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The Emerging Beyond-Silicon Technologies: Gallium Oxide (β-Ga_2O_3) for Next-Generation Power Electronics

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Abstract. Silicon-based power electronics are approaching their fundamental physical limits. Ultra-wide bandgap (UWBG) semiconductors are the most promising beyond-silicon candidates, and β-phase gallium oxide (β-Ga_2O_3) stands out among them. This review covers β-Ga_2O_3 as a beyond-silicon technology for next-generation power electronics. The material has an ultra-wide bandgap of about 4.8 eV, a theoretical critical electric field of approximately 8 MV/cm, and a Baliga figure of merit of roughly 3300, several times higher than those of SiC and GaN. It is also the only UWBG semiconductor that can be grown from the melt at low cost. We discuss the two main bottlenecks, the lack of p-type doping and the low thermal conductivity, along with current mitigation strategies. We conclude that, as hetero-integrated thermal management and p-type-free device architectures continue to improve, β-Ga_2O_3 has a realistic chance of becoming a commercially competitive power semiconductor platform.

Keywords: Ultra-Wide Bandgap Semiconductors; Power Electronics; Thermal Management; p-Type Doping.

1. Introduction

Currently, electricity accounts for approximately 40% of primary energy consumption in developed countries. With the continuous development of electric vehicles, renewable energy, and energy storage technologies, power electronic devices have become the key to modern energy conversion [1]. The performance of a power device mainly depends on whether it can effectively block high voltage during turn-off and transmit large current with extremely low loss during turn-on. These two performances are mainly determined by the material, especially its critical electric field and electron mobility [2]. Silicon-based devices have been continuously optimized for decades, but they are now approaching these limits. Due to the critical electric field of silicon being only about 0.3 MV/cm, designers have to adopt thicker and lightly doped structures to suppress high voltage, resulting in significant increases in conduction and switching losses [2]. Wide bandgap semiconductors (WBG), such as 4H-SiC and GaN, have partially solved this problem and have been commercially applied in electric vehicles, fast chargers, and data centers. However, SiC substrates are still expensive and difficult to grow in large sizes, while GaN power devices lack a more economically advantageous natural substrate, so they still rely on heteroepitaxy technology [2]. These limitations explain why people continue to research non-silicon materials with better intrinsic properties and lower production costs.

β-Ga_2O_3 has been studied for about 70 years, but during most of this period, its importance as a semiconductor was relatively low. Since 2010, the demand for high-voltage and low-loss electronic devices has significantly increased [3]. This material has several advantages: Firstly, its bandgap width is extremely wide, ranging from 4.5–4.9 eV, and the theoretical critical field is approximately 8 MV/cm, resulting in a Barilla factor (BFOM) of about 3300, which is 3 to 10 times higher than that of SiC and GaN [1]. Secondly, it is the only WBG material that can be directly grown from wafers, opening the way for high-diameter and high-quality native substrates that can be doped and have potential cost advantages [4]. Currently, there are commercial substrates with a diameter of 2 inches on the market, and their diameters are expanding towards 4 inches and 6 inches, a trend that silicon (SiC) and gallium nitride (GaN) cannot achieve [3,4]. Thirdly, by doping with silicon or tin during

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growth, its n-type conductivity can be adjusted over a wide range [2]. The development pace of devices is also advancing simultaneously: β-Ga_2O_3 barrier Schottky diodes (SBDs) have exceeded 3 kV and have extremely low reverse leakage; while SiC hetero-integrated field-effect transistors (FETs) have achieved new records for RF output power density [5]. Previous reviews have mostly focused on material properties, crystal growth, and device processing [1-4], but most are limited to a specific device type or specific aspects, making it difficult for beginners to fully understand the entire chain from material physics to device evaluation.

Therefore, this article links material physics, device evaluation models, and experimental results, enabling readers to clearly understand the achieved results, how device performance is quantified, and why the current challenges are significant. The article mainly serves three functions: Firstly, it derives an evaluation model that links material intrinsic parameters with device performance; Secondly, it compares the latest research results of SBD and FET devices and highlights the core of their structural innovations; Finally, it analyzes the two main obstacles currently faced and proposes corresponding mitigation strategies. The remaining parts of the article are organized as follows: The second part starts from the intrinsic parameters of the material, explaining the device evaluation model; The third part focuses on Schottky barrier diodes in β-Ga_2O_3; The fourth part explores the performance of β-Ga_2O_3 field-effect transistors in power switching and RF (RF) applications; The fifth part discusses the existing limitations and future prospects; the sixth part serves as the summary of the article.

2. Methodology: Device Performance Evaluation Models for UWBG Power Semiconductors

For power switching devices, the most important performance metrics are the breakdown voltage (V_B), the specific on-resistance ($R_{on,sp}$), and the corresponding figures of merit. The theoretical breakdown voltage of a one-sided parallel-plane junction is given by [6].

$$V_B = \varepsilon_s E_c^2/(2qN_d) \tag{1}$$

where ε_s is the dielectric permittivity, E_c is the critical electric field, q is the elementary charge, and N_d is the doping concentration of the drift layer. The specific on-resistance of a uniformly doped drift layer can be expressed as.

$$R_{on,sp} = 4V_B^2/(\varepsilon_s \mu_n E_c^3) \tag{2}$$

where μ_n is the electron mobility. This equation shows that the specific on-resistance scales inversely with the cube of the critical field, which is the reason why materials with a high E_c can achieve a given blocking voltage with much lower conduction loss.

Combining Eqs. (1) and (2) yields the Baliga figure of merit.

$$BFOM = \varepsilon_s \mu_n E_c^3 \tag{3}$$

Table 1 compares the main intrinsic parameters of silicon (Si), 4H-SiC, gallium nitride (GaN), and β-gallium oxide (β-Ga_2O_3). Among them, β-Ga_2O_3 has the largest band gap and the highest critical field strength, and its BFOM is several orders of magnitude higher than that of silicon, approximately 3 to 10 times that of SiC and GaN.

In terms of device structure, lateral structures are easier to manufacture and integrate with other components, while vertical structures can provide higher current density and achieve better electric field management in high-voltage applications. Schottky barrier diodes are favored due to their single-pole fast-switching characteristics, as only majority carriers participate in conduction; while MOSFETs can achieve active control of the gate and are crucial for safe power conversion in fault conditions.

Table 1. Key intrinsic parameters of power semiconductor materials[2,6,7]

Parameter	Si	4H-SiC	GaNe	β-Ga_2O_3
Bandgap (eV)	1.12	3.26	3.4	4.8
Critical field (MV/cm)	0.3	2.5	3.3	8
Electron mobility ($cm^2/V·s$)	1350	900	1000	250
Thermal conductivity (W/m·K)	150	370	130	10-27
BFOM (relative to Si)	1	340	870	3300
Native substrate cost	Low	High	High	Potentially low

3. Results I: Progress in β-Ga_2O_3 Schottky Barrier Diodes

When metal deposits on a lightly doped n-type semiconductor, a Schottky barrier diode is formed. The height of the rectifying barrier depends on the performance of the metal and the affinity of the semiconductor electrons. Since only majority carriers can conduct, Schottky diodes have extremely fast switching speeds and negligible reverse recovery current, making them particularly suitable for high-frequency rectification [8]. Planar β-Ga_2O_3 Schottky diodes directly benefit from the material's high critical field strength, but their turn-off voltage is limited by the reverse scattering at the metal-semiconductor interface. Xia et al. demonstrated that in planar vertical rectifiers, scattering is mainly dominated by thermal emission under low polarization fields, while the tunneling effect gradually takes the lead under high polarization fields, and its transition voltage decreases with increasing temperature [9].

Based on the trench SBD (Schottky diode), the problem was solved by the surface field reduction effect (RESURF): the trench filled with dielectric can reduce the electric field away from the junction angle, enabling the device to withstand higher voltages. Li et al. quantitatively proved that in kilovolt-level operation conditions, trench SBDs not only outperform traditional structures but may even be necessary for high-efficiency Ga_2O_3 rectifiers. For example, a 1375 V trench SBD has a forward voltage drop of less than 1 V at a current density of 100 A/cm^2 [8]. The high dielectric constant dielectric effectively suppresses leakage at the bottom of the trench, and its stored charge and switching energy are also lower than those of commercial SiC SBDs with equivalent performance - this indicates that such devices have high switching efficiency [10].

Moule et al. studied the breakdown mechanism in trench-MOS SBDs with voltages exceeding 1 kV, and by analyzing the dissipated current noise, identified two different behavior patterns. At low bias conditions, the dissipation is mainly dominated by the Schottky interface barrier tunneling effect; higher polarization leads to irreversible soft break events at the oxide interface, followed by the diffusion path of local Al_2O_3 [11]. These results directly affect the rated voltage and service life of devices that rely on the oxide layer to enhance the breakdown field. From a thermodynamic perspective, β-Ga_2O_3 vertical rectifiers have been tested up to 600 K and still maintain a reverse breakdown voltage of 750 V. Therefore, β-Ga_2O_3 rectifiers have special appeal in high-temperature and high-voltage applications.

Figure 1 shows the breakdown voltages reported in different structures of β-Ga_2O_3 SBDs. The model is clear: by using RESURF dielectric materials and a trench structure with high k value, the breakdown voltage can be raised to multiple kilovolts while maintaining extremely low current consumption.

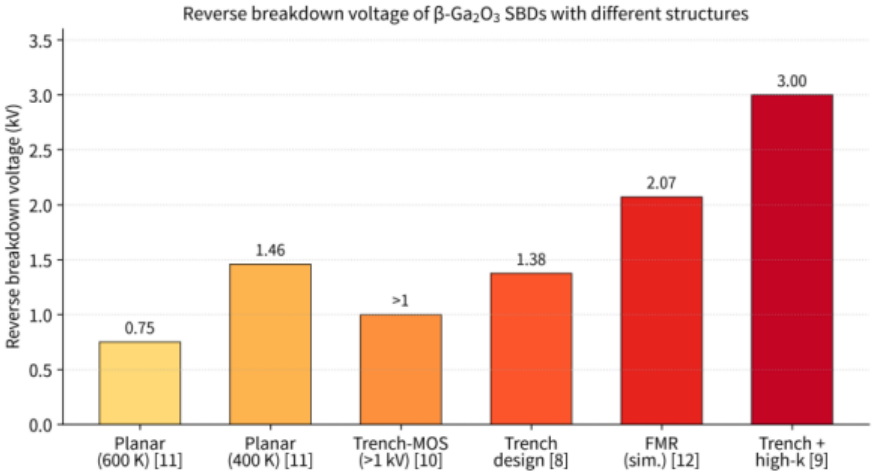

Fig. 1 Reverse breakdown voltage of β-Ga_2O_3 SBDs with different structures [8-12]

4. Results II: Progress in β-Ga_2O_3 Field-Effect Transistors

A field-effect transistor regulates channel conductance through the gate voltage, and a stable threshold voltage plus low gate leakage depends on the quality of the gate dielectric interface [5]. β-Ga_2O_3 FETs come in two operation modes, depletion and enhancement, and three architectures, lateral, vertical, and nanomembrane. Depletion-mode devices are easier to fabricate but need a negative gate voltage to turn off, while enhancement-mode devices are essential for fail-safe power switching in real converters [5]. Several recent reviews have surveyed the transistor designs reported so far, covering channel materials, gate dielectrics, and fabrication processes [1,5].

For power switching, the main advances are improved gate dielectrics such as Al_2O_3 and HfO_2, better ohmic contacts, and β-$(AlxGa1-x)_2O_3$ heterostructures that enable modulation doping and higher channel charge [1]. Field-plated and gate-recessed designs reshape the electric-field distribution and push the breakdown voltage toward the material limit [5]. Lateral FETs fit the planar process flow and have been the main vehicle for demonstrating the material's potential, but they suffer from current crowding and a relatively large footprint. Vertical FETs are harder to fabricate, but they offer higher current density and better heat spreading, and are generally seen as the preferred route for high-current power switching [1]. The trade-off between breakdown voltage and specific on-resistance is captured by the theoretical BFOM limit: the best reported β-Ga_2O_3 FETs already operate close to it, far beyond what Si devices can manage.

The biggest recent advance is heterogeneous integration for thermal management. Zhou et al. transferred heavily doped β-Ga_2O_3 channels onto SiC substrates, which cuts on-resistance and improves heat dissipation, and combined this with an insulated, recessed T-gate to improve frequency performance and field management. The resulting β-Ga_2O_3-on-SiC RF MOSFETs set a record output power density of 2.3 W/mm, with 30% power-added efficiency at 2 GHz, a maximum on-current of 1.1 A/mm, and f_T/f_max of 27.6/57 GHz, extending power amplification up to 8 GHz. These values are 25× and 3× those of the previous best β-Ga_2O_3 RF devices, respectively, and show the Ga_2O_3-on-SiC platform can deliver high power at high frequency without sacrificing efficiency [13].

Since reliable p-type doping of β-Ga_2O_3 is still unavailable, designers replace p-n junctions with alternative field-management structures. Yao et al. showed by TCAD simulation that floating metal rings (FMR) raise the breakdown voltage to 2072 V at a doping concentration of 10^{16} cm^{-3}, about 2.5 times that of the device without FMR [12]. Figure 2 shows the key metrics of the record β-Ga_2O_3-on-SiC RF MOSFET, and Table 2 lists representative β-Ga_2O_3 FET results. These device-level strategies, together with the material-level approaches in Section 5, point the way to practical β-Ga_2O_3 power electronics [2].

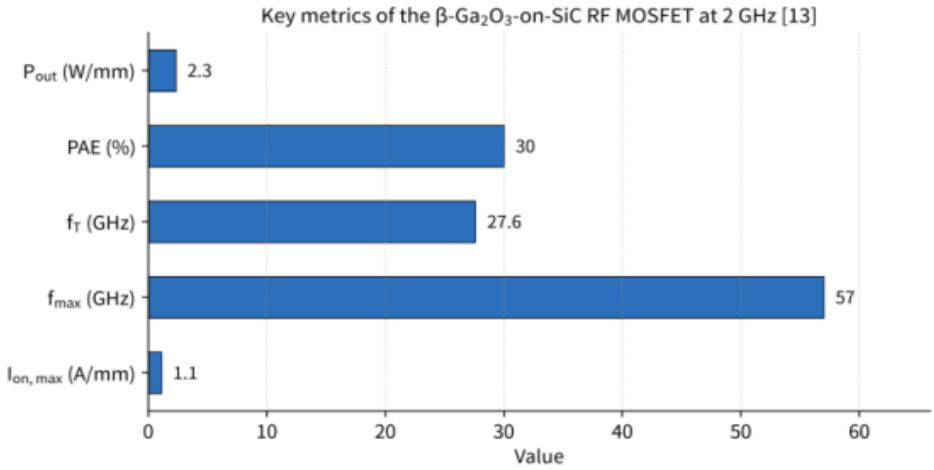

Fig. 2 Key metrics of the β-Ga_2O_3-on-SiC RF MOSFET at 2 GHz [13]

Table 2. Representative β-Ga_2O_3 field-effect transistor results

Device	Architecture	Key results	Ref.
RF MOSFET	β-Ga_2O_3-on-SiC, recessed T-gate	P_out = 2.3 W/mm at 2 GHz; PAE = 30%; f_T/f_max = 27.6/57 GHz; I_on,max = 1.1 A/mm	[13]
Power switching FETs	Lateral, field-plated / gate-recessed	BV–R_on trade-off approaching the theoretical limit	[1,5]
D-mode and E-mode FETs	Lateral and nanomembrane	Both operation modes demonstrated	[5]
FMR design (TCAD)	Field management without p-n junction	BV = 2072 V at 10^{16} cm^{-3}	[12]

5. Limitations and Future Outlooks

The progress is rapid, but there are still two major material limitations. The first is the lack of reliable p-type doping. The valence band maximum of β-Ga_2O_3 mainly comes from the O 2p state and is relatively flat, resulting in severe deep-level acceptors and self-compensation effects. Multiple research teams have attempted other methods. Islam et al. proved that by controlling the incorporation of hydrogen, p-type and n-type conductivity can be achieved simultaneously in β-Ga_2O_3, where hydrogen acts as a surface donor in one configuration and as a receptor in another configuration [14]. Chi et al. reported that phosphorus-doped films exhibit p-type-like conductivity through the Anderson disorder mechanism, with an hole concentration of approximately 4–6×10^{18} cm^{-3}, but the hole mobility is only 1.2–2.1 $cm^2/V{\cdot}s$ [15]. These results are of great significance in science, but the mobility is too low to be used in practical devices. The iridium impurities inevitably introduced during the Czochralski melt growth process further exacerbate this problem: they introduce deep-levels harmful to p-type conductivity [16]. The absence of the p-type layer also excludes the junction extension and isolation structures commonly found in silicon carbide (SiC) technology, so designers must rely on field plates and dielectric substrate terminals, which are more sensitive to charges at the interface. In addition to the doping issue, large-area defects, deep wells, and immature processing techniques - such as dry cutting, dielectric interfaces, and ohmic contacts - still continue to limit the reliability and performance of β-Ga_2O_3 devices [2].

Several directions seem to show promise. Firstly, integrating thin-layer β-Ga_2O_3 heterostructures onto high thermal conductivity substrates (such as SiC or diamond) is the most practical solution to address the thermal management problem in the short term, as existing RF Ga_2O_3-SiC MOSFET records indicate [13]. Secondly, to address the challenges of p-type materials, hydrogen engineering research is still advancing, exploring receptor doping in metastable polycrystalline phases (such as α- and ε-Ga_2O_3), as well as methods based on disordered structures [15]. Meanwhile, the most practical approach is to design device architectures without p-n junctions: such as trench SBD, suspended metal rings, and conventional off-state designs based on gate trenches and heterostructure engineering [12]. Thirdly, it is expected that in future high-current, high-voltage applications, vertical structure architectures will dominate, as they can better control the electric field and achieve higher current

densities. Fourthly, adopting wafer-level production (i.e., based on 6-inch or larger silicon wafers, combined with standardized MOCVD, MBE, and HVPE epitaxial technologies) will become a key to reducing costs and promoting commercialization [3]. Beyond the power electronics field, β-Ga_2O_3 is gradually evolving into a platform for solar-blind ultraviolet light detectors and high-temperature electronic devices [4]. From a market perspective, in the short term, β-Ga_2O_3 will not replace silicon carbide (SiC) or gallium nitride (GaN), but will be targeted at the medium-high voltage range, with voltage ranging from 600 volts to several thousand volts. Thanks to these advancements, it is expected to occupy a unique position in cost-sensitive areas of the power electronics market.

6. Conclusion

This paper reviewed β-Ga_2O_3 from material physics to device applications, as an emerging beyond-silicon technology for next-generation power electronics. The material has an ultra-wide bandgap of about 4.8 eV, a theoretical critical electric field of 8 MV/cm, and a Baliga figure of merit of about 3300, and it can be grown from the melt into low-cost native substrates — a combination that gives it better intrinsic power-handling capability than Si, SiC, or GaN. On the device side, trench-based Schottky barrier diodes have exceeded 3 kV breakdown with ultra-low reverse leakage, and field-effect transistors have reached record RF output power densities through heterogeneous integration onto SiC. The two main bottlenecks, the lack of p-type doping and the low thermal conductivity, are being tackled with p-type-free device architectures and hetero-integrated thermal management. With continued progress in materials, devices, and packaging, β-Ga_2O_3 has a realistic path to becoming a commercially competitive power semiconductor platform.

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