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β-Ga_2O_3 Ultra-Wide Bandgap Semiconductors: Bridging Material Synthesis, Defect Mechanisms, and Power Applications

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Abstract. With the continuous growth in demand for high-efficiency and high-voltage power electronic devices, β-gallium oxide (β-Ga_2O_3) has become a key ultra-wide bandgap (UWBG) semiconductor material. Owing to its ultra-wide bandgap of approximately 4.8 eV and far exceeding the theoretical Baliga Figure of Merit (BFOM) of silicon carbide and gallium nitride, β-Ga_2O_3 demonstrates great potential in the next-generation power systems. This article systematically summarizes the latest advancements in the research of β-Ga_2O_3, with a particular focus on the transition from basic material science to device engineering. By employing a systematic review and comparative analysis approach, this paper focuses on evaluating mainstream crystal growth techniques, the intrinsic defect engineering and doping mechanisms, and the performance of cutting-edge power devices such as Schottky barrier diodes (SBDs). This paper looks into the remaining technical obstacles and future prospects, aiming to provide a comprehensive reference path for the commercialization process of β-Ga_2O_3 electronic devices.

Keywords: Gallium Oxide, Ultra-Wide Bandgap Semiconductors, Defect Engineering, Doping Mechanisms

1. Introduction

The generational evolution of semiconductor materials has consistently been driven by the industrial imperative for higher operational efficiency, greater power density, and superior thermal resilience. The historical transition from first-generation silicon (Si) and second-generation gallium arsenide (GaAs) to third-generation wide bandgap (WBG) materials like silicon carbide (SiC) and gallium nitride (GaN) precipitated a paradigm shift in power electronics. However, as global energy infrastructure aggressively pivots toward carbon neutrality—driven by the "dual carbon" goals of peaking carbon emissions and achieving carbon neutrality—the demands placed on power conversion systems are escalating rapidly. High-voltage applications in electric vehicles, grid-tied energy storage, and rail transportation are beginning to approach the theoretical physical limits of SiC and GaN. In this context, fourth-generation ultra-wide bandgap (UWBG) semiconductors, particularly β-Ga_2O_3, have emerged as the most promising candidates to bypass these limitations [1]. The primary fundamental advantage of β-Ga_2O_3 lies in its extraordinary critical breakdown field,

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which allows devices to operate at significantly higher voltages while maintaining extremely low conduction losses and switching inefficiencies. Furthermore, unlike other UWBG materials such as diamond or aluminum nitride (AlN), β-Ga_2O_3 is uniquely positioned as the only UWBG semiconductor that can be synthesized from the melt at standard atmospheric pressure. This critical material property eliminates the need for complex, high-temperature, and high-pressure vapor-phase sublimation, offering a highly scalable and cost-effective pathway to large-area native substrates. This unique convergence of superlative electrical properties and industrial scalability positions β-Ga_2O_3 to fundamentally disrupt the high-power electronics market. This paper structurally reviews the current state-of-the-art in β-Ga_2O_3 research, tracing the technological trajectory from bulk crystal growth and epitaxial layer deposition to defect engineering, device fabrication, and advanced thermal management strategies. By bridging fundamental material science with practical device architectures, this review serves as a valuable reference for the semiconductor industry to overcome current technical bottlenecks and design next-generation energy-efficient electronics.

2. Physical properties and inherent advantages

Gallium oxide exhibits complex polymorphism, existing in five distinct structural phases: corundum (α), monoclinic (β), defect spinel (γ), cubic (δ), and orthorhombic (ε). Among these polytypes, the thermodynamic stability follows the order of γ , δ , α , ε and β . Because the monoclinic β-phase is the most thermodynamically stable under high temperatures, it is the exclusive focus for melt-based bulk crystal growth and subsequent wafer manufacturing.

The intrinsic material properties of β-Ga_2O_3 dictate its superiority in power applications. As shown in Table 1, β-Ga_2O_3 possesses an ultra-wide bandgap (E_g) ranging from 4.7 to 4.9 eV, which is significantly larger than that of 4H-SiC (3.26 eV) and GaN (3.4 eV). This massive energy separation between the conduction and valence bands directly correlates to an exceptionally high critical breakdown electric field (E_c) of approximately 8 MV/cm, compared to 2.5 MV/cm for SiC and 3.3 MV/cm for GaN [2].

The superiority of a semiconductor for unipolar power switching applications is mathematically quantified by the Baliga Figure of Merit (BFOM), which is proportional to $BFOM = \varepsilon\mu E_c^3$, (where (ε) is the dielectric constant and (μ) is the electron mobility). Because the BFOM scales with the cube of the breakdown field, the 8 MV/cm E_c of β-Ga_2O_3 yields a theoretical BFOM of approximately 3,300 to 3,444—roughly 10 times higher than that of SiC and 4 times higher than that of GaN. While the electrical properties are outstanding, the complex monoclinic lattice of β-Ga_2O_3 induces severe phonon-phonon scattering, resulting in an intrinsically low thermal conductivity (10-30 $W / m \cdot K$). This severe thermal limitation presents the most significant engineering hurdle for high-power density applications, necessitating advanced device architectures and heterogeneous integration [3].

Table 1. Comparison of key physical properties

Physical Property	Silicon (Si)	4H-SiC	GaN
Bandgap E_g (eV)	1.12	3.26	3.4
Breakdown Field E_C (MV/cm)	0.3	2.5	3.3
Electron Mobility μ ($cm^2 / (V \cdot s)$)	1400	1000	1200

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Table 1. (continued)

Thermal Conductivity ($W / (m \cdot K)$)	150	490	230
Baliga Figure of Merit (Normalized to Si)	1	340	870

3. Crystal growth and epitaxy technologies

The most pronounced commercial advantage of β-Ga_2O_3 over SiC and GaN is its compatibility with low-cost, high-throughput melt growth technologies. The industry has heavily invested in several primary melt-growth techniques to scale up wafer dimensions while suppressing thermodynamic decomposition at extreme temperatures.

Currently, the most commercially advanced method, EFG utilizes capillary action through an iridium (Ir) die to shape the crystal. This method has successfully yielded high-quality single-crystal slabs up to 6 inches in diameter. However, the EFG interface has limited exposure to the oxygen atmosphere. At high temperatures (~1800°C), this lack of oxygen overpressure can induce melt decomposition and the formation of elemental gallium, leading to the propagation of void-type defects known as nanopipes [4].

The VB method involves melting raw materials in a crucible within a highly controlled thermal gradient. Unlike EFG, VB grows crystals in a cylindrical boule, which drastically reduces material kerf loss during wafer slicing. Recent advancements in 2024 have demonstrated 6-inch VB growth with superior dopant uniformity and reduced defect densities compared to EFG, aligning with industry standards for silicon.

The CZ method is highly favored for producing defect-free substrates. Because the solid-liquid growth interface remains in direct contact with an oxygen-saturated atmosphere, CZ completely avoids the formation of void-type nanopipes [5]. Although currently limited to smaller diameters due to Ir crucible oxidation issues, CZ substrates provide the ultimate foundation for high-quality, defect-free homoepitaxy.

4. Defect engineering and doping mechanisms

The commercialization of advanced β-Ga_2O_3 devices is heavily dependent on mastering defect chemistry and dopant activation.

4.1. N-type doping and carrier control

N-type doping in β-Ga_2O_3 is highly controllable across a massive range (10^{14} to 10^{20} cm^{-3}) using shallow donors such as Silicon (Si), Tin (Sn), Germanium (Ge), and Zirconium (Zr). Si is particularly favored in chemical vapor deposition environments, where precursors like tetraethoxysilane (TEOS) are utilized. Elevating growth temperatures to 875°C during MOCVD has been shown to increase the probability of Si substitution on Ga lattice sites, significantly reducing epilayer resistivity and suppressing oxygen vacancy formation [6]. Furthermore, these shallow donors typically exhibit extremely low activation energies (10–30 meV), ensuring near-complete ionization at room temperature. While Si predominantly substitutes at the tetrahedral Ga(I) sites, dopants like Sn prefer the octahedral Ga(II) sites, providing flexibility across different epitaxial techniques like molecular beam epitaxy (MBE). However, pushing the doping concentration toward the 10^{20} cm^{-3} limit introduces severe ionized impurity scattering. This phenomenon inevitably

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degrades electron mobility, requiring a precise trade-off between carrier concentration and conductivity for optimal power device performance.

4.2. The fundamental P-type doping bottleneck

Achieving effective p-type conductivity represents the most profound physical challenge in β-Ga_2O_3 research. The fundamental limitation arises from the material's electronic band structure. The valence band maximum (VBM) exhibits a shallow dispersion curve with minimal curvature, originating from strongly localized O 2p orbitals. Consequently, any generated holes undergo strong electron-phonon coupling, distorting the local lattice and transforming into small polarons known as "self-trapped holes" (STHs). These STHs possess colossal effective masses and near-zero mobility. Therefore, even if an acceptor impurity (such as Mg or Fe) is successfully incorporated, the resulting holes remain deeply localized and cannot contribute to macroscopic electrical conduction.

4.3 Groundbreaking P-type engineering strategies

Despite these theoretical barriers, recent empirical breakthroughs have introduced novel mechanisms to circumvent or resolve the p-type limitation:

A landmark 2025 study from Nagoya University demonstrated the formation of stable p-type layers using Nickel (Ni) ion implantation [7]. By subjecting the implanted material to a two-step process: low-temperature oxygen plasma treatment followed by a 950°C thermal anneal-researchers created a localized NiO diffusion layer seamlessly integrated into the Ga_2O_3 crystal. This resulted in the world's first functional bipolar pn diode on a native Ga_2O_3 substrate, capable of sustaining twice the current capacity of traditional unipolar designs.

Recent theoretical and experimental investigations have explored various co-doping strategies, such as integrating shallow donors with deep acceptors, to modulate the valence band and reduce acceptor ionization energy [8].

To bypass the native p-type constraint entirely, engineers have utilized p-type foreign materials. High-performance heterojunctions have been fabricated using p-type NiO, p-type GaN, and p-type diamond integrated directly onto n-type β-Ga_2O_3 drift layers. For instance, recent integrations of space-modulated junction termination extensions in NiO/Ga_2O_3 diodes have yielded massive breakdown voltages exceeding 3kV and robust avalanche characteristics [9].

5. Power device applications and architectures

The continuous refinement of material quality and interface engineering has led to record-breaking device performance metrics, pushing β-Ga_2O_3 closer to widespread commercialization.

5.1. Advanced schottky barrier diodes (SBDs)

SBDs represent the most mature class of β-Ga_2O_3 power devices. To mitigate the severe electric field crowding at the electrode edges, modern β-Ga_2O_3 SBDs rely on advanced termination techniques such as field plates, trench structures, and Junction Termination Extensions (JTE). In a notable 2025 development, a multi-fin trench Schottky barrier diode (TSBD) fabricated via self-aligned planarization achieved a catastrophic breakdown voltage of 4 kV without utilizing any complex edge terminations, reaching a power figure of merit (PFOM) of approximately 1 GW/cm^2. Furthermore, vertical SBDs employing a sputtered p-GaN layer as a JTE demonstrated a breakdown

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voltage of 3 kV combined with an extremely low specific on-resistance ($R_{on,sp}$) of 6.15 $m\Omega \cdot cm^2$ [10].

5.2. High-voltage field-effect transistors (FETs)

To achieve normally-off operation and ultra-high voltage blocking, lateral and vertical FET architectures have undergone rapid evolution. A highly notable achievement involves the implementation of the Reduced Surface Electric Field (RESURF) principle. By integrating an optimized p-NiO layer over an n-β-Ga_2O_3 channel, a heterojunction FET (HJ-FET) achieved a staggering breakdown voltage exceeding 10 kV and a PFOM of 63 MW/cm^2. Additionally, vertical FinFET structures featuring inter-fin field oxides demonstrated 1.8 kV breakdown capabilities while effectively suppressing off-state gate leakage.

Exploring metastable phases, researchers recently demonstrated a heterostructure FET comprising $\varepsilon - Ga_2O_3$ on $\alpha - Ga_2O_3$ layers. This unique architecture leverages the ferroelectric characteristics of the ε-phase to induce a high-density two-dimensional electron gas (2DEG) at the heterojunction without modulation doping, resulting in an off-state breakdown voltage of 1725 V and an $R_{on,sp}$ of 49.2 $m\Omega \cdot cm^2$ [11].

5.3. Bipolar transport and heterojunction diodes

The realization of bipolar transport has fundamentally shifted the performance ceiling of Ga_2O_3 devices. A study demonstrated that by implementing hole injection in Ga_2O_3 heterojunction PN diodes, conductivity modulation could be induced in low-doped drift layers. This allowed the device to simultaneously achieve high blocking voltage and low resistance—a historically contradictory engineering goal. The resulting device delivered a breakdown voltage of 8.32 kV, a specific on-resistance of 5.24 $m\Omega \cdot cm^2$, and a monumental PFOM of 13.2 GW/cm^2 , firmly surpassing the 1-D unipolar limit of both GaN and SiC [12].

6. Thermal management and heterogeneous integration challenges

The commercial viability of β-Ga_2O_3 is severely hindered by its exceptionally low thermal conductivity, which induces destructive self-heating effects (SHE) and premature device failure during high-power operation [13]. To overcome this bottleneck, the industry widely adopts heterogeneous integration, transferring active β-Ga_2O_3 layers onto highly thermally conductive substrates like SiC and polycrystalline diamond.

6.1. Ion-cutting and SiC wafer bonding

The most scalable technique for heterogeneous integration is the ion-cutting (often referred to as "Smart Cut") process. High-energy H+ ions are implanted into a bulk β-Ga_2O_3 donor wafer to create a specific subsurface damage layer. The surface is then hydrophilically bonded to a highly conductive SiC substrate at elevated temperatures. A subsequent thermal anneal induces mechanical exfoliation along the damage plane, resulting in a wafer-scale, single-crystalline β-Ga_2O_3 thin film permanently bonded to the SiC heat sink. Post-exfoliation high-temperature annealing at 1200°C effectively heals the residual implantation defects, restoring the effective channel electron mobility (μ_{eff}) to levels consistent with bulk native substrates. Devices fabricated on these β-Ga_2O_3-on-SiC

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heterogeneous wafers exhibit up to a 64% reduction in steady-state temperature rise during DC operation.

6.2 Diamond integration and thermal boundary conductance

For extremely high-frequency and high-power-density applications, where transient thermal spikes are severe, diamond integration is crucial. Researchers have successfully utilized Microwave Plasma Chemical Vapor Deposition (MP-CVD) to deposit highly Sp^3 -bonded nanocrystalline diamond (NCD) passivation layers directly onto lateral β-Ga_2O_3 transistor channels. By performing this at a reduced temperature of 400°C, a 42% reduction in total thermal resistance at the gate was achieved [14].

However, the efficacy of diamond integration is heavily dictated by the Thermal Boundary Conductance (TBC) at the hetero-interface. Time-Domain Thermoreflectance (TDTR) measurements reveal that van der Waals-bonded interfaces yield a relatively low TBC of approximately 17 MW/(m² · K) due to a severe acoustic impedance mismatch between the two materials [15]. Conversely, engineering direct covalent bonds between the diamond and β-Ga_2O_3 surfaces increases the TBC by an order of magnitude. Optimizing the interface chemistry—such as ensuring a perfectly clean, stoichiometric bond rather than an excessively Ga-rich or O-rich interface—mitigates interfacial phonon scattering. This ensures efficient heat dissipation, thereby unlocking the true power-handling potential of the β-Ga_2O_3 layer.

7. Conclusion

This study systematically investigated the technological trajectory of β-Ga_2O_3 semiconductors, tracing the advancement from fundamental material properties to advanced device architectures. The analysis revealed that while β-Ga_2O_3 possesses extraordinary intrinsic electrical advantages and highly scalable melt-growth capabilities, its practical deployment relies heavily on mastering defect chemistry and thermal management. By connecting crystal growth, doping mechanisms, device design, and heterogeneous integration into a coherent logical chain, this research contributes to the existing body of knowledge by bridging the gap between basic material science and industrial power applications. Consequently, this study has significant practical and theoretical value for the field of next-generation wide-bandgap power electronics. However, this study is limited by its review-based analytical scope and a lack of direct empirical or simulation data to validate specific multi-phase interface behaviors. Future study could focus on performing targeted numerical modeling and experimental testing of the thermal boundary conductance at the β-Ga_2O_3-diamond covalent interface. Overall, this study provides new insights into fourth-generation semiconductors and highlights the importance of synergistic material-device engineering, thereby paving the way for the commercialization of high-efficiency electronic devices.

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