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Normally-off β -Ga₂O₃ MOSFET with an Epitaxial Drift Layer

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Abstract: A normally-off β -Ga₂O₃ metal-oxide-semiconductor field-effect transistor (MOSFET) is proposed using a technology computer-aided design (TCAD) device simulation, which employs an epitaxial drift layer grown on an n -type low-doped body layer. The low-doped body layer under the MOS gate enabled normally-off operation, whereas the epitaxial drift layer determined the on-resistance and breakdown characteristics. The effects of the doping concentration of each layer and thickness of the drift channel layer on the device characteristics were investigated to design a device with a breakdown voltage of 1 kV. A threshold voltage of 1.5 V and a breakdown voltage of 1 kV were achieved by an n -type body layer with a doping concentration of $1 \times 10^{15} \text{ cm}^{-3}$ and an n -type drift layer with a doping concentration of $3 \times 10^{17} \text{ cm}^{-3}$, a thickness of 150 nm, and a gate-to-drain distance of 9.5 μm ; resulting in an on-resistance of $25 \text{ m}\Omega\cdot\text{cm}^2$.

Keywords: accumulation channel; β -Ga₂O₃; epitaxial drift layer; metal-oxide-semiconductor field-effect transistor; normally-off



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1. Introduction

Wide bandgap (WBG) semiconductors, such as GaN, SiC, and Ga₂O₃, have been intensively studied to overcome the limitations of Si technology [1–3] for the development of next-generation power switching devices. Ga₂O₃ has a wider energy bandgap (4.5–4.9 eV) than GaN and SiC, with a significantly higher critical electric field of approximately 6–8 MV/cm [2–5]. Among the various polymorphs, monoclinic β -Ga₂O₃ is the most stable polymorph [6–10]. Furthermore, Baliga's figure of merit (BFOM) of β -Ga₂O₃ is significantly higher than those of GaN and SiC, making it a promising material for high-power switching applications [10]. However, the absence of p -type doping technology for β -Ga₂O₃ is disadvantageous for the implementation of power switching devices [11–17]. Although several studies have reported the normally-off operation of β -Ga₂O₃ field-effect transistors (FET), the experimental results are still far off from the theoretical limits of the material [15–18].

Chabak et al., demonstrated enhancement-mode FETs using a wrap-gate fin structure in 2016 [15] and a gate recess process in 2018 [16]. In 2017, Wong et al., reported that the utilization of an unintentionally doped β -Ga₂O₃ channel in MOSFET was able to completely deplete the channel electrons at a gate voltage (V_{GS}) of 0 V, resulting in a positive threshold voltage [19]. In 2019, Singh et al., proposed a T-shaped recessed gate β -Ga₂O₃ MOSFET to achieve a normally-off operation [16]. The T-shaped recessed gate depleted the channel at a gate bias of 0 V, where the gate oxide (Al₂O₃) thickness was 20 nm, gate recess depth was 250 nm, and thickness of the active channel under the recess region was 30 nm [17]. The maximum drain current was 40 mA/mm at $V_{GS} = +8 \text{ V}$ due to the limited channel thickness required to achieve a positive threshold voltage [17].

In this study, we propose a recessed β -Ga₂O₃ MOSFET with an epitaxial drift layer on top of a low-doped body layer to overcome the trade-off relationship between the threshold voltage and on-current density. The proposed structure does not require precise control of recess depth. Moreover, the threshold voltage could be independently controlled

by the drift layer. The output and transfer characteristics of the proposed device were validated using Silvaco ATLAS technology computer-aided design (TCAD) simulation. After investigating the effects of doping concentration on the body layer and additional design parameters of the drift layer, a normally-off MOSFET structure was designed to achieve a breakdown voltage of 1 kV.

2. Simulation and Device Structure

Two-dimensional (2D) device simulations were performed in a Silvaco ATLAS TCAD environment using several physical models, including a drift-diffusion transport model, Fermi–Dirac statistics, concentration and temperature-dependent analytical mobility model, Shockley–Read–Hall recombination model, and an impact ionization model [20–26]. The material and physical model parameters used in the TCAD simulations are presented in Table 1. Although the simulation process could have been further optimized by employing more comprehensive models [27], the classical models provided by TCAD are sufficient to validate the proposed concept.

Table 1. Material and physical model parameters used for TCAD simulations [20–26,28,29].

Material Parameters	
Affinitivity	4.0 eV
Band gap (300 K)	4.8 eV
Permittivity	10.2
Mobility Model	
μ_{min}	20 cm ² /Vs
μ_{max}	155 cm ² /Vs
α	0
β	0
γ	0
δ	0.8
N_{ref}	1.0×10^{18} cm ^{−3}
T_L	300 K
Impact Ionization Model	
A_N	2.16×10^6 cm ^{−1}
B_N	1.77×10^7 V/cm
Shockley–Read–Hall Recombination Model	
τ_{n0}	1.2×10^{-8} s
τ_{p0}	1.2×10^{-8} s

2.1. Mobility Model

The mobility model used in the simulation included concentration and temperature-dependent relationships based on an analytical function of Caughey–Thomas’ work [25], which is given by:

$$\mu_{n0} = \mu_{min} \left(\frac{T_L}{300} \right)^\alpha + \frac{\mu_{max} \left(\frac{T_L}{300} \right)^\beta - \mu_{min} \left(\frac{T_L}{300} \right)^\beta}{1 + \left(\frac{T_L}{300} \right)^\gamma \left(\frac{N_D}{N_{ref}} \right)^\delta} \quad (1)$$

where α , β , γ , and δ are material-dependent coefficients [20], N_D is the impurity concentration, and T_L is the temperature in Kelvins. Using the experimental data [28,29], these parameters were determined to be $\alpha = 0$, $\beta = 0$, $\gamma = 0$, $\delta = 0.8$, $N_{ref} = 1.0 \times 10^{18}$ cm^{−3}, and $T_L = 300$ K.

2.2. Impact Ionization Model

Selberherr's model, which is a modification of Chynoweth's law, has been widely used to predict the breakdown characteristics of wide-bandgap semiconductors [20,21]. The impact ionization coefficient (α_n) is given by

$$\alpha_n = A_N \exp \left[-\frac{B_N}{E} \right] \quad (2)$$

where A_N and B_N are the material coefficients and E is the electric field. In this study, $A_N = 2.16 \times 10^6 \text{ cm}^{-1}$ and $B_N = 1.77 \times 10^7 \text{ V/cm}$ were used while considering the crystal direction of $\beta\text{-Ga}_2\text{O}_3$ in the [010] direction and a critical electric field of approximately 5 MV/cm [11,20,21].

2.3. Shockley–Read–Hall Recombination

In our simulations, the recombination rate was obtained using the Shockley–Read–Hall recombination model [26]:

$$R_{SRH} = \frac{pn - n_{ie}^2}{\tau_{p0} \left[n + n_{ie} e^{\left(\frac{E_{trap}}{kT_L} \right)} \right] + \tau_{n0} \left[p + n_{ie} e^{\left(\frac{-E_{trap}}{kT_L} \right)} \right]} \quad (3)$$

where n , p , and n_{ie} are the electron, hole, and intrinsic carrier concentrations, respectively, and k and T_L are the Boltzmann constant and lattice temperature, respectively. E_{trap} is the difference between the trap energy level and the intrinsic Fermi level, and τ_{n0} and τ_{p0} are the electron and hole lifetimes, respectively, which are used as $1.2 \times 10^{-8} \text{ s}$.

2.4. Device Structure

Figure 1 shows a cross-sectional schematic of the $\beta\text{-Ga}_2\text{O}_3$ MOSFET proposed in this study. The epitaxial structure consisted of a 20 nm thick ohmic contact layer with an n -type doping concentration of $1 \times 10^{20} \text{ cm}^{-3}$, an n -type drift layer, a 300 nm thick low-doped n -type body layer, and a 1 μm thick buffer layer with an n -type doping concentration of $1 \times 10^{12} \text{ cm}^{-3}$. In this study, a highly doped ohmic contact layer was employed instead of an ion-implantation process. The structural variables investigated in this study were the thickness (t_{DRIFT}) and doping concentration ($N_{\text{D,DRIFT}}$) of the drift layer and the doping concentration ($N_{\text{D,BODY}}$) of the body layer. A highly doped ohmic contact layer is etched between the source and drain contacts. The gate region was etched down to the body layer to achieve normally-off characteristics. A 20 nm-thick gate oxide (Al_2O_3) layer was used, and its interface charges were considered during the simulation.

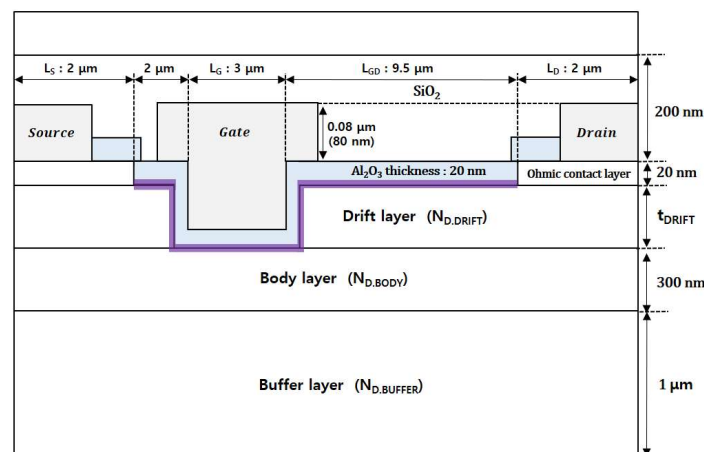


Figure 1. Cross-sectional schematic of recessed $\beta\text{-Ga}_2\text{O}_3$ MOSFET with a dual epitaxial structure.

Figure 2a,b show the electron density distributions at $V_{GS} = 0$ V and +3 V, respectively, which were simulated using the variables $N_{D,DRIFT} = 3 \times 10^{17} \text{ cm}^{-3}$, $t_{DRIFT} = 300 \text{ nm}$, and $N_{D,BODY} = 1 \times 10^{15} \text{ cm}^{-3}$. For $V_{GS} = 0$ V, the electrons in the region under the gate were completely depleted, which blocked the flow of current, confirming the normally-off characteristics. For $V_{GS} = +3$ V, the depletion region under the gate disappeared, creating an electron accumulation channel layer and allowing for current flow.

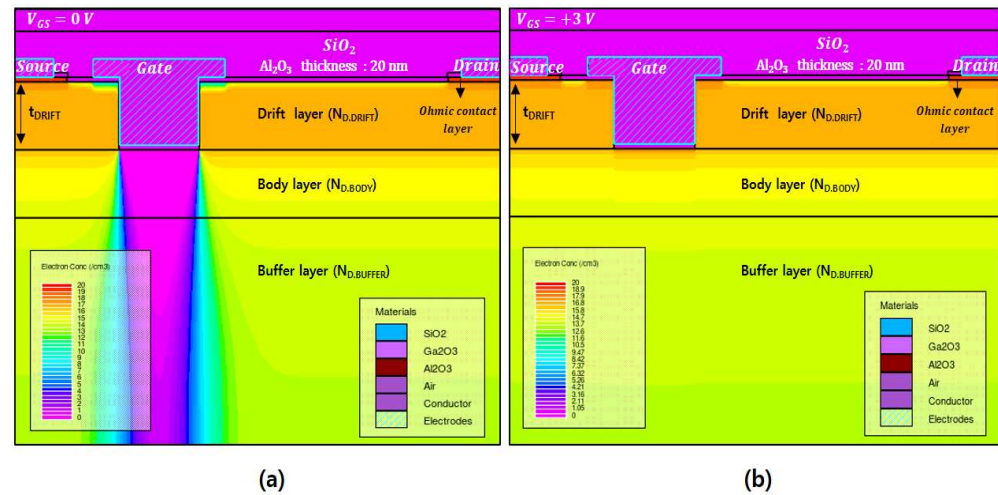


Figure 2. Electron density distributions simulated with a gate voltage of (a) $V_{GS} = 0$ V and (b) $V_{GS} = +3$ V.

3. Results and Discussions

3.1. Effects of $\text{Al}_2\text{O}_3/\beta\text{-Ga}_2\text{O}_3$ Interface Charge

Previous studies have reported the presence of negative interface charges at the $\text{Al}_2\text{O}_3/\beta\text{-Ga}_2\text{O}_3$ interface with a density in the range of 1×10^{12} to $4 \times 10^{12} \text{ cm}^{-2}$ [18,21,23,30,31]. In this section, the effects of charge density at the $\text{Al}_2\text{O}_3/\beta\text{-Ga}_2\text{O}_3$ interface are investigated, where the negative interface charge density varied from 0 to $2 \times 10^{12} \text{ cm}^{-2}$. The transfer characteristics simulated at a drain voltage (V_{DS}) of 5 V as a function of the interface charge density are shown in Figure 3. A positive shift in the threshold voltage was observed with a reduction in drain current density as the negative interface charge density increased. Therefore, based on these prior experimental reports [18,20], a negative interface charge density of $1 \times 10^{12} \text{ cm}^{-2}$ was selected for the simulations.

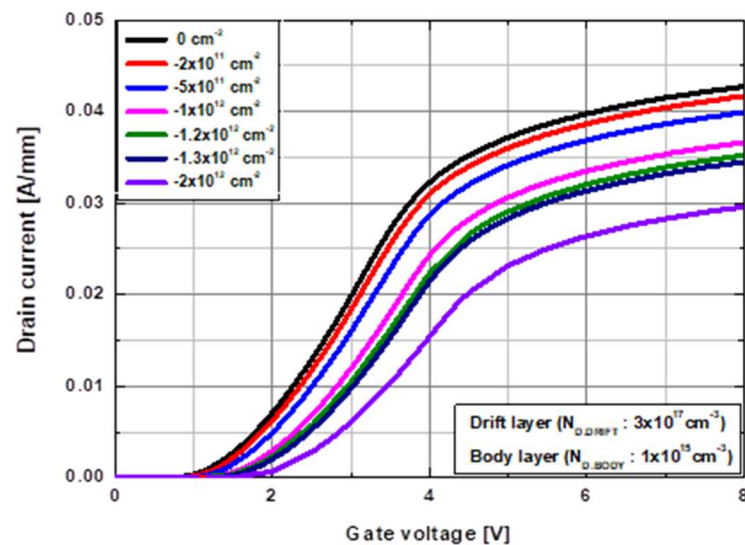


Figure 3. Shift in threshold voltage with different interface charge densities at the $\text{Al}_2\text{O}_3/\beta\text{-Ga}_2\text{O}_3$ interface.

3.2. Effects of Doping Concentrations in Body and Drift Layer

Initially, the effects of the doping concentration of the body layer ($N_{D,BODY}$) on the threshold voltage were investigated. $N_{D,BODY}$ varied from $1 \times 10^{13} \text{ cm}^{-3}$ to $1 \times 10^{17} \text{ cm}^{-3}$, while the drift layer had a thickness of $t_{DRIFT} = 300 \text{ nm}$ and a doping concentration of $N_{D,DRIFT} = 3 \times 10^{17} \text{ cm}^{-3}$. Figure 4a,b show the linear and logarithmic transfer characteristics at $V_{DS} = 5 \text{ V}$ as a function of $N_{D,BODY}$, respectively. A significant negative shift in the threshold voltage was observed when $N_{D,BODY}$ was equal to or greater than $1 \times 10^{16} \text{ cm}^{-3}$, resulting in normally-on characteristics, whereas only a negligible difference was observed when $N_{D,BODY}$ was equal to or less than $1 \times 10^{15} \text{ cm}^{-3}$. Therefore, to design a normally-off device, $N_{D,BODY} = 1 \times 10^{15} \text{ cm}^{-3}$ was selected for the simulations.

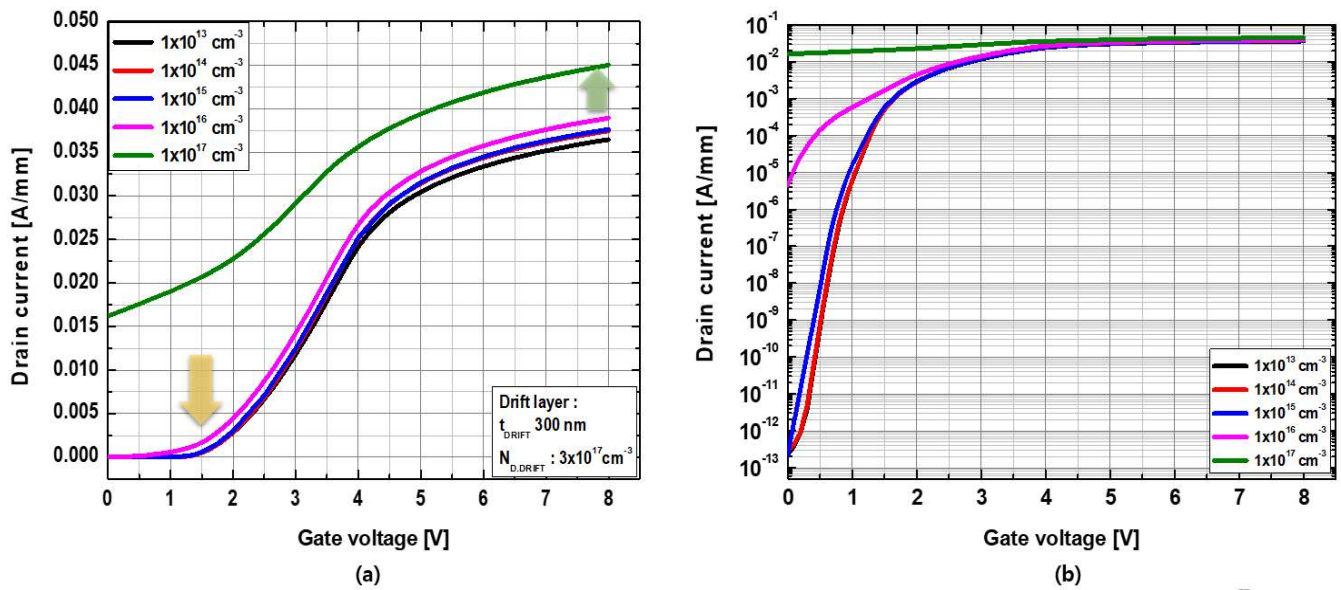


Figure 4. (a) Linear and (b) logarithmic transfer characteristics at $V_{DS} = +5 \text{ V}$ as a function of the doping concentration of the body layer.

Additionally, the effects of the doping concentration of the drift layer ($N_{D,DRIFT}$) on the drain current density were investigated, where $N_{D,DRIFT}$ varied from $1 \times 10^{17} \text{ cm}^{-3}$ to $9 \times 10^{17} \text{ cm}^{-3}$ with a fixed body doping concentration of $N_{D,BODY} = 1 \times 10^{15} \text{ cm}^{-3}$. The drift layer thickness was $t_{DRIFT} = 300 \text{ nm}$. The transfer characteristics as a function of $N_{D,DRIFT}$ are shown in Figure 5a,b. It is evident that the drain current density increases with an increase in $N_{D,DRIFT}$, whereas the threshold voltage remains the same because it is determined by the recessed MOS region on the body layer. The normally-off characteristics were maintained even at $N_{D,DRIFT} = 9 \times 10^{17} \text{ cm}^{-3}$. The threshold voltage was 0.8 V at $1 \mu\text{A/mm}$ and 1.5 V at 1 mA/mm . Figure 5c shows the conduction band energy diagrams as a function of $N_{D,DRIFT}$ along the vertical direction below the gate metal, and it is obvious that increasing $N_{D,DRIFT}$ does not change the conduction band energy such that the threshold voltage remains the same regardless of $N_{D,DRIFT}$. On the other hand, Figure 5d shows the conduction band energy diagrams as a function of $N_{D,DRIFT}$ along the vertical direction in the region between the gate and drain. It can be seen that the depletion width in the $\beta\text{-Ga}_2\text{O}_3$ drift layer is reduced when increasing the $N_{D,DRIFT}$, leading to a higher drain current.

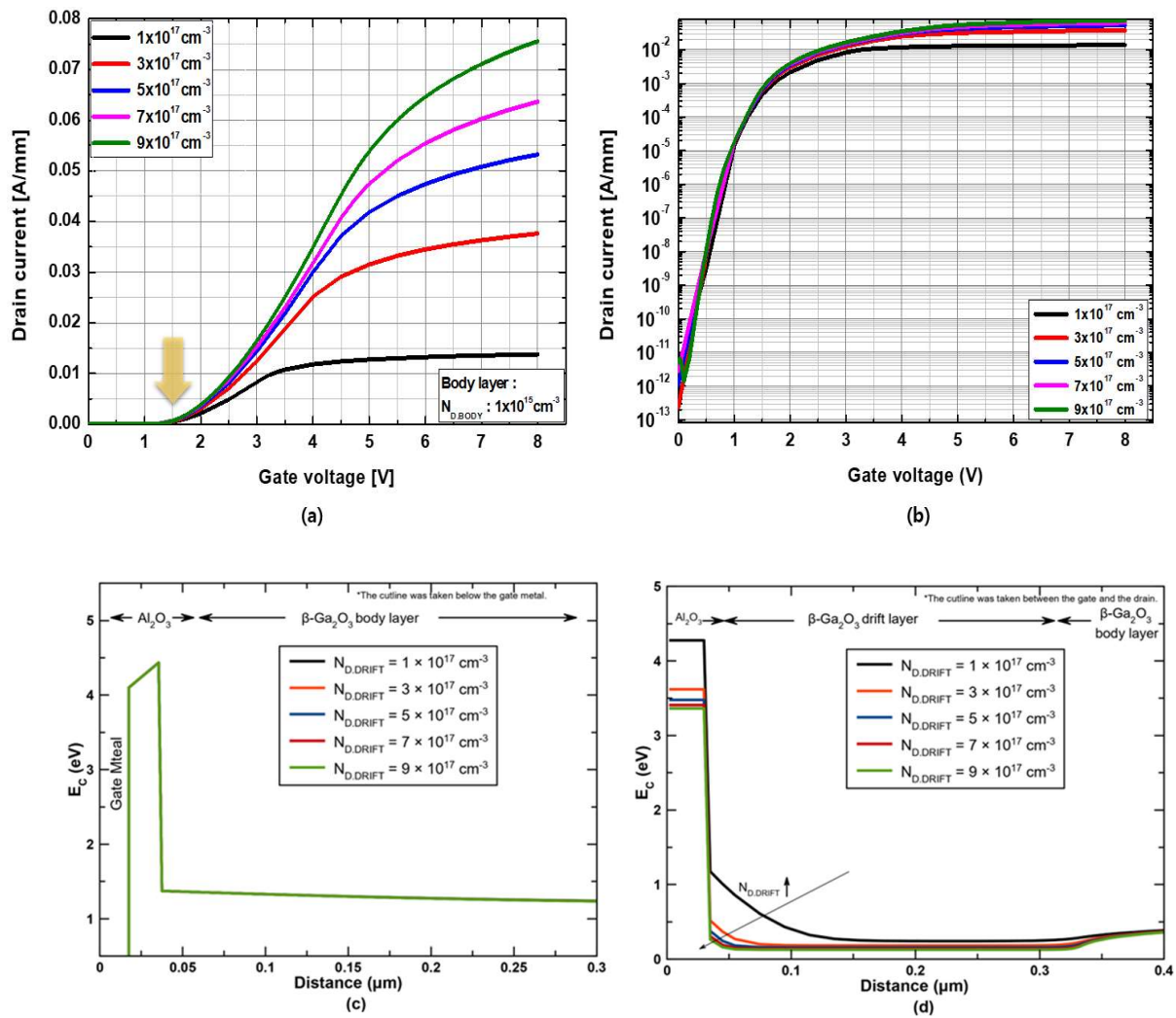


Figure 5. (a) Linear and (b) logarithmic transfer characteristics at $V_{DS} = +5 \text{ V}$ as a function of the doping concentration of the drift channel layer. Conduction band energy diagrams as a function of $N_{D,DRIFT}$ along the vertical direction (c) under the gate metal and (d) in the region between the gate and drain at zero gate bias condition.

3.3. Effects of Drift Layer Thickness

3.3.1. Transfer and Output Characteristics

To investigate the effects of the thickness of the drift layer (t_{DRIFT}), the doping concentrations of the body and drift channel layers were fixed as $N_{D,BODY} = 1 \times 10^{15} \text{ cm}^{-3}$ and $N_{D,DRIFT} = 3 \times 10^{17} \text{ cm}^{-3}$, respectively. The t_{DRIFT} was varied to 75, 150, and 300 nm. As shown in Figure 6, the drain on-current density decreased with a decrease in t_{DRIFT} , while the threshold voltage remained constant as the series resistance of the drift layer increased with a decrease in the thickness. The output current–voltage characteristics are compared in Figure 7. The maximum drain current density ($I_{D,MAX}$) and on-resistance (R_{ON}) for the thicknesses of $t_{DRIFT} = 300, 150,$ and 75 nm were $I_{D,MAX} = 190, 136,$ and 80 mA/mm , respectively, and $R_{ON} = 12.7, 25,$ and $61.7 \text{ m}\Omega \text{ cm}^2$, respectively.

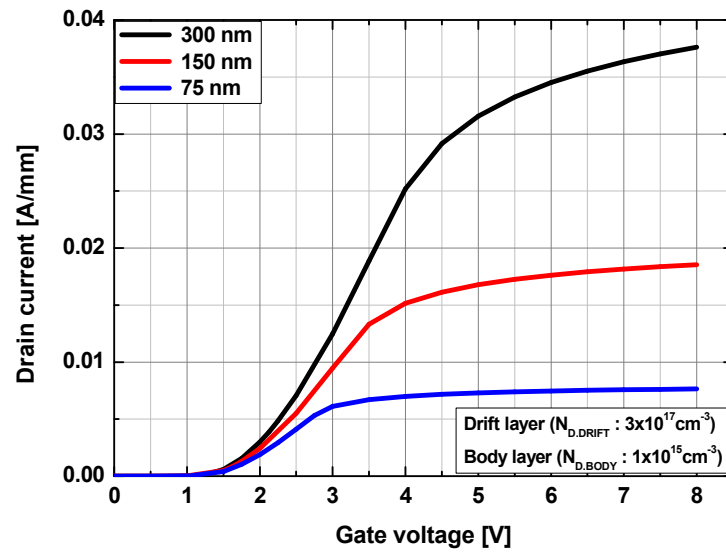


Figure 6. Transfer characteristics at $V_{DS} = +5$ V as a function of the thickness of the drift channel layer. The drift channel layer has a doping concentration of $3 \times 10^{17} \text{ cm}^{-3}$.

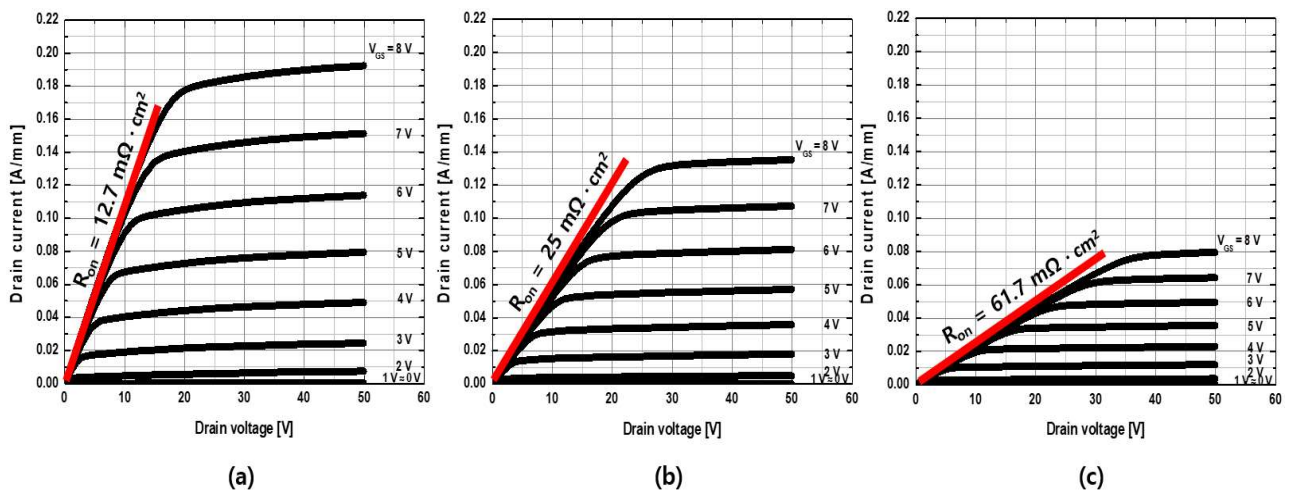


Figure 7. Output current–voltage characteristics for a drift channel layer thickness of (a) 300 nm, (b) 150 nm, and (c) 75 nm. The drift channel layer has a doping concentration of $3 \times 10^{17} \text{ cm}^{-3}$.

3.3.2. Breakdown Characteristics

Breakdown characteristics with different drift layer thicknesses were simulated at $V_{GS} = 0$ V, and the results are compared in Figure 8. The catastrophic breakdown voltages were 680, 1012, and 1380 V for the thickness values of $t_{DRIFT} = 300, 150,$ and 75 nm, respectively. With the same doping concentration of the drift layer, the breakdown voltage exhibited a significant dependence on t_{DRIFT} . The electron density and electric field distributions for different t_{DRIFT} values were examined to investigate the reasons for this. Figures 9 and 10 show the electron density and electric field distributions simulated at $V_{DS} = 600$ V for different t_{DRIFT} values, and the electron concentration and electric field distributions along the cutline from a to a' are plotted in Figures 9d and 10d, respectively. As shown in Figures 9d and 10d, the depletion region extended towards the drain side with decreasing thickness, resulting in a lower peak electric field near the gate. This is because the total number of electrons depleted by a given gate voltage is the same for all cases. Therefore, the thinner drift layer had a longer depletion edge. Consequently, a higher breakdown voltage can be achieved with a thinner drift layer. The tradeoff relationship between R_{on} and the breakdown voltage as a function of the drift layer thickness is shown in Figure 11.

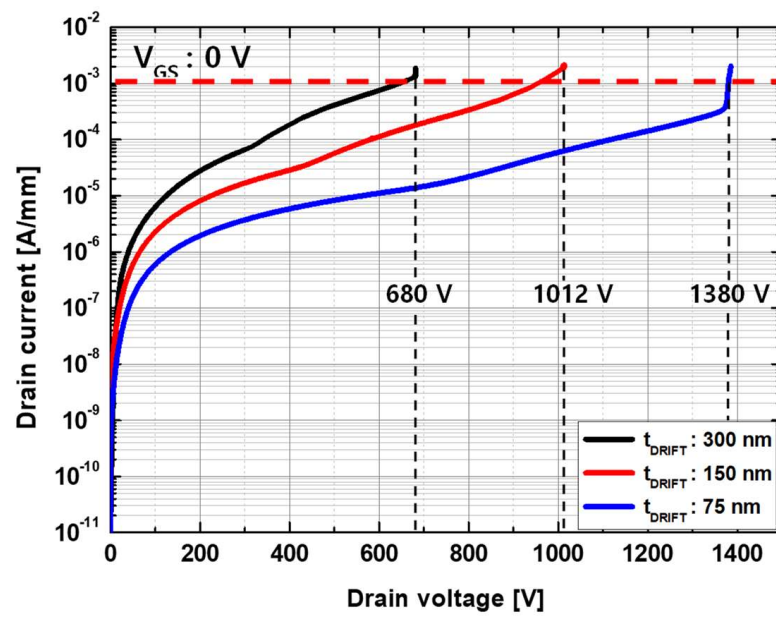


Figure 8. Breakdown voltage characteristics simulated at $V_{GS} = 0$ V as a function of the drift channel layer thickness. The drift channel layer has a doping concentration of $3 \times 10^{17} \text{ cm}^{-3}$.

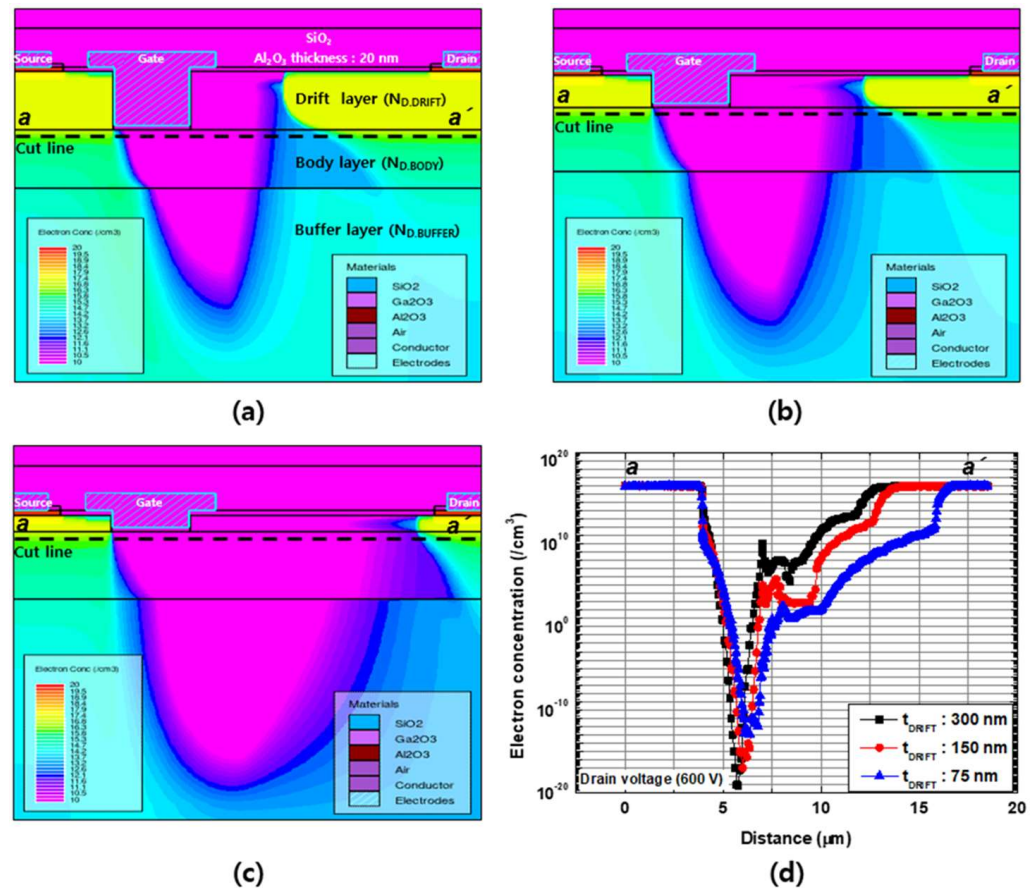


Figure 9. Electron density distributions simulated with $V_{GS} = 0$ V and $V_{DS} = + 600$ V for a drift channel layer thicknesses of (a) 300 nm, (b) 150 nm, and (c) 75 nm. (d) Electron density distribution along the cutline between a and a'.

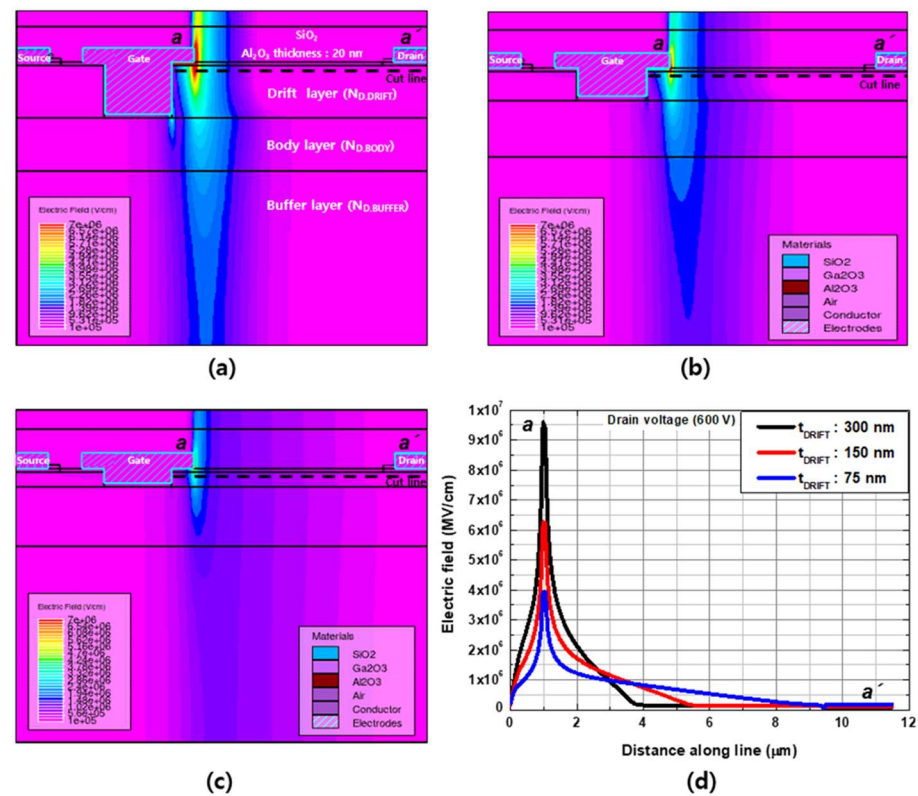


Figure 10. Electric field distributions simulated with $V_{GS} = 0$ V and $V_{DS} = +600$ V for a drift channel layer thicknesses of (a) 300 nm, (b) 150 nm, and (c) 75 nm. (d) Electric field distribution along the cutline between a and a'.

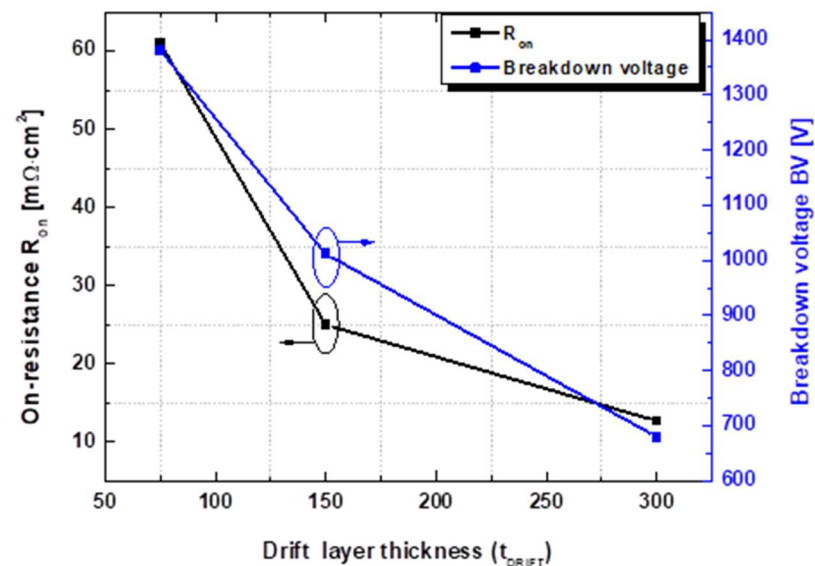


Figure 11. On-resistance and breakdown voltage characteristics as a function of drift layer thickness. The drift layer has a doping concentration of $3 \times 10^{17} \text{ cm}^{-3}$.

In summary, using a body layer with a doping concentration of $1 \times 10^{15} \text{ cm}^{-3}$ and a drift layer with a doping concentration of $3 \times 10^{17} \text{ cm}^{-3}$, a thickness of 150 nm, and a gate-to-drain distance of 9.5 μm resulted in a threshold voltage of 0.8 V at 1 $\mu\text{A}/\text{mm}$, a breakdown voltage of ~ 1 kV, and an on-resistance of 25 $m\Omega \cdot \text{cm}^2$.

4. Conclusions

A normally-off β -Ga₂O₃ MOSFET structure was proposed, which employed an epitaxial drift layer in conjunction with a recessed MOS gate. A positive threshold voltage was achieved by employing a low-doped *n*-type body layer, which led to the formation of an electron-accumulation channel layer. An additional drift layer grown on top of the body layer is crucial for determining the on-resistance and breakdown voltage characteristics. The proposed dual epitaxial structure enables normally-off operation without employing an ion implantation process. Considering the difficulty of *p*-type ion implantation or epitaxial growth with β -Ga₂O₃, the proposed structure is a promising candidate for the implementation of a normally-off β -Ga₂O₃ FET.

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Conflicts of Interest: The authors declare no conflict of interest.

References

- Lee, I.; Kumar, A.; Zeng, K.; Singiseti, U.; Yao, X. Mixed-mode circuit simulation to characterize Ga₂O₃ MOSFETs in different device structures. In Proceedings of the IEEE 5th Workshop on Wide Bandgap Power Devices and Applications (WiPDA), Albuquerque, NM, USA, 30 October–1 November 2017. [\[CrossRef\]](#)
- Kim, K.H.; Choa, S.H. Recent overview on power semiconductor devices and package module technology. *J. Microelectron. Packag. Soc.* **2019**, *26*, 15–22. [\[CrossRef\]](#)
- Ly, Y.; Zhou, X.; Long, S.; Liang, S.; Song, X.; Zhou, X.; Dong, H.; Wang, Y.; Feng, Z.; Cai, S. Lateral source field-plated β -Ga₂O₃ MOSFET with recorded breakdown voltage of 2360 V and low specific on-resistance of 560 m Ω cm². *Semicond. Sci. Technol.* **2019**, *34*, 11LT02. [\[CrossRef\]](#)
- Kim, H.S.; Mingi, J.; Cha, H.Y. Schottky barrier diode fabricated on single crystal β -Ga₂O₃ semiconductor. *J. Inst. Electron. Inf. Eng.* **2017**, *54*, 21–25. [\[CrossRef\]](#)
- Chabak, K.; Walker, D.E.; Green, A.J. Sub-Micron Gallium Oxide Radio Frequency Field-Effect Transistors. In Proceedings of the IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), Ann Arbor, MI, USA, 16–18 July 2018. [\[CrossRef\]](#)
- Singh, R.; Lenka, T.R.; Panda, D.K.; Velpula, R.T.; Jain, B.; Bui, H.Q.T.; Nguyen, H.P.T. The dawn of Ga₂O₃ HEMTs for high power electronics—A review. *Mater. Sci. Semicond. Process* **2020**, *119*, 105216. [\[CrossRef\]](#)
- Mun, J.K.; Cho, K.; Chang, W.; Jung, H.W.; Do, J. 2.32 kV breakdown voltage lateral β -Ga₂O₃ MOSFETs with source-connected field plate. *ECS J. Solid State Sci. Technol.* **2019**, *8*, Q3079. [\[CrossRef\]](#)
- Roberts, J.W.; Chalker, P.R.; Ding, B.; Oliver, R.A.; Gibbon, J.T.; Jones, L.A.H.; Dhanak, V.R.; Philips, L.J.; Major, J.D.; Massabuau, F.C.P. Low temperature growth and optical properties of α -Ga₂O₃ deposited on sapphire by plasma enhanced atomic layer deposition. *J. Cryst. Growth* **2019**, *528*, 125254. [\[CrossRef\]](#)
- Ren, F.; Yang, J.C.; Fares, C.; Pearton, S.J. Device processing and junction formation needs for ultra-high power Ga₂O₃ electronics. *MRS Commun.* **2019**, *9*, 77. [\[CrossRef\]](#)
- Xue, H.; He, Q.; Jian, G.; Long, S.; Pang, T.; Liu, M. An overview of the ultrawide bandgap Ga₂O₃ semiconductor-based schottky barrier diode for power electronics application. *Nanoscale Res. Lett.* **2018**, *13*, 290. [\[CrossRef\]](#)
- Ghosh, K.; Singiseti, U. Impact ionization in β -Ga₂O₃. *J. Appl. Phys.* **2018**, *124*, 085707. [\[CrossRef\]](#)
- Labad, M.; Swngouga, N.; Meftah, A.; Labad, M.; Kyoung, S.; Kim, H.; Rim, Y.S. Leakage Current Modelling and Optimization of β -Ga₂O₃ Schottky Barrier Diode with Ni Contact under High Reverse Voltage. *ECS J. Solid State Sci. Technol.* **2020**, *9*, 125001. [\[CrossRef\]](#)
- Krytsos, A.; Matsubara, M.; Bellotti, E. On the feasibility of p-type Ga₂O₃. *Appl. Phys. Lett.* **2018**, *112*, 032108. [\[CrossRef\]](#)
- Ly, Y.; Mo, J.; Song, X.; He, Z.; Wang, Y.; Tan, X.; Zhou, X.; Gu, G.; Guo, H.; Feng, Z. Influence of gate recess on the electronic characteristics of β -Ga₂O₃ MOSFETs. *Superlattices Microstruct.* **2018**, *117*, 132–136. [\[CrossRef\]](#)
- Chabak, K.D.; Moser, N.; Green, A.J.; Walker, D.E., Jr.; Tetlak, S.E.; Heller, E.; Crespo, A.; Fitch, R.; McCandless, J.P.; Leedy, K.; et al. Enhancement-mode Ga₂O₃ wrap-gate fin field-effect transistors on native (100) β -Ga₂O₃ substrate with high breakdown voltage. *Appl. Phys. Lett.* **2016**, *109*, 213501. [\[CrossRef\]](#)
- Chabak, K.D.; McCandless, J.P.; Moser, N.A. Recessed-gate enhancement-mode β -Ga₂O₃ MOSFETs. *IEEE Electron Device Lett.* **2018**, *39*, 67–70. [\[CrossRef\]](#)

17. Singh, R.; Lenka, T.R.; Velpula, R.T.; Thang, B.H.Q.; Nguyen, H.P.T. Investigation of E-mode beta-gallium oxide MOSFET for emerging nanoelectronics. In Proceedings of the IEEE 14th Nanotechnology Materials and Devices Conference, Stockholm, Sweden, 27–30 October 2019; Volume 27–30. [\[CrossRef\]](#)
18. Lv, Y.; Liu, H.; Zhou, X.; Wang, Y.; Song, X.; Cai, Y.; Yan, Q.; Wang, C.; Liang, S.; Zhang, J.; et al. Lateral β -Ga₂O₃ MOSFETs With High-Power Figure of Merit of 277 MW/cm². *IEEE Electron Device Lett.* **2020**, *41*, 537. [\[CrossRef\]](#)
19. Wong, M.H.; Nakata, Y.; Kuramata, A.; Yamakoshi, S.; Higashiwaki, M. Enhancement-mode Ga₂O₃ MOSFETs with Si-ion-implanted source and drain. *Appl. Phys. Express* **2017**, *10*, 041101. [\[CrossRef\]](#)
20. Park, J.; Hong, S.M. Simulation study of enhancement mode multi-gate vertical gallium oxide MOSFETs. *ECS J. Solid State Sci. Technol.* **2019**, *8*, Q31116. [\[CrossRef\]](#)
21. Huang, X.; Liao, F.; Li, L.; Liang, X.; Liu, Q.; Zhang, C.; Hu, X. 3.4 kV breakdown voltage Ga₂O₃ trench Schottky diode with optimized trench corner radius. *ECS J. Solid State Sci. Technol.* **2020**, *9*, 045012. [\[CrossRef\]](#)
22. Choi, J.H.; Cho, C.-H.; Cha, H.-Y. Design consideration of high voltage Ga₂O₃ vertical Schottky barrier diode with field plate. *Results Phys.* **2018**, *9*, 1170. [\[CrossRef\]](#)
23. Madadi, D.; Orouji, A.A. Investigation of Short Channel Effects in SOI MOSFET with 20 nm Channel Length by a β -Ga₂O₃ Layer. *ECS J. Solid State Sci. Technol.* **2020**, *9*, 045002. [\[CrossRef\]](#)
24. *Silvaco Atlas User's Manual Device Simulation Software*; SILVACO International: Santa Clara, CA, USA, 2012; 169p.
25. Caughey, D.; Thomas, R. Carrier mobilities in silicon empirically related to doping and field. *Proc. IEEE* **1967**, *55*, 2192–2193. [\[CrossRef\]](#)
26. Shockley, W.; Read, W.T. Statistics of the Recombinations of Holes and Electrons. *Phys. Rev.* **1952**, *87*, 835. [\[CrossRef\]](#)
27. Khodadadiana, A.; Parvizia, M.; Heitzinger, C. An adaptive multilevel Monte Carlo algorithm for the stochastic drift-diffusion-Poisson system. *Comput. Methods Appl. Mech. Eng.* **2020**, *368*, 113163. [\[CrossRef\]](#)
28. Poncé, S.; Li, W.; Reichardt, S.; Giustino, F. First-principles calculations of charge carrier mobility and conductivity in bulk semiconductors and two-dimensional materials. *Rep. Prog. Phys.* **2020**, *83*, 036501. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Parisini, A.; Fornari, R. Analysis of the scattering mechanisms controlling electron mobility in β -Ga₂O₃ crystals. *Semicond. Sci. Technol.* **2016**, *31*, 035023. [\[CrossRef\]](#)
30. Tetzner, K.; Treidel, E.B.; Hilt, O.; Popp, A.; Anooz, S.B.; Wagner, G.; Thies, A.; Ickert, K.; Gargouri, H.; Wurfl, J. Lateral 1.8 kV β -Ga₂O₃ MOSFET with 155 MW/cm² power figure of merit. *IEEE Electron Device Lett.* **2019**, *40*, 1503. [\[CrossRef\]](#)
31. Hung, T.-H.; Sasaki, K.; Kuramata, A.; Nath, D.N.; Park, P.S.; Polchinski, C.; Rajan, S. Energy band line-up of atomic layer deposited Al₂O₃ on β -Ga₂O₃. *Appl. Phys. Lett.* **2014**, *104*, 162106. [\[CrossRef\]](#)