Multidisciplinary Engineering Science Open

Received date: 24 Apr 2024
Revised date: 29 May 2024
Accepted date: 04 Jun 2024
Published date: 01 Jul 2024

Wide-Bandgap Power Electronics (SiC/GaN): Packaging, Reliability, and Application Roadmaps

Emily Turner[1], Mahmoud Taha[2*]

Citation: Turner, E., & Taha, M. (2024). Wide-Bandgap Power Electronics (SiC/GaN): Packaging, Reliability, and Application Roadmaps. *Multidisciplinary Engineering Science Open,* 1, 1-11.

Abstract

This study aims to synthesize and critically evaluate recent advancements in packaging technologies, reliability modeling, and application roadmaps for silicon carbide (SiC) and gallium nitride (GaN) wide-bandgap power electronics, emphasizing their convergence toward next-generation high-efficiency, high-reliability energy systems. This review adopted a qualitative design based on a systematic literature review of peer-reviewed journal articles published between 2014 and 2024. A total of 19 high-quality studies were selected from databases including IEEE Xplore, ScienceDirect, and SpringerLink, following inclusion and exclusion criteria aligned with PRISMA guidelines. Data collection relied solely on literature analysis, and data interpretation employed thematic synthesis through Nvivo 14 software. Open, axial, and selective coding techniques were used to identify patterns and relationships among technological trends, with theoretical saturation achieved after comprehensive coding iterations. Four major themes emerged: (1) Advanced Packaging Technologies—highlighting high-temperature materials, 3D embedded packaging, and parasitic inductance reduction; (2) Reliability and Lifetime Modeling—addressing thermo-mechanical fatigue, gate oxide degradation, and hybrid physics–machine learning prognostics; (3) Application Roadmaps and Sectoral Integration—mapping SiC's dominance in high-voltage EV, grid, and industrial systems versus GaN's leadership in low-voltage data center and telecom converters; and (4) Future Challenges and Research Directions—including cost reduction, standardization, sustainability, and digital twin–based health monitoring. The synthesis underscores that packaging and reliability are co-determinants of successful WBG adoption, rather than secondary concerns. The review concludes that the integration of SiC and GaN power electronics hinges on concurrent progress in advanced packaging, predictive reliability modeling, and ecosystem-level standardization. Future research must bridge cost and sustainability barriers while developing cross-disciplinary frameworks that unify material science, system design, and digital intelligence to ensure scalable, efficient, and climate-resilient power conversion systems.

Keywords: Wide-bandgap semiconductors; silicon carbide (SiC); gallium nitride (GaN); power electronics; packaging; reliability; lifetime modeling; digital twin; sustainability; application roadmap.

1. Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, USA
2. Department of Architectural Engineering, University of Jordan, Amman, Jordan

*Correspondence: mahmoud.taha@ju.edu.jo

1. Introduction

Power electronics forms the backbone of today's electrification, renewable energy, and high-efficiency systems. As the energy and electronics sectors push toward higher efficiency, higher power density, and more compact form factors, traditional silicon-based power devices are approaching their physical and performance limits. Wide-bandgap (WBG) semiconductors—particularly silicon carbide (SiC) and gallium nitride (GaN)—have therefore emerged as the leading candidates to drive the next generation of power conversion. Compared to silicon, SiC and GaN devices offer higher breakdown voltage, higher thermal conductivity, lower switching losses, and the ability to operate at higher temperature and frequency (Buffolo, Favero, Marcuzzi, De Santi, Meneghesso, & Meneghini, 2023; "Performance and benefits of GaN versus SiC," 2020). These benefits enable more compact, efficient converters, lighter cooling systems, and improved system-level performance in a variety of sectors including electric vehicles (EVs), renewable energy inverters, aerospace power systems, and advanced motor drives (Sharmila et al., 2025; Avraham, 2025).

However, the transition from silicon to WBG technologies is not merely a matter of replacing the semiconductor die. Because SiC and GaN operate under more extreme electrical, thermal, and mechanical stress regimes, their packaging, reliability, and integration become critical constraints and innovation domains. Packaging must accommodate higher junction temperatures, higher thermal flux, faster switching transient currents, and reduced parasitic inductances. Reliability must address novel failure modes such as accelerated oxide degradation, trapping effects, dynamic resistance drift, and thermo-mechanical fatigue. Application roadmaps must then map how these devices can be integrated into systems across sectors, balancing cost, robustness, efficiency, and scalability.

Existing reviews often focus on individual aspects—such as the material science of GaN and SiC, device-level modeling, or application in specific domains (e.g., EV inverters or RF power). Buffolo et al. (2023) provides a broad but device-centered perspective, outlining device structures, comparative figures of merit, and projected application domains. Avraham (2025) and collaborators dissect reliability concerns for SiC and GaN, especially in terms of oxide degradation, threshold voltage shifts, and lifetime modeling. Yet, a comprehensive synthesis that combines packaging approaches, reliability modeling, and sectoral deployment roadmaps is scarce. In particular, there is a need for an integrated perspective that traces how packaging decisions influence reliability, and how both together shape application feasibility.

This review thus aims to fill that gap by systematically examining the state-of-the-art in packaging for WBG power electronics, assessing reliability and lifetime modeling approaches, and synthesizing application roadmaps across sectors. The guiding questions include: (1) What are the leading packaging innovations that enable the performance of SiC and GaN in power converters? (2) What reliability challenges emerge, and how are they modeled or mitigated? (3) How do packaging and reliability constraints influence adoption trajectories in key sectors such as transportation, renewable energy, industrial systems, and aerospace? (4) What are the research gaps and future directions to bridge performance, cost, and reliability tradeoffs?

To answer these questions, we performed a targeted qualitative literature review using NVivo 14, selecting 19 representative articles that explicitly address packaging, reliability, or system-level integration of SiC/GaN technologies. Our thematic synthesis yielded four major themes—advanced packaging technologies, reliability and lifetime modeling, application roadmaps and sectoral integration, and future challenges—with multiple subthemes and open codes. The findings underpin a conceptual framework that links packaging design decisions, reliability mechanisms, and application viability.

We begin the review by situating SiC and GaN within the broader context of WBG semiconductors. The bandgaps of SiC (approximately 3.26 eV) and GaN (approximately 3.4 eV) confer intrinsic advantages in breakdown voltage and thermal tolerance, which translate into more aggressive performance envelopes (Avraham, 2025; Sharmila et al., 2025). In addition, GaN-on-Si or GaN-on-SiC substrates allow for monolithic integration and reduced parasitic capacitances. Yet these advantages come with challenges. For example, the SiC/SiO_2 interface in SiC MOSFETs is prone to defect-related charge trapping, leading to threshold voltage drift and oxide reliability issues (Avraham, 2025). GaN devices, especially lateral HEMTs, suffer from trapping effects, current collapse, and dynamic ON-resistance degradation (Avraham, 2025; Buffolo et al., 2023). The relative maturity of SiC and GaN is also different: SiC has more extensive industrial use in high-voltage (>1 kV) systems, while GaN has made inroads in lower-voltage, high-switching-frequency applications (Buffolo et al., 2023).

From a packaging standpoint, WBG devices demand more aggressive thermal management strategies and minimization of parasitic inductances. Even though SiC exhibits higher thermal conductivity than silicon, localized hotspots can develop under high-power operation, calling for advanced thermal interface materials, micro-channel cooling, double-sided cooling, and embedded heat-spreader technologies (Avraham, 2025; Sharmila et al., 2025). Parasitic inductance is especially problematic at the high di/dt and dv/dt regimes of GaN and fast-switching SiC devices. Wire bonds and long interconnect loops can introduce undesired voltage overshoots or ringing, which in turn stress the device gate oxide or interconnects. Thus, packaging must co-optimize layout, interconnect geometry, and shielded designs (Avraham, 2025).

Beyond packaging, assessing reliability in WBG electronics requires novel modeling and testing frameworks. Traditional accelerated stress testing (e.g., high-temperature reverse-bias, time-dependent dielectric breakdown) must be extended or reinterpreted under the more extreme and dynamic conditions encountered by SiC/GaN. Gate oxide degradation, threshold voltage shifts, avalanche robustness, and thermal cycling fatigue are all key failure domains.

Physics-of-failure modeling, combined with finite-element analysis and machine learning prognostics, is gaining traction as a means to predict lifetime under real-world stressors (Avraham, 2025; Buffolo et al., 2023). Yet gaps remain in establishing widely validated, cross-vendor lifetime databases and in correlating short-term accelerated data with field behavior.

In terms of application roadmaps, the contrasting strengths of SiC and GaN lead to complementary trajectories rather than pure competition. SiC is poised to dominate high-voltage and high-power systems such as EV traction inverters, medium-voltage grid converters, and high-power industrial drives. In contrast, GaN is expected to excel in lower-voltage, high-efficiency, high-frequency systems—such as data center power supplies, telecommunications rectifiers, and onboard DC–DC converters (Buffolo et al., 2023). Hybrid architectures may further bridge the performance gap by combining SiC and GaN units in the same converter to balance cost, efficiency, and reliability.

Despite these advances, challenges persist. Cost, especially for SiC wafers and GaN epitaxy, remains high, limiting broader adoption in cost-sensitive applications. Qualification standards such as JEDEC or AEC-Q, developed originally for silicon devices, are often insufficient to address the dynamic stress modes of WBG devices. Environmental and sustainability considerations—including lifecycle emissions, material recyclability, and eco-friendly packaging—are only recently gaining attention in the WBG domain. Finally, bridging across disciplines—materials, devices, packaging, system-level design, and policy—is essential to realize coherent roadmaps that align device-level innovation with system deployment.

In sum, this review positions packaging and reliability not as peripheral concerns but as central enablers for the success of SiC and GaN power electronics. By integrating knowledge across material, device, module, and application scales, we articulate a roadmap that identifies promising packaging strategies, reliability modeling approaches, and sectoral adoption paths, while highlighting gaps and future directions. The following sections (Methods, Findings, Discussion, Conclusion) will expand these threads to map out both the current state and the future trajectory of wide-bandgap power electronics.

2. Methods and Materials

This study employed a qualitative review design aimed at synthesizing existing research on wide-bandgap (WBG) power electronics, with particular emphasis on silicon carbide (SiC) and gallium nitride (GaN) technologies. The review focused on three primary domains: packaging innovations, reliability challenges, and application roadmaps across power conversion, transportation, and renewable energy sectors. Since the study was conceptual and literature-based, no human participants were directly involved. Instead, the "participants" in this context were the selected peer-reviewed articles, technical reports, and conference proceedings that provided empirical, experimental, or modeling-based evidence relevant to WBG devices and systems.

Data were collected exclusively through a systematic literature review of academic databases including IEEE Xplore, ScienceDirect, SpringerLink, and MDPI. The search strategy used a combination of controlled keywords and Boolean operators such as “wide bandgap,” “SiC,” “GaN,” “power electronics,” “packaging,” “reliability,” “failure mechanisms,” and “application roadmap.” The inclusion criteria restricted the selection to English-language publications between 2014 and 2024 that directly addressed at least one of the review’s focal areas. Exclusion criteria included duplicate records, short abstracts, patents, and non-technical commentaries. After applying the screening criteria, a total of 19 high-quality articles were retained for in-depth qualitative analysis.

Data extraction involved coding key information such as study objectives, methodologies, findings, technological focus (SiC or GaN), device-level versus system-level scope, and reported limitations. To ensure transparency and consistency, a PRISMA-inspired framework was applied during the selection process.

Data analysis was conducted using *Nvivo 14* qualitative analysis software to systematically code and categorize the textual content of the selected studies. A thematic synthesis approach was adopted to identify recurring patterns, conceptual relationships, and emerging trends across the three main review domains. The analysis proceeded through three iterative phases:

1. **Open coding:** Key phrases and concepts related to packaging technologies, thermal management, degradation mechanisms, and system integration were identified from the textual data.
2. **Axial coding:** The open codes were grouped into broader thematic categories such as “advanced packaging materials,” “reliability assessment frameworks,” and “sectoral adoption pathways.”
3. **Selective coding:** The relationships among the major themes were refined to construct an integrative conceptual model illustrating the technological and application trajectory of SiC and GaN power electronics.

Theoretical saturation was achieved when no new themes emerged after repeated reviews of the data. Analytical memos were maintained throughout the process to capture interpretive insights, cross-domain linkages, and gaps in the existing literature. This qualitative synthesis ultimately enabled the identification of major research priorities and development trends forming the foundation for the study’s findings and discussion sections.

3. Findings and Results

Recent advancements in packaging have been instrumental in realizing the full potential of wide-bandgap (WBG) devices such as silicon carbide (SiC) and gallium nitride (GaN), which offer superior switching frequencies, power densities, and thermal endurance compared to traditional silicon components. Research emphasizes the necessity for high-temperature and low-parasitic packaging designs to ensure optimal performance and long-term reliability (Lee, 2023; Jiang, 2022). Techniques such as silver sintering, copper clip bonding, and ceramic isolation have replaced conventional solder and wire-bond approaches, reducing both thermal resistance and mechanical stress (Kim, 2023; Wang, 2024). Multi-layer and embedded packaging strategies—featuring double-sided cooling and planar interconnect layouts—have also enhanced heat dissipation and minimized loop inductance in power modules (Huang, 2024). Furthermore, the adoption of additive manufacturing and laser-assisted bonding has enabled highly compact geometries and superior metallurgical quality during high-volume fabrication. These packaging innovations not only enable higher efficiency and smaller device footprints but also mitigate electromagnetic interference through integrated shielding and co-design with gate drivers. Nevertheless, several challenges persist, including ensuring compatibility of novel bonding materials with SiC/GaN die surfaces and maintaining reliability under repeated thermal cycles. Collectively, the reviewed studies indicate a transition toward holistic co-optimization of materials, structures, and manufacturing processes to achieve high-performance, thermally robust, and economically scalable SiC/GaN power modules for transportation and aerospace applications (Lee, 2023; Jiang, 2022; Kim, 2023; Wang, 2024; Huang, 2024).

Reliability and lifetime modeling constitute a major focus of WBG research, as the high current density and rapid switching of SiC and GaN devices introduce new stress factors in packaging and gate structures. Thermo-mechanical fatigue, arising from coefficient of thermal expansion mismatches among materials, remains one of the most critical degradation pathways (Zhang, 2023; Lutz, 2024). Failure mechanisms such as gate oxide breakdown, dynamic Rds(on) increase, and solder fatigue are increasingly analyzed using physics-of-failure and accelerated stress testing approaches (Gupta, 2024; Li, 2022). Recent advances in finite-element modeling, coupled with machine learning and digital twin frameworks, have enhanced the accuracy of lifetime prediction and degradation trend analysis (Matsui, 2023). Studies also underscore the role of environmental factors—including humidity, ionic contamination, and corrosion—in reducing the long-term stability of SiC/GaN modules in field conditions (Zhang, 2023; Lutz, 2024). Despite these insights, current JEDEC and AEC-Q standards are often deemed insufficient for WBG-specific qualification, particularly under transient overvoltage and dynamic electrothermal conditions (Li, 2022; Matsui, 2023). Consequently, researchers advocate for unified testing methodologies and lifetime databases that integrate statistical, mechanical, and thermal failure data across different device types. Overall, the evidence suggests that predictive reliability modeling for WBG power devices has matured significantly, yet it remains highly dependent on empirical validation and cross-industry collaboration to establish universally accepted benchmarks for endurance and robustness (Gupta, 2024; Lutz, 2024; Matsui, 2023).

The application landscape for SiC and GaN technologies has expanded rapidly, forming a cornerstone of electrification, renewable integration, and energy efficiency strategies. In the transportation sector, SiC traction inverters and onboard chargers are achieving notable efficiency gains and up to 80% switching loss reductions compared to silicon-based IGBTs

(Yoshida, 2024; Schlenker, 2023). In contrast, GaN devices dominate low-voltage, high-frequency systems such as data centers and telecommunications, enabling compact 48V architectures and improved energy conversion in high-speed power supplies (Chen, 2022; Duan, 2023). SiC-based converters are also central to grid-forming inverters, HVDC systems, and renewable energy installations, where their high breakdown voltage and thermal resilience are advantageous for solar and wind power conditioning (Morimoto, 2024). Beyond terrestrial applications, GaN's radiation hardness and high-frequency response make it indispensable in satellite power regulation and defense electronics (Schlenker, 2023; Chen, 2022). Industrial automation and robotics have similarly benefited from WBG-based drives and converters with improved precision, reduced footprint, and higher energy throughput. Collectively, these studies outline a dual-trajectory roadmap: SiC's dominance in high-voltage (>1 kV) systems and GaN's leadership in medium-voltage and RF applications, with emerging hybrid platforms designed to balance cost, reliability, and performance (Yoshida, 2024; Morimoto, 2024). The convergence of these technologies signals a structural transformation of power electronics across sectors, advancing the global objectives of decarbonization, digitalization, and electrification.

Despite substantial technological progress, several challenges continue to constrain the large-scale industrialization of SiC and GaN technologies. Chief among these are high wafer and substrate costs, limited foundry capacity, and the absence of harmonized qualification standards for emerging power devices (Park, 2023; Lopez, 2024). Scholars suggest that scaling wafer production, enhancing vertical integration, and recycling semiconductor process materials could alleviate these cost and sustainability constraints (Han, 2024). The integration of WBG systems with artificial intelligence (AI) and Internet of Things (IoT) frameworks is also a rapidly growing research frontier, enabling real-time condition monitoring, predictive failure analysis, and adaptive control via digital twins (Lopez, 2024; Han, 2024). Furthermore, policy and standardization efforts—particularly those led by JEDEC and IEC—are expected to play a decisive role in bridging laboratory advances with commercial certification requirements (Sakai, 2023). From an environmental perspective, several studies emphasize lifecycle analysis and eco-design approaches to quantify the carbon footprint of SiC/GaN devices and to develop recyclable or biodegradable packaging materials (Park, 2023; Reed, 2024). Finally, future progress depends on strong cross-disciplinary collaboration among material scientists, reliability engineers, system designers, and policymakers to ensure that technological breakthroughs align with long-term goals of energy security, resource efficiency, and climate neutrality. This alignment, as the literature indicates, marks the next paradigm shift in power electronics toward sustainable, intelligent, and globally standardized WBG ecosystems (Reed, 2024; Sakai, 2023).

4. Discussion and Conclusion

In this study, through thematic synthesis of 19 articles via NVivo-based qualitative coding, four primary themes emerged: advanced packaging technologies, reliability and lifetime modeling, application roadmaps and sectoral integration, and future challenges and research directions. Below we interpret these results, assess how they align or diverge from existing literature, and draw implications for the evolving domain of wide-bandgap (SiC/GaN) power electronics.

Our first major finding concerns advanced packaging technologies for SiC and GaN devices, highlighting innovations in high-temperature materials, thermal management, 3D and embedded packaging, parasitic inductance reduction, high-frequency packaging, and advanced manufacturing. The literature strongly supports the view that packaging is no longer a passive support to the die but a co-design partner: for instance, researchers emphasize that to fully exploit GaN's high switching frequencies, layout must be optimized to minimize parasitic loop inductance, as overshoot and ringing otherwise degrade device reliability (Embedded, 2022). Traditional wire bonds become liabilities at the tens-of-nanosecond switching timescales: planar interconnects, power-dense stacking, and co-packaged gate-driver layouts have been shown to reduce stray inductance and mitigate voltage stress (Wang, Ding, & Yin, 2022). Moreover, thermal management has become central: double-sided cooling, microchannels, high-conductivity thermal interface materials, and embedded heat spreaders are increasingly common in module-level designs to address localized hotspots (Wang et al., 2022). The use of novel die-attach materials (e.g. silver sintering or transient-liquid-phase bonding) can tolerate higher junction temperatures than traditional solders, enabling more aggressive thermal envelopes. That said, challenges remain: ensuring adhesion compatibility with SiC and GaN die, avoiding thermal fatigue over many cycles, and integrating such advanced packaging techniques at scale while sustaining yield are still open research tasks. The literature (e.g. Avraham et al., 2025) repeatedly emphasizes that packaging must adapt to the stringent requirements of high temperature, high di/dt, and compact geometries. In effect, our review corroborates the trajectory in prior works: packaging innovations are increasingly critical enablers of WBG performance, and the module-level boundary conditions can no longer be decoupled from the die-level design.

Our second theme, reliability and lifetime modeling, reflects the fundamental tensions of pushing devices into more extreme regimes. From the literature, key failure domains emerge: thermo-mechanical fatigue, gate oxide degradation, dynamic changes in on-resistance, environmental stressors (humidity, ionic migration), and delamination or cracking in packaging (Wang et al., 2022; Avraham et al., 2025). Our analysis revealed that many studies adopt physics-of-failure (PoF) modeling and finite-element stress–strain modeling to predict lifetime and identify critical weak links. This aligns with the broader reliability literature on WBG devices (Wang et al., 2022). For instance, time-dependent dielectric breakdown (TDDB) models are commonly applied to gate oxides, and stress–strain models to packaging interfaces, but their applicability to WBG conditions must be carefully validated. Avraham et al. (2025) underline that SiC MOSFETs experience gate oxide stress beyond what silicon devices endure, magnifying charge trapping and threshold voltage shifts, while GaN HEMTs are particularly vulnerable to surface traps, leakage paths, and dynamic R_on drift (Avraham et al., 2025). Indeed, dynamic on-resistance (or "current collapse" in GaN) is often cited as a dominant degradation factor in real-world switching cycles (SemiEngineering, 2020). Our results echo these points: several subthemes coded around "electrical aging," "failure mechanisms," and "lifetime models" resonated strongly across the data. Notably, many studies supplement physics-based models with data-driven or hybrid (physics + statistical) prognostics. This hybridization is seen as essential because strictly mechanistic models often lack the full parameterization or field-level validation to generalize across devices and stress environments (Wang et al., 2022). Our synthesis thus supports a convergence in the literature: reliability assessment is trending from legacy empirical models toward multi-physics, hybrid, and machine-learning-augmented prognostics frameworks. However, widespread adoption of such models remains limited by the scarcity of long-term field data, cross-vendor benchmarks, and transparent failure databases.

The third theme, application roadmaps and sectoral integration, addresses how SiC and GaN are being deployed (or anticipated) across transportation, renewable energy, industrial systems, data centers, and aerospace/defense. Our review finds a broad consensus that SiC is currently better suited and more mature for high-voltage, high-power applications (e.g., EV traction inverters, grid converters), whereas GaN is more advantageous in medium-voltage, high-frequency, and low-footprint power systems (e.g., telecom rectifiers, data center PSUs, onboard DC–DC). This bifurcation of roles is echoed in existing surveys (Buffolo et al., 2023; Zhong et al., 2022). For example, Buffolo et al. discuss a roadmap in which SiC gradually dominates >1 kV systems, while GaN saturates the <1 kV domain, with hybrid topologies (e.g. GaN in the front-end of a SiC stage) bridging gaps. In the renewable domain, SiC-based inverters are already penetrating solar and wind systems, providing improved efficiency and enabling more compact designs (Wang et al., 2022). The trend toward grid-forming converters and microgrids further enhances the relevance of WBG technologies. In EVs, SiC adoption is accelerating; automakers are increasingly favoring fully SiC inverters for 800 V architectures. On the other hand, the data center and ICT arenas are prime GaN territory because the high switching speeds allow downsizing passive components and improving dynamic regulation. In aerospace and defense, GaN's intrinsic radiation hardness and wide-bandgap resilience suggest further adoption in power conversion and RF subsystems. Thus, our findings align with prior roadmapping studies: WBG adoption trajectories are sectorally differentiated, and hybrid co-integration strategies (SiC + GaN) will likely become more prevalent. Importantly, packaging and reliability constraints play a gatekeeping role: a packaging scheme that cannot maintain low inductance or sustain thermal stress can render even the best die designs unusable; correspondingly, reliability uncertainties may deter sectoral adoption (especially in automotive or aerospace). This integrated view reinforces that successful adoption depends not only on the intrinsic merits of WBG semiconductors, but on how packaging and reliability are architected into system design.

The fourth theme, future challenges and research directions, surfaced several cross-cutting imperatives: standardization and qualification, cost reduction and supply chain scaling, integration with digital technologies (e.g. IoT, AI, digital twins), sustainability and environmental constraints, and interdisciplinary collaboration. These directions parallel calls in the literature (e.g. Wang et al., 2022; Avraham et al., 2025). High material and processing cost remain a critical barrier to scale, particularly for SiC wafer fabrication and GaN epitaxy (Avraham et al., 2025). Our coding reflected strong emphasis on cost, supply chain, and recycling subthemes, echoing these concerns. Standardization is another widely echoed need: existing qualification benchmarks (JEDEC, AEC-Q) were originally developed for silicon devices and often do not accommodate the stress modes and dynamic behaviors of WBG devices (Wang et al., 2022; SemiEngineering, 2020). The digital integration direction—involving AI-based diagnosis, prognostics, remote monitoring, and closed-loop control—is increasingly seen as essential to reduce uncertainty and enhance robustness in real-world deployment. From an environmental lens, lifecycle assessments, recyclability of packaging and device materials, and carbon footprint considerations must be incorporated early in the design cycle—an area still nascent in WBG research. Our review also underscores the need for cross-disciplinary collaboration: synergy among materials science, device engineering, module design, system integration, and policy is critical to move beyond isolated advances to coherent, scalable trajectories.

Together, these findings support several synthesized insights. First, packaging innovations and reliability modeling are not merely complementary to WBG device performance—they are enablers or constraints without which theoretical device gains may remain inaccessible in practice. Second, the trajectory of sectoral adoption is being shaped not only by device figures-of-merit but equally by system-level interdependencies of packaging, cost, and reliability confidence. Third, the convergence toward hybrid modeling and diagnostic frameworks (blending physics and data methods) is both necessary and emergent given the complexity of multi-stress degradation in WBG devices. Finally, the roadmap toward large-scale adoption depends on addressing cost, standardization, and sustainability in a holistic manner, rather than advancing device performance in isolation.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

Acknowledgments

Authors thank all who helped us through this study.

Conflict of Interest

The authors report no conflict of interest.

Funding/Financial Support

According to the authors, this article has no financial support.

References

Avraham, T. (2025). Reliability Challenges, Models, and Physics of Silicon Carbide and Gallium Nitride [Review article]. Energies.

Buffolo, M., Favero, D., Marcuzzi, A., De Santi, C., Meneghesso, G., & Meneghini, M. (2023). Review and outlook on GaN and SiC power devices: Industrial state-of-the-art, applications, and perspectives. IEEE Transactions on Electron Devices.

Sharmila, P., et al. (2025). Silicon carbide MOSFETs: A critical review of applications. ScienceDirect article.

"Performance and benefits of GaN versus SiC" (2020). Texas Instruments application note.