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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 AlGaIn/GaN high-electron-mobility transistors (HEMTs) have been investigated. SiO_x films with different oxygen contents ($1.10 \leq x \leq 1.71$) and root-mean-square (RMS) roughnesses ($0.55 \leq \text{RMS} \leq 1.01$ 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 SiO₂ [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 ($I_{\text{g leak}}$) after SiN_x passivation were reported. Large $I_{\text{g leak}}$ is a main limiting factor in high power and high voltage applications of GaN HEMTs.

It has been demonstrated that the $I_{\text{g leak}}$ 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, $I_{\text{g leak}}$ 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 AlGaIn/GaN HEMTs. Room-temperature Hall effect measurements, SiO_x film morphology and stoichiometry

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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 $\text{SiO}_{1.23}$ film resulted in a 20 times decrease in both $I_{\text{g leak}}$ and I_{off} as well as a large increase in V_{br} 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 AlGaIn/AlN/GaN HEMTs with SiO_x passivation is shown in Fig. 1. The source-drain spacing (L_{sd}) and gate-drain spacing (L_{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 AlGaIn/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 AlGaIn layer with an Al content of 22%. Hall effect measurements at room temperature revealed a sheet carrier density (n_s) of $9.4 \times 10^{12} \text{ cm}^{-2}$, a sheet resistance of 290 Ω/Sq and a carrier mobility (μ_n) of 1850 $\text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$. 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 $^\circ\text{C}$ for 50 s in nitrogen ambient. The contact resistivity was $3.0 \times 10^{-6} \Omega \cdot \text{cm}^2$ 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 AlGaIn 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 $\text{\AA}/\text{s}$. The background pressure in the thermal evaporator chamber was 1×10^{-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 1×10^{-6} Torr without intentionally introduced oxygen. The other samples were produced in oxygen ambient with sample B at 1×10^{-5} Torr, sample C at 5×10^{-5} Torr,

sample D at 1×10^{-4} Torr, and sample E at 6×10^{-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 Spectroscopy (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.

Fig. 1. Schematic cross-section of AlGaIn/AlN/GaN HEMTs with SiO_x passivation.

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 $5 \mu\text{m} \times 5 \mu\text{m}$. 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 [30] but smaller than typical sputtered SiO_2 [31] or PECVD

TABLE I

SUMMARY OF THE EXPERIMENTAL RESULTS

Sample	Un-passivated	A	B	C	D	E
Pressure (Torr)	N/A ^a	1×10^{-6}	1×10^{-5}	5×10^{-5}	1×10^{-4}	6×10^{-4}
n_s (10^{12} cm^{-2})	9.4	10.8	10.7	9.8	9.9	10.3
μ_n ($\text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$)	1850	1795	1810	1818	1815	1810
Oxygen content (x)	N/A	1.10	1.23	1.41	1.54	1.71
RMS (nm)	N/A	0.55	0.56	0.62	0.83	1.01
Current collapse (%)	28.2	13.6	11.5	20.2	25.7	28.1
g_m ($\text{mS} \cdot \text{mm}^{-1}$)	116	137	139	133	123	120
V_{th} (V)	-3.25	-3.50	-3.53	-3.30	-3.41	-3.48
ΔI_{dmax} (%)	N/A	19	13	3	3	10
ΔI_{off} (%)	N/A	-1000	-2000	-1700	-1400	280
ΔI_g (%)	N/A	-1000	-2000	-1800	-500	800
V_{br} (V)	99	138	151	143	124	87

^aN/A stands for not applicable.

grown SiO_x [32] in the literature. Figure 3 summarises the change of RMS roughness as a function of the residual pressure. The RMS roughness first increases gradually from 0.55 to 0.62 nm as the residual pressure increases from 1×10^{-6} to 5×10^{-5} Torr, and then rapidly to 1.01 nm by further increases of the residual pressure to 1×10^{-4} and 6×10^{-4} Torr (samples D and E). Accordingly, some larger particles can be observed in Fig. 2(c), (d), and (e). Particularly, the RMS roughness for the SiO_x film prepared at 6×10^{-4} Torr (sample E) is as high as 1.01 nm, nearly twice that of sample A. The increased surface roughnesses may be related to the increased molecule collisions inside the evaporator chamber due to the introduction of oxygen molecules in the evaporation.

Nevertheless, it should be noted that the SiO_x 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 SiO_x 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 oxidation of SiO by the introduced oxygen in the growth process [29].

Figure 4 illustrates the dependence of n_s and μ_n of the two-dimensional gas (2DEG) in the AlGaIn/GaN heterostructure on the residual oxygen pressure during the evaporation of the SiO_x films. In the unpassivated sample, n_s is $9.40 \times 10^{12} \text{ cm}^{-2}$. After the SiO_x passivation, n_s increases and ranges from 9.80×10^{12} to $1.08 \times 10^{13} \text{ cm}^{-2}$. 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 AlGaIn layer which changes the piezoelectric polarization in the AlGaIn/GaN heterostructure [33, 34].

The Hall measurements also indicate that the electron mobility μ_n slightly drops from $1850 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ in

Fig. 3. Oxygen content (x) and root-mean-square roughness of the SiO_x films thermally evaporated at different residual pressures.

Fig. 4. 2DEG sheet concentration and Hall mobility of AlGaIn/GaN heterostructures with SiO_x films thermally evaporated at different residual pressures (Sample A: 1×10^{-6} Torr, B: 1×10^{-5} Torr, C: 5×10^{-5} Torr, D: 1×10^{-4} Torr, E: 6×10^{-4} Torr).

unpassivated sample to $1795 - 1818 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ after the SiO_x 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 $n_s \cdot \mu_n$ 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 1×10^{-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 $345 \text{ mA} \cdot \text{mm}^{-1}$ and increases to $390 \text{ mA} \cdot \text{mm}^{-1}$ after SiO_x passivation (at residual pressure of 1×10^{-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

Fig. 5. (a) DC, (b) pulsed output characteristics and (c) DC-transfer characteristics of the AlGaIn/AlN/GaN HEMTs before and after the SiO_x passivation thermally evaporated at 1×10^{-5} Torr. The pulse width and pulse period were 50 μs and 100 ms, respectively.

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 $\Omega \cdot \text{mm}$, much lower than those of the unpassivated device (3.4 V, 9.8 $\Omega \cdot \text{mm}$) 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 μs 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 1×10^{-5} Torr) has a much smaller

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 $V_{ds} = 10$ V) calculated from the DC-transfer characteristics also improves from $116 \text{ mS}\cdot\text{mm}^{-1}$ in the unpassivated device to $139 \text{ mS}\cdot\text{mm}^{-1}$ in device with $\text{SiO}_{1.23}$ 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].

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

The changes in the maximum drain current (at $V_{gs} = 1$ V) and off-state drain current (at $V_{gs} = -6$ V, $V_{ds} = 10$ 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_{dmax} 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 AlGaIn layer and varied $\text{SiO}_x/\text{AlGaIn}$ interface stoichiometry due to the passivation under different deposition conditions [40, 41]. It should be mentioned that I_{dmax} of all SiO_x passivated devices has increased by some extent, which correlates to the improved $n_s \cdot \mu_n$ 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 $I_{g leak}$ 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 the film E passivated devices where the SiO_x roughness is the highest. I_{off} of $\text{SiO}_{1.23}$ (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].

Fig. 7. Variations of gate leakage current (at $V_{gs} = -5$ V) and off-state (at $V_{gs} = -6$ V) breakdown voltage of AlGaIn/AlN/GaN HEMTs with SiO_x passivations thermally evaporated at different residual pressures.

TABLE II
COMPARISON OF DEVICE CHARACTERISTICS

Variation (%)	Δg_m	ΔI_{dmax}	ΔV_{br}	ΔI_{off}	ΔI_g
This work	20	13	53	-2000	-2000
	24	34	56	-1000	-1000
Reference	Ref.[44]: USPD ^b - Al_2O_3	Ref.[44]: PECVD- SiN_x	Ref.[9]: PECVD- SiN_x		

^bUSPD 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 $V_{gs} = -5$ V), $I_{g leak}$, 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. $I_{g leak}$ is nearly 20 times lower than that of the unpassivated HEMTs, which indicates a higher breakdown voltage [23]. However, the $I_{g leak}$ 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 AlGaIn 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 $I_{g leak}$ 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_{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 1×10^{-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 $1 \text{ mA} \cdot \text{mm}^{-1}$. A trend closely related to the variations of I_{off} and I_{leak} has been obtained in V_{br} . The film B passivated devices exhibit the highest V_{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_{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 $\text{SiO}_{1.23}$ passivated devices in this work and the typical values published on GaN HEMTs with other passivations in literature. Even though the values of Δg_m , ΔI_{dmax} , and ΔV_{br} for our devices are slightly lower [44], the values of ΔI_{off} and ΔI_g for our $\text{SiO}_{1.23}$ 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 AlGaIn/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 AlGaIn layer caused by the SiO_x passivation, a larger product of $n_s \mu_n$ was obtained in all passivated samples. Accordingly, obvious increases in I_{dmax} and g_m were observed. The devices passivated with SiO_x deposited at 1×10^{-5} Torr, i.e. $\text{SiO}_{1.23}$, showed the lowest current collapse, lowest leakage currents as well as the best breakdown characteristics in comparison with other samples. Both I_{off} and I_{leak} decreased by a factor of ~ 20 and V_{br} 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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