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Gate controllability of HfSiO$_x$/AlGaN/GaN MOS high-electron-mobility transistor

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ABSTRACT
Hafnium silicate (HfSiO$_x$) has been applied to AlGaN/GaN high-electron-mobility transistors (HEMTs) as a high κ gate dielectric. The (HfO$_2$)/(SiO$_2$) laminate structure was deposited on the AlGaN surface by a plasma-enhanced atomic layer deposition, followed by a post-deposition annealing at 800 °C. The HfSiO$_x$-gate HEMT showed good transfer characteristics with a high transconductance expected from its κ value and a subthreshold swing of 71 mV/decade. For the metal–oxide-semiconductor (MOS) HEMT diode, we observed excellent capacitance–voltage (C–V) characteristics with negligible frequency dispersion. The detailed C–V analysis showed low state densities on the order of 10$^{11}$ cm$^{-2}$ eV$^{-1}$ at the HfSiO$_x$/AlGaN interface. In addition, excellent operation stability of the MOS HEMT was observed at high temperatures up to 150 °C.

I. INTRODUCTION
GaN high-electron-mobility transistors (HEMTs) with high-frequency and high-power performances are very attractive for the fifth generation communication system, where the W- and E-band frequency operations with an output power of over 1 W will be required for power amplifier transistors. At present, because of several advantages including simplicity, ease of fabrication, and high transconductance, the Schottky-gate (SG) structure is generally used in GaN HEMTs. In the high input RF power regime, however, the SG GaN HEMT may suffer from marked leakage currents due to input swings high enough to drive the gate to forward bias. In addition, Gao et al. recently reported that the forward gate-bias stress applied to the SG AlGaN/GaN HEMT significantly increased gate leakage currents. They concluded from photoemission microscope and transmission electron microscope observations that the chemical degradation of the Ni/AlGaN contact during the forward bias stress is responsible for such an increase in gate leakage currents.

To overcome these issues related to a SG structure, a metal–insulator (oxide)-semiconductor (MIS or MOS) structure is desirable for advanced GaN HEMTs. In fact, it was reported that the SiN-gate AlGaN/GaN HEMT effectively controlled the gate leakage current even under high input power conditions. To develop stable and high-performance MIS GaN HEMTs, it is important to consider bandgap, permittivity, breakdown field, and chemical stability of insulators. In addition, high band offsets and low state density at insulator/GaN(AlGaN) interfaces are requisites for an excellent gate dielectric. Recently, we have developed and investigated hafnium silicate (HfSiO$_x$) as a gate dielectric for GaN-based devices. After a post-deposition annealing (PDA) at around 800 °C, we achieved chemically stable amorphous HfSiO$_x$ layers with a high κ,
a high breakdown field, and low state densities at the HfSiO$_x$/GaN interfaces. In addition, Miyazaki and Ohta$^9$ reported a relatively large bandgap ($E_G = 6.5$ eV) for Hf$_{0.66}$Si$_{0.34}$O$_x$. These physical properties are very attractive for robust and high-transconductance ($g_m$) operation of GaN-based HEMTs, which provides more degrees of freedom in the design of device structures. Li and co-workers$^{10,11}$ applied the HfSiO$_x$ gate to the AlGaN/GaN HEMT structure on Si. However, they reported polycrystalline HfSiO$_x$ without a composition ratio and high interface state densities in the MOS structure.$^{11}$ Accordingly, in this paper, we fabricated HfSiO$_x$/AlGaN/GaN HEMTs and carried out electrical characterization of the MOS HEMTs, focusing on gate controllability and MOS interface properties.

II. DEVICE STRUCTURE AND FABRICATION PROCESS

Figure 1 shows the MOS-HEMT structure. We used the Al$_{0.2}$Ga$_{0.8}$N/GaN heterostructure grown by metalorganic chemical vapor deposition on the free-standing GaN substrate, provided by SCIOCS.$^{12}$ The C-doped GaN acts as a high-resistivity layer. The density and the mobility of the two-dimensional electron gas (2DEG) were $6.5 \times 10^{12}$ cm$^{-2}$ and 1750 cm$^2$ V$^{-1}$ s$^{-1}$, respectively. We fabricated two kinds of MOS HEMTs using Al$_2$O$_3$- and HfSiO$_x$-gate dielectrics, and compared their DC characteristics. The gate–drain and gate–source distances are 10 $\mu$m.

To prevent partial crystallization in the Al$_2$O$_3$ film at high temperatures, an ohmic electrode process was first carried out for the Al$_2$O$_3$-gate HEMT.$^{13}$ After the metallization annealing at 800 $\degree$C, the Al$_2$O$_3$ layer was deposited on the AlGaN surface at 300 $\degree$C by atomic layer deposition (ALD) using H$_2$O and trimethylaluminum as precursors. The specific permittivity and the thickness of Al$_2$O$_3$ were 8.5 nm and 29 nm, respectively. After the MOS-HEMT fabrication, we carried out post-metallization annealing (PMA) at 300 $\degree$C in N$_2$ for 10 min.$^{14-17}$ The PMA process is effective in controlling the state densities in the order of $10^{10}$ cm$^{-2}$ eV$^{-1}$ at the Al$_2$O$_3$/GaN interface.$^{15}$ We also observed that gate controllability and operation stability of MOS HEMTs were remarkably improved by PMA.$^{12,16,17}$

For the HfSiO$_x$-gate HEMT, the (HfO$_2$)$_m$/(SiO$_2$)$_n$ laminate structure, as shown in Fig. 2, was deposited on the AlGaN surface via plasma-enhanced ALD at 300 $\degree$C using tetrakis(dimethylamino) hafnium and tris(dimethylamino) silane precursors, along with a gaseous oxygen plasma. The subscript indexes (m and n) indicate the numbers of ALD cycles for HfO$_2$ and SiO$_2$, respectively. In this study, we used $m = 2$ and $n = 1$, resulting in the Hf$_{0.57}$Si$_{0.43}$O$_x$ film. To obtain chemically stable hafnium silicate with an amorphous...
structure, we carried out PDA at 800 °C for 5 min in N₂. The specific permittivity and the thickness of Hf₀.₅₇S𝑖₀.₄₃Oₓ were 13 nm and 32 nm, respectively.

III. RESULTS AND DISCUSSION

Typical drain I–V characteristics of MOS HEMTs with Hf₀.₅₇S𝑖₀.₄₃Oₓ and Al₂O₃ gates are shown in Fig. 3. Both devices exhibited good I–V behavior. The transfer characteristics of MOS HEMTs are shown in Fig. 4(a). For comparison, their transfer curves are plotted as functions of gate overdrive voltage in excess of threshold voltage (V̂G − V̂TH), where V̂TH was defined as V̂G giving an I_D of 1 μA/mm. It was found that the Hf₀.₅₇S𝑖₀.₄₃Oₓ-gate HEMT showed a higher maximum g_m, as anticipated due to the higher κ of Hf₀.₅₇S𝑖₀.₄₃Oₓ than that of Al₂O₃. From the total capacitance of the insulator and AlGaN barrier in series, an 18% increase in g_m is expected for the Hf₀.₅₇S𝑖₀.₄₃Oₓ-gate HEMT. The result in Fig. 3(a) is in good agreement with the simple estimation.

Figure 4(b) shows the semi-log scale I_D–V_G characteristics. The Hf₀.₅₇S𝑖₀.₄₃Oₓ-gate HEMT showed a deeper V̂TH than the Al₂O₃-gate HEMT. In the case of the HfSIOₓ/GaN diode structure, the negative shift of the flatband voltage was observed in the C–V curve, probably owing to the existence of positive fixed charges in the HfSIOₓ film or near the HfSIOₓ/GaN interface. It is likely that a similar effect caused the deeper V̂TH for the HfSIOₓ-gate HEMT. For both devices, we observed low values of subthreshold swing (SS), indicating excellent gate controllability of the MOS HEMTs. In addition, both devices exhibited very low leakage currents, corresponding to “gate” leakage currents. This means extremely low “drain” leakage currents below the detection limit as a result of the high-quality HEMT structure are grown on the GaN substrate with a low dislocation density that prevents bulk leakage conduction. In fact, we observed a high on/off current ratio of around 5 × 10⁹.

To investigate interface state properties of HfSIOₓ/AlGaN and Al₂O₃/AlGaN structures, we carried out capacitance–voltage (C–V) characterization on MOS diodes fabricated on the same AlGaN/GaN heterostructures. A Ni circular gate with a diameter of 100 μm was prepared on oxide surfaces of the MOS diodes. C–V curves measured at frequencies of 1 kHz–1 MHz are shown in Fig. 5. Both diodes showed the two-step feature typically observed in C–V curves of HEMT-MOS structures, indicating good gate control of the AlGaN surface potential. In particular, an extremely small frequency dispersion was observed in C–V curves for the HfSIOₓ-gate HEMT, as evident in the enlarged view shown as the inset of Fig. 5(a). To evaluate the effects of interface states on the C–V characteristics quantitatively, we carried out a one-dimensional simulation with self-consistent Poisson–Schrödinger calculations for MOS HEMTs. The detailed simulation procedure is described in Ref. 21.

![FIG. 4](image1.png) (a) Transfer characteristics of MOS HEMTs with HfSIOₓ and Al₂O₃ gates. For comparison, transfer curves are plotted as functions of gate overdrive voltage in excess of threshold voltage (V̂G − V̂TH). (b) Semi-log scale I_D–V_G and I_G–V_G characteristics of MOS HEMTs.

![FIG. 5](image2.png) C–V curves measured at frequencies of 1 kHz–1 MHz for MOS diodes with (a) HfSIOₓ and (b) Al₂O₃ gates fabricated on AlGaN/GaN heterostructures. The insets show enlarged C–V curves.
In the calculation, we assumed interface state density \( (D_{it}) \) distributions consisting of acceptor- and donor-like states separated by the charge neutrality level. Physical parameters reported in Ref. 16 were used in the calculation. For the HfSiO\(_x\)-HEMT sample, in addition, we used 13.0 eV, 6.5 eV, and 1.1 eV as \( \kappa, E_G \), and the conduction band offset of the HfSiO\(_x\)/AlGaN interface,\(^{22,23} \) respectively.

An example of the fitting result for the HfSiO\(_x\)/AlGaN sample is shown in Fig. 6(a). The calculation well reproduced the experimental capacitance within the entire range of applied gate bias. From the best fit of the calculated and measured C–V curves, \( D_{it} \) distributions were estimated for both MOS-HEMT diodes. Figure 6(b) shows \( D_{it} \) distributions at Al\(_2\)O\(_3\)/AlGaN and HfSiO\(_x\)/AlGaN interfaces. In this case, we estimated electron emission time constants (\( \tau_e \)) from interface states to the conduction band at RT, using Shockley–Read–Hall (SRH) statistics.\(^{16,21} \) The calculation showed that electrons once captured at interface states at energies below \( E_C - 0.8 \text{ eV} \) remain trapped, owing to large \( \tau_e \) at RT, even when large negative bias is applied to the gate electrode. Then, we ruled out the possibility of such “frozen states” for the calculation fitting of experimental C–V results, as shown in Fig. 6(b).

The HfSiO\(_x\)/AlGaN interface showed low interface state densities in the order of \( 10^{11} \text{ cm}^{-2} \text{ eV}^{-1} \) almost throughout the given energy range. The minimum density is \( 2 \times 10^{11} \text{ cm}^{-2} \text{ eV}^{-1} \). This is consistent with extremely small frequency dispersion in C–V curves, as shown in Fig. 5(a). Hori et al.\(^{23} \) reported that interface states at energies close to \( E_C \) can respond to the ac measurement signal, resulting in a parasitic capacitance in addition to the true MOS capacitance. The lower ac frequency corresponds to the wider energy range of states, contributing to the larger parasitic capacitance. Moreover, the higher the density of interface states, the higher the degree of frequency dispersion in C–V curves.\(^{23} \) In the case of the HfSiO\(_x\)-HEMT diode, therefore, the negligibly small frequency dispersion shown in Fig. 5(a) also reflected low state densities at the HfSiO\(_x\)/AlGaN interface. It is likely that the PDA process at 800 \( ^\circ \text{C} \) is effective in recovering surface defects such as vacancies and in terminating dangling bonds with O atoms at the AlGaN surface.\(^{15,24} \)

The temperature dependence of transfer characteristics under \( V_{DS} = 15 \text{ V} \) is shown in Fig. 7. Although on-state drain current decreases with increasing temperature, mainly owing to the decrease in electron mobility,\(^{25,26} \) we observed smooth and steep subthreshold curves at high temperatures for the HfSiO\(_x\)-gate MOS HEMT. Even at 150 \( ^\circ \text{C} \), the MOS HEMT showed stable operation with the \( V_{TH} \) drift of only 150 mV from its RT value, indicating excellent gate controllability. In addition, the leakage current almost remained unchanged at high temperatures, well controlled by extremely low gate leakage currents close to the detection limit. This robust operation demonstrates the strong potential of the HfSiO\(_x\)-gate AlGaN/GaN HEMT for high-power applications.

**IV. CONCLUSION**

In summary, we carried out comparative characterization of AlGaN/GaN MOS HEMTs with HfSiO\(_x\)- and Al\(_2\)O\(_3\)-gate dielectrics. For the HfSiO\(_x\)-gate HEMT, the (HfO\(_2\))/(SiO\(_2\)) laminate structure was deposited on the AlGaN surface by plasma-enhanced ALD, followed by PDA at 800 \( ^\circ \text{C} \). This process realized an amorphous Hf\(_{0.57}\)Si\(_{0.43}\)O\(_x\) layer with \( \kappa = 13 \). The HfSiO\(_x\)-gate HEMT showed good transfer characteristics with high \( g_m \) expected from its \( \kappa \) value.
and a subthreshold swing of 71 mV/decade. From the corresponding MOS-HEMT diode, we observed excellent C–V characteristics with negligible frequency dispersion. The detailed C–V analysis using a self-consistent Poisson–Schrödinger calculation showed low state densities in the order of $10^{11} \text{cm}^{-2}\text{eV}^{-1}$ at the HfSiO$_x$/AlGaN interface. In addition, good operation stability of the HfSiO$_x$-gate HEMT was observed at high temperatures. Even at 150 °C, the HEMT showed a low leakage current of $1.0 \times 10^{-10} \text{A/mm}$ and a $V_{TH}$ drift of only 150 mV from its RT value. Thus, the present MOS technology using the HfSiO$_x$ gate leads to further progress of GaN MIS HEMTs as high-performance and reliable RF power transistors.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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