Asymmetric Double-Gate $\beta$-Ga$_2$O$_3$ Nanomembrane Field-Effect Transistor for Energy-Efficient Power Devices

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The ultra-wide bandgap and cost-effective melt-growth of $\beta$-Ga$_2$O$_3$ ensure its advantages over other wide bandgap materials, and competitive electrical performance has been demonstrated in various device structures. In this paper, an asymmetric double-gate (ADG) $\beta$-Ga$_2$O$_3$ nanomembrane field-effect transistor (FET) comprised of a bottom-gate (BG) metal-oxide field-effect transistor and a top-gate (TG) metal-semiconductor field-effect transistor (MESFET) is demonstrated. Schottky contact properties are validated by characterizing the lateral Schottky barrier diode (SBD), which exhibits high rectification ratio and low ideality factor. The top-gate $\beta$-Ga$_2$O$_3$ MESFET shows reasonable electrical performance with a high breakdown voltage, as anticipated by three terminal off-state breakdown measurement. These properties are further enhanced by double-gate operation, and superior device performance is demonstrated; positive-shifted threshold voltage and reduced subthreshold slope enable the asymmetric double-gate $\beta$-Ga$_2$O$_3$ FET to operate at low power, and almost twice as much transconductance is demonstrated for high-frequency operation. These results show the great potential of asymmetric double-gate $\beta$-Ga$_2$O$_3$ FETs for energy-efficient high-voltage and -frequency devices with optimal material and structure co-designs.

1. Introduction

Beta-gallium oxide ($\beta$-Ga$_2$O$_3$) has attracted great attention in recent years due to its superior electrical properties for next generation power electronics; ultra-wide bandgap estimated to be about 4.6–4.9 eV allows high-temperature and high-voltage operation with an estimated large breakdown field ($E_{br}$) of up to 8 MV cm$^{-1}$.[1–3] Therefore, $\beta$-Ga$_2$O$_3$ possesses high Baliga’s figure-of-merit (FOM) used for evaluating applicability of a material to power device performance, and the estimated FOM is several times higher than that of current viable solutions such as silicon carbide (SiC) and gallium nitride (GaN).[4,5] In addition, cost-effective high-quality $\beta$-Ga$_2$O$_3$ wafer from bulk single crystal obtained from melt-growth methods provides a significant advantage over other wideband gap materials because SiC and GaN wafers require expensive high temperature vacuum synthesis.[6–9] Furthermore, $\beta$-Ga$_2$O$_3$ exhibits a comparable Johnson FOM intended for high-frequency operation in spite of its relatively lower saturation velocity.[10,11]

Aforementioned unique properties of $\beta$-Ga$_2$O$_3$ have facilitated intensive research efforts for high-power and radio-frequency (RF) electronics, and various device structures have been demonstrated as a building block such as Schottky barrier diode (SBD), metal-oxide field-effect transistors (MOSFET), metal-semiconductor field-effect transistors (MESFET), and even heterostructures with low dimensional materials.[12–16] In particular, $\beta$-Ga$_2$O$_3$ MOSFET not only eliminates problems with oxide reliability and interface traps but also provides better size scaling, and thus $\beta$-Ga$_2$O$_3$ MESFET is a promising structure for the applications.[6,17] On the other hand, back- and top-gate modulation of $\beta$-Ga$_2$O$_3$ MOSFET is reported, showing that the electrical characteristics can be beneficially tuned.[18]

In this work, we fabricate asymmetric double-gate (DG) $\beta$-Ga$_2$O$_3$ nanomembrane FET having bottom-gate (BG) MOSFET and top-gate (TG) MESFET. Specifically, a high crystal quality $\beta$-Ga$_2$O$_3$(100) channel is obtained from a bulk $\beta$-Ga$_2$O$_3$ crystal substrate using a mechanical exfoliation method. The asymmetric DG $\beta$-Ga$_2$O$_3$ FET is comprised of a lateral Schottky barrier diode, BG-MOSFET, and TG-MESFET, which are characterized separately to validate and compare their electrical performance. Benefiting from performance modulations of the individual devices, high performance asymmetric DG $\beta$-Ga$_2$O$_3$ FET is achieved for energy-efficient high voltage and frequency devices. Moreover, detailed analysis has been conducted to assess the modulation of electrical properties as well as enhanced performance based on energy band model and TCAD simulations.
between gate and drain ($L_{GD}$) are 13.7 and 3.7 µm, respectively, and the channel thickness of ≈300 nm is confirmed. A cross-sectional high resolution transmission electron microscopy (HR-TEM) images of β-Ga2O3/SiO2 in Figure 1c show the smooth interface between β-Ga2O3 and SiO2, indicating that clear transfer onto SiO2 is achieved without faults and the exfoliated flake preserves high crystal quality of bulk crystal with no damage or strain. The calculated angle ($\beta = 103.5^\circ$) confirms [100] and [001] direction. This facile and clean cleavage along the [100] direction can be achieved due to a monoclinic crystal structure having a much larger lattice constant in the [100] direction. Figure 1d shows the selected-area electron diffraction pattern revealing the lattice constants and directions of the β-Ga2O3 flake by calculating d-spacing; the β-Ga2O3(100) crystal plane on the channel surface is confirmed. Although the mechanical exfoliation method is not a scalable approach, it preserves high crystal quality of β-Ga2O3 and allows to investigate electrical performance in various device structures. Schottky contact properties of the TG metal (Ni/Au) on β-Ga2O3(100) channel is studied by characterizing a lateral Schottky barrier diode (SBD); Figure 2a shows its semi-logarithmic $I$–$V$ characteristics with a schematic diagram. The Schottky contact between Ni and β-Ga2O3 is associated with work function difference (Nickel: 5.04–5.35 eV, β-Ga2O3: 4.11 eV). The ohmic contact (D) is grounded as a cathode, and a sweeping bias is applied to the TG as an anode.
contact behaviors under different configurations are shown in Figure S1, Supporting Information. The SBD exhibits high rectification ratio of ~10⁶, and additional parameters are extracted using $I = I_s \left( \exp \left( \frac{qV}{nkT} \right) - 1 \right)$, where $q$ is the electronic charge, $V$ is the forward bias, $n$ is ideality factor, $k$ is the Boltzman constant, $T$ is the absolute temperature. The built-in potential ($V_b$) of ~0.9 V and ideality factor ($n$) of ~1.2 are extracted from a linear extrapolation method. The Schottky barrier height ($\phi_b$) of 1.2 eV is also calculated from $\phi_b = \frac{kT}{q} \ln \left( \frac{AA^*T^4}{I_s} \right)$, where $A$ is the area, and $A^*$, the Richardson constant is 41.1 A cm⁻² K⁻² at room temperature. The corresponding energy band diagram of Ni/β-Ga₂O₃ (100) Schottky contact is established in Figure 2b. Figure 3a shows hysteretic transfer curves ($I_{DS}$–$V_{GS}$) of the fabricated BG β-Ga₂O₃ MOSFET with floating TG and output curves ($I_{DS}$–$V_{DD}$) with good current saturation as well as ohmic contact behavior at low $V_{DS}$ region in the inset. Threshold voltage ($V_{TH}$) of ~57.7 V is calculated using a linear extrapolation method in a linear regime (at $V_{DS} = 1$ V) and the amount of hysteresis ($\Delta V$) is 2.0 V. Maximum transconductance ($g_m$) of 0.05 mS mm⁻¹ and subthreshold slope (SS) of 470 mV per dec are extracted using $SS = \frac{\partial V_{TH}}{\partial \log(I_{DS})}$ and $g_m = \frac{\partial I_{DS}}{\partial V_{GS}}$, respectively. Moreover, the field-effect mobility ($\mu_{FE}$) is ~102 cm²V⁻¹s⁻¹ which is extracted using $\mu_{FE} = \left( \frac{L}{W} \right) \left( \frac{g_{max}}{C_{BOX} \cdot V_{DS}} \right)$ where $L$ is channel length, $W$ is channel width, $d$ is channel thickness, $g_{max}$ is maximum transconductance, and $C_{BOX}$ is SiO₂ capacitance. It is noted that positive $V_{TH}$ shift of 25.6 V and enhanced $g_m$ of 1.6 times were observed after depositing the TG metal (Ni/Au) on the β-Ga₂O₃ channel while SS was degraded from 180 to 470 mV per dec as shown in Figure S2, Supporting Information. Depleted region on the β-Ga₂O₃ surface induced by the Schottky contact makes the effective channel thickness thinner, resulting in positive $V_{TH}$ shift. Figure 3b shows the evolution of $g_m$–$V_{GS}$ characteristics at $V_{DS} = 1$ V by applying opposite $V_{TG}$ from ~2 to ~10 V with 2 V step. The max. $g_m$ can be enhanced gradually through the TG bias effect. More details will be discussed in the following based on energy band diagram model and physics-based TCAD Sentaurus simulation.

Similarly, we characterized the fabricated BG β-Ga₂O₃ MESFET. Figure 3c shows the transfer curves ($I_{DS}$–$V_{GS}$) with negligible hysteretic behavior ($\Delta V = 0.02$ V) with floating BG, and output curves ($I_{DS}$–$V_{DD}$) with good current saturation in the inset of Figure 3c. Positively shifted $V_{TH}$ of ~13.2 V, reduced SS of 130 mV per dec and significantly enhanced max. $g_m$ (0.68 mS mm⁻¹) were obtained in comparison to the BG β-Ga₂O₃ MOSFET. The nearly zero $\Delta V$ implies that interface traps between Ni and β-Ga₂O₃ are successfully eliminated. The evolution of $g_m$–$V_{GS}$ curve at $V_{DS} = 1$ V by applying $V_{BG}$ from ~40 to ~10 V with 10 V step is shown in Figure 3d, and max. $g_m$ of TG-MESFET can be further enhanced by the BG bias effect. The $\mu_{FE}$ is ~153 cm²V⁻¹s⁻¹, and this is extracted using $\mu_{FE} = \frac{1}{\epsilon_s C_{BOX}}$ in the equation, where $C_s = \epsilon_s / d$, $\epsilon_s$ is a dielectric constant of β-Ga₂O₃, and $d$ is the channel thickness. Although the Schottky contact TG would leave only limited margin to the gate-bias, the electrical performance as summarized in Table 1 is significantly better compared with β-Ga₂O₃ MOSFET structure.
Energy band diagram model is proposed and related TCAD simulations are performed to describe the observed $V_{TH}$ shift and improved $g_m$. Figure 4a shows the energy band diagram after the TG (Ni/Au) metal contact deposition. For the BG MOSFET shown in Figure 4b, applied negative $V_{TG}$ bias expands the depletion width induced by Ni Schottky contact further into the $\beta$-Ga$_2$O$_3$ channel and thus reduces effective channel thickness. Corresponding carrier density distribution underneath the TG region is presented in Figure 4d. On the other hand, Figure 4c depicts energy band of $\beta$-Ga$_2$O$_3$ MESFET showing upward band bending at SiO$_2$/ $\beta$-Ga$_2$O$_3$ interface under negative $V_{BG}$ bias, and the corresponding carrier distribution is also shown in Figure 4e. As compared in Figure 4f, therefore, the MESFET has thinner effective channel thickness with higher peak carrier density.

To evaluate the potential of the fabricated $\beta$-Ga$_2$O$_3$ MESFET for power device application, we performed three terminal off-state breakdown measurements. Figure 5a shows a measured result under off-state gate bias ($V_{GS} = -15$ V) from the TG-MESFET operation in comparison with the afore-discussed output characteristics; The p++-Si BG is floated during the measurement. Although gate leakage current via the Schottky contact as well as charging/discharging of the traps states results in the increased off-state drain leakage current as shown in Figure 5b, a destructive hard breakdown is not observed in our measurement setup of $V_{DS}$ up to 210 V. Additional extended breakdown measurement exhibits BV of 293 V as shown in Figure S3, Supporting Information. The result indicates that the $\beta$-Ga$_2$O$_3$ nanomembrane TG-MESFET is promising for high power devices.

Last, we evaluate electrical performance of the proposed asymmetric DG (ADG) $\beta$-Ga$_2$O$_3$ FET by modulating both gate-bias simultaneously. Figure 6a,b shows transfer curves ($I_{DS}$–$V_{GS}$) and $g_m$–$V_{GS}$ curves at $V_{DS} = 1$ V of the asymmetric DG $\beta$-Ga$_2$O$_3$ FET compared with TG MESFET. $V_{TH}$ further shifts toward positive direction by the amount of $\Delta V_{TH} = 6.1$ V, and the max. $g_m$ (0.68 mS per ss) was improved by 1.9 times, and the $\mu_{FE}$ of ADG-FET increased to $\approx 184$ cm$^2$V$^{-1}$·s$^{-1}$. A total capacitance ($C_{OX}$) value of two parallel capacitors ($C_S$/$C_{BOX}$) is used for the mobility extraction. Table 1. Summary of the characterized electrical performance.

<table>
<thead>
<tr>
<th>$V_D = 1$ V</th>
<th>$g_m$ (max) [mS mm$^{-1}$]</th>
<th>$\mu_{FE}$ [cm$^2$V$^{-1}$·s$^{-1}$]</th>
<th>$V_{TH}$ [V]</th>
<th>SS [mV per dec]</th>
<th>$\Delta V$ [V]</th>
<th>On/off</th>
</tr>
</thead>
<tbody>
<tr>
<td>BG-MOSFET</td>
<td>0.05</td>
<td>102</td>
<td>–57.7</td>
<td>470</td>
<td>2</td>
<td>$1.7 \cdot 10^8$</td>
</tr>
<tr>
<td>TG-MESFET</td>
<td>0.36</td>
<td>153</td>
<td>–13.2</td>
<td>130</td>
<td>0.02</td>
<td>$1.9 \cdot 10^9$</td>
</tr>
<tr>
<td>ADG-FET</td>
<td>0.68</td>
<td>184</td>
<td>–7.1</td>
<td>110</td>
<td>0.05</td>
<td>$1.2 \cdot 10^9$</td>
</tr>
</tbody>
</table>

Bottom-gate (BG) $\beta$-Ga$_2$O$_3$ MOSFET, top-gate (TG) $\beta$-Ga$_2$O$_3$ MESFET, and asymmetric double-gate (DG) $\beta$-Ga$_2$O$_3$ FET.

Figure 4. a) Band diagram of asymmetric double-gate $\beta$-Ga$_2$O$_3$ nanomembrane field-effect transistor with both floating BG and TG. Band diagram of b) BG MOSFET under negative TG and c) TG MESFET under negative BG. Simulated on-state electron density (eDensity) maps of d) BG MOSFET and e) TG MESFET; f) their direct comparison across the $\beta$-Ga$_2$O$_3$ channel at the same effective gate-bias ($V_{GS}$–$V_{TH}$).
enhanced up to 2.76 mS mm$^{-1}$ as $V_{DS}$ increases to 10 V as presented in $I_{DS}$–$V_{GS}$–$g_m$ curves of Figure 6d. The positive $\Delta V_{TH}$ is ascribed to decreased effective channel thickness under double-gate modulation. Therefore, the thinner and more effectively gate-controlled channel layer results in the significantly improved carrier transport properties, which can be further enhanced by designing higher W/L as well as doping level.

3. Conclusion

In summary, we fabricate asymmetric double-gate (DG) $\beta$-Ga$_2$O$_3$ nanomembrane FET comprised of bottom-gated MOSFET and top-gated MESFET. Due to the excellent Schottky contact formed at Ni/$\beta$-Ga$_2$O$_3$ interface, as characterized by measuring the SBD, TG $\beta$-Ga$_2$O$_3$ MESFET
exhibits high on/off ratio, low subthreshold slope, and high transconductance with negligible hysteresis. In addition, the high breakdown voltage as anticipated by the three terminal off-state breakdown measurements is promising for power devices. On the basis of the energy band model supported by the simulation study, the asymmetric gate modulation is beneficial toward high-performance DG \( \beta \text{Ga}_2\text{O}_3 \) nanomembrane FET. Consequently, positive-shifted threshold voltage, reduced subthreshold slope, almost two times enhanced transconductance, and 1.2 times increased mobility are achieved through DG operation. All these results suggest the proposed asymmetric DG \( \beta \text{Ga}_2\text{O}_3 \) nanomembrane FET to be promising for energy-efficient high voltage and frequency device applications with further optimal material and structure co-designs.

4. Experimental Section

Device Fabrication and Characterization: Mechanically exfoliated \( \beta \text{Ga}_2\text{O}_3 \) flakes from \( \beta \text{Ga}_2\text{O}_3 \) (201) bulk substrate with unintentional n-type doping (UID) concentration of \( 4.8 \times 10^{17} \text{ cm}^{-3} \) (Tamura Corp., Japan) by a conventional scotch-tape method were transferred on to a heavily doped p-type Si substrate with thermally grown 300 nm SiO\(_2\) layer. Then source and drain (S/D) electrodes of Ti/Au (20/80 nm) were deposited by thermal evaporation and patterned using a conventional photolithography and lift-off process. The channel length (L) between source and drain was 21.6 \( \mu \text{m} \) and width (W) was 7.1 \( \mu \text{m} \). After that, a top-gate (TG) electrode of Ni/Au (20/80 nm) was deposited on the top of \( \beta \text{Ga}_2\text{O}_3 \) (100) channel layer by thermal deposition and then finished with the lift-off process. Electrical properties of the fabricated individual devices and double-gate operation were characterized by using semiconductor parameter analyzer (SCS-4200A, Keithley) in dark ambient conditions. The \( \beta \text{Ga}_2\text{O}_3 \) channel thickness was measured by atomic force microscopy (AFM) (XE100, PSIA) and structural analysis was conducted using HR-TEM (Talos F200X).

TCAD Simulations: A commercial TCAD Sentaurus was used to study the fabricated device and to understand asymmetric gate modulation effect.\(^{[29,30]}\) Standard \( \beta \text{Ga}_2\text{O}_3 \) material parameters such as electron effective mass (\( m^* \)) and conduction band density of state (\( N_c \)) were adopted at first. Then some of the parameters were calibrated to the experimental results; the model parameter \( \beta_0 \) (beta0) and saturation velocity (vsat0) for high-field dependence were set to be 0.4 and \( 1 \times 10^3 \text{ cm s}^{-1} \), respectively. \( N_c/\beta \text{Ga}_2\text{O}_3 \) interface was defined as a Schottky contact. Although the \( \beta \text{Ga}_2\text{O}_3 \) channel was modeled with n-type doping concentration of \( 2.0 \times 10^{17} \text{ cm}^{-3} \), which was lower than the nominal value of the initial bulk substrate, the thickness was set to be 150 nm in order to fully deplete the channel without modifying other parameters. Then a device mesh was constructed to match the fabricated asymmetric DG \( \beta \text{Ga}_2\text{O}_3 \) FET and then perform electron-density (\( e\text{Density} \)) simulation.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

asymmetric-gate, beta-gallium oxide, metal-semiconductor field-effect transistor, metal-oxide field-effect transistor

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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