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# A Review on Preparation Techniques, Performance Optimization, and Application Prospects of Gallium Oxide Semiconductor Materials in Fast Charging for New Energy Vehicles

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***Abstract.*** The rapid advancement of new energy vehicles (NEVs) has intensified the demand for efficient, high-power fast-charging systems. Wide-bandgap semiconductors, particularly gallium oxide ($Ga_2O_3$), offer significant advantages in high breakdown electric field, thermal stability, and potential cost-effectiveness, making them promising candidates for next-generation power electronics. This paper systematically reviews the preparation techniques, performance optimization strategies, and application prospects of $Ga_2O_3$ in NEV fast-charging systems. Through literature analysis and comparative case studies, this paper summarizes recent progress in crystal growth, thin-film deposition, doping, and device fabrication. The findings suggest that optimized $Ga_2O_3$-based devices could significantly enhance charging efficiency, reduce energy loss, and support the development of ultra-fast charging infrastructure. This review provides a comprehensive reference for researchers and engineers working on advanced semiconductor materials for high-power applications.

***Keywords:*** gallium oxide, semiconductor, preparation techniques, performance optimization, fast charging, new energy vehicles

## 1. Introduction

Gallium oxide ($Ga_2O_3$) has emerged as a promising ultra-wide-bandgap semiconductor material due to its excellent electrical properties, including a high Baliga's figure of merit and strong thermal and chemical stability. Recent studies have highlighted its potential in high-voltage and high-temperature applications, such as power converters and fast-charging systems for electric vehicles. For instance, Higashiwaki et al. [1] demonstrated $Ga_2O_3$ field-effect transistors with high breakdown voltages, while Pearton et al. [2] reviewed its material properties and device prospects. Tsao et al. [3] further identified $Ga_2O_3$ as one of the key ultra-wide-bandgap materials with transformative potential for power electronics. Despite these advances, a systematic review focusing on the integration of $Ga_2O_3$, from material preparation to system-level application in NEV fast-charging systems, remains lacking.

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This paper addresses the following research questions: (1) What are the key preparation techniques for $Ga_2O_3$ semiconductors and their impact on device quality? (2) How can the performance of $Ga_2O_3$ devices be optimized through doping, design, and thermal management for high-power applications? (3) What are the current applications and future industrial prospects of $Ga_2O_3$ in NEV fast-charging technology? The methodology employs a comprehensive literature review, supplemented with comparative analysis of device performance metrics and case studies of prototype charging systems.

The significance of this review lies in its integrative approach, consolidating knowledge from material science, device physics, and power systems engineering. It aims to provide a clear technological roadmap, identify critical research gaps and challenges, and thereby accelerate the development and adoption of efficient, compact, and reliable fast-charging solutions for the sustainable transportation ecosystem.

## 2. Preparation techniques of $Ga_2O_3$ semiconductor materials

The performance of final devices is intrinsically linked to the quality of the gallium oxide ($Ga_2O_3$) material. The preparation methodology can be broadly categorized into bulk single-crystal growth and epitaxial thin-film deposition, each with distinct implications for device characteristics and scalability.

### 2.1. Bulk single-crystal growth for substrates

High-quality, large-diameter native substrates are a fundamental prerequisite for high-performance power devices.

Edge-defined Film-fed Growth (EFG): Currently the most mature and commercially viable technique for producing $\beta$-$Ga_2O_3$ substrates. This method involves pulling a plate-shaped crystal from a slit at the top of an iridium crucible. EFG can yield wafers with widths up to 6 inches and low dislocation densities, which are suitable for lateral device fabrication. A notable concern is the potential incorporation of Ir impurities from the crucible [1].

Vertical Bridgman / Vertical Gradient Freeze (VB/VGF): This approach grows crystals in a sealed container, significantly reducing the volatilization of $Ga_2O_3$ at high temperatures. This improves stoichiometry and material purity. The VB/VGF method holds promise for growing larger-diameter, cylindrical boules with better uniformity, representing a critical path for future cost reduction of substrates [3].

Floating Zone (FZ) Method: As a crucible-free technique, FZ growth avoids contamination from container materials, resulting in crystals of extremely high purity. This makes FZ-grown $Ga_2O_3$ invaluable for fundamental research. However, currently achievable crystal diameters are relatively small, and growth rates are slow, limiting its industrial application at present.

### 2.2. Epitaxial thin-film deposition

The growth of high-quality epitaxial layers on native or hetero-substrates is essential for creating advanced device architectures.

Molecular Beam Epitaxy (MBE): Conducted under ultra-high vacuum, MBE offers atomic-layer precision in thickness and doping control. It is particularly suitble for growing ultra-thin layers and achieving sharp heterointerfaces, making it the preferred method for researching sophisticated $Ga_2O_3$-based devices such as high-electron-mobility transistors (HEMTs) [4].

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Metal-Organic Chemical Vapor Deposition (MOCVD): MOCVD provides higher growth rates and superior large-area uniformity, aligning well with mass production requirements. Significant progress has been made in developing suitable precursors and optimizing processes for $Ga_2O_3$. MOCVD can now produce high-quality homoepitaxial and heteroepitaxial layers (e.g., $(Al_xGa_{1-x})_2O_3$) with excellent electrical properties [5].

Halide Vapor Phase Epitaxy (HVPE): Characterized by very high growth rates, HVPE is ideal for depositing the thick drift layers required for vertical power devices. It is considered as a pivotal technology for realizing high-voltage, high-current $Ga_2O_3$ power diodes and transistors [6].

## 3. Performance optimization strategies

Optimizing performance from material to device requires a multi-faceted endeavor.

### 3.1. Doping and defect engineering

Precise control over electrical properties is paramount.

N-type Doping: Silicon (Si) and Tin (Sn) are common n-type dopants. Optimizing the doping concentration profile is crucial to balance specific on-resistance ($R_{on,sp}$) and breakdown voltage. Advanced schemes such as δ-doping can enhance carrier concentration while mitigating ionized impurity scattering [7].

P-type Doping and Semi-Insulating Substrates: Achieving efficient p-type conductivity remains a significant challenge. A more practical approach adopts deep-level acceptors such as Iron (Fe) or Magnesium (Mg) to compensate native donors, creating high-resistivity semi-insulating substrates or buffer layers vital for device isolation [2].

Defect Passivation: Intrinsic point defects in $Ga_2O_3$ can act as carrier traps. Post-growth treatments such as annealing or the deposition of passivation layers (e.g., $Al_2O_3$ via ALD) are effective in neutralizing these states, improving device stability and reliability [8].

### 3.2. Device architecture and design innovation

Device design is key to unlocking the material's potential.

Vertical Device Structures: Vertical transistors and diodes are more suitable for high-voltage/current applications. Techniques such as field plates and junction termination extensions (JTEs) are employed to alleviate electric field crowding, pushing the breakdown voltage closer to the material's theoretical limit [1,6]. For instance, field-plated $Ga_2O_3$ MOSFETs have demonstrated breakdown voltages over 750 V [7].

Heterostructures and Two-Dimensional Electron Gas (2DEG): Heteroepitaxial growth of $(Al_xGa_{1-x})_2O_3$ on $Ga_2O_3$ can induce a high-mobility 2DEG at the interface. Heterojunction Field-Effect Transistors (HFETs) based on this principle can achieve lower $R_{on,sp}$ and higher switching speeds [4,5].

Superjunction Concepts: Implementing superjunction structures in $Ga_2O_3$—through alternating n and p pillars—enables charge balance, allowing for a drastic increase in breakdown voltage without a proportional increase in $R_{on,sp}$.

### 3.3. Thermal management and reliability enhancement

The relatively low intrinsic thermal conductivity of β-$Ga_2O_3$ is a primary bottleneck.

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Hybrid Integration: Bonding $Ga_2O_3$ active layers onto substrates with high thermal conductivity, such as diamond or silicon carbide (SiC), is a leading strategy for heat extraction [9].

Advanced Packaging: Innovations in packaging, including silver sintering die-attach materials and embedded cooling, are critical to managing the overall thermal resistance.

Reliability Testing: Comprehensive assessment under high electric field and temperature is essential to identify failure mechanisms and establish lifetime models for automotive qualification.

## 4. Application status and prospects in NEV fast charging

### 4.1. Current application status and prototypes

$Ga_2O_3$ technology is transitioning from laboratory research to prototype demonstration.

Discrete Devices: High-performance $Ga_2O_3$ SBDs and MOSFETs have been demonstrated with breakdown voltages exceeding 2 kV. These devices are being integrated into evaluation boards for DC-DC converters and power factor correction (PFC) circuits, which are core components of charging systems [1,6,7].

System-Level Demonstrations: Research consortia have begun showcasing $Ga_2O_3$ power modules in converter prototypes. Early results show significant reductions in switching losses and the ability to operate at higher junction temperatures, leading to potential improvements in power density and efficiency for charging systems [6,10].

Supply Chain Development: While commercial 4-inch $\beta$-$Ga_2O_3$ substrates are available, the ecosystem for epitaxy and fabrication remains nascent compared to SiC and GaN.

### 4.2. Future market and industrial prospects

The trajectory of $Ga_2O_3$ is closely tied to the evolving demands of electric mobility.

Target Applications: The primary near-term opportunity lies in ultra-fast charging (UFC) stations (>350 kW). The high breakdown voltage and potential cost advantage of $Ga_2O_3$ could enable more compact and efficient power conversion. Traction inverters represent a long-term goal, which depends on solving thermal management and reliability challenges.

Synergy with System Trends: The trend towards higher battery voltages (800V and above) in next-generation EV platforms directly benefits wide-bandgap semiconductors like $Ga_2O_3$.

Challenges and Roadmap: Key hurdles include scaling up wafer diameter, improving thermal management solutions, and establishing a robust reliability database for automotive standards. Success will depend on continued collaborative R&D across the supply chain to reduce technology risks and lower costs [10].

## 5. Conclusion

This review systematically summarizes the state-of-the-art in $Ga_2O_3$ semiconductor technology, tracing the pathway from material preparation to device application in NEV fast charging. Key preparation techniques such as EFG, MOCVD, and HVPE form the foundation for device fabrication. Performance optimization through strategic doping, innovative device designs (vertical structures, heterojunctions), and advanced thermal management strategies is actively expanding achievable limits. Prototype applications in power conversion circuits demonstrate the tangible potential of $Ga_2O_3$ to enhance efficiency and power density in fast-charging systems.

However, several limitations and challenges must be acknowledged and addressed. The most prominent is the material's relatively low thermal conductivity, which requires sophisticated and

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potentially costly integration and cooling solutions. The absence of viable p-type $Ga_2O_3$ limits certain device architectures. Furthermore, the industrial supply chain and long-term reliability data under automotive operating conditions are still under development, representing a gap between laboratory promise and market readiness.

Future research directions should focus on four key areas: (1) Develop novel material designs, such as alloys or composite structures, to inherently improve thermal conductivity; (2) Pioneernew device concepts and circuit topologies that mitigate material limitations; (3) Intensify efforts in heterogeneous integration technologies with high-thermal-conductivity substrates; and (4) Conduct standardized, accelerated lifetime testing to build the required reliability database. Addressing these challenges will allow $Ga_2O_3$ to solidify its role as a disruptive technology. This will ultimately promote faster, more efficient, and more widespread electric vehicle adoption.

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