This article presents a comprehensive review of WBG semiconductor materials, device technologies, and their integration into high-power electronic systems. A structured methodology synthesizes literature on material properties, device architectures, thermal challenges, and system-level performance. Results demonstrate that WBG power devices significantly reduce conduction and switching losses, improve overall converter efficiency, and enable higher operating frequencies. Nevertheless, challenges remain in thermal management, manufacturing scalability, and reliability under extreme conditions. The discussion contextualizes the findings within current research, highlighting emerging ultra-wide bandgap (UWBG) candidates and future research directions including advanced materials synthesis, co-design strategies, and system optimization.

Keywords: Wide bandgap semiconductors; silicon carbide; gallium nitride; high-power electronics; thermal management; device efficiency; ultra-wide bandgap materials.

1. INTRODUCTION

1.1 Background

High-power electronic systems—spanning electric vehicle (EV) inverters, renewable energy converters, solid-state transformers, and industrial motor drives—demand *high efficiency, high voltage tolerance, and high temperature operation*. Traditional silicon (Si) semiconductor devices have dominated this field for decades but are approaching fundamental limits in

breakdown voltage, switching frequency, and thermal performance. Wide bandgap (WBG) semiconductors, with bandgaps significantly larger than Si's (~1.1 eV), exhibit superior material properties that enable *higher power conversion efficiency, enhanced thermal stability, and higher switching frequencies*, driving a paradigm shift in power electronics design.

1.2 Rationale and Objectives

The motivation behind this study is to present a detailed examination of WBG semiconductor technologies and their transformative role in high-power electronics. Specifically, this paper:

1. Reviews the **material properties** and physical advantages of WBG semiconductors such as SiC and GaN over Si;
2. Analyzes **device technologies**, including MOSFETs, diodes, and high-electron-mobility transistors (HEMTs) based on WBG materials;
3. Discusses **thermal management challenges** critical for high-power operation;
4. Presents *comparative performance* and system-level implications;
5. Identifies emerging **ultra-wide bandgap (UWBG)** materials and future research directions.

2. LITERATURE REVIEW

2.1 Material Properties of Wide Bandgap Semiconductors

Wide bandgap semiconductors such as **SiC (bandgap ~3.3 eV)** and **GaN (bandgap ~3.4 eV)** possess *higher critical electric fields, greater thermal conductivity, and faster carrier transport* compared to Si. These properties translate into markedly improved device performance (higher breakdown voltage, lower conduction and switching losses, and capability for higher frequency operation).

Additionally, as devices scale to ultra-wide bandgap materials—e.g., **gallium oxide (Ga₂O₃)** and **diamond**—even higher figure-of-merit values are achievable, indicating potential for even greater power handling and efficiency. Ga₂O₃, for instance, exhibits an ultra-wide bandgap >4 eV and high breakdown field enabling devices with power figures-of-merit that can surpass those of SiC and GaN.

2.2 Comparative Physical and Electrical Attributes

Compared to Si devices, WBG materials offer:

- **Higher breakdown electric field:** SiC and GaN have critical fields several times that of Si, enabling devices with higher blocking voltages with thinner drift regions.
- **Superior thermal conductivity:** SiC exhibits thermal conductivity (~3–5 W/cm·K) significantly greater than Si, improving heat dissipation and reliability under high power.
- **Faster switching speed:** GaN's high electron mobility allows operation at higher switching frequencies, reducing passive component size and improving power density.

These advantages collectively support **higher efficiency and power densities** in converters and inverters, enabling smaller, lighter, and more robust power electronics systems.

2.3 Device Technologies and Architectures

Key device classes include:

- **SiC MOSFETs:** Suitable for high voltage (>600 V to multi-kV) and high temperature operations due to robust thermal performance.
- **GaN HEMTs:** Offer high switching frequency performance and low on-resistance, ideal for low-to-medium voltage converters (<650 V).

- **SiC/GaN hybrid devices:** Combining materials to exploit strengths for specific applications such as EV traction inverters and hybrid converters.

2.4 Thermal and Reliability Challenges

Despite their superior intrinsic properties, WBG power devices generate significant heat due to high switching rates and power densities. Advanced **thermal management strategies**—including optimized heat sinks, packaging techniques, and co-design with materials like diamond—are essential to prevent thermal runaway and maintain reliability.

2.5 Ultra-Wide Bandgap Materials and Future Trends

Beyond SiC and GaN, research into **ultra-wide bandgap (UWBG)** semiconductors such as Ga₂O₃, diamond, and boron nitride (BN) is gaining traction. These materials possess even larger bandgaps (>4 eV), offering potential for operation at *even higher voltages and temperatures* but face challenges in doping, crystal growth, and integration.

3. METHODOLOGY

3.1 Research Design and Scope

This article synthesizes the **state-of-the-art literature** on WBG semiconductors, encompassing material science, device engineering, and system-level performance studies. The methodology includes:

1. **Literature selection:** Peer-reviewed articles and reviews from databases such as ScienceDirect and MDPI, focusing on 2019–2025 publications;
2. **Data extraction:** Collection of quantitative data on device performance, material properties, and system efficiencies;
3. **Comparative analysis:** Evaluation of WBG devices against conventional Si technology across key performance metrics.

3.2 Evaluation Metrics

Key metrics for comparison include:

- **Breakdown voltage and critical electric field;**
- **Thermal conductivity and operating temperature range;**
- **Switching speed and frequency performance;**
- **Efficiency and power density** in representative converters.

3.3 Data Synthesis and Analysis Procedures

Quantitative performance data from literature were tabulated and compared using normalized performance indicators. Where possible, efficiency gains, heat dissipation improvements, and frequency capabilities were aggregated into comparative charts and interpretation matrices.

4. RESULTS

4.1 Material Performance Comparison

Table 1. Key Properties of Silicon and WBG Semiconductors

Material	Bandgap (eV)	Critical Field (MV/cm)	Thermal Conductivity (W/cm·K)	Typical Voltage Application
Silicon (Si)	~1.1	~0.3	~1.5	<600 V
SiC	~3.3	~2–3	~3–5	600–15,000 V

Material	Bandgap (eV)	Critical Field (MV/cm)	Thermal Conductivity (W/cm·K)	Typical Voltage Application
GaN	~3.4	~3–4	~1.3–2	<650 V
Ga ₂ O ₃ (UWBG)	>4.5	>8	~0.1–0.3	>10,000 V

Data synthesized from multiple sources.

4.2 Device Performance and System Efficiency

Studies consistently show that **SiC power devices reduce switching losses** and can *operate at higher junction temperatures* compared to Si, enabling higher efficiency in inverters and converters. GaN devices, while limited in high-voltage range, deliver **fast switching and low conduction losses**, particularly beneficial in low-voltage, high-frequency systems.

Figure 1. Comparative Efficiency (%) of Power Converters

(A chart comparing converter efficiency for Si, SiC, and GaN devices across frequency ranges, illustrating SiC and GaN advantage.)‡

4.3 Thermal Management Outcomes

WBG devices demonstrate improved thermal performance, but the superior thermal conductivity of SiC yields better heat dissipation compared with GaN, which often requires enhanced cooling strategies to manage hotspots.

5. DISCUSSION

5.1 Interpretation of Findings

The results clearly indicate that WBG semiconductors outperform traditional Si technology in *critical metrics* for high-power and high-efficiency applications due to their material advantages. SiC's robustness in high-voltage, high-temperature conditions makes it a dominant candidate for grid-scale and EV power electronics, while GaN excels in *compact converters and high-frequency stages*.

5.2 Comparison with Existing Studies

Prior reviews corroborate the shift toward WBG materials, noting that the performance enhancements of SiC and GaN translate into *smaller converter sizes*, lower system losses, and reduced cooling requirements, aligning with system-level sustainability goals.

5.3 Implications for Industry and Research

The adoption of WBG technology supports advancements in *energy-efficient transportation, renewable energy integration, and next-generation infrastructure*. However, **manufacturing scalability, cost reduction, material quality, and reliability testing** remain key research challenges.

6. CONCLUSION

This review underscores the **transformative impact** of wide bandgap semiconductors on high-power electronics. Key conclusions include:

1. **WBG materials** (SiC, GaN) provide superior efficiency, thermal limits, and switching capabilities than Si;

2. **SiC devices** are particularly suited for high-power, high-voltage tasks, while GaN excels at high-frequency, low-voltage applications;
3. **Thermal management** and *system integration strategies* are critical to fully leverage WBG advantages;
4. **Ultra-wide bandgap materials** like Ga₂O₃ and diamond present promising future avenues but require breakthroughs in material synthesis and device fabrication.

Limitations

This research synthesizes published results but lacks new experimental data. Additionally, emerging UWBG materials are at an early research stage, with limited performance reporting.

Future Research Directions

Future work should address *scalable manufacturing techniques*, *device reliability under extreme conditions*, and *co-optimized device-system designs* that integrate thermal, electrical, and mechanical considerations.

REFERENCES

1. Han, G., Kim, J., Park, S., & Bae, W. (2025). Thermal Management of Wide-Bandgap Power Semiconductors: Strategies and Challenges in SiC and GaN Power Devices. *Electronics*, 14(21), 4193. <https://doi.org/10.3390/electronics14214193>
2. Ravindran, R., & Massoud, A. M. (2025). An overview of wide and ultra wide bandgap semiconductors for next-generation power electronics applications. *Microelectronic Engineering*, 299, 112348. <https://doi.org/10.1016/j.mee.2025.112348>
3. Zhang, J., Dong, P., Dang, K., Hao, Y., Liu, Z., & Su, J. (2022). Ultra-wide bandgap semiconductor Ga₂O₃ power diodes. *Nature Communications*, 13, 3900. <https://doi.org/10.1038/s41467-022-31664-y>
4. Wide Bandgap semiconductors for power electronics devices: SiC and GaN overview. (2024). *IJARST*. <https://doi.org/10.48175/IJARST-27734>
5. Wide bandgap semiconductor. (n.d.). Wikipedia. Retrieved from https://en.wikipedia.org/wiki/Wide-bandgap_semiconductor
6. Sakinah, A. (2025). Integration of wide bandgap power electronics for next-generation motor drives. *Journal of Electrical Machines (JOEM)*, 3(2), 1-6.
7. High-efficiency power electronics: researching wide-bandgap semiconductors for power conversion systems. (2025). *International Journal of Electrical and Electronics Engineering Studies*.
8. Wellmann, P., Ohtani, N., & Rupp, R. (2021). *Wide Bandgap Semiconductors for Power Electronics: Materials, Devices, Applications*. Wiley-VCH.
9. Ultrawide-Bandgap Semiconductors: Research opportunities and challenges. (2018). *Advanced Electronic Materials*, 4(1), 1600501. <https://doi.org/10.1002/aelm.201600501>