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Research on Simulation Methodology for Gallium Oxide-Based MOSFETs: Electrothermal Characteristics and Reliability Degradation Mechanism

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Abstract: Beta-phase gallium oxide (β-Ga_2O_3), as an ultra-wide bandgap semiconductor (4.5–4.9 eV), demonstrates superior critical breakdown field strength (8 MV/cm) compared to SiC and GaN material systems, showing significant potential for next-generation high-power electronics. Nevertheless, inherent limitations including the absence of stable p-type doping leading to depletion-mode operation and low thermal conductivity (~27 W/m·K) causing severe self-heating effects hinder practical applications. This study establishes a multi-physics coupled simulation platform using Sentaurus TCAD to systematically investigate the steady-state electrical characteristics and thermal reliability of β-Ga_2O_3 MOSFETs. A self-consistent electrothermal model reveals a threshold voltage of -3.5 V and breakdown voltage of 100 V at 300 K. Thermal stability analysis demonstrates that elevated temperature (600 K) increases leakage current by two orders of magnitude due to thermally excited carrier accumulation, accompanied by a 0.8 V negative shift in threshold voltage. Defect density gradient simulations further uncover that bulk trap concentrations exceeding 1×10^{17} cm^{-3} under off-state conditions induce significant recombination in space charge regions, triggering anomalous conduction phenomena. This work provides theoretical guidance for overcoming thermal management challenges and enhancing reliability in Ga_2O_3-based devices.

Keywords: β-Ga_2O_3, Electrothermal coupling, reliability, trap

1. Introduction

Ga_2O_3 LDMOSFET is a power device in which all electrodes are located on the device surface, resulting in lateral carrier transport during operation. Owing to its ease of fabrication and seamless integration into power integrated circuits, the Ga_2O_3 LDMOSFET has attracted significant attention in recent years. Research has primarily focused on the N-channel β-Ga_2O_3 LDMOSFET, which features a negative threshold voltage; by applying a sufficiently negative bias to the gate, a depletion region is formed that effectively pinches off the conductive channel, thereby turning off the device[1].

In 2012, the Higashiwaki group at Japan's NICT successfully demonstrated the first Sn-doped N-channel β-Ga_2O_3 MESFET (see Figure 1)[2]. Building on this work, in 2013 Higashiwaki et al. introduced a basic depletion-mode β-Ga_2O_3 LDMOSFET with a threshold voltage (V_{th}) of -15 V, a breakdown voltage of 370 V, and an on/off current ratio exceeding 10^{10}[3]. In 2016, Wong and colleagues proposed the first depletion-mode β-Ga_2O_3 LDMOSFET with an integrated field plate.

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This design was realized by epitaxially growing on an unintentionally doped (UID) Ga_2O_3 buffer layer and employing multi-step silicon ion implantation to form a box-like N-type channel along with heavily doped N^+ source and drain regions[4]. In 2017, Chabak et al. introduced an enhancement-mode β-Ga_2O_3 LDMOSFET featuring a trench gate structure, which achieved a threshold voltage of 3 V, an on/off current ratio over 10^9, and a breakdown voltage of 505 V[5]. The following year, Zeng et al. improved upon the gate field plate design by dividing the underlying dielectric layer into two parts: a 50 nm high-quality SiO_2 layer deposited via atomic layer deposition (ALD) and a 350 nm SiO_2 layer deposited by plasma-enhanced chemical vapor deposition (PECVD)[6]. In 2022, Sharma et al. further refined the gate field plate dielectric by replacing the conventional dielectric with a polymer passivation layer[7], while Wang et al. presented the first lateral superjunction β-Ga_2O_3 LDMOSFET (see Figure 2)[8].

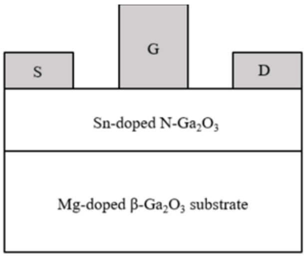

Figure 1: Sn-doped N-channel β-Ga_2O_3 MESFET Device[2]

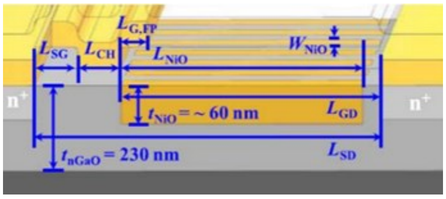

Figure 2: Lateral Superjunction β-Ga_2O_3 LDMOSFET Device[8]

Despite these advances, studies on the thermal effects and the impact of bulk defects on β-Ga_2O_3 MOSFET performance remain limited—especially concerning device behavior under high-temperature conditions and the influence of bulk defects on off-state characteristics. In this work, we employ SENTAURUS TCAD simulation software to systematically investigate the static characteristics, thermal effects, and the influence of bulk defects in β-Ga_2O_3 MOSFETs.

In this paper, section 1 illustrates the application scenarios of power devices, the material properties of Ga_2O_3, and the development history and current status of Ga_2O_3 power devices, with a focus on lateral Ga_2O_3 LDMOSFETs. Section 2 details the structure, parameters, and physical models used in the simulations of Ga_2O_3 devices. Section 3 analyzes the basic static characteristics of the device, including its transfer and output characteristics, and introduces an avalanche model to extract key performance parameters from its breakdown behavior. Section 4 incorporates a thermal model to compare the transfer characteristics at 300 K and 600 K, thereby exploring the effects of temperature on the threshold voltage and leakage current. Finally, the influence of bulk defects on the device is examined by analyzing how variations in trap charge concentration affect the conduction state in the off condition.

2. Structure and Simulation

In this section, a simple β-Ga_2O_3 LDMOSFET device structure is constructed(see figure 3). The structure is based on a p-type Ga_2O_3 substrate, on which an n-type Ga_2O_3 drift region is formed, followed by the sequential definition of heavily doped source and drain regions on the n-type region.

An insulating layer of Al_2O_3 is then deposited above the n-type region, with the gate metal subsequently deposited on top of the Al_2O_3. A highly doped n^{++} β-Ga_2O_3 region with a doping concentration of 3×10^{19} cm^{-3} is introduced beneath the contacts in order to reduce the contact resistance. A 20 nm thick Al_2O_3 layer is implemented as the gate dielectric. In the simulated structure, the source-to-drain spacing is set at 30 µm, the gate length at 2 µm, and the gate width at 20 µm, while the thickness of the ungated β-Ga_2O_3 channel region is defined as 0.3 µm to further optimize device performance.

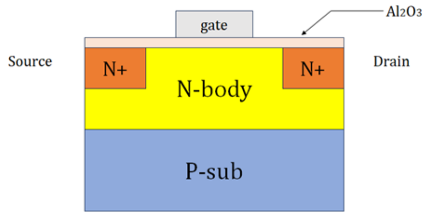

Figure 3: Ga_2O_3 MOSFET structure used in the simulation

For the simulation of basic static characteristics, the OldSlotboom bandgap narrowing model is employed to account for the intrinsic carrier concentration, which is influenced by the semiconductor's bandgap and the states density at the band edges; additionally, a doping-dependent Shockley-Read-Hall (SRH) recombination model is used to describe carrier generation and recombination processes, emphasizing the impact of doping concentration on carrier lifetime. To simulate the breakdown characteristics, an avalanche model is incorporated on top of the SRH model, thereby simultaneously considering SRH recombination and avalanche breakdown effects. In order to achieve higher simulation accuracy, the transient scan algorithm is replaced by a quasi-static scan algorithm. Furthermore, given the significant impact of self-heating effects on the electrical characteristics of power devices with large active areas, high current densities, and high power densities, a thermodynamic model is also included in the simulation. The parameters used in the Ga_2O_3 device simulation are provided in Table 1.

3. The static performance Simulation

To analyze the static performance of the β-Ga_2O_3 MOSFET, simulations were performed using Sentaurus TCAD, from which the transfer, output, and breakdown characteristic curves were extracted.

Table 1: β − Ga2O3- Parameters

Parameter	**Gallium Oxide**	**Units**
Band Gap	4.6	eV
Critical breakdown electric field	8	MV/cm
Dielectric Constant	10.0	N/A
Electron Mobility	300	$cm^2/V\cdot s$
Electron Affinity	4.0	eV

3.1. The transfer characteristics

Figure 4 presents the transfer characteristics: under a fixed source-drain voltage of 1V, the gate voltage was incrementally scanned to observe the device's on/off behavior. The results indicate that when the gate voltage becomes more negative, the drain current (I_d) remains extremely low, signifying that the device is in the off state; as the gate voltage increases to approximately -3.5V, the

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drain current rises significantly, indicating that the device enters the on state; further increases in V_g cause I_d to grow exponentially. This behavior suggests that the device's threshold voltage (V_{th}) is around -3.5V, consistent with the characteristics of a depletion-mode (D-mode) MOSFET. However, the current simulation does not include the effects of interface roughness scattering, gate oxide interface traps, fixed interface charges, or bulk defect models, which may affect the accurate simulation of mobility variations[9].

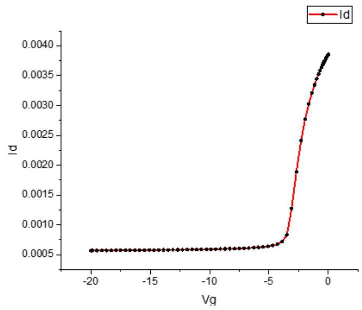

Figure 4: the transfer characteristic curve

3.2. The output characteristics

Figure 5 illustrates the output characteristics of the β-Ga_2O_3 MOSFET, specifically the variation of the drain current (I_d) with the drain voltage (V_d). As observed in Figure 5, in the low V_d region, I_d increases approximately linearly, indicating that the device operates in the linear region. In this region, the carriers in the MOSFET channel are driven by the source-to-drain voltage, and the current is mainly controlled by the channel resistance $R_{ds(on)}$, resulting in an approximately linear relationship between I_d and V_d. The current can be approximately expressed as:

$$I_D \approx \mu_n C_{ox} \frac{W}{L}\left(V_G - V_{th} - \frac{V_D}{2}\right) V_D \tag{1}$$

Where W/L is the channel width-to-length ratio, C_{ox} is the gate oxide capacitance, μn is the electron mobility, V_g is the gate voltage, and V_{th} is the threshold voltage. In this region, the device current is primarily determined by the channel's conductive properties, and the on-resistance can be estimated from the slope of the linear region; a lower on-resistance implies lower power consumption, which is advantageous for efficient power electronic applications.

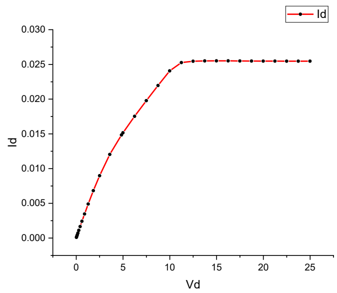

Figure 5: the output characteristic curve

As V_d increases to approximately 10 V, the rate of increase of I_d gradually diminishes and eventually saturates, indicating that the MOSFET has entered the saturation region. At this stage, the carrier velocity in the channel reaches saturation, so that further increases in V_d do not lead to a significant increase in current; the saturation current can be approximated by:

$$I_D \approx \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_G - V_{th})^2 \tag{2}$$

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In the saturation region, the current is primarily limited by the velocity saturation of the carriers, causing I_d to remain almost constant with further increases in V_d. This characteristic is particularly important for power devices as it determines the maximum current carrying capability of the MOSFET. Moreover, for β-Ga_2O_3 MOSFETs—being wide bandgap semiconductor devices—the high breakdown electric field (approximately 8 MV/cm) enables operation at higher voltages; however, the relatively low thermal conductivity may lead to self-heating effects, potentially affecting the long-term stability of the device.

3.3. The breakdown characteristics

As introduced earlier, owing to the 4.6 eV bandgap, Ga_2O_3's excellent voltage withstand capability has attracted significant attention. In simulations of the β-Ga_2O_3 MOSFET structure, breakdown occurs mainly in two regions: source–drain lateral breakdown and gate breakdown[10].

Source–Drain Breakdown: Source–drain breakdown refers to the phenomenon in which, under the condition that the device channel is off, a reverse voltage is applied between the source and drain and gradually increased. When the voltage reaches a certain value, the gate's barrier effect weakens, leading to a sudden jump in current that forms a closed loop between the source and drain. Internationally, the voltage at which the reverse current reaches 1 mA/mm is defined as the breakdown voltage. This process is typically called "soft breakdown" because the device is not physically damaged—only its characteristics are altered. Under test conditions, the breakdown voltage determined from the soft breakdown test result is taken as the actual breakdown voltage of the device. the static performance.

Gate Breakdown: Gate breakdown is caused by leakage current induced by the reverse bias of the Schottky gate. Some reports suggest that when the device operates at a high drain voltage, the presence of defects or surface states prevents the gate's Schottky contact from acting as an ideal unidirectional conductor. As a result, a small portion of electrons may leak out from the gate, generating gate leakage current. When this gate leakage current reaches 1 mA/mm before the source–drain current does, a closed loop is formed between the source and the gate.

According to breakdown characteristics presented in this paper, the gate voltage (V_g) is fixed at -10 V to ensure that the device is completely turned off. Then, the drain–source voltage (V_d) is gradually increased while observing the change in drain current (I_d). The simulation results are shown in Figure 6.

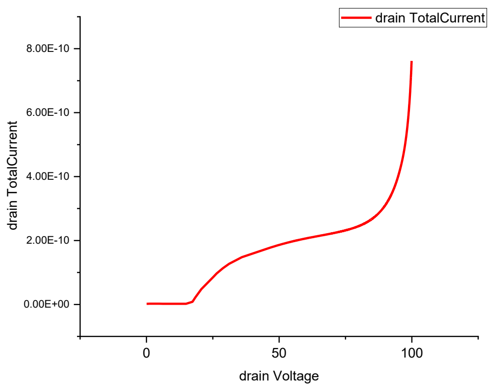

Figure 6: the breakdown characteristic curve

It can be seen that when V_d is in a relatively low range, the device's drain current remains extremely low ($< 10^{-10}$ A), indicating that the device is off—this shows that under low electric field conditions, there are very few carriers in the channel, resulting in almost no leakage current. When

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V_d increases to around 100 V, the drain current exhibits an exponential increase, indicating that 100V has reached the breakdown voltage(BV) of the β-Ga_2O_3 MOSFET.

4. Temperature Characteristics Simulation

The majority of power dissipation in high-voltage devices occurs within the channel region, causing localized temperatures to exceed ambient conditions by tens to approximately one hundred degrees Celsius. This temperature elevation intensifies electron-phonon scattering within the material, consequently altering the electrical performance of MOSFET devices. Beyond intrinsic self-heating, environmental temperature variations also significantly impact device behavior[11].

Unlike gallium nitride (GaN) – a relatively mature material system characterized by wide phononic bandgaps that suppress phonon-phonon Umklapp scattering – β-Ga_2O_3 exhibits narrower bandgaps and shorter relaxation times, resulting in substantially lower thermal conductivity. Notably, the charge transport mechanism in n-type β-Ga_2O_3 fundamentally differs from GaN's two-dimensional electron gas (2DEG) conduction, leading to distinct temperature-dependent characteristics. Comparative thermal conductivity data for relevant materials are presented in Table 2.

Table 2: Thermal Conductivity of different Materials

Material	AlN	GaN	Diamond	Ga_2O_3
Thermal Conductivity	50	130	220~700	13~30

Following room-temperature (300 K) simulations of baseline electrical properties, this section investigates temperature-dependent characteristics through thermodynamic model-based simulations. Transfer characteristics at 300 K and 600 K are systematically compared, with simulation results presented in Figure 7.

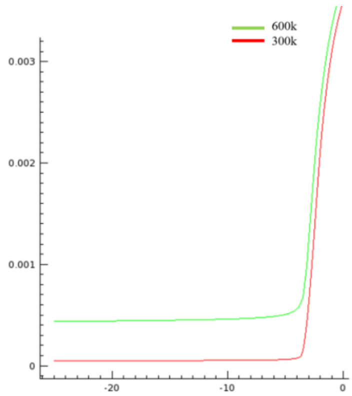

Figure 7: Temperature Characteristics Curves (Linear)

After the temperature increase, the on/off ratio does not show any obvious change, but the device's threshold voltage V_{th} shifts from -3.5V to -4V. This indicates that the channel barrier is reduced in a high-temperature environment, making the device easier to turn on. This phenomenon is mainly attributed to the fact that, at high temperatures, the valence band electrons in the semiconductor material acquire higher thermal excitation energy, which leads to an increased carrier concentration in the channel and, consequently, a lower threshold voltage. Moreover, by comparing the transfer curves at the two temperatures on a logarithmic scale (as shown in Figure 8), it is obvious that the saturation current at 600 K is significantly higher than at 300 K at the same gate voltage.

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$$I_{leak} \propto e^{-\frac{q\Phi_B}{k_B T}} \quad (3)$$

From (3), it is evident that at high temperatures, the enhanced thermal excitation of electrons accelerates the generation–recombination rate of carriers in the channel, thereby increasing the device's saturation current [12]. Meanwhile, the rise in the drain current over the same drain voltage range results in a decrease in the device's on-state resistance (R_{on}), which improves the conduction characteristics.

Overall, the simulation results show that the β-Ga_2O_3 MOSFET exhibits a lower threshold voltage, higher saturation current, and reduced on-state resistance at elevated temperatures, which is significant for the device's high-temperature stability. However, due to the low thermal conductivity of β-Ga_2O_3, further optimization of its thermal management is required to enhance the device's reliability and long-term operational stability.

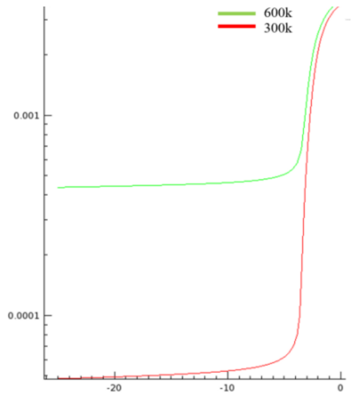

Figure 8: Temperature Characteristics Curves (logarithmic)

5. The Impact of Bulk Defects on MOSFET Devices

5.1. Impact of Bulk Defects on Transfer and Output Characteristics

To study the influence of bulk defects on the electrical characteristics of β-Ga_2O_3 MOSFET devices, this paper introduces bulk defects with different concentrations into the channel region and compares their effects on the transfer and output curves[13].

As shown in Figure 9, as the concentration of bulk defects increases, the drain current increases significantly, and the threshold voltage (V_{th}) gradually decreases. At a low defect concentration (N_t= 10^{14} cm^{-3}), the device exhibits a small off-current, and the threshold voltage remains essentially stable. However, when the defect concentration increases to 10^{17} cm^{-3}, the drain current increases markedly, and the threshold voltage shifts to more negative values, indicating that the device becomes easier to turn on.

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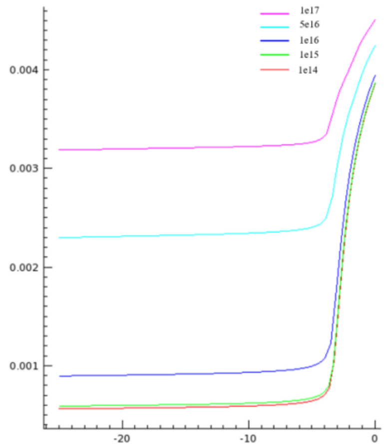

Figure 9: Transfer Curves Considering Bulk Defects

Since bulk defects can supply additional electrons, this leads to an increased carrier concentration in the channel and causes the threshold voltage to drift. This effect can be described using a trap charging model:

$$\Delta V_{th} = -\frac{qN_t d}{\varepsilon_{ox}} \tag{4}$$

Where Nt is the trap state density, d is the oxide thickness, and ε is the dielectric constant of the oxide.

As shown in Figure 10, under the same drain-source voltage V_d, the drain current I_d gradually increases with the increasing concentration of bulk defects. This phenomenon can be explained using the SRH recombination model:

$$R_{SRH} = \frac{np - n_i^2}{\tau_n(p + p_t) + \tau_p(n + n_t)} \tag{5}$$

Where n and p denote the electron and hole concentrations, respectively; n_i is the intrinsic carrier concentration; τ_n and τ_p represent the electron and hole lifetimes, respectively; and n_t is the trap state density.

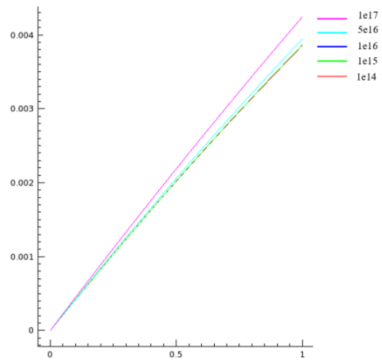

Figure 10: Output Curves Considering Bulk Defects

When the defect density is high, the SRH recombination rate decreases, resulting in an increase in the free carrier concentration, which leads to a significant rise in leakage current. Meanwhile, in the low V_d region, the current still exhibits a linear relationship, indicating that the MOSFET's channel control capability remains effective. However, the overall conduction current increases with the defect concentration, suggesting a decrease in the device's on-state resistance (R_{on}).

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5.2. Impact of Bulk Defects on Device Off-State Characteristics

With the β-Ga_2O_3 MOSFET initially set to the off-state, the study investigates how the current density distribution of the leakage current varies with the concentration of bulk defects. As shown in Figure 11, as the defect density gradually increases from 1×10^{14} cm^{-3} to 1×10^{17} cm^{-3}, the device's leakage current correspondingly rises, indicating a transition from the off-state toward the on-state. This phenomenon can be explained in terms of carrier concentration and band modulation [14].

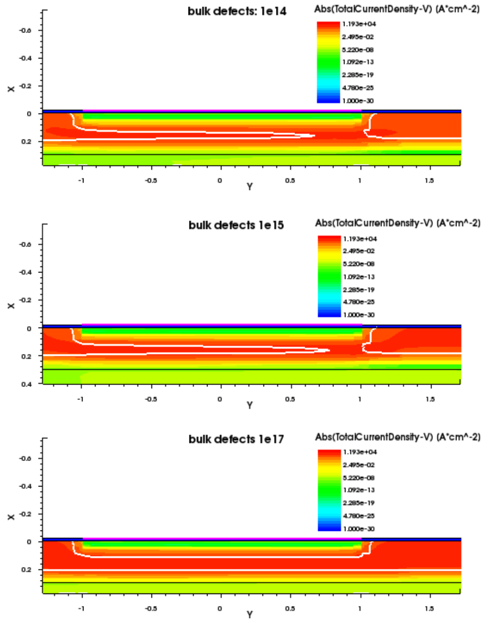

Figure 11: The current density distribution of different bulk defect

At a low defect density of 1×10^{14} cm^{-3}, the influence of bulk traps is minimal, and the channel can still effectively maintain a high barrier to prevent electrons from passing through; hence, the leakage current remains small and the device stays in the off-state. However, when the defect density increases to 1×10^{16} cm^{-3}, the device's leakage current begins to rise noticeably. This is because a high concentration of defects introduces more shallow donor states or additional carrier recombination centers, which increases the intrinsic carrier concentration in the channel region. As a result, the channel barrier is lowered, allowing a small number of electrons to leak through the barrier to the drain, thereby forming a higher leakage current.

When the defect density is further increased to 1×10^{17} cm^{-3}, the device's ability to remain off is almost completely lost, exhibiting a clear on-state. At this point, the large number of bulk defects provides extra carriers, significantly boosting the effective electron concentration in the channel and causing a self-doping effect. Consequently, the channel can no longer maintain the high barrier necessary for the off-state, and the device shows strong leakage current characteristics. The simulation images clearly illustrate this trend, with the current density gradually increasing with the defect concentration. Particularly at high defect densities, the current density distribution in the channel region approaches that of a normally on-state device, indicating that the device has lost its ability to turn off.

Overall, bulk defects have a significant impact on the off-state characteristics of β-Ga_2O_3 MOSFETs. High defect densities cause the device to transition from an off-state to an on-state. Therefore, in practical device design, it is essential to strictly control the quality of material growth and reduce the bulk defect concentration to ensure the reliability and low leakage current performance of MOSFETs under high-voltage off-state conditions.

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6. Conclusion

This paper presents a systematic simulation study of the static characteristics, thermal effects, and bulk defect impacts on β-Ga_2O_3 MOSFETs using Sentaurus TCAD software. The results reveal a V_{th} of −3.5 V and a BV of 100 V, demonstrating promising potential for power applications. However, thermal effects significantly degrade device stability, as evidenced by a pronounced leakage current increase and a negative threshold voltage shift with rising temperature (e.g., 300 K to 600 K). Furthermore, bulk defect concentration exceeding 1×10^{17} cm^{-3} induces an anomalous off-to-on state transition, characterized by drain current elevation and threshold voltage reduction, highlighting the critical role of defect engineering. While β-Ga_2O_3 MOSFETs exhibit advantages in ultra-wide bandgap and high critical breakdown electric field for high-power applications, challenges including low thermal conductivity (~27 W/m·K) and defect sensitivity necessitate further optimization. Future efforts should focus on improving crystal growth quality, developing advanced thermal management strategies, and suppressing bulk defects to enhance operational stability and long-term reliability.

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