# Wide Band Gap Semiconductor Devices in Power Converter Design for Electric Vehicle Applications

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***Abstract*— The rapid growth in electric vehicle (EV) adoption has generated an imperative demand for power electronic converters that exhibit high efficiency, compactness, and reliability. Conventional silicon (Si)-based semiconductors are reaching their theoretical limits and hence open the door for exploring wide band gap (WBG) and ultrawide band gap (UWBG) materials. This article provides an extensive review of the recent advancements in WBG semiconductor devices and their application to EV power converters. We assess the material properties, fabrication issues, and device performance of well-established WBG materials such as silicon carbide (SiC) and gallium nitride (GaN) and emerging UWBG materials such as diamond and gallium oxide ($Ga_2O_3$). Special focus is given to performance parameters important to EV systems, including on-state resistance, switching losses, thermal management, and operation at harsh conditions, e.g., cryogenic temperatures. Based on a comparative evaluation, we explore the applicability of each material to various EV power converter topologies, such as traction inverters, on-board chargers (OBCs), and DC-DC converters. The paper concludes by combining the technology readiness levels, establishing the current research gaps, and forecasting future trends in WBG device deployment to facilitate the development of electric mobility.**

**Keywords— Wide Band Gap (WBG) Semiconductors, Electric Vehicles (EV), Power Converters, Silicon Carbide (SiC), Gallium Nitride (GaN), Diamond, Gallium Oxide ($Ga_2O_3$), Cryogenic Electronics.**

## I. Wide Band Gap Semiconductors: Materials and Properties

### A. Introduction to WBG Materials

The transition to electric mobility is one of the most significant technological shifts of the 21st century, driven by the necessity to reduce carbon emissions and increase energy efficiency. Power electronic converters are the keystone in the transition by enabling the control of energy exchange between the battery, motor, and charging systems. The performance of the converters is extremely dependent on the semiconductor switches. Silicon (Si) has dominated power electronics as the material of choice for the last several decades. However, its relatively narrow band gap limits operating voltage, temperature, and switching frequency, thereby inhibiting the realization of the next-generation high-density, high-efficiency electric vehicle powertrains [1, 2,6,11].

WBG semiconductors are a class of materials with a much wider energy gap between the valence and conduction bands, generally greater than 2 eV. This built-in property translates into much better theoretical power device performance. The WBG material physics allows much greater breakdown electric field, enabling devices of higher voltage rating or, alternatively, enabling thinner and more heavily doped drift regions of the same voltage rating. This translates into a very significant reduction in specific on-state resistance, an important parameter for the assessment of conduction losses. Additionally, the strong atomic bonding in WBG materials allows for superior thermal conductivity and the ability to operate at much higher junction temperatures, simplifying the thermal management systems in EVs. These materials, such as SiC, GaN, and UWBG materials like diamond and $Ga_2O_3$, are not incremental technologies; they are revolutionary technologies that allow radical changes in power converter designs [3, 4]. From the perspective of electric vehicle applications, the benefits are significant. Higher efficiency directly translates into a longer driving range or the need for lighter and smaller batteries. Higher switching frequencies enable the use of more compact passive entities, including inductors and capacitors, which leads to the creation of more streamlined and lighter on-board chargers and DC-DC converters. Better thermal performance reduces the size and complexity of cooling systems, thus leading to a weight reduction of the vehicle and related costs. As technology evolves towards faster charging solutions, higher battery voltages, and higher powertrain integration, the use of WBG technology has shifted from optional to mandatory [5]. This paper reviews the leading WBG materials, evaluates their device-level performance, and evaluates their suitability for the demanding conditions offered by modern EV power electronics.

## B. Silicon Carbide (SiC)

Silicon carbide has emerged as the most mature WBG technology for high-power electric vehicle (EV) use, offering an appealing balance of efficiency, reliability, and supply chain, becoming increasingly well-established. It is a direct drop-in replacement for silicon Insulated Gate Bipolar Transistors (IGBTs) deployed in high-voltage traction inverters, providing significantly lower losses and improved thermal management.

SiC is a compound semiconductor material with more than 250 crystalline polytypes. In power electronics, the 4H-SiC polytype is nearly universally used because of its better electrical properties, such as a high band gap of ~3.2 eV, high isotropic electron mobility, and high critical breakdown electric field of 2-4 MV/cm [3]. Its largest strength in EV applications is its high thermal conductivity of up to 4.9 W/cm K, greater than three times that of silicon. This facilitates more effective heat extraction from the device, allowing higher power densities and less complex thermal management systems, an important factor in space-limited EV powertrains [4,15].

One of the most significant problems of SiC power devices, especially metal-oxide-semiconductor field-effect transistors (MOSFETs), has been the SiC substrate/silicon dioxide ($SiO_2$) gate dielectric interface reliability. Unlike silicon, for which developing a good native oxide is simple, the $SiC/SiO_2$ interface is afflicted by high interface trap density (D_it), which can hinder charge carrier transport, reduce channel mobility, and be the cause of threshold voltage instability [2,15]. However, enormous advances in interface engineering, such as nitrogen-based passivation techniques, have greatly improved channel mobility and device reliability [2].

At cryogenic temperatures, SiC device performance is a multifaceted situation. Results shown in [1] suggest that for 1.2 kV SiC MOSFETs, the on-state resistance rises significantly as the temperature is lowered to cryogenic levels (93K) [12,13]. The reason is carrier trapping at the problematic $SiC/SiO_2$ interface, where large quantities of electrons are captured, with few free electrons to conduct the current. This kind of behaviour renders SiC less desirable for certain cryogenic applications than Si or GaN.

Commercialization of silicon carbide (SiC) has been a long and difficult journey, conquering significant manufacturing hurdles. High temperatures above 2000 °C and high pressures required for SiC crystal growth by sublimation, i.e., physical vapor transport, render the process challenging and costly. Historically, SiC wafers have been marred by a high incidence of crystallographic defects, most notably including micropipes, threading screw dislocations (TSDs), and Basal Plane Dislocations (BPDs). While micropipes have been significantly eliminated, BPDs remain a problem since they can evolve into stacking faults during device operation, leading to an increase in on-state resistance and eventually to device failure [4].

Ion implantation for selective area doping of SiC is also difficult owing to the hardness of the material. High-energy implantation is necessary, which leads to severe lattice damage that has to be annealed out at high temperature (>1600 °C). Incomplete activation of the dopant and residual damage can lead to harmful effects on device performance and reliability [3]. All these have been overcome despite all the challenges, and the industry has made tremendous strides. 150 mm (6-inch) wafer availability is now common, with 200 mm (8-inch) wafers just around the corner, decreasing costs. Advances in epitaxial growth and defect reduction techniques have resulted in a very considerable enhancement in commercial SiC MOSFETs and diode quality and reliability.

SiC is best suited for high-voltage EV systems, especially those at 800V and higher. Commercial SiC MOSFETs have 1.2 kV and 1.7 kV blocking voltages, and even higher voltage devices have been demonstrated in the laboratory [12,13]. SiC MOSFETs in EV traction inverters have a significant lowering of conduction and switching losses compared to Si IGBTs [14]. The lack of a "knee" voltage and low on-state resistance minimize conduction losses, and high switching speeds minimize losses where efficiency is maximized at the higher switching frequencies employed in new motor drives. This combined loss reduction can raise inverter efficiency several percentage points, which adds vehicle range [5,11].

**TABLE 1**: COMPREHENSIVE MATERIAL PROPERTIES TABLE

| Property | Silicon (Si) | 4H-SiC | GaN | Diamond | $\beta$-$Ga_2O_3$ |
|---|---|---|---|---|---|
| Band Gap (eV) | 1.12 | 3.26 | 3.4 | 5.47 | 4.5-4.9 |
| Breakdown Field (MV/cm) | 0.3 | 3-5 | 3.3 | 20 | 8 |
| Thermal Conductivity ($W/cm\cdot K$) | 1.5 | 3.0-4.9 | 1.3-2.3 | 22 | 0.1-0.3 |
| Electron Mobility ($cm^2/V\cdot s$) | 1400 | 800-1000 | 1200-2000 | 4500 | 100-300 |
| Hole Mobility ($cm^2/V\cdot s$) | 450 | ~120 | ~200 | 3800 | - (N/A) |

However, dynamic SiC MOSFET behaviour is strongly temperature dependent. At cryogenic temperatures, 1.2 kV SiC MOSFET switching speed shows a sharp decline, leading to a sharp increase in switching losses [1]. The turn-on switching loss observed for a 1.2 kV SiC MOSFET was found to rise by 83% at 143K with respect to room temperature, corresponding to a phenomenon referred to as "long tail turn-on voltage." Similarly, the turn-off switching loss was found to be up by 158% [1]. Such reduced performance is contributed primarily by a reduction in inversion carrier mobility at reduced temperatures. Alternatively, for lower voltage (650 V and 900 V) SiC MOSFETs, switching speed is found to be significantly unaffected by low temperatures, indicating strong similarity between the voltage class of the device and its internal structure [1]. This would mean that while high-voltage SiC devices are unsuitable for cryogenic electric vehicle applications, their lower-voltage counterparts could be acceptable [14].

## C. Gallium Nitride (GaN)

While SiC dominates the high-voltage market, GaN dominates high-frequency, high-density power converters in EVs, including on-board chargers, DC-DC converters, and wireless power transfer systems. Its inherent characteristics provide record-breaking switching speeds and power densities.

The benefits that are related to GaN are due to its direct band gap of 3.4 eV and, more importantly, due to its unique heterostructure physics. With the deposition of thin Aluminum Gallium Nitride (AlGaN) on a GaN layer, a two-dimensional electron gas (2DEG) forms at the interface. This 2DEG forms a sheet of highly mobile electrons with mobility values up to 2000 $cm^2/V \cdot s$, the channel of a High Electron Mobility Transistor (HEMT) without doping [3, 4]. Such a structure provides very low specific on-state resistance and very low gate capacitance, thus enabling switching frequencies that go well into the megahertz range with significantly lower losses.

For EV use, this high-frequency operation permits a dramatic reduction in the size and weight of passive devices. In an on-board charger, operating at several hundred kilohertz rather than tens of kilohertz enables the primary transformer and filter inductors to be substantially smaller, resulting in a smaller, lighter, and less costly unit. This is an important benefit for vehicle integration [5].

GaN devices also possesses improved cryogenic operation performance than SiC. Contrary to SiC, the on-state resistance of GaN HEMTs reduces at low temperatures, and the dynamic switching speed is enhanced. Studies in [1,7] indicate that for a 650 V GaN HEMT, the dynamic on-state resistance reduces to 143 K. The turn-on switching speed is also greatly improved, with the dv/dt and di/dt of the device effectively doubling from room temperature. This enhanced cryogenic performance renders GaN a highly viable candidate for niche EV applications. These will operate in extreme cold or need cryogenic cooling, for instance, in future aerospace or heavy-duty transportation systems [1].

The largest challenge to GaN power devices is the absence of a low-cost, commercially available native GaN substrate. GaN is therefore grown heteroepitaxially on foreign substrates, commonly silicon, sapphire, or SiC. The most economic route to commercialization is growth on Si, but it is plagued by large thermal expansion and lattice mismatches that create stress and high dislocation densities in the GaN layers. These defects can be leakage paths and trapping sites, reducing device performance and reliability [4]. Multilayer buffer layers need to be used to accommodate this stress and screen dislocations, making the manufacture more complex.

One of the biggest challenges in the field has been the development of normally-off (enhancement-mode) devices, which are essential for the secure operation of power converters. GaN HEMTs are typically normally-on (depletion-mode) devices. Various strategies have been examined to enable enhancement-mode operation, including p-GaN gate, recessed gate, and cascode topologies, where a low-voltage Si MOSFET is employed to gate a normally-on GaN HEMT. The p-GaN gate is the prevalent commercial technology; however, it necessitates close monitoring of the gate fabrication process [5]. Reliability is still a significant area of research interest, with dynamic on-state resistance and threshold voltage stability being of utmost importance, parameters that are still being optimized. Because of the very high power density of GaN, it is the best technology for applications where space and weight are limited.

- **On-Board Chargers (OBCs)**: GaN-based OBCs are capable of accommodating power densities greater than 3-5 kW/L, a significant rise from Si-based solutions. This allows for chargers that are more compact and lighter, with easier integration into the vehicle body.
- **DC-DC Converters**: 48V-400V or 400V-800V DC-DC converters take advantage of GaN's high frequency, resulting in smaller magnetics and simpler design.
- **Wireless Power Transfer (WPT):** Effective WPT (at hundreds of kHz to MHz) demanded by high-frequency resonant converters is a natural application field for GaN's intrinsic strengths and allows for more efficient and smaller wireless charging systems.
- **Lidar**: GaN transistors' high-speed switching is also making it possible to create more sophisticated, compact, and cost-effective Lidar systems for autonomous vehicles.

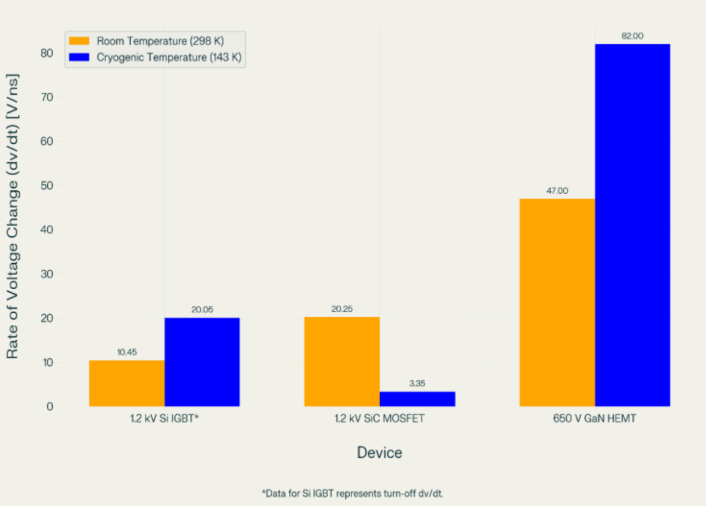

**FIGURE 1**: SWITCHING PERFORMANCE COMPARISON CHART

But GaN's very high switching rates (high dv/dt and di/dt) are challenging to handle in gate driver design and PCB layout. Parasitic inductances in package and PCB layout need to be minimized to avoid excessive voltage overshoot and ringing, which can cause device failure and electromagnetic interference (EMI) problems [1, 5].

Fig.1 illustrates the turn-on/off dv/dt for different devices at room and cryogenic temperatures, based on data from [1]. For instance, it would show the dv/dt of a GaN HEMT increasing from ~47 V/ns to ~82 V/ns when cooled to 143 K, while the dv/dt for a 1.2 kV SiC MOSFET decreases from ~20 V/ns to ~3.3 V/ns.

## D. Emerging WBG Materials (Diamond, $Ga_2O_3$) and Properties

Aside from SiC and GaN, a new generation of UWBG materials will further extend power electronics' capabilities. Diamond and $\beta$-$Ga_2O_3$ are strong contenders, both of which possess unique characteristics as well as accompanying problems [8].

Diamond has also been referred to as the ultimate semiconductor because of its special collection of material properties. With a very wide band gap of 5.47 eV, it has the highest thermal conductivity of any material at room temperature (22 W/cmK, more than five times that of SiC), and a very high theoretical breakdown field of 20 MV/cm [2]. All these together result in a theoretical performance much better than any other semiconductor.

There has been outstanding progress in diamond devices in recent studies. There have been reports of the presence of vertical Schottky diodes with breakdown voltages of almost 10 kV [2]. Diamond MOSFETs have even achieved Baliga's Figure of Merit (BFOM) of 874.6 $MW/cm^2$, a value significantly greater than that of SiC or GaN [2,9]. Bipolar diodes have even achieved current densities of 60 $kA/cm^2$.

Nevertheless, significant challenges persist. The recent challenge is the enormous challenge of achieving effective n-type doping. In contrast to the established doping method of p-type doping using boron, common n-type dopants such as nitrogen and phosphorus possess very deep energy levels in the diamond band gap, leading to very low carrier activation at room temperature. This limitation has predominantly restricted diamond devices to unipolar structures, thereby limiting the development of more efficient bipolar devices such as IGBTs. In addition, the production of large, high-quality, and low-cost single-crystal diamond wafers is still a significant challenge, although recent breakthroughs in heterogeneous epitaxy and wafer stitching are encouraging [2]. Commercialization of diamond power devices is likely to remain 5 to 10 years away; however, their potential applications to ultra-high-voltage applications and high-temperature applications are unparalleled.

**Gallium Oxide ($\beta$-$Ga_2O_3$):** Gallium oxide has been a promising UWBG candidate largely because of its high band gap of 4.5-4.9 eV and, more importantly, due to the existence of large-diameter single-crystal substrates synthesized from the melt by processes such as the Czochralski process. This presents an important manufacturing advantage over SiC, GaN, and diamond, potentially translating to reduced-cost devices [4]. $\beta$-$Ga_2O_3$ also features a high breakdown field of ~8 MV/cm, and high-voltage Schottky diodes and MOSFETs have been reported.

The main drawback of $Ga_2O_3$ is its very low thermal conductivity of about 0.1-0.3 W/cm·K, lower than silicon. This is a significant drawback for thermal management in high-power devices, requiring high-end packaging and cooling technologies to effectively dissipate waste heat. Like diamond, $Ga_2O_3$ also has the drawback of inefficient p-type doping, limiting devices to unipolar operation. Aside from these limitations, $Ga_2O_3$ is an extremely promising material for next-generation high-voltage rectifiers and switches, expected to propel commercialization at a faster rate than diamond [4].

**TABLE 2**: TECHNOLOGY READINESS AND COST ANALYSIS

| Material | Technology Readiness Level (TRL) | Substrate Availability & Size | Relative Cost |
|---|---|---|---|
| SiC | 9 (Commercial, Mature) | High (150 mm standard, 200 mm emerging) | Medium |
| GaN | 8-9 (Commercial, Growing) | High (on Si, SiC, Sapphire) | Medium-Low |
| Diamond | 4-5 (Research/Demonstration) | Low (< 1-inch, R&D) | Extremely High |
| $\beta$-$Ga_2O_3$ | 5-6 (Demonstration/Prototyping) | Medium (Melt-grown, up to 4-inch) | High |

## E. Comparison of Si, SiC, GaN, Diamond, $Ga_2O_3$ for EV Power Converters

The choice of the semiconductor material for an EV power converter is determined through a compromise between performance, cost, and maturity for the application in question.

**Material and Device Performance**

- **Si**: The reference technology. Low cost and highly mature but with limited low breakdown voltage, poor thermal properties, and low switching frequency.
- **SiC**: The high-power, high-voltage volume leader (>650V). Offers maximum thermal conductivity of WBG materials, permitting high power density and minimal cooling. The main drawback is higher cost compared to Si and a challenging $SiC/SiO_2$ interface [10].
- **GaN**: The leader in high-frequency, medium-voltage applications (<650V). Enables the smallest and lightest converters due to its high switching speed. Less costly than

SiC but with inferior thermal conductivity and poor high-voltage ratings.

- **Diamond** is the peak material in terms of theoretical performance. It has the potential to revolutionize ultra-high-voltage applications but is currently limited by serious manufacturing challenges and the lack of n-type doping.

- **$Ga_2O_3$:** A high-voltage candidate of much interest because of its high band gap and potential to be produced at low cost on a substrate. It's very low thermal conductivity, however, is a significant engineering challenge.

Cryogenic Performance: The properties of such materials at cryogenic temperatures exhibit spectacular variations, which are significant to electric vehicles in cold climates or to emerging aerospace missions.

- **Si and GaN**: Both share better performance, with reduced on-state resistance and quicker switching. GaN's improvement is, in fact, spectacular, and it is thus extremely well-matched for cryogenic operation [1].

- **SiC:** Shows decreased performance with a drastic rise in on-state resistance and switching losses at cryogenic temperatures, particularly for high-voltage devices [1]. Hence, this renders it unsuitable for such devices.

**TABLE 3**: EV APPLICATION SUITABILITY MATRIX

| **Application** | **Si** | **SiC** | **GaN** | **Diamond & $Ga_2O_3$** |
|---|---|---|---|---|
| Traction Inverter | Legacy (Low Power) | Excellent (800V+) | Good (400V systems) | Future (>10 kV) |
| On-Board Charger | Legacy | Good | Excellent (High Density) | Future |
| DC-DC Converter | Legacy | Good | Excellent (Compactness) | Future |
| Wireless Charging | Not suitable | Possible | Excellent (High Freq) | Not applicable |

## Selection Criteria

For a manufacturer of an EV, the choice is simply based on the application:

- For the main traction inverter, particularly 800V systems, SiC is the leading technology because of its high voltage capability and high temperature capability.
- For on-board chargers and DC-DC converters, where both power density and high-frequency efficiency are of utmost concern, GaN is the go-to option.
- For next-generation ultra-high-voltage systems, for example, in heavy trucks or grid stations, Diamond and $Ga_2O_3$ are the research direction in the long term.

# II. Ga2O3-Based Power MOSFET Development for High-Efficiency EV Charging Infrastructure

Gauging from the comparative analysis of wide bandgap semiconductors covered in Section 1, this section covers the engineering application of gallium oxide (Ga2O3) technology in the future paradigm of electric vehicle charging infrastructure.

While Section 1 pointed out Ga2O3's superior breakdown field strength of 8 MV/cm and ultrawide bandgap of 4.5-4.9 eV, placing it at Technology Readiness Level (TRL) 5-6, this section covers the engineering approaches towards harnessing these material advantages into commercially viable high-power charging systems.

## A. Ga2O3 Material Optimization and MOSFET Fabrication

Development of high-efficiency Ga2O3 MOSFETs for charging applications for electric vehicles requires the close monitoring of material synthesis routes as well as device processing routes. The latest epitaxial growth techniques, i.e., mist chemical vapor deposition (CVD) and molecular beam epitaxy (MBE), are employed to achieve the crystalline quality necessary for power devices.

### *1. Advanced Synthesis and Device Architecture*

These are synthesized using mist CVD with substrate temperatures ranging from 500°C to 1000°C, and this also enables precise control of film composition and crystalline quality. Metal-organic precursors are delivered by carrier gas flow via mass flow controllers to provide the right stoichiometry. These enable high-purity Ga2O3 layers with low defect densities necessary for breakdown voltages of over 8 kV.

The optimized MOSFET structure comprises some design parameters specifically tailored for high-power applications:

**Epitaxial Layer**: 100 nm thick with $2\times10^{17}$ cm$^{-3}$ dopant concentration

**Source/Drain Regions**: Depth of 50 nm with dopant concentration of $9\times10^{19}$ cm$^{-3}$

**Substrate**: 50 nm thickness with a concentration of $1\times10^{14}$ cm$^{-3}$

**Channel Length**: 6 μm optimized for high-voltage operation

The device exploits Ga2O3's intrinsic material properties: 4.8 eV bandgap, 118 cm$^2$/V·s electron mobility, and 4.0 eV electron affinity. These are used for precise modeling and prediction of device performance parameters using Technology Computer-Aided Design (TCAD) simulation software.

### *2. Fabrication Process and Doping Strategies*

Ion implantation delivers selective area doping with dopant concentration and depth profiles at a very high level of precision. High-k dielectric thin films deposited by atomic layer deposition (ALD) work as gate oxides needed for low leakage current and high breakdown voltage. Sophisticated lithography and etching methods regulate device geometry at the sub-micron level.

Metal contacts are established with work function-optimized materials to reduce contact resistance. Annealing processes after fabrication at well-controlled temperatures activate dopants and repair implant damage. Fabrication processing focuses on defect control and interface quality, which directly affect device switching speed and reliability.

Comprehensive material analysis utilizes Secondary Ion Mass Spectrometry (SIMS) alongside Hall effect measurement for dopant distribution and activation determination. X-ray diffraction (XRD) coupled with scanning electron microscopy (SEM) confirms the structural uniformity and surface morphology, consequently guaranteeing uniform device performance over different manufacturing batches.

## B. Power Converter Integration and System Design

High-power EV charging hardware demands the implementation of Ga2O3 MOSFETs to necessitate state-of-the-art converter topologies and high-end thermal management systems to maximize the material's ultra-high voltage performance while overcoming thermal conductivity limitations.

### *1.Converter Topology and Control Strategy*

The fast-charging system proposed utilizes a three-module parallel 165 kW modular 500 kW setup, as shown in Figure 2. The Ga2O3 ultra-high voltage capability is utilized to directly interface with the grid, along with system redundancy and a scalable power supply.

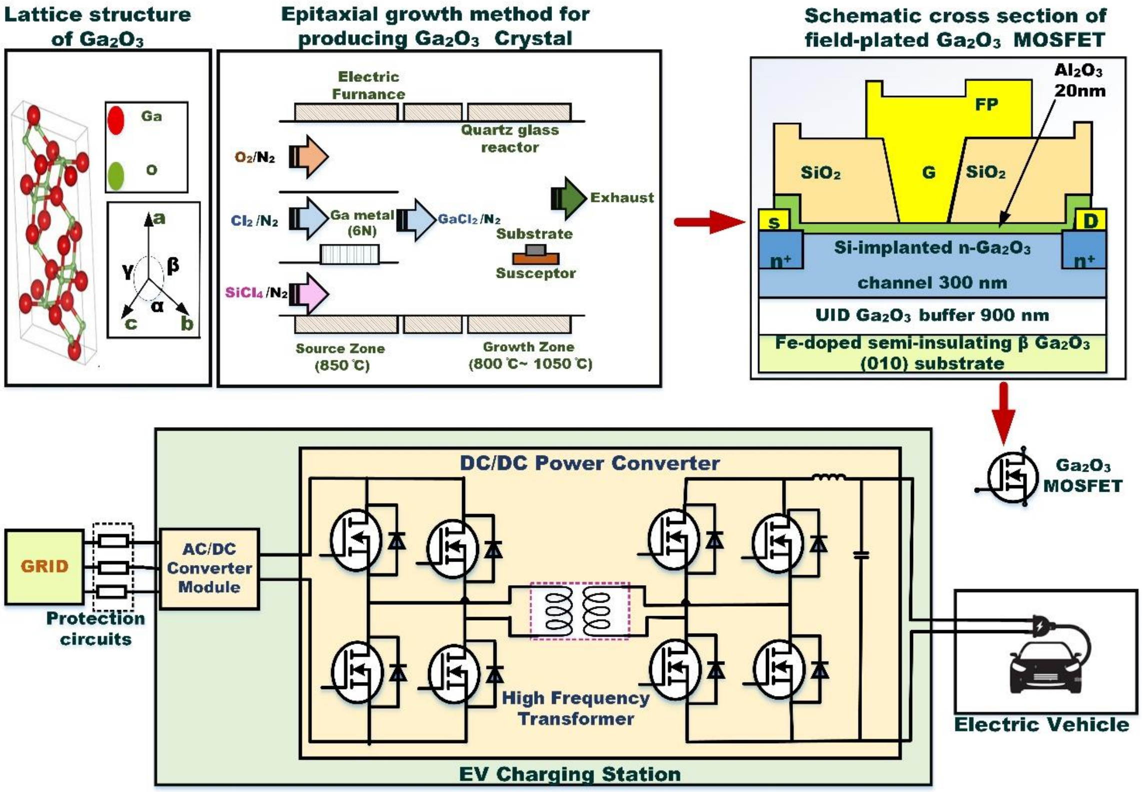

**FIGURE 2:** PROPOSED GA2O3 BASED FAST CHARGER SYSTEM ARCHITECTURE

The converter topology exploits the breakdown voltage of Ga2O3 directly above 8 kV to enable simplified topologies with fewer series devices compared to SiC or GaN designs. Dual active control systems with enhanced power management share power across modules, and this leads to stabilized charging start within 0.15 seconds of initiation. The control strategy includes several key features:

**Smart Load Balancing**: Adaptive power distribution among modules according to temperature and electrical status

**Grid Synchronization**: Improved power factor correction provides a better-quality grid interface.

**Adaptive Charging Profiles**: Dynamic optimization based on battery characteristics and environmental conditions.

**Fault Tolerance**: Automatic reconfiguration maintains operation even with single module failures.

### *2. Thermal Management and Packaging Solutions*

Ga2O3's thermal conductivity limit (0.1-0.3 W/cm·K) needs to be overcome with innovative approaches much more advanced than SiC systems (3.0-4.9 W/cm·K). The thermal management system comprises a variety of complementary measures:

**Advanced packaging technologies**: integrating multi-layer heat spreading architectures and high-performance thermal interface materials, maximize heat transfer from silicon junctions to coolers. Direct liquid cooling by microchannel heat exchangers guarantees thermal efficiency for long-term operation at 500 kW.

**Smart Thermal Management**: Proactive monitoring of device temperatures allows for anticipatory temperature management, thus preventing thermal runaway and improving power delivery. The system prevents junction temperatures beyond safe operating limits by coordinated control of cooling flow rates and power distribution.

**Package Design Optimization**: Parasitic inductance and resistance were minimized, and thermal conduction to the cooling systems was enhanced. The packaging also eliminates coefficient of thermal expansion mismatches between Ga2O3 and common materials to provide long-term reliability under thermal cycling conditions.

### *3. Performance Comparison and Validation*

The comparative study of the existing silicon-based charging systems and the proposed Ga2O3 model shows significant advancements in several key parameters, as outlined in Table 4.

**TABLE 4**: CHARGING COMPARISON OF EXISTING AND PROPOSED CHARGER SYSTEMS

| Parameter | Existing (Si-based) | Proposed (Ga2O3-based) |
|---|---|---|
| Semiconductor Material | Si Material | Ga2O3 Material |
| Electron Mobility | 1000 $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ | 1000 $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ |
| Target SOC | 80% SOC | 80% SOC |
| Battery Capacity | 100 kWh | 100 kWh |
| Charging Time | 15 mins – 45 mins | 10 mins – 15 mins |
| Thermal Conductivity | 1.5 $\text{WK}^{-1}\text{cm}^{-1}$ | 0.11 $\text{WK}^{-1}\text{cm}^{-1}$ |
| System Efficiency | ~95% | >98% |
| Breakdown Voltage | <2 kV | >8 kV |

Charging time performance is according to the following relationship: $T = (BC \times (1 - SOC)) / PC$, where BC is battery capacity, SOC is state of charge, and PC is charger power. The given system is offering a 30% reduction in charging time, where a 100-kWh battery is charged from 20% to 80% SOC in 10 minutes as opposed to 15-45 minutes for traditional systems.

## C. Performance and Reliability Analysis

### *1.Electrical Performance and Efficiency Analysis*

System efficiency is more than 98% while operating at full power, a huge improvement over the usual 95% efficiency of silicon-based converters. This is because of a number of reasons:

**Lower switching losses**: Ga2O3's better switching behavior allows for more frequent switching operations at lower losses, improving converter efficiency directly. The wide bandgap allows for fast switching transitions with minimal switching losses.

**Simplified Converter Topology**: The ultra-high breakdown voltage (>8 kV) capability avoids the necessity of complicated series-connected device configurations found in SiC-based systems, reducing conduction losses and enhancing overall system reliability.

**Increased Power Density**: Increased operating voltages and enhanced thermal management allow for smaller converter sizes with better power-to-weight ratios than traditional systems.

### *2.Reliability and Thermal Validation*

Thorough test procedures confirm uniform reliability under exposure to normal operating conditions:

**High-Temperature Testing**: HTGB and HTRB testing simulate real operating conditions and hence confirm the reliability of devices during long-term high-power operation.

**Thermal Cycling Validation**: Cyclic testing between -40°C and +150°C continues to prove device performance under thermal stress conditions characteristic of EV charging use.

**Power Cycling Test**: Repetitive power cycling at rated conditions demonstrates long-term reliability, with careful observation of significant parameters like threshold voltage stability, on-resistance variation, and leakage current evolution.

**Accelerated Life Testing**: Predictive reliability evaluation through accelerated aging at elevated temperature and bias conditions enables estimation of life and failure mode determination.

### *3.System-Level Performance Metrics*

The combined charging system shows improved performance in the majority of domains:

**Charging Speed**: Has 0.15-second startup time for stable high-power charging, 20% to 80% SOC full charge within 10 minutes for 100 kWh batteries.

**Grid Integration**: Sustains power factor >0.99 with total harmonic distortion <3% to provide high-quality grid interface even during dynamic power switching.

**Scalability**: Modular architecture ensures future scalability to 200 kWh battery capacity needs with reliability and efficiency upheld.

**Environmental Performance**: Lower energy consumption with >98% efficiency equates to substantial carbon footprint reductions versus traditional charging infrastructure.

## D. Comparative Assessment and Future Outlook

The technology application of Ga2O3 is a revolutionary move ahead of state-of-the-art SiC and GaN technologies, with the 8 MV/cm breakdown field showing significant improvements over SiC's 3-5 MV/cm and GaN's 3.3 MV/cm established in Section 1. The 8 kV+ ultra-high voltage rating of direct grid connection applications positions Ga2O3 above the state-of-the-art operation of advanced SiC (TRL 9) and GaN technologies with reduced converter topologies and system complexity. The thermal conductivity issue of 0.1-0.3 W/cm·K versus SiC's 3.0-4.9 W/cm·K requires advanced cooling, but the resulting system efficiency gain (>98% versus 95%) and charging time improvement (30%) show convincing performance benefits. With Ga2O3 as an advanced technology at TRL 5-6, commercialization is 3-5 years behind mature alternatives, but melt-grown substrate availability offers cost-performance benefits over diamond manufacturing limitations, and Ga2O3 is the enabling technology for future ultra-high voltage EV charging infrastructure for future 200+ kWh battery needs.

## CONCLUSION

Wide band gap semiconductors are thus revolutionizing power electronics in electric cars. The silicon-dominated age is being replaced by a new paradigm of innovation, with material selection being optimized to suit the precise needs of each application.

- **Silicon Carbide (SiC)** has certainly become the material of choice for high-voltage and high-power electric vehicle traction inverters. Its properties, such as enhanced breakdown voltage, enhanced thermal conductivity, and an emerging manufacturing ecosystem, point clearly towards a path towards more efficient and durability-driven drivetrains.
- **Gallium Nitride (GaN)** is the outstanding choice for high-frequency, high-density applications. Its better switching performance is reducing on-board chargers and DC-DC converters to smaller, lighter, and more efficient sizes, and they are central to optimizing overall vehicle design and cost.
- **Diamond and Gallium Oxide ($Ga_2O_3$)** are the future. In spite of daunting manufacturing and doping hurdles, their ultra-wide band gaps hold the promise of an ultra-high-voltage and high-temperature power electronics future that goes well beyond automotive to grid, industrial, and aerospace applications.

The comparative study demonstrates evident segmentation of application and performance. The optimum selection of materials is governed by the trade-offs between voltage rating, switching frequency, heat transfer, and cost. An interesting remark highlighted from the literature so far is the varying behaviour of these materials when subjected to cryogenic temperatures, with GaN demonstrating significant improvement in performance, whereas high-voltage SiC demonstrates degradation. This underlines the importance of thorough characterization across all possible operating conditions.

More studies will have to be conducted to further address the major challenge areas: the optimization of the SiC/$SiO_2$ interface, GaN device voltage tolerance and reliability improvement, and overcoming the intrinsic doping and substrate problems of diamond and $Ga_2O_3$. As these technologies mature, they will be looked to improve electric vehicle performance at the same time as being a power electronics innovation leader in the industry at large.

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