Improved operation stability of Al₂O₃/AlGaN/GaN MOS high-electron-mobility transistors grown on GaN substrates

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This paper presents electrical characterization of Al₂O₃/AlGaN/GaN metal–oxide–semiconductor (MOS) high-electron-mobility transistors (HEMTs) grown on GaN substrates. The postmetallization annealing (PMA) at 300 °C achieved effective reduction of electronic states at the Al₂O₃/AlGaN interface, leading to improved gate controllability and current linearity of the MOS HEMTs. The MOS HEMT with PMA showed a subthreshold slope of 68 mV dec⁻¹. In addition, excellent operation stability of the MOS HEMT was observed at high temperatures. Even at 150 °C, the HEMT showed low leakage current of 1.5 × 10⁻² A mm⁻¹ and a threshold voltage drift of only 0.25 V from its room temperature value.

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The fifth generation wireless system requires further progress in device performance and operation stability for GaN power HEMTs. At present, GaN-based HEMT structures are generally grown on foreign substrates such as Si, SiC and sapphire. However, these substrates are not lattice-matched to GaN, resulting in high dislocation densities in the range of 10⁸ cm⁻². It can be supposed that such defects are related to the degradation of transport properties and reliability of GaN HEMTs. Thus, it is expected that a fundamental approach of using AlGaN/GaN heterostructures grown on native GaN substrates can lead to substantially improved electrical performances and higher reliability. In fact, Ref. 1 reported that threading dislocation density (N_DIS) significantly affected electron mobility in AlGaN/GaN heterostructures, and that such structures grown on GaN substrates (N_DIS < 5 × 10¹⁰ cm⁻²) exhibited higher mobility than those grown on SiC and sapphire. Reference 2 demonstrated that AlGaN/GaN HEMTs grown on ammornothal GaN substrates (N_DIS < 1 × 10¹⁴ cm⁻²) showed atomically smooth surface and pronounced reduction of leakage currents in Schottky gate (SG) structures. As compared with AlGaN/GaN HEMTs on SiC substrates, reduction of current collapse was observed in HEMTs on GaN substrates grown by hydride vapor phase epitaxy (HVPE).³ Very recently, Ref. 4 also reported improved electrical performance as well as significant reduction of drain leakage current in AlGaN/GaN HEMTs on HVPE GaN substrates.

Power amplifiers using SG GaN HEMTs often suffer from reduced gain and efficiency with increasing input RF power owing to significant gate leakage currents caused by a large input swing that may drive the devices into the forward bias regime.²,³ A metal–insulator (oxide–semiconductor (MIS or MOS) structure) is very effective in overcoming such problems related to SG structures. In fact, Ref. 5 demonstrated that gate leakage current was sufficiently controlled in the AlGaN/GaN MIS-HEMT even under high input power operation. Different insulator materials have been applied to GaN-based MIS HEMTs on Si and SiC substrates.⁶,⁷ Reference 8 demonstrated good RF performance in HfO₂/AlN/GaN HEMTs on GaN substrates. However, advantages of GaN-based MIS HEMTs on GaN over those on foreign substrates are yet unclear. Accordingly, in this paper, we present electrical characterization of Al₂O₃-gate AlGaN/GaN HEMTs on HVPE GaN substrates, focusing on gate controllability and operation stability.

Figure 1(a) shows a schematic illustration of the MOS HEMT structure on GaN substrate. We used Al₀.2Ga₀.8N/GaN layers grown by metalorganic chemical vapor epitaxy on HVPE GaN substrates, provided by SCIOMS. The C-doped GaN acts as a high-resistivity layer. An atomic force microscope image of the AlGaN surface is shown in Fig. 1(b). As expected, the sample exhibited an atomically flat surface with RMS roughness of only at most 0.25 nm, which is similar to those reported on HEMTs grown on GaN substrates.²,⁵ The two-dimensional electron gas (2DEG) density and mobility of the heterostructure were 6.5 × 10¹² cm⁻² and 1750 cm² V⁻¹ s⁻¹, respectively. For source and drain electrodes, Ti/Al/Ti/Au (=20/50/20/50 nm) layers were deposited on the AlGaN surface, followed by an annealing at 830 °C for 1 min in N₂ ambient. As a surface protection layer during ohmic annealing, a 20 nm thick SiN film was deposited to prevent damage to the AlGaN surface.⁹,¹⁰ After the ohmic metallization process, the SiN film was removed using a buffered HF solution. Then, the Al₂O₃ layer with a nominal thickness of 30 nm was deposited on the AlGaN surface at 300 °C by atomic layer deposition (ALD). In the deposition process, water vapor and trimethylaluminium were introduced into a reactor in alternate pulse forms. Each precursor was injected into the reactor for 15 ms, and the purging time was set to 5 s. In this case, the deposition rate is 0.11 nm/cycle, indicating formation of Al₂O₃ in a layer-by-layer fashion. From an ellipsometry measurement, the refractive index of the ALD Al₂O₃ was estimated to be in the range of 1.60–1.65, which is close to values reported for amorphous Al₂O₃ films prepared by ALD.¹¹ The gate length, gate width, gate–drain (G–D) and gate–source (G–S) distances are 10, 100, 10, and 10 μm, respectively.

After the MOS HEMT fabrication, we carried out postmetallization annealing (PMA) at 300 °C for some samples. As described in Ref. 12, we found that excellent C–V...
Al₂O₃ deposition. HEMT on HVPE GaN substrate. (b) AFM image of AlGaN surface before without and (b) with PMA at 300 °C for 10 min.

The transfer characteristics of Al₂O₃/AlGaN/GaN MOS HEMTs without and with PMA at 300 °C for 10 min. For comparison, transfer curves are plotted as a function of gate overdrive voltage in excess of threshold voltage ($V_{G} - V_{TH}$).

Fig. 1. (Color online) (a) Schematic illustration of Al₂O₃-gate AlGaN/GaN HEMT on HVPE GaN substrate. (b) AFM image of AlGaN surface before Al₂O₃ deposition.

Fig. 2. (Color online) Typical drain $I$–$V$ characteristics of MOS HEMTs (a) without and (b) with PMA at 300 °C for 10 min.

characteristics without frequency dispersion were observed in the Al₂O₃/GaN diode after PMA in N₂ at 300 °C–400 °C for 10 min. The PMA sample showed state densities of at most $4 \times 10^{10} \text{cm}^{-2} \text{eV}^{-1}$. The high-resolution transmission electron microscope analysis showed that the PMA process led to the improved bonding order configuration at the Al₂O₃/GaN interface. It is likely that the resulting reduction of the interface states afforded excellent $C$–$V$ characteristics without frequency dispersion. In this work, we expect that the same desirable effects of PMA can be extended to Al₂O₃/AlGaN/GaN MOS HEMT system.

Figures 2(a) and 2(b) respectively show typical drain $I$–$V$ characteristics of MOS HEMTs without and with PMA. Both devices showed relatively good $I$–$V$ behavior at low gate bias ($V_{G}$). For the MOS HEMT without PMA, however, a limited increase in drain current ($I_{D}$) was observed at the gate bias higher than 0 V. On the other hand, the MOS HEMT with PMA at 300 °C showed good gate control of $I_{D}$ even at forward gate bias, as shown in Fig. 2(b). After PMA, in addition, the on-state resistance slightly decreased. It is probable that the annealing reduced Al₂O₃/AlGaN interface states in G–D and G–S access regions, leading to change in surface potential of AlGaN. As a result, a slight increase of 2DEG density in the access region can be responsible for the reduction of access resistance in the MOS HEMT with PMA.

The transfer characteristics of MOS HEMTs without and with PMA are shown in Fig. 3. For comparison, their transfer curves are plotted as a function of gate overdrive voltage in excess of threshold voltage ($V_{G} - V_{TH}$).
bonding order configuration at the Al₂O₃/GaN interface, correlating closely with significant reduction of interface states.\(^{12}\) As shown in Fig. 4, a similar bonding modification can occur at the Al₂O₃/AlGaN interface. Although the PMA mechanism is yet unclear, there is a possibility that change in electric field distribution and/or stress distribution underneath the gate metal enhances relaxation of surface defects and dangling bonds at the AlGaN surface during the PMA process.

We then investigated subthreshold characteristics of MOS HEMTs. Figure 5 shows semi-log scale \(I_D-V_G\) characteristics of Al₂O₃/AlGaN/GaN HEMTs without and with PMA at 300 °C for 10 min. positive charges arising from donor-type interface states and/or defect levels in the bulk Al₂O₃. A possible candidate for defect levels in Al₂O₃ is an oxygen-vacancy related defect.\(^{19,20}\) It is highly probable that the PMA process at 300 °C decreased such levels, resulting in the \(V_{TH}\) recovery toward the expected value of \(-6.2\) V. Reference 21 reported a similar recovery of a flat-band voltage in Ni/Al₂O₃/GaN structures by PMA at 400 °C–550 °C. As shown in Fig. 5, in addition, we observed decrease in gate leakage current in the GaN-based MIS HEMTs using Al₂O₃, SiN, and AlTiO. 22–25 In the same way as the \(V_{TH}\) recovery, decrease in defect levels in the Al₂O₃ layer is responsible for the reduction of leakage current, contributing to the suppression of the PF hopping conduction.

Although the \(V_{TH}\) stability is undoubtedly important for reliable operation of MOS transistors, GaN MIS HEMTs have been suffering from \(V_{TH}\) instability issues under positive gate stress and high-temperature operation. Figure 6 shows \(I_D-V_G\) characteristics in semi-log scale after applying positive \(V_G\) stress. In this case, we initially applied the \(V_G\) stress for 5 s with \(V_D = 15\) V. The \(I_D-V_G\) characteristics of the MOS HEMT with PMA at 300 °C for 10 min after applying positive \(V_G\) stress. In this case, we initially applied the \(V_G\) stress for 5 s with \(V_D = 15\) V.
under the $V_G$ sweeping from 0 to $-10$ V. The MOS HEMT with PMA at 300 °C showed only slight $V_{TH}$ shifts under the positive gate stress. At positive gate bias, the Fowler–Nordheim tunneling mechanism can enhance electron injection into trap levels in Al$_2$O$_3$ and/or at the Al$_2$O$_3$/AlGaN interface, resulting in the $V_{TH}$ shift toward the positive bias direction owing to excess negative charges. As mentioned above, the PMA process at 300 °C decreased such traps, leading to mitigation of the gate stress induced $V_{TH}$ shift,\(^{15}\) as shown in Fig. 6.

The temperature dependence of transfer characteristics under $V_{DS} = 15$ V is shown in Fig. 7(a). The inset indicates corresponding data plotted in a linear scale. The drain current decreases with increasing temperature, mainly owing to decrease of electron mobility with optical phonon scattering at high temperatures.\(^{26-27}\) References 28, 29 reported marked $V_{TH}$ shifts and increase in leakage currents at high temperatures in Al$_2$O$_3$/AlGaN/GaN HEMTs on Si substrates. They proposed that trap levels at the Al$_2$O$_3$/AlGaN interface caused such thermally-induced $V_{TH}$ instability. In contrast, we observed stable operation of Al$_2$O$_3$-gate MOS HEMTs at high temperatures, as evident in Fig. 7(a). Even at 150 °C, for example, the HEMT showed excellent subthreshold curve and a $V_{TH}$ drift of only 0.25 V from its RT value.

The SS value as a function of temperature is shown in Fig. 7(b). The MOS HEMT with PMA showed SS values close to the ideal ones at temperatures up to 100 °C. In fact, SS of 80 mV dec$^{-1}$ was observed even at 100 °C, demonstrating excellent gate controllability of Al$_2$O$_3$-gate MOS HEMTs with PMA. In addition, the MOS HEMT exhibited low leakage current of $1.5 \times 10^{-9}$ A mm$^{-1}$ at 150 °C, as shown in Fig. 7(a). By using a well-designed buffer layer on sapphire substrate, Ref. 30 reported sufficiently low drain current at off-state bias (drain leakage) and high on/off current ratio in Al$_2$O$_3$/AlGaN/GaN HEMTs. However, some studies showed much higher drain leakage than gate leakage current in MIS AlGaN/GaN HEMTs using foreign substrates.\(^{15,29}\) In spite of relatively thin GaN layer ($1.5 \mu$m) on n$^+$-GaN substrate, as shown in Fig. 1(a), the present HEMT exhibited low drain leakage current, indicating that homo-epitaxial GaN layers with low dislocation density effectively control bulk leakage conduction.

In summary, we carried out electrical characterization of Al$_2$O$_3$-gate AlGaN/GaN HEMTs on HVPE GaN substrates, focusing on gate controllability and operation stability. The PMA process at 300 °C in N$_2$ achieved effective reduction of electronic states at the Al$_2$O$_3$/AlGaN interface, leading to improved gate controllability and current linearity of the MOS HEMTs. The MOS HEMT with PMA showed a SS of 68 mV dec$^{-1}$ and excellent $V_{TH}$ stability. It was found that the $V_{TH}$ shift was 0.3 V or lower when applying a positive $V_G$ stress of 10 V to the device. In addition, we observed excellent operation stability of the MOS HEMT at high temperatures. Even at 150 °C, the HEMT showed a low leakage current of $1.5 \times 10^{-9}$ A mm$^{-1}$ and a $V_{TH}$ drift of only 0.25 V from its RT value. Thus, the present MOS technology using PMA and low bulk leakage feature of the HEMT on GaN are responsible for excellent gate controllability and operation stability of the Al$_2$O$_3$-gate AlGaN/GaN HEMT on the HVPE GaN substrate, predicting further progress of GaN MIS HEMTs as high-performance and reliable RF power transistors.

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