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Performance enhancement of AlGaN/AlN/GaN high electron mobility transistors by thermally evaporated SiO passivation

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A surface passivation technique has been developed for AlGaN/AlN/GaN high electron mobility transistors (HEMTs) by simple thermal evaporation of silicon monoxide (SiO) at room temperature. Detailed device characteristics were studied and compared with the most commonly used SiN_x passivation grown by plasma enhanced chemical vapor deposition at elevated temperatures. Both passivation techniques lead to similar enhancement in on-state drain current and transconductance as compared with the unpassivated HEMTs. However, we discovered that the gate leakage current in SiO passivated devices was more than two orders of magnitude lower than the devices passivated by SiN_x. Furthermore, while SiN_x passivated HEMTs exhibited a two orders of magnitude increase in off-state drain current, SiO passivation substantially reduced it, resulting in an overall improvement by a factor of 1429. The extent of device surface damage caused by passivation was also investigated by characterizing other parameters. The subthreshold slope of SiO passivated HEMTs was 95 mV·dec⁻¹, nearly 5 times better than SiN_x passivated devices. The extracted interface trap density was $1.16 \times 10^{12} \text{ cm}^{-2} \text{ eV}^{-1}$, about ten times lower than that in SiN_x passivated HEMTs. Moreover, SiO passivation was found to enhance the gate Schottky barrier height by 60 meV whereas SiN_x passivation reduced it, which could partially explain the differences in gate leakage current. Finally, SiO passivation enabled twice high breakdown voltage than SiN_x passivation. The relevant physical mechanisms were discussed.

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AlGaIn/GaN high electron mobility transistors (HEMTs) have great advantages in high power density, high frequency, and high voltage applications¹⁻³. However, there are still some performance issues in GaN-based HEMTs, one of which is the well-known current collapse⁴, which refers to a significant reduction in the drain current when measured under large amplitude high-frequency gate swings. This phenomenon can be described by the concept of “virtual gate”⁵. Surface passivation is usually applied to suppress drain current collapse by reducing surface state densities⁶. In recent years, the passivation effects of different dielectrics like SiN_x^{7,8}, SiO₂^{7,9}, SiON⁷, Al₂O₃¹⁰, Sc₂O₃¹¹, AlN¹², and MgCaO¹³ deposited by plasma enhanced chemical vapor deposition (PECVD), sputtering, electron-beam evaporation, atomic layer deposition (ALD) etc. have been studied. Sputtering has been found to commonly induce surface damage due to the high sputtering power¹⁴. The process of electron-beam evaporation is complex and expensive. Despite ALD yields good quality materials, the slow growth rate prevents it from being widely used in preparation of passivation layers. So far, SiN_x grown by PECVD is the most commonly used passivation technique for GaN-based HEMTs. It is typically deposited at temperatures of approximately 300 °C before or after the formation of gate in the HEMT fabrication process. Since the active layer is very thin, any plasma damage or shallow ion implantation may affect the electrical characteristics of GaN HEMTs.

Despite that drain current collapse can be mitigated to a certain extent, published data on GaN-based HEMTs performance after passivation show many controversial results. For example, an increase¹⁵ as well as a decrease⁷ of gate leakage current (I_g) after SiN_x passivation was reported. High gate leakage current is the other major limiting factor in GaN-based HEMTs applications. Reducing gate leakage is very important for GaN-based HEMTs in noise sensitive applications, and closely related to the off-state breakdown voltage (V_b) of high power and high voltage HEMT devices¹⁶, both of which were considered to be sensitive to the method of surface preparation¹⁷. Compared with PECVD and other techniques, thermal evaporation has many advantages such as no ion damage^{14, 16, 18, 19}, technical simplicity, and low cost. SiO has a higher dielectric constant K (5.0) and a similar breakdown field strength E_b (10 MV/cm) as compared with SiO₂ ($K = 3.9$, $E_b = 10$ MV/cm), which makes it an attractive material in the semiconductor fabrication. Thermally evaporated

SiO has been used in In-Ga-Zn-O thin-film transistors (IGZO TFTs)¹⁴, organic light-emitting diode (OLED)²⁰, graphene optical devices²¹ etc. However, to date very little work has been carried out on the study of surface passivation of GaN-based HEMTs with thermally evaporated SiO. In particular, the impact of thermally evaporated SiO on the breakdown and RF characteristics of GaN-based HEMTs has not been reported yet.

In this letter, we have investigated the influence of thermally evaporated SiO on the performance of AlGaN/AlN/GaN HEMTs and compared with SiN_x deposited by PECVD. The room-temperature Hall effect measurements, DC characteristics and RF performance of the HEMT devices with and without passivation are analyzed in detail. Apart from the expected improved drain current and transconductance, our SiO passivation has resulted in a one order of magnitude decrease in both I_g and I_{off} , demonstrating that thermally grown SiO is a very promising passivation material for GaN-based HEMTs.

The AlGaN/AlN/GaN heterostructure was grown on 2-inch-diameter 6H-SiC using metal-organic chemical vapor deposition (MOCVD). The epi-layers consisted 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 Al content of 22%. Hall effect measurements at room temperature revealed a sheet carrier density (n_s) of $1.05 \times 10^{13} \text{ cm}^{-2}$, a sheet resistance of 298 Ω/Sq and a carrier mobility (μ_n) of $1810 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$. The device fabrication process started with inductively coupled plasma reactive ion etching (ICP-RIE) for device isolation using BCl_3/Cl_2 gas mixture. Then, Ti/Al/Ni/Au (30/150/50/60 nm) source and drain ohmic contacts were defined by conventional lithography and electron-beam evaporation, and subsequently alloyed using rapid thermal annealing (RTA) at 900 °C for 50 s in the nitrogen ambient. The measured ohmic contact resistivity ρ_c was $3.0 \times 10^{-6} \Omega \cdot \text{cm}^2$ using the transmission-line method (TLM) at room temperature. The Ni/Au (50/60 nm) Schottky gate was also achieved by conventional lithography and e-beam evaporation. And then, a 100-nm-thick SiO passivation layer was deposited on the surface of HEMTs by conventional lithography, thermal evaporation and subsequent lift-off processes. As a comparison, a 100-nm-thick SiN_x passivation layer was deposited on the same sample by PECVD at 300 °C. Openings of contact pads were made by ICP etching to enable on-wafer measurements. The schematic cross-section of our device is shown in Fig. 1(a). The dimensions of the devices

used in this study are as follows: $L_g/L_{sd}/L_{gd}/W_g = 2/13/6/100$ μm . The DC characteristics of the HEMTs were measured using a Keysight (Agilent) B2902A Precision Source/Measure Unit at room temperature. RF characteristics of the devices were examined by S-parameter measurements using a Keysight (Agilent) N5247A PNA Vector Network Analyzer at room temperature.

TABLE I. Summary of measurement results.

Sample	Unpassivated	SiO	SiN _x
n_s [10^{13}cm^{-2}]	1.05	1.25	1.32
μ_n [$\text{cm}^2\cdot\text{V}^{-1}\cdot\text{s}^{-1}$]	1810	1760	1690
$I_{D\text{max}}$ [$\text{mA}\cdot\text{mm}^{-1}$]	309	369	385
g_m [$\text{mS}\cdot\text{mm}^{-1}$] @ $V_{DS} = 10$ V	116	137	144
I_{off} [$\text{mA}\cdot\text{mm}^{-1}$] @ $V_{GS} = -5$ V	2.0×10^{-3}	2.1×10^{-4}	3.0×10^{-1}
$I_{\text{on}}/I_{\text{off}}$	1.5×10^5	1.8×10^6	1.3×10^3
SS [$\text{mV}\cdot\text{dec}^{-1}$]	181	95	447
D_{it} [$10^{12}\text{cm}^{-2}\cdot\text{eV}^{-1}$]	3.76	1.16	11.30
I_g [$\text{mA}\cdot\text{mm}^{-1}$] @ $V_{GS} = -5$ V	3.3×10^{-3}	3.3×10^{-4}	4.1×10^{-2}
n	1.77	1.75	1.83
Φ_B [eV]	0.79	0.85	0.73
V_b [V] @ $V_{GS} = -5$ V	175	206	111
f_T [GHz] @ $V_{DS} = 10$ V, $V_{GS} = 0$ V	4.0	5.2	5.8

The n_s and μ_n measured before and after passivation at room temperature are shown in Table I, which summarizes the main measurement results of our study. The n_s of the unpassivated sample is $1.05 \times 10^{13} \text{ cm}^{-2}$, which increases to 1.25×10^{13} and $1.32 \times 10^{13} \text{ cm}^{-2}$ after passivated with SiO and SiN_x, respectively. This indicates that the electron trapping by the surface states at the device surface has been alleviated by passivation. On the other hand, the electron mobility decreases from 1810 to 1760 and 1690 $\text{cm}^2\cdot\text{V}^{-1}\cdot\text{s}^{-1}$ after passivated with SiO and SiN_x, respectively, possibly due to the enhanced Coulomb scattering in the 2-DEG channel with a higher electron sheet concentration. As a whole, a larger product of $n_s\cdot\mu_n$ in the conducting channel for passivated HEMTs relative to the unpassivated HEMTs has been obtained, indicating better electron conduction characteristics for the passivated HEMTs.

Fig.1. (a) Schematic cross-section of AlGaIn/AlN/GaN HEMTs. (b) Output and (c) transfer characteristics of unpassivated, SiO passivated and SiN_x passivated AlGaIn/AlN/GaN HEMTs.

The typical output and transfer characteristics of the unpassivated, SiO passivated and SiN_x passivated AlGaIn/AlN/GaN HEMTs are displayed in Fig. 1(b) and (c), respectively. The drain current versus drain voltage (I_{DS} - V_{DS}) characteristics were measured with the gate bias (V_{GS}) ranged from +1 V to -4 V ($\Delta V_{GS} = 1$ V). Increases in the maximum drain current (I_{Dmax}) and transconductance (g_m) of 19% and 18% for SiO, and 25% and 24% for SiN_x passivated HEMTs, respectively, are obtained when compared with the unpassivated HEMTs (see Table I). The I_{Dmax} of the devices without passivation is $309 \text{ mA} \cdot \text{mm}^{-1}$ and increases to 369 and $385 \text{ mA} \cdot \text{mm}^{-1}$ after passivated with SiO and SiN_x, respectively, as shown in Fig. 1(b), which corresponds well to the larger product of $n_s \cdot \mu_n$ in the 2-DEG channel of the passivated HEMTs as indicated by Hall data. Similarly, the g_m (at $V_{DS} = 10$ V) of the unpassivated devices increases from $116 \text{ mS} \cdot \text{mm}^{-1}$ to 137 and $144 \text{ mS} \cdot \text{mm}^{-1}$ after passivated with SiO and SiN_x, respectively, as shown in Fig. 1(c), which clearly demonstrates that a

better gate control has been resulted from passivation of the surface states. In addition, the threshold voltage (V_{th}) of the HEMTs decreases in the sequence of unpassivated, SiO and SiN_x passivated devices, which corresponds to the different carrier concentrations in the 2-DEG channel as a result of surface passivation, as shown from Hall data. Due to the reduction of surface traps, increases in I_{Dmax} and g_m of GaN-based HEMTs after surface passivation have also been reported by many others^{7, 22, 23}.

Fig.2. (a) Subthreshold drain current and (b) gate leakage current characteristics of unpassivated, SiO passivated and SiN_x passivated AlGaIn/GaN HEMTs.

Though the same trend in I_{Dmax} and g_m is observed after passivation with SiO and SiN_x, the subthreshold and Schottky characteristics are quite different for the two passivations. Fig. 2(a) shows the subthreshold drain current characteristics of the unpassivated, SiO passivated and SiN_x passivated AlGaIn/GaN HEMTs (at $V_{DS}=10$ V). The I_{off} increases by almost two orders of magnitude after SiN_x passivation but decreases by one order of magnitude after SiO passivation (see Table I). The different values of I_{off} of the HEMTs may be caused by different activation energies of the electron hopping conduction at the device surface²⁴. Due to the slight change of I_{on} caused by passivation, the highest I_{on}/I_{off} ratio of 1.8×10^6 is obtained for the SiO passivated HEMTs. The subthreshold slope (SS) and interface trap density (D_{it}) calculated from SS at 300 K are shown in the inset of Fig. 2(a). The SS of the devices without passivation is $181 \text{ mV} \cdot \text{dec}^{-1}$, which decreases to $95 \text{ mV} \cdot \text{dec}^{-1}$ and increases to $447 \text{ mV} \cdot \text{dec}^{-1}$ after passivated with SiO and SiN_x, respectively. The change of SS is associated with the interface traps and can be expressed in terms of the barrier capacitance C_i and the interface trap density D_{it} as

$$SS = \frac{kT \ln 10}{q} \left[1 + \frac{q^2}{C_i} D_{it} \right], \quad (1)$$

where k is the Boltzmann constant, T is the temperature in Kelvin, and q is the electronic charge. An obvious decrease from 3.76×10^{12} to $1.16 \times 10^{12} \text{ cm}^{-2} \cdot \text{eV}^{-1}$ for D_{it} is obtained after SiO passivation, while the D_{it} of SiN_x passivated HEMTs increases to $1.13 \times 10^{13} \text{ cm}^{-2} \cdot \text{eV}^{-1}$. The increased density of interface traps for SiN_x passivated HEMTs is probably caused by the ion bombardment during the PECVD process, which can be avoided by applying the thermally evaporated SiO. Better subthreshold behavior is clearly shown for the SiO passivated devices.

The gate leakage current (I_g) characteristics of the passivated and unpassivated AlGaIn/GaN HEMTs are plotted in Fig. 2(b). During the measurements of gate leakage current, the source was shorted to the drain. Similar with I_{off} , compared to the unpassivated HEMTs, an increase of about one order of magnitude in the I_g is observed after SiN_x passivation. In contrast, the I_g decreases by an order of magnitude for SiO passivated HEMTs (Table I). From the forward gate leakage current characteristics, the Schottky barrier height (Φ_B) and ideality factor (n) are extracted using the standard thermionic emission (TE) theory for electron transport from a metal-semiconductor. The Φ_B and n are 0.79/0.85/0.73 eV and 1.77/1.75/1.83 for unpassivated, SiO passivated and SiN_x passivated HEMTs, respectively. An increase in barrier height can lead to a reduction of gate leakage. It should be pointed out that the n of HEMTs with or without passivation is not close to 1, which means that it is not the ideal TE current. Another leakage current mechanism such as trap-assisted tunneling (TAT) may also be taken into account²⁵. The leakage current caused by TAT is associated with the trap density and the trap energy. Reduction in trap density can lead to gate leakage current reduction. It has been demonstrated that the surface related traps with activation energy of 0.21 eV are accounting for the gate leakage current mechanism of the GaN HEMTs¹⁷, which can be influenced by the different passivation processes. The ion damage of semiconductors caused by PECVD is much more severe than that caused by thermal evaporation^{14, 16}, which may lead to different densities and activation energies of the gate leakage related surface traps. The low I_g of SiO passivated HEMTs would probably result in a high breakdown voltage and low RF noise.

Fig.3. Off-state ($V_{GS} = -5$ V) breakdown characteristics of unpassivated, SiO passivated and SiN_x passivated AlGaN/AlN/GaN HEMTs.

The influence of SiO and SiN_x passivations on the off-state breakdown voltage (V_b) of the devices was also investigated. Fig. 3 plots the off-state breakdown characteristics of SiO, SiN_x passivated, and unpassivated AlGaN/AlN/GaN HEMTs, which were measured at $V_{GS} = -5$ V to fully turn off the conducting channel. In order not to destroy the devices, the compliance drain current was set to 10^{-4} A. The HEMTs with SiO passivation exhibit a higher V_b (206 V) when compared with the unpassivated (175 V) and SiN_x passivated (111 V) HEMTs (see Table I). The higher V_b for SiO passivated HEMTs is in agreement with the lower I_g and I_{off} values.

Fig.4. Current-gain cut off frequency (f_T) of unpassivated, SiO passivated and SiN_x passivated AlGaN/AlN/GaN HEMTs.

In addition to the DC characteristics, the current-gain cut off frequency (f_T) of the HEMTs with and without passivation were also studied and measured at $V_{DS} = 10$ V and $V_{GS} = 0$ V, as shown in Fig. 4. Significant increases of f_T value from 4.0 GHz to 5.2 and 5.8 GHz are

observed after passivated with SiO and SiN_x, respectively (see Table I). This is the only study available on the effect of SiO passivation on RF characteristics of GaN-based HEMTs until now. On the other hand, previous reports on the effect of SiN_x passivation on RF characteristics of GaN-based HEMTs are controversial. An increase as well as a decrease of f_T were both observed after SiN_x passivation^{23, 26}. Since f_T can be expressed by

$$f_T = \frac{g_m}{2\pi(C_{GD}+C_{GS})}, \quad (2)$$

where C_{GD} is the parasitic gate-drain capacitance, and C_{GS} is the parasitic gate-source capacitance. Increase of f_T for SiO passivated and SiN_x passivated HEMTs is attributed to the increased g_m and decreased overall capacitance of C_{GD} and C_{GS} . These results are associated with the different passivation materials and deposition methods.

In conclusion, we have investigated the surface passivation effects of the thermally evaporated SiO on the performance of AlGaN/AlN/GaN HEMTs and compared with the PECVD grown SiN_x. Obvious increases in I_{Dmax} and g_m were observed for both the SiO and SiN_x passivated HEMTs when compared with unpassivated HEMTs. However, the SiO passivated devices showed better subthreshold and Schottky characteristics as well as higher V_b . The SiO passivation was found to decrease the I_g by two orders of magnitude and decrease the I_{off} by a factor of 1429, when compared with SiN_x passivated HEMTs. Furthermore, the HEMTs passivated with SiO exhibited three orders of magnitude higher I_{on}/I_{off} ratio (1.8×10^6), five times better SS ($95 \text{ mV} \cdot \text{dec}^{-1}$), ten times lower D_{it} ($1.16 \times 10^{12} \text{ cm}^{-2} \cdot \text{eV}^{-1}$) than SiN_x passivated devices. Moreover, SiO passivation enhanced the gate Schottky barrier height by 60 meV while SiN_x passivation reduced it, which could partially explain the differences in gate leakage current. Besides, SiO passivation enabled twice high breakdown voltage (206 V) than SiN_x passivation (111 V). Because of the good passivation effectiveness, no ion damage, simple preparation technology and low cost, the thermally evaporated SiO is a promising candidate as a surface passivation for GaN-based HEMTs, especially for the high power and noise sensitive applications.

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