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Reactive evaporation of SiO_x films for passivation of GaN high-electron-mobility transistors

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Abstract — The surface passivation effects of silicon suboxide (SiO_x) prepared by the reactive evaporation of silicon monoxide in oxygen atmosphere on the performance of AlGaN/AlN/GaN high-electron-mobility transistors (HEMTs) have been investigated. SiO_x films with different oxygen contents (1.10 ≤ x ≤ 1.71) and root-mean-square (RMS) roughnesses (0.55 ≤ RMS ≤ 1.01 nm) were prepared under residual pressures from 1 × 10^-6 to 6 × 10^-4 Torr. Hall measurements revealed obvious increases in the product of sheet carrier concentration and electron mobility after the passivation. Accordingly, increases in drain current and transconductance were observed for all the SiO_x passivated HEMTs. Both the gate and drain leakage currents first decreased and then increased with the increase of oxygen content. The lowest gate leakage current was observed in the devices with SiO_{1.23}, passivation, and it was almost 20 times lower than that of the unpassivated devices. The same devices also exhibited the lowest current collapse and off-state drain current. The variations in leakage currents as a function of the residual pressure were found to correlate with the surface roughness of the passivation layer. Finally, the breakdown voltage of the SiO_{1.23} passivated HEMTs increased to 151 V, up from 99 V in unpassivated devices.

Keywords — reactive evaporation, SiO_x, passivation, GaN, HEMTs

1. INTRODUCTION

GaN high-electron-mobility transistors (HEMTs) have been extensively investigated for high-power, high-frequency, and high-voltage applications due to their wide band gap, high thermal stability, high electron saturation velocity, and high breakdown electrical field[1-4]. However, there are still some limitations to commercial applications of GaN HEMTs. For instance, the current collapse effect resulting from the surface trapping could have a severe effect on the device performance [5]. Surface passivation is a very effective solution to alleviate drain current collapse by reducing surface traps [6-8]. Therefore, strong interest has been directed towards development of passivation materials and processes in the past decade. Besides conventional passivation materials such as SiN_x and SiO_2 [9], other dielectrics like SiON [9, 10], Al2O3 [11-14], HfO2 [15-17], Sc2O3 [18, 19], and MgO [18, 20] prepared by plasma-enhanced chemical-vapour deposition (PECVD), sputtering, atomic-layer deposition (ALD), molecular-beam epitaxy (MBE) etc. have been studied. However, controversial results of the passivation effects have been published, probably resulting from different material properties and deposition processes. For example, an increase [21] as well as a decrease [9, 22] in the gate leakage current (I_{g leak}) after SiN_x passivation were reported. Large I_{g leak} is a main limiting factor in high power and high voltage applications of GaN HEMTs.

It has been demonstrated that the I_{g leak} is closely related to the off-state breakdown voltage (V_{br}) of HEMT devices [23]. PECVD and other above-mentioned techniques have common limitations of higher equipment cost and/or longer processing duration as compared with thermal evaporation. Furthermore, in commonly used PECVD and sputtering techniques, plasma damage or shallow ion implantation may occur during the device fabrication process, which could have detrimental effects on the electrical characteristics of GaN HEMTs [24, 25]. Due to the simple technique and being free of ion damage, thermally evaporated SiO has been used in many devices such as In-Ga-Zn-O thin-film transistors [24], self-switching diodes [26] and graphene field-effect transistors [27]. Recently, we have demonstrated that thermally evaporated SiO is a very promising passivation material for GaN HEMTs [28]. Besides enhancements in drain current and transconductance, I_{g leak} and off-state drain current (I_{off}) of the SiO passivated HEMTs decreased by more than two orders of magnitude compared with the devices passivated with PECVD grown SiN_x. Moreover, due to the reduction of leakage current [23], the SiO passivation enabled about two times higher breakdown voltage than in the device with standard SiN_x passivation.

Oxygen content in SiO_x films could be manipulated by changing the oxygen flow rate during the thermal evaporation of SiO [29]. This may have strong influence on the performance of SiO_x passivated GaN HEMTs, which is so far not studied. In this work, we investigate the surface passivation effect of SiO_x films reactively evaporated under different oxygen pressures on the performance of AlGaN/AlN/GaN HEMTs. Room-temperature Hall effect measurements, SiO_x film morphology and stoichiometry...
characterisations, and current-voltage measurements of HEMT devices with and without the passivation are performed. A large number of SiO$_x$ film properties and HEMT device performance parameters are found to closely depend on the residual oxygen pressure during the reactive evaporation, such as the SiO$_x$ film roughness, SiO$_x$ film stoichiometry, HEMT on-state and off-state drain currents, transconductance, etc. Apart from the improvements in drain current and transconductance, our results show that passivation with SiO$_{2.23}$ film resulted in a 20 times decrease in both $I_{\text{on}}$ and $I_{\text{off}}$ as well as a large increase in $V_{\text{th}}$ by 52 V. The study therefore demonstrates that reactively evaporated SiO$_x$ film may provide very effective surface passivation for GaN HEMTs, particularly for high power and noise sensitive applications.

2. DEVICE FABRICATION

The schematic cross-sectional view of our fabricated AlGaN/AlN/GaN HEMTs with SiO$_x$ passivation is shown in Fig. 1. The source-drain spacing ($L_{\text{sd}}$) and gate-drain spacing ($L_{\text{gd}}$) of the devices are 13 and 6 µm, respectively. The gate length ($L_g$) is 2 µm and gate width ($W_g$) is 100 µm. The AlGaN/AlN/GaN heterostructure was grown on a 2-in.-diameter SiC substrate by a metal-organic chemical-vapour deposition (MOCVD) system. The epi-layers used in this study consist of a 100 nm AlN nucleation layer, a 1.8 µm semi-insulating GaN layer, a 1 nm AlN interlayer and a 25 nm unintentionally doped AlGaN layer with an Al content of 22%. Hall effect measurements at room temperature revealed a sheet carrier density ($n_s$) of $9.4 \times 10^{12}$ cm$^{-2}$, a sheet resistance of 290 Ω/Sq and a carrier mobility ($\mu$) of 1850 cm$^2$/V·s$^{-1}$. The device fabrication process started with mesa isolation using BCl$_3$/Cl$_2$ plasma-based inductively coupled plasma reactive ion etching (ICP-RIE). The source and drain Ohmic contacts (Ti/Al/Ni/Au: 30/150/50/80 nm) were formed by electron-beam evaporation, and subsequently alloyed by rapid thermal annealing at 880 °C for 50 s in nitrogen ambient. The contact resistivity was $3.0 \times 10^{-6}$ Ω·cm$^2$ measured using the transmission-line method at room temperature. The Schottky gate (Ni/Au: 50/80 nm) was also achieved using electron-beam evaporation. Finally, a 100 nm SiO$_x$ passivation layer was deposited on the surface of the HEMTs by reactive thermal evaporation in low-pressure oxygen. All device patterns were defined by conventional photo-lithography and lift-off processes. Before the metal or SiO$_x$ film depositions, the AlGaN surface was cleaned by HCl solution.

The SiO$_x$ films were obtained by thermal evaporation of high purity (99.99%) SiO powders in a tungsten boat. The deposition rate was monitored by a quartz microbalance. The thickness of SiO$_x$ films was 100 nm, deposited at a constant rate of 2 Å/s. The background pressure in the thermal evaporator chamber was $1 \times 10^{-6}$ Torr if no oxygen was intentionally introduced. The residual pressure increased when introducing a small amount of oxygen gas. Five samples were fabricated under different residual pressures. Sample A was deposited at $1 \times 10^{-6}$ Torr without intentionally introduced oxygen. The other samples were produced in oxygen ambient with sample B at $1 \times 10^{-5}$ Torr, sample C at $5 \times 10^{-5}$ Torr, sample D at $1 \times 10^{-4}$ Torr, and sample E at $6 \times 10^{-4}$ Torr, respectively. The surface morphology and roughness of the SiO$_x$ films were studied by a Benyuan CSPM5500 atomic-force microscope (AFM). The oxygen content (x) of the SiO$_x$ films was determined by an Energy Dispersive X-ray Spectroscope (EDS) attached to an FEI Nova NanoSEM450 scanning electron microscope (SEM). Hall measurements were performed using the Van der Pauw technique at room temperature. The DC and pulsed characteristics of the HEMTs were measured using a Keysight (Agilent) B2902A Precision Source/Measurement Unit at room temperature.

3. RESULTS AND DISCUSSION

To clarify the influence of residual pressure on the film properties, we first characterised the SiO$_x$ films deposited under different pressures. The surface morphologies obtained by AFM are shown in Fig. 2 and the roughness values are given in Table I, which summarises the main measurement results of our study. The AFM scan area is 5 µm × 5 µm. The SiO$_x$ film evaporated with no additional oxygen (sample A) has a smooth surface with a root-mean-square (RMS) roughness of 0.55 nm. This value is similar to that of thermally oxidised SiO$_2$ [1] but smaller than typical sputtered SiO$_2$ [31] or PECVD
molecule collisions inside the evaporator chamber due to the introduction of oxygen molecules in the evaporation.

Nevertheless, it should be noted that the SiOₓ film roughness in all samples is relatively small.

The dependence of oxygen content (x) determined by EDS on the residual oxygen pressure is shown in Fig. 3. The x value of the SiOₓ film deposited with no intentionally introduced oxygen is 1.10. By changing the oxygen pressure in the chamber, films with varied stoichiometry up to x = 1.71 are produced. This is due to the oxidization of SiO by the introduced oxygen in the growth process [29].

Figure 4 illustrates the dependence of nₛ and µₓ of the two-dimensional gas (2DEG) in the AlGaN/AlN/GaN heterostructure on the residual oxygen pressure during the evaporation of the SiOₓ films. In the unpassivated sample, nₛ is 9.40 × 10¹² cm⁻². After the SiOₓ passivation, nₛ increases and ranges from 9.80 × 10¹² to 1.08 × 10¹³ cm⁻². The increase in the 2DEG density could be due to reduced surface traps by the passivation. Another factor may be passivation induced stress in the AlGaN layer which changes the piezoelectric polarization in the AlGaN/AlN/GaN heterostructure [33, 34].

The Hall measurements also indicate that the electron mobility ²µₓ slightly drops from 1850 cm²·V⁻¹·s⁻¹ in the unpassivated sample to 1795 - 1818 cm²·V⁻¹·s⁻¹ after the SiOₓ passivation. This is likely due to the increased...
interface-roughness scattering and increased Coulomb scatterings in the 2DEG with higher electron sheet concentrations [35, 36]. Overall, a larger product of $n_s \mu_n$ in all passivated samples (A, B, C, D and E) as compared to the unpassivated sample has been obtained, implying improved electron conduction characteristics in the SiO$_x$ passivated HEMTs.

The output characteristics in DC and pulsed modes as well as the DC-transfer characteristics of the HEMTs before and after the SiO$_x$ passivation (evaporated at $1 \times 10^{-5}$ Torr) are shown in Fig. 5. The drain current versus drain voltage ($I_{ds}$-$V_{ds}$) characteristics were measured at the gate bias ($V_{gs}$) ranging from +1 V to -4 V. Increases in the maximum drain current ($I_{dmax}$) and transconductance ($g_m$) by 13\% and 20\% for the passivated device are obtained when compared with the unpassivated HEMT. The $I_{dmax}$ of the device without passivation is 345 mA·mm$^{-1}$ and increases to 390 mA·mm$^{-1}$ after SiO$_x$ passivation (at residual pressure of $1 \times 10^{-5}$ Torr), as shown in Fig. 5(a). The observed increase in carrier concentration following the deposition of SiO$_x$ passivation layer may be the key factor for the reduction in the source-drain series resistance and increase in the drain current [37]. Figure 5(a) also illustrates the methodology to determine the on resistance $R_{on}$ and knee voltage $V_k$. The passivated device shows a knee voltage of 3.0 V and an on resistance of 7.5 $\Omega$·mm, much lower than those of the unpassivated device (3.4 V, 9.8 $\Omega$·mm) as shown in Fig. 5(a).

The pulsed $I_{ds}$-$V_{ds}$ curves in Fig. 5(b) were measured with a pulse width of 50 $\mu$s and a pulse period of 100 ms under quiescent biases of $V_{gs} = -5$ V and $V_{ds} = 0$ V. In comparison, the unpassivated device shows a drastic drain current collapse (28.2\% decrease in $I_{dmax}$) while the HEMT passivated with film B (evaporated at $1 \times 10^{-5}$ Torr) has a much smaller

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**Fig. 5.** (a) DC, (b) pulsed output characteristics and (c) DC-transfer characteristics of the AlGaN/AlN/GaN HEMTs before and after the SiO$_x$ passivation thermally evaporated at $1 \times 10^{-5}$ Torr. The pulse width and pulse period were 50 $\mu$s and 100 ms, respectively.
collapse (11.5%). The improvement can be explained by the reduction of surface traps discussed above [38]. The current collapse effect has also been alleviated by different degrees in other passivated devices as shown in Table I. Similarly, \( g_m \) (at \( V_{ds} = 10 \, \text{V} \)) calculated from the DC-transfer characteristic also improves from 116 mS mm\(^{-1} \) in the unpassivated device to 139 mS mm\(^{-1} \) in device with SiO\(_x\) passivation as shown in Fig. 5(c) and Table I. In addition, the threshold voltage \( V_{th} \) of the passivated HEMTs decreases as compared to the unpassivated devices (also see Table I) due to the increased 2DEG concentration after SiO\(_x\) passivation [9, 39].

![Graph](image)

**Fig. 6.** Variations of maximum drain current (at \( V_{gs} = 1 \, \text{V} \) and off-state (at \( V_{gs} = -6 \, \text{V}, V_{ds} = 10 \, \text{V} \)) drain current of AlGaN/AlN/GaN HEMTs with SiO\(_x\) passivations thermally evaporated at different residual pressures.

The changes in the maximum drain current (at \( V_{gs} = 1 \, \text{V} \) and off-state drain current (at \( V_{gs} = -6 \, \text{V}, V_{ds} = 10 \, \text{V} \)) in HEMTs with SiO\(_x\) passivation evaporated at different residual pressures are illustrated in Fig. 6. The values are the averages of three devices fabricated under the same condition and the error-bars show the standard deviation of the measurements. The improvement of \( I_{d\text{max}} \) varies among the different samples with different SiO\(_x\) passivations, which may be attributed to factors including the different surface trap state densities, different amount of stress in the AlGaN layer and varied SiO\(_x\)/AlGaN interface stoichiometry due to the passivation under different deposition conditions [40, 41]. It should be mentioned that \( I_{d\text{max}} \) of all SiO\(_x\) passivated devices has increased by some extent, which correlates to the improved \( n_s \) in all passivated samples as compared to the unpassivated sample [42-44].

The off-state and leakage characteristics of the HEMTs are often as important as the on-state characteristics for high power and low noise applications [45, 46]. For instance, a correlation is known between the off-state drain current (or drain leakage current) \( I_{off} \), the gate leakage current \( I_{\text{g\text{leak}}} \) and the breakdown voltage \( V_{br} \) [23]. Figure 6 shows the dependence of \( I_{off} \) on the residual pressure. Clearly, the drain leakage current in most passivated HEMTs is suppressed except in thefilm E passivated devices where the SiO\(_x\) roughness is the highest. \( I_{off} \) of SiO\(_x\) (sample B) passivated HEMTs decreases by almost a factor of 20 as compared to the unpassivated devices, which is significant. The difference in \( I_{off} \) among the HEMTs may be caused by different densities of surface traps, SiO\(_x\) roughnesses, and/or activation energies of the electron hopping conduction at the device surface [47].

![Graph](image)

**Fig. 7.** Variations of gate leakage current (at \( V_{gs} = -5 \, \text{V} \) and off-state (at \( V_{gs} = -6 \, \text{V} \)) breakdown voltage of AlGaN/AlN/GaN HEMTs with SiO\(_x\) passivations thermally evaporated at different residual pressures.

**Table II**

<table>
<thead>
<tr>
<th>Variation (%)</th>
<th>( \Delta g_m )</th>
<th>( \Delta I_{d\text{max}} )</th>
<th>( \Delta V_{th} )</th>
<th>( \Delta I_{off} )</th>
<th>( \Delta g )</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>20</td>
<td>13</td>
<td>53</td>
<td>-2000</td>
<td>-2000</td>
</tr>
</tbody>
</table>
| Reference    | Ref.[44]: Ref[44]: USPD\(^{*}\) Al\(_2\)O\(_3\)
|              | PECVD-SiN\(_x\)|             |                |                |                |

\(^{*}\)USPD stands for ultrasonic spray pyrolysis deposition.

In addition to the drain leakage current, the dependence of the two-terminal (gate-source) gate leakage current (at \( V_{gs} = -5 \, \text{V} \)), \( I_{\text{g\text{leak}}} \), on the residual pressure has also been investigated. During the measurements, the source and drain were grounded and the gate current was measured as a function of the reverse gate bias. As shown in Fig. 7, a significant difference in the gate leakage current has been observed. Similar to the off-state drain current, the film B passivated devices exhibit the best gate leakage current characteristic. \( I_{\text{g\text{leak}}} \) is nearly 20 times lower than that of the unpassivated HEMTs, which indicates a higher breakdown voltage [23]. However, the \( I_{\text{g\text{leak}}} \) of the film E passivated HEMTs rises by almost one order of magnitude. Such a trend has also been observed in SiO\(_2\) passivated HEMTs by others [9, 48] and it will have implications for increased radio-frequency (RF) noise and reduced breakdown voltage. The surface passivation effects on the gate leakage observed for SiO\(_x\) films are believed to be related to the density of interface traps between the passivation layer and the AlGaN surface [49]. It has been demonstrated that the surface related traps with an activation energy of 0.21 eV can lead to gate leakage in GaN HEMTs [47], and surface traps can be influenced by the different passivations and/or different process conditions. Lugani et al. [50] proposed that the existence of trap assisted tunnelling can be a possible mechanism of the gate leakage current. In this study, the variation of \( I_{\text{g\text{leak}}} \) may be influenced by the interface traps...
related to different SiO$_x$ roughnesses since a larger roughness may lead to larger densities of the gate leakage related interface traps [51, 52]. Moreover, oxygen vacancies in the SiO$_x$ films may act as the current leakage paths. It has been reported that adding oxygen in the sputtering gas can improve the oxide quality by introducing oxygen atoms into the film to reduce oxygen vacancies [53]. Therefore, the variation of $I_{\text{leak}}$ in our study may be explained by the combined effect of roughness and oxygen vacancies of SiO$_x$. The oxygen vacancies play a key role at low residual pressures below $1 \times 10^{-5}$ Torr, while the influence of roughness becomes dominant under higher residual pressures.

The off-state breakdown characteristics of the HEMTs with different SiO$_x$ passivations have been measured as shown in Fig. 7. The gate was biased at -6 V to fully pinch off the conducting channel. In order not to destroy the devices, the compliance drain current density was set to 1 mA mm$^{-1}$. A trend closely related to the variations of $I_{\text{off}}$ and $I_{\text{leak}}$ has been obtained in $V_{\text{br}}$. The film B passivated devices exhibit the highest $V_{\text{br}}$ (151 V) when compared with the unpassivated (99 V), films A (138 V), C (143 V), D (124 V), and E (87 V) passivated HEMTs, which correlates to their lowest leakage currents. It has been demonstrated that the gate leakage is closely related to the off-state breakdown voltage of GaN HEMTs [23]. The improvements of breakdown voltage in most of the passivated HEMTs are largely due to the passivation of surface trapping centers [39]. $V_{\text{br}}$ of film E passivated HEMTs reduces nearly 12% as compared with the unpassivated devices, which is also in good agreement with their highest leakage currents most likely due to the largest SiO$_x$ film roughness.

Table II compares the results of SiO$_{1.23}$ passivated devices in this work and the typical values published on GaN HEMTs with other passivations in literature. Even though the values of $\Delta g_m$, $\Delta V_{\text{th}}$, and $\Delta V_{\text{fs}}$ for our devices are slightly lower [44], the values of $\Delta I_{\text{on}}$ and $\Delta I_{\text{c}}$ for our SiO$_{1.23}$ passivated devices are nearly two times lower than the reported values [9], which may be due to the low ion damage and low temperature process of thermal evaporation.

4. CONCLUSION

In conclusion, we have investigated the suitability of SiO$_x$ films reactively evaporated under different oxygen pressures for surface passivation of AlGaN/AlN/GaN HEMTs. Both the oxygen content and surface roughness of SiO$_x$ films varied significantly with the oxygen pressure. Due to the reduction of surface traps and possibly introduced changes in stress and piezoelectric polarization in the AlGaN layer caused by the SiO$_x$ passivation, a large product of $I_{\text{on}}$-$g_m$ was obtained across all passivated samples. Accordingly, obvious increases in $I_{\text{th}}$ and $g_m$ were observed. The devices passivated with SiO$_x$ deposited at $1 \times 10^{-5}$ Torr, i.e. SiO$_{1.23}$, showed the lowest current collapse, lowest leakage currents as well as the best breakdown characteristics in comparison with other samples. Both $I_{\text{off}}$ and $I_{\text{leak}}$ decreased by a factor of ~20 and $V_{\text{fs}}$ increased by 52 V when compared with the unpassivated HEMTs. The reactively evaporated SiO$_x$ is therefore shown to be capable of providing promising low-damage surface passivation for GaN HEMTs by not only enhancing the output characteristics but also suppressing the leakage currents and increasing the breakdown voltage.

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