Article

Journal of
Nanoscience and Nanotechnology
Vol. 20, 516–519, 2020
www.aspbs.com/jnn

Electrical Properties of Top-Gate β-Ga_2O_3 Nanomembrane Metal-Semiconductor Field-Effect Transistor

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We fabricate top-gate β-Ga_2O_3 nanomembrane metal-semiconductor field-effect transistor (MESFET) using a mechanical exfoliation method, and investigate its electrical performance. The Schottky contact between top-gate metal and β-Ga_2O_3 (100) channel is evaluated by characterizing properties of Schottky barrier diode, exhibiting an on/off ratio of $\sim 10^6$, an ideality factor of 2.8 and a turn-on voltage of 1.1 V. The proposed top-gate β-Ga_2O_3 nanomembrane MESFET exhibits maximum transconductance of $\sim$0.23 mS/mm, field-effect mobility of 1.2 $cm^2/V \cdot s$ at $V_{DS} = 1$ V and subthreshold slope (SS) of 180 mV/dec with high on/off ratio of $>10^7$. These results suggest that β-Ga_2O_3 nanomembrane MESFET could be a promising component toward β-Ga_2O_3-based high power device applications.

Keywords: Gallium-Oxide, Nanomembrane, Top-Gate, MESFET.

1. INTRODUCTION

Gallium oxide (Ga_2O_3) has attracted much attention recently as a promising candidate for next generation power device and deep ultraviolet (DUV) detector application due to its superior electrical properties of gallium oxide; Its wide bandgap of about 4.6~4.9 eV allows solar-blind DUV response, high-temperature and high-voltage operation [1–4]. Among five different polymorphs of Ga_2O_3, its beta(β)-polymorph is the most stable form and has been widely investigated [5]. Even with nominal electron mobility of 100 cm^2/Vs at room temperature, β-Ga_2O_3 is estimated to possess several times higher Baliga's figure-of-merit (FOM) than current viable solutions such as silicon carbide (SiC) and gallium nitride (GaN) [6, 7]. In addition to these aforementioned superior properties, a high-quality native Ga_2O_3 substrate from bulk single crystal obtained from melt-growth methods, such as Czochralski and edge-defined film-fed growth (EFG), provides a significant cost competitiveness over other competing wideband gap materials [8, 9].

On the other hand, the monoclinic structure of β-Ga_2O_3 has a relatively large lattice constant of 12.2 Å along the [100] direction, compared to 3.0 Å and 5.8 Å along [010] and [001] directions, respectively [10]. This unique structure allows a facile cleavage into flakes along [100] direction, thus providing high crystal quality of β-Ga_2O_3 with (100) surface orientation in order to facilitate research on its material and electrical properties [11–16]. Consequently, electrical and optical properties, thermal issues, and various device structures have been reported; However, these are mostly based on bottom-gate metal-oxide semiconductor field-effect transistor structure (MOSFET).

In this work, we fabricate top-gate (TG) β-Ga_2O_3 (100) nanomembrane metal-semiconductor field-effect transistor (MESFET) and investigate its electrical performance. Specifically, using a mechanical exfoliation method, β-Ga_2O_3 (100) nanomembrane channel was obtained from an unintentionally n-type doped bulk crystal substrate with (−201) surface orientation. The fabricated β-Ga_2O_3 MESFET exhibits transconductance (g_m) of $\sim$0.23 mS/mm and field-effect mobility (μ_{ef}) of 1.2 $cm^2/V \cdot s$ with subthreshold slope (SS) of 180 mV/dec. In addition to the electrical performance of β-Ga_2O_3 MESFET, the quality of Schottky and ohmic contacts known to limit the performance is also investigated and discussed.

2. EXPERIMENTAL DETAILS

Mechanically exfoliated β-Ga_2O_3 nanomembranes from an unintentional n-type doped (UID) β-Ga_2O_3 (−201)

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1533-4880/2020/20/516/004 doi:10.1166/jnn.2020.17259

bulk substrate (Tamura Corp., Japan) by a conventional scotch-tape method were transferred onto thermally grown 300 nm SiO_2 layer on a heavily doped p-type Si substrate. Source and drain (S/D) electrodes of Ti/Au (20/80 nm) were then deposited by thermal evaporation and patterned using a conventional photolithography and lift-off process. The channel length (L) between source and drain was 18.1 μm and width (W) was 4.6 μm. In order to fabricate metal semiconductor field effect transistor (MESFET) structure, top-gate (TG) electrode of Ni/Au (20/80 nm) was then deposited onto the top of β-Ga_2O_3 channel layer by the same thermal evaporation method followed by the lift-off. The length between gate and source (L_{GS}) and between gate and drain (L_{GD}) were 2.3 μm and 11.1 μm, respectively. Electrical properties of the fabricated MESFET and SBD were measured using a semiconductor parameter analyzer (SCS-4200A, Keithley) in a dark ambient condition at room temperature. Channel thickness and structural analysis were conducted using a high resolution transmission electron microscopy (HR-TEM, Talos F200X).

3. RESULTS AND DISCUSSION

Figure 1 shows cross-sectional schematic with an optical microscope image of the fabricated TG β-Ga_2O_3 MEFET. We confirmed the thickness of β-Ga_2O_3 channel was about 450 nm using high-resolution transmission electron microscopy (HR-TEM). The channel width (W) and length (L) are 18.1 μm and 4.6 μm, respectively, and oxide capacitance of 300 nm thick thermal SiO_2 (C_{OX}) is 1.2×10^{-8} F/cm^2.

Figure 2(a) presents a high-resolution transmission electron microscope (HR-TEM, Talos F200X) image. The exfoliated β-Ga_2O_3 flake preserved high crystal quality of bulk β-Ga_2O_3 crystal without damage or strain. The monoclinic structure of β-Ga_2O_3, having a relatively large lattice constant along the [100] direction, allows simple cleavage into flakes or nanomembranes similar to

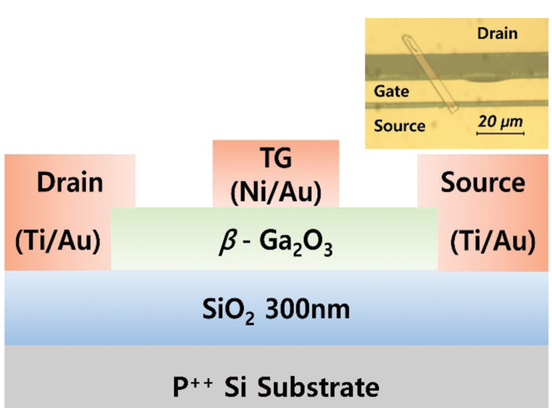

Figure 1. Cross sectional schematic of the fabricated top-gate (TG) β-Ga_2O_3 (100) MESFET. (Inset) an optical image of the fabricated device.

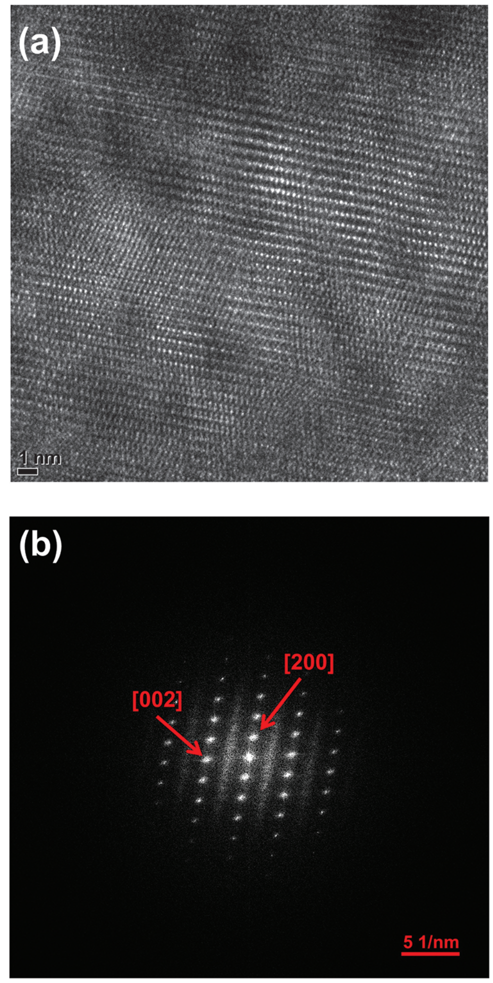

Figure 2. (a) A cross-sectional high-resolution transmission electron microscope (HR-TEM) image of the exfoliated β-Ga_2O_3 channel. (b) Its selected area electron diffraction pattern with unit of 5 1/nm indicating 5 reserved nanometers, confirming the surface orientation of (100).

two-dimensional layered materials [17, 18]. The selected-area electron diffraction (SAED) pattern in the Figure 2(b) confirms the lattice parameters and directions of the exfoliated flake; A clean and facile cleavage along the [100] direction was achieved, and so the β-Ga_2O_3 (100) crystal plane formed the channel surface of the fabricated device.

Since electrical performance of the fabricated TG β-Ga_2O_3 (100) MESFET is determined by the quality of TG (Ni/Au) Schottky contact and the S/D (Ti/Au) ohmic contact on the β-Ga_2O_3 (100) channel, performance of a Schottky barrier diode (SBD) made on the device was first evaluated; A lateral SBD structure has the TG metal (Ni/Au) as anode and source contact (Ti/Au) as cathode. The Schottky contact formation between nickel (Ni) and β-Ga_2O_3 is known to be associated with work function difference (Ni: 5.04–5.35 eV, β-Ga_2O_3: 4.11 eV) [19]. Figure 3(a) shows I–V curves of the measured SBD exhibiting a rectification behavior with on/off ratio of about 10^6. Ohmic contact behaviors

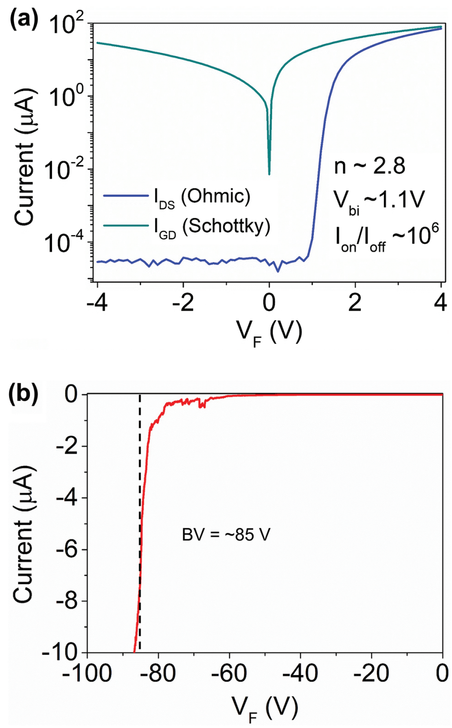

Figure 3. (a) I–V curves of the ohmic contact between (Ti/β-Ga_2O_3) and the fabricated Schottky barrier diode (Ni/β-Ga_2O_3) on a semilog scale. (b) I–V curve in a reverse bias region, exhibiting a breakdown voltage (BV) of about 85 V.

between S/D electrodes and β-Ga_2O_3 (100) channel are also shown. We analyzed the I–V characteristics of the fabricated SBD using thermal emission model $I = I_S\,(\exp(qV/nkT) - 1)$ [19], where q is a unit charge, I_s is reverse saturation current, V is a forward bias, n is ideality factor, k is the Boltzman constant, T is the absolute temperature. The built-in potential (V_{bi}) was extracted to be about 1.1 V, using a linear extrapolation of the current to x-axis, and the ideality factor (n) was about 2.8 from a linear region of forward I–V characteristics. Moreover, breakdown characteristics of the β-Ga_2O_3 SBD is shown in the Figure 3(b), and a breakdown voltage (BV) of ~85 V was obtained. The reason of a relatively low BV is attributed to the lateral SBD structure and/or the interface quality between the Ni and β-Ga_2O_3 channel. Further investigation is needed to determine both structural and material impacts on the BV.

Figure 4(a) presents I_{DS}–V_{GS} transfer characteristics of the fabricated β-Ga_2O_3 MESFET for $V_{DS} = 1$ V; It exhibits a high on/off ratio of $>10^7$ and sub-threshold slope (SS) of 0.18 V/dec, which was calculated from $SS = \partial(V_{GS})/\partial(\log_{10}(I_{DS}))$. The low SS indicates that a high quality of the interface between Ni and β-Ga_2O_3 is achieved. It can be further improved via a tight cleaning process of the SiO_2 surface prior to mechanical exfoliation of β-Ga_2O_3. A threshold voltage (V_{TH}) is extracted to be about -32.6 V using a linear extrapolation of the transfer curve, and the decent maximum transconductance (g_m) of 0.23 mS/mm at $V_{DS} = 1$ V, calculated from $g_m = \partial(I_{DS})/\partial(V_{GS})$, is obtained in comparison with other reported values based on similar mechanical exfoliation methods [18, 21]. The field-effect mobility (μ_{ef}) of 1.2 $cm^2/V \cdot s$ at $V_{DS} = 1$ V was calculated from $g_m = (W/L) \cdot (d \cdot q \cdot N_d \cdot \mu_{ef})$, where d is the channel thickness, q is the elementary charge, and N_d is the carrier concentration of bulk β-Ga_2O_3 [22]. The transconductance and field-effect mobility can be further improved because they dependson device dimension (W/L), doping concentration and drain-bias conditions. Figure 4(b) shows output curves of I_{DS}–V_{DS} for $V_{GS} = -35$ to 0 V with good saturation due to a pinch-off at high V_{DS} bias, indicating that the thick β-Ga_2O_3 channel is successfully modulated via the Schottky contacted top-gate bias.

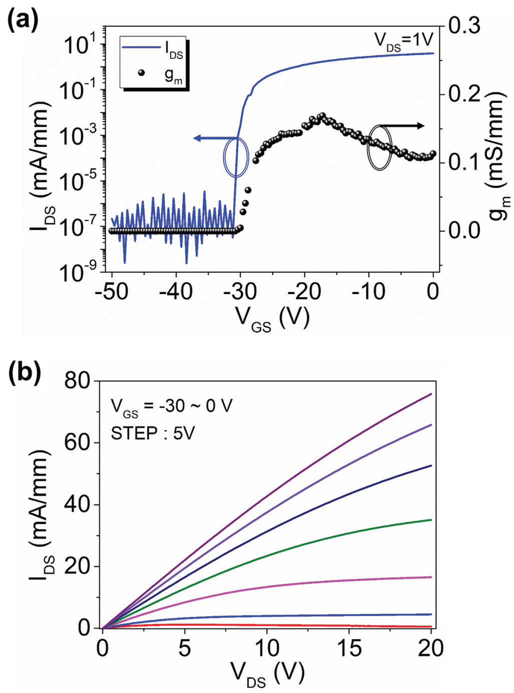

Figure 4. (a) I_{DS}–V_{GS}-g_m curves of the top-gate β-Ga_2O_3 (100) MESFET at $V_{DS} = 1$V. (b) I_{DS}–V_{DS} output curves of the β-Ga_2O_3 (100) MESFET for $V_{GS} = -30$ to 0 V with 5 V step.

4. CONCLUSION

In conclusion, we have demonstrated top-gate β-Ga_2O_3 (100) MESFET using a mechanical exfoliation of β-Ga_2O_3 nanomembranes from an unintentional n-type doped (UID) β-Ga_2O_3 (-201) bulk substrate. A high-quality Schottky contact between TG metal (Ni/Au) and β-Ga_2O_3 (100) channel is confirmed by analyzing electrical performance of the lateral SBD, showing an on/off ratio of ~10^6, an ideality factor of 2.8 and a turn-on voltage of 1.1 V. The fabricated TG β-Ga_2O_3 nanomembranes MESFET exhibits decent electrical performance such as $SS \sim 0.18$ V/dec, max. g_m of 0.23 mS/mm at $V_{DS} = 1$ V, μ_{ef} of 1.2 $cm^2/V \cdot s$

and high on/off ratio of $>10^7$. Further improvement on its electrical performance is expected via optimal device design and bias conditions. These results demonstrate that TG β-Ga_2O_3 nanomembrane MESFET is a promising building block toward power electronics and microwave devices applications.

Acknowledgments: This research was funded and conducted under the Competency Development Program for Industry Specialists of the Korean Ministry of Trade, Industry and Energy (MOTIE), operated by Korea Institute for Advancement of Technology (KIAT). (No. N0001883, HRD program for Software-SoC convergence).

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Received: 5 December 2018. Accepted: 22 March 2019.