Gate leakage current and threshold voltage characteristics of β-Ga_2O_3 passivated AlGaN/GaN based heterojunction field effect transistor

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ABSTRACT

We report the gate leakage current and threshold voltage characteristics of $Al_{0.3}Ga_{0.7}N$/GaN heterojunction field effect transistor (HFET) with metal-organic chemical vapor deposition (MOCVD) grown β-Ga_2O_3 as a gate dielectric for the first time. In this study, GaN channel HFET and β-Ga_2O_3 passivated metal-oxide-semiconductor-HFET (MOS-HFET) structures were grown in MOCVD using N_2 as carrier gas on a sapphire substrate. X-ray diffraction (XRD) and atomic force microscopy (AFM) were used to characterize the structural properties and surface morphology of the heterostructure. The electrical properties were analyzed using van der Pauw, Hall, and the mercury probe capacitance-voltage (C-V) measurement systems. The 2-dimensional electron gas (2DEG) carrier density for the heterostructure was found to be in the order of ~10^{13} cm^{-2}. The threshold voltage shifted more towards the negative side for the MOSHFET. The high-low (Hi-Lo) frequency-based C-V method was used to calculate the interface charge density for the oxide-AlGaN interface and was found to be in the order of ~10^{12} cm^2eV^{-1}. A remarkable reduction in leakage current from xxx A/cm^2 for HFET to yyy A/cm^2 for MOSHFET was observed demonstrating the viability of MOCVD-grown Ga_2O_3 as a gate dielectric.

Keywords: GaN, MOSHFET, Leakage Current, Threshold Voltage, β-Ga_2O_3.

1. INTRODUCTION

Due to wide bandgap (3.4 eV), polarization-induced properties, and high breakdown field, gallium nitride (GaN) based devices have excellent high power and high-frequency performance[1,2]. There are different types of GaN-based devices that have been reported like high electron mobility transistors (HEMT), heterojunction field effect transistors (HFET), metal oxide heterojunction field effect transistors (MOSHFET), p-n diode, etc[3]. Among those, HFETs or MOSHFETs are worth mentioning because of their use of GaN's excellent polarization-dependent property to screen the material-related defects[4]. Still, the high frequency and high-power performance can be limited by gate leakage, conduction phenomena at different locations of the devices, virtual gate effect, etc[5]. To overcome these limitations, different dielectric materials have been used to create the MOSHFET structures and minimize gate leakage current, improving the breakdown voltage [1]. The most common methods used to develop dielectric layers on top of HFET structure are atomic layer deposition (ALD), pulsed laser deposition (PLD), and plasma-enhanced chemical vapor deposition (PECVD) making mostly amorphous dielectric layers. For the choice of dielectric materials, chemically and thermally stable with high bandgap, high dielectric constant, and low interface trap states are desired with low threshold voltage shift and leakage current[6]. Different type of oxide and nitride dielectric has been used such as Al_2O_3, HfO_2, ZrO_2, SiO_2, SiN_x etc[6].

β-Ga_2O_3 is a promising material with potential applications for high-power devices because of its high bandgap (~4.9 eV) and high breakdown voltage (~5.7 $MVcm^{-1}$). It has a dielectric constant (10.6) higher than traditional dielectrics like SiO_2 (3.9) and SiN_x (7.4)[7]. ALD-grown Ga_2O_3 has been reported before to be used as a dielectric layer using different precursors, however, the MOCVD growth to use as a dielectric has never been reported[8].

This paper reports on the structural and electrical properties *e.g.* gate leakage current and the threshold voltage of $Al_{0.3}Ga_{0.7}N$/GaN based heterojunction field effect transistor with metal-organic chemical vapor deposition (MOCVD) grown β-Ga_2O_3 as a passivation layer for the first time to understand the feasibility of the use of crystalline β-Ga_2O_3 as a gate dielectric.

2. GROWTH AND EXPERIMENTAL METHOD

The growth of the epilayers of devices for this study was performed in a metal-organic chemical vapor deposition (MOCVD) system using nitrogen vector gas on a sapphire substrate. Trimethylaluminum (TMAl), Trimethylgallium, Ammonia (NH3), and ultra-high purity oxygen were used as reaction precursors. A thin 150 nm aluminum nitride (AlN) layer was grown first, then, on top of the AlN layer[9–11], a 500 nm thick gallium nitride (GaN) channel layer, 2 nm AlN spacer, and 25 nm aluminum gallium nitride, with 30% aluminum composition ($Al_{0.3}Ga_{0.7}N$), barrier layers were grown at 100 torr chamber pressure. As measured by the van der Pauw and Hall measurement methods, the sheet resistance (R_{sh}) and electron mobility of the HEMT structure was found to be ~ 500 Ω/□ and ~ 800 $cm^2V^{-1}s^{-1}$, respectively, The GaN alone layer was insulating. The schematic of the HFET structure is shown in Figure 1(a). For this study, a 30 nm thick β-Ga_2O_3 layer was grown, using the MOCVD process, as a gate dielectric, on the HFET structure described above. This creates MOSHFET, as shown in Figure 1(b). The β-Ga_2O_3 growth process was done at 700 °C with a III/IV ratio of 2000 and chamber pressure of 50 Torr. Figure 1(c) shows the schematic band diagram of the MOSHFET structure.

The device epilayers were characterized for their structural quality, surface morphology, and electrical properties. Rigaku Miniflex II Desktop X-ray diffractometer with Cu-Kα1 x-ray source (λ = 1.5406 Å) operated at 30 mA and 15 kV was used to understand the structural properties of the epilayers. The capacitance-voltage (C-V) measurements were performed using a mercury probe controller model 802B connected with a HP 4284A Precision LCR Meter capable of measuring frequency-dependent measurements. Gate leakage current was measured in the same mercury probe set up with Keysight B2910 Precision Source / Measure Units (SMU). The gate diameter of the mercury probe was 797 µm. van der Pauw and Hall measurements were performed on the samples using MMR Technologies Inc. H-50 Hall van der Pauw controller and MPS-50 Programmable power supply.

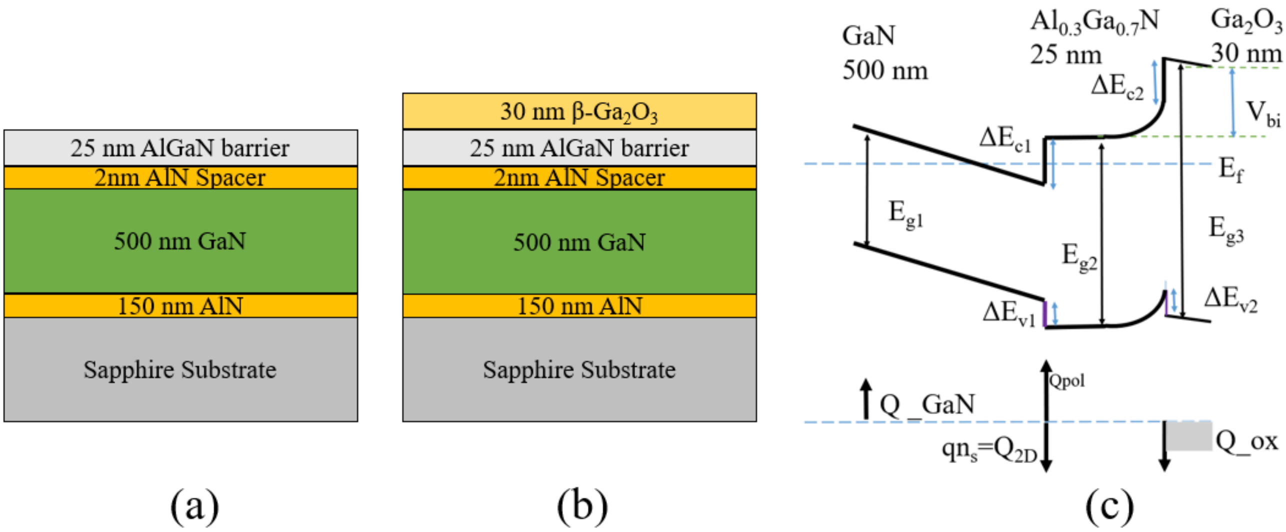

Fig. 1. The device epilayer structure of the (a) AlGaN/GaN HFET, (b) MOSHFET, (c) Band diagram of β-Ga_2O_3 MOSHFET, where, E_{g1} = 3.4 eV, E_{g2} = 4.03 eV, E_{g3} = 4.9 eV ΔE_{v1} = 0.19 eV, ΔE_{c1} = 0.44 eV, ΔE_{v2} = 0.261 eV, ΔE_{c2} = 0.609 eV, V_{bi}= 2.2 V and Q_{ox}= -2×10^{13} Ccm^{-2}.

3. RESULTS AND DISCUSSIONS

Figure 2 shows the XRD 2θ scan of the MOSHEMT structure. The peak at 38.2° is related to the (-401) plane of the crystalline phase pure β-Ga_2O_3. The peak at 34.5° and the adjacent hump are related to the (002) GaN channel and (002) AlGaN barrier[12,13]. The GaN channel was grown on 0.15 um AlN. The peak close to 36.1° is related to (002) AlN. The peak at 41.6° corresponds to (004) sapphire. As shown in Figures 2(b), 2(c), and 2(d), the surface morphology of GaN, AlGaN, and Ga_2O_3 layers was found to be less than 1 nm root means square (RMS) roughness.

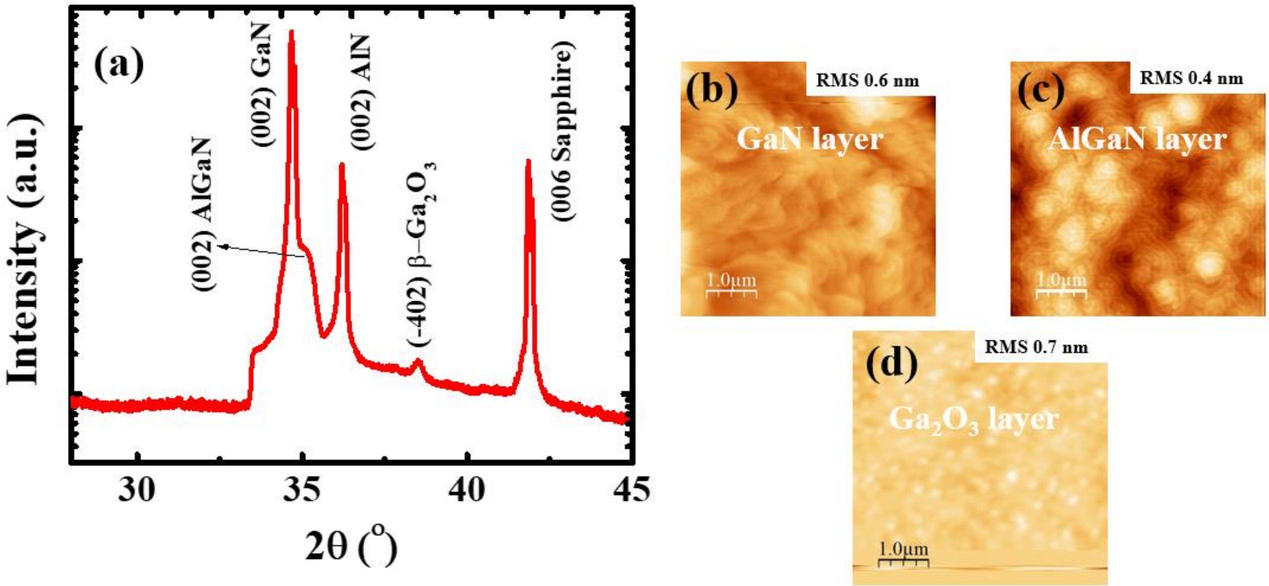

Fig. 2. (a) XRD data for the MOSHFET structure showing (-402) β-Ga_2O_3 peak for the dielectric layer, AFM image of (b) GaN channel layer, (c) AlGaN barrier layer and (d) Ga_2O_3 dielectric layer.

The capacitance-voltage (C-V) measurements were done using a HP 4284A Precision LCR Meter using mercury probe gate contact. Usually, in III-Nitride-based HEFT devices, the barrier layer is isolated from the metal contact layer by a dielectric layer that helps to improve the device's performance. The key parameters that are impacted by the inclusion of the dielectric layer are the threshold voltage (V_{th}) and gate leakage current. Threshold voltage shift depends on the dielectric constant and the thickness of the oxide layer. So, a higher dielectric constant and lower dielectric thickness are desirable for minimum threshold voltage shifts. Figure 3(a) shows the 1 MHz C-V data for HFET and MOSHFET. The dielectric constant for the barrier layer and the β-Ga_2O_3 layer is very close to each other. So, there is no drastic change in capacitance value close to the zero-gate voltage, and depletion only extends up to the barrier or barrier/dielectric layer. When 2DEG starts to deplete, capacitance starts to decrease drastically ultimately leading to pinch-off, then depletion extends to the channel epitaxial layer. From Figure 3(a), we can see that as the oxide layer was added, the V_{th} shifted more toward the negative side. So, with the addition of the dielectric layer, more voltage is required to deplete the 2DEG. The addition of oxide on the HFET barrier adds capacitance in series to the existing barrier layer capacitance. So, as the oxide layer thickness increases, the zero voltage capacitance decreases. Figure 3(b) shows the 2DEG carrier density (n_s) dispersion with respect to the gate voltage. The carrier density (N_d) can be calculated using Hall, van der Pauw method and was found to be in the order of $\sim 10^{18}$ cm^{-3}. The built-in voltage (V_{bi}) (as shown in Figure 1(c) band diagram), can be measured from the $1/C^2$ graph's x-intercept. The oxide charge (Q_{ox}) of -2×10^{13} Ccm^{-2} was calculated using the method described in the literature[4]. Figure 3(d) shows the frequency-dependent C-V data for the MOSHFET. The high-low frequency method was used to calculate the interface trap density (D_{it}) as described in reference [14] at the oxide barrier interface and the value was found to be 4.98×10^{12} $cm^{-2}eV^{-1}$.

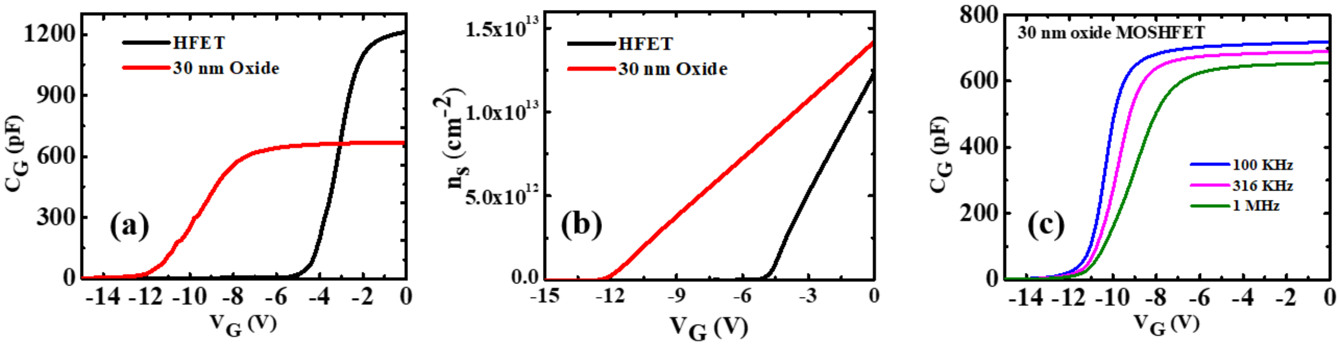

Fig. 3. (a) 1 MHz frequency C-V data for HFET and MOSHFET, (b) 2DEG carrier density dispersion for HFET and MOSHFET, (c) frequency-dependent C-V data for MOSHFET to calculate D_{it}.

Figure 4 shows the gate leakage current in the HFET and MOSHFET structure. We can see a significant reduction in leakage current for the MOSHFET structure compared to the HFET structure both in positive and negative bias voltage direction. The leakage current at -6 V for HFET is 2.33×10^{-2} A/cm^2 and it reduces to 1.03×10^{-8} A/cm^2 for MOSHFET. This remarkable improvement in the gate leakage current shows that β-Ga_2O_3 can be used as an effective dielectric layer for GaN/AlGaN MOSHFETs.

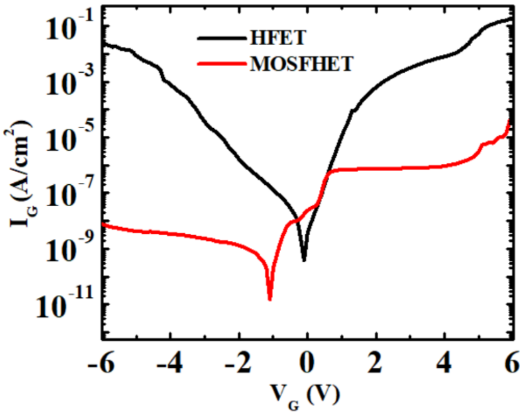

Fig. 4. Gate leakage current in the HFET and MOSHFET structure.

4. CONCLUSIONS

We have demonstrated MOCVD-grown Ga_2O_3 crystalline thin films as gate dielectric on AlGaN/GaN HFETs. We have found that the inclusion of gate dielectric has an impact on the V_{th} shift, moving it more towards the negative side and reducing the zero capacitance as the additional C_{ox} is added. The sheet carrier density for HFET and MOSHFETs was found to be in the order of $\sim10^{13}$ cm^{-2}. Moreover, the addition of the oxide layer did not significantly change the sheet carrier concentration but had an impact on the calculated value of the Q_{ox} making it negative. The oxide barrier interface trap density was found to be in the order of $\sim10^{12}$ cm^{2}eV^{-1}. There was a significant reduction of leakage current (6 order) in the case of Ga_2O_3 passivated MOSHFET which supports the the use of Ga_2O_3 as an effective gate dielectric grown by using MOCVD.

Acknowledgments: This research was supported by National Science Foundation (NSF) award No. 2124624 managed by Dr. Dominique M. Dagenais. The authors also acknowledge the material of Sensor Electronic Technology, Inc, Columbia SC, USA.

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