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Influence of Oxygen–Plasma Treatment on In-Situ SiN/AlGa_N/Ga_N MOSHEMT with PECVD SiO₂ Gate Insulator

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Abstract: The influence of oxygen–plasma treatment on in situ SiN/AlGa_N/Ga_N MOS high electron mobility transistor with SiO₂ gate insulator was investigated. Oxygen–plasma treatment was performed on in situ SiN, before SiO₂ gate insulator was deposited by plasma-enhanced chemical vapor deposition (PECVD). DC I-V characteristics were not changed by oxygen plasma treatment. However, pulsed I-V characteristics were improved, showing less dispersion compared to non-treated devices. During short-term gate bias stress, the threshold voltage shift was also smaller in a treated device than in an untreated one. X-ray photoemission spectroscopy also revealed that SiO₂ on in situ SiN with oxygen–plasma treatment has an O/Si ratio close to the theoretical value. This suggests that the oxygen plasma treatment-modified surface condition of the SiN layer is favorable to SiO₂ formation by PECVD.

Keywords: gallium nitride; heterostructure; in situ SiN; SiO₂; oxygen plasma; interface trap

1. Introduction

AlGa_N/Ga_N heterojunction-based metal insulator semiconductor high electron mobility transistors (MISHEMTs) have demonstrated excellent performance for high-efficiency power switching applications [1–3]. Although one can employ a gate dielectric in MISHEMTs to suppress gate leakage current and magnify gate swing, the bulk properties of the gate dielectric and the dielectric/III-nitride interface quality strongly influence the device performance because this dielectric layer also plays an important role in alleviating the current slump caused by the surface trapping. However, high-density interface trap states present at the dielectric/AlGa_N barrier interface are in the order of $\sim 10^{13}$ – 10^{14} cm⁻²eV⁻¹ [4–6]. Although ex-situ deposition, such as low pressure CVD and atomic layer deposition, is a common method for gate dielectrics of Ga_N transistors, an in situ SiN dielectric can be epitaxially grown immediately as a final layer of the AlGa_N/Ga_N HEMT epi-structure in a metal–organic chemical vapor deposition (MOCVD) system [7–9]. Without the exposure of the as-grown Ga_N HEMT barrier to the ambient air, the damage or contamination caused by subsequent processing can be minimized. Therefore, in situ SiN passivation or a protection layer has recently been widely accepted in a commercial Ga_N-on-Si wafer.

Among dielectric materials, SiO₂ is a very attractive material for MIS structure, since it possesses a large band gap and large conduction band discontinuity from AlGa_N. Chemical vapor deposition of SiO₂ on AlGa_N/Ga_N heterostructure has been reported by several research teams, and AlGa_N/Ga_N MOSHEMT demonstrated a promising performance [10–12]. As mentioned above, an in situ SiN layer has been employed as standard surface passivation for commercially available AlGa_N/Ga_N heterostructure substrate. SiN can be etched away prior to SiO₂ deposition for MOSEMT device

fabrication. However, plasma-based dry-etching, which is prone to induce plasma damage on the surface, is required, because in situ SiN cannot be removed easily by wet etching. If a SiO₂ layer can be deposited on in situ SiN with the dielectric quality maintained, we can gain all the advantages of employing in situ SiN passivation and a SiO₂ gate insulator. Although SiO₂ can be thermally grown on SiN, the process takes place at very high temperatures and causes damage to the material.

In this work, we carried out oxygen plasma treatment on in situ SiN on AlGa_N/Ga_N-on-Si substrate before SiO₂ deposition. The effect of oxygen plasma treatment on the characteristics of the SiO₂ layer deposited on in situ SiN was investigated by measuring MOSHEMT's electrical characteristics, including I-V, C-V and gate lag measurements. Short-term gate stress test and X-ray photoemission spectroscopy (XPS) were also performed to analyze the characteristics of the SiO₂/in situ SiN/AlGa_N MOS structure.

2. Materials and Methods

As presented in Figure 1, AlGa_N/Ga_N MOSHEMTs were fabricated on commercially available in situ SiN/AlGa_N/Ga_N heterostructures grown on 6 in silicon substrates by MOCVD. The epilayers, from bottom to top, consist of a 4.5 μm Ga_N buffer, a 490 nm unintentionally doped Ga_N channel layer, a 22 nm Al_{0.25}Ga_{0.75}N barrier, a 4 nm Ga_N cap, and a 10 nm in situ SiN cap. The layer structure information was provided by the wafer provider, Enkris Semiconductor Inc. in Suzhou, China. The Hall mobility (μ) and sheet carrier concentration (n_{sh}) of the 2DEG channel at heterojunction was 1890 cm²/V·s and 8.85×10^{12} , respectively. Circular-type MOS capacitors were also fabricated on the same sample. The device fabrication was done at Inter-university Semiconductor Research Center in Seoul National University, Korea. It started with a recess etching of the AlGa_N barrier through in situ SiN to reduce a contact resistance [recess]. A Ti/Al/Ni/Au metal stack (20/120/25/50 nm) was deposited by e-beam evaporation for source/drain electrodes. The ohmic contacts were alloyed by rapid thermal annealing at 830 °C for 30 s in N₂. Device isolation was performed using mesa formation with a depth of 300 nm. The surface was submitted to oxygen plasma treatment using a microwave asher with 50 W power and 40 sccm flow rate for 2 min, before SiO₂ deposition. Following that, a 20 nm PECVD SiO₂ layer was deposited for gate insulation and device passivation. Finally, an Ni/Au-based metal stack (20/200 nm) was deposited to form the gate and probe pad. The average ohmic contact resistance was determined to be 0.85 Ω·mm, and the sheet resistance of 2-DEG was ~470 Ω/sq, as measured by the transfer length method (TLM) after the fabrication was complete. Gate length and width of the MOSHEMT were 2 and 100 μm, respectively.

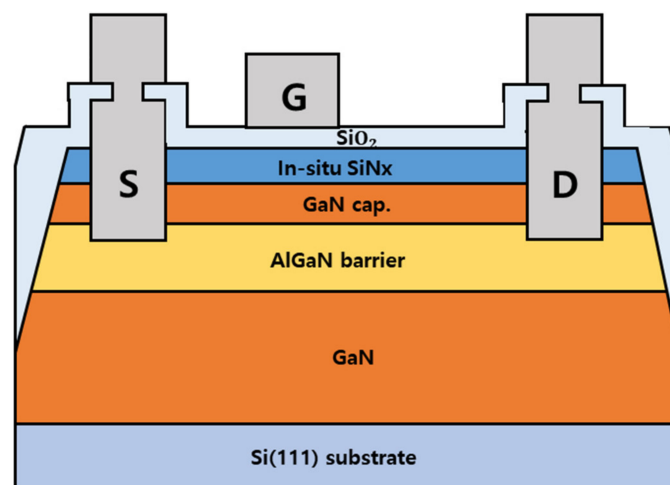


Figure 1. Cross-sectional diagram of in situ SiN/AlGa_N/Ga_N metal–organic semiconductor high electron mobility transistor (MOS-HEMT) on Si (not scaled).

3. Results

Transfer I-V characteristics of the fabricated devices were measured at room temperature by Agilent 4155 semiconductor parameter analyzer. As shown in Figure 2a, oxygen plasma treatment did not change device characteristics including on-current, a threshold voltage (V_{th}) and transconductance. Figure 2b shows that neither gate leakage current nor subthreshold swing was degraded by plasma treatment. Time-zero-breakdown characteristics were also evaluated to compare the integrity of the gate oxide and did not show significant differences between the two samples, as given in Figure 3.

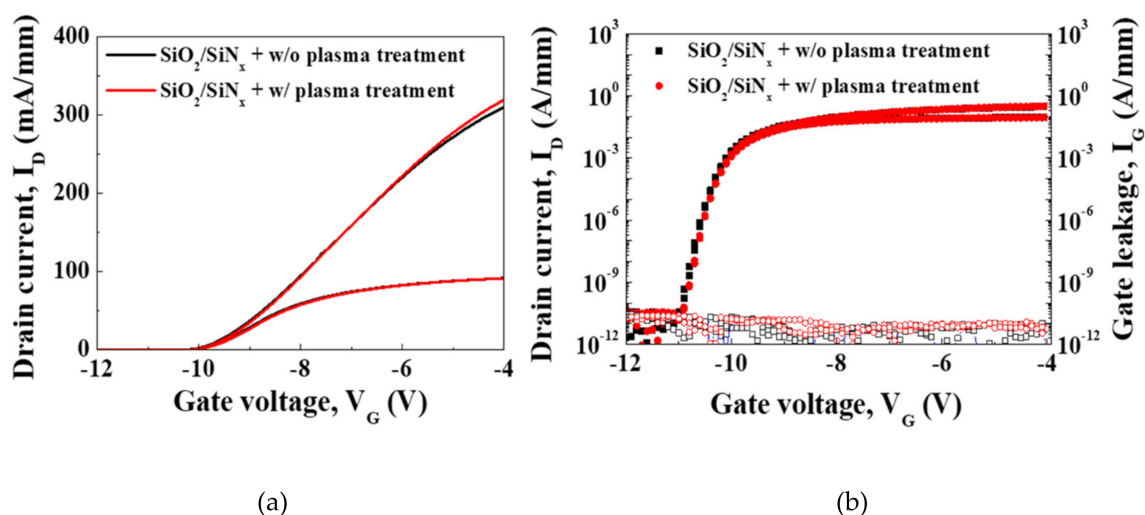


Figure 2. (a) Transfer I-V characteristics measured at $V_D = 1$ and 10 V. (b) Subthreshold (solid mark) and gate leakage (open mark) characteristics measured at $V_D = 1$ and 10 V.

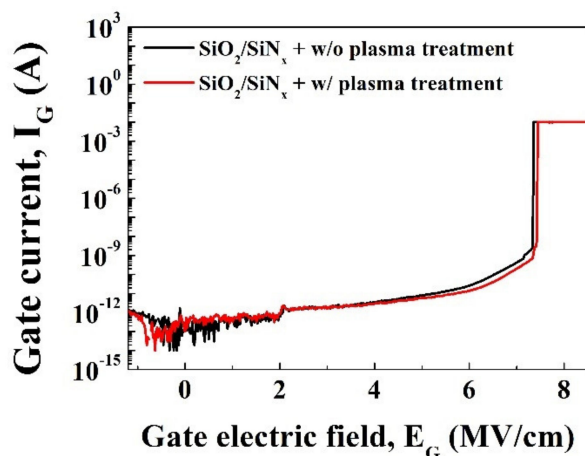


Figure 3. Time-zero-breakdown characteristics of $\text{SiO}_2/\text{in situ SiN}/\text{AlGaIn}/\text{GaIn}$ MOS structure.

C-V characteristics were measured at $f = 1$ MHz from a circular-shaped C-V pattern with radius = 100 μm using Agilent B1500A. Figure 4 shows negligible differences in C-V characteristics between two types of devices with or without plasma treatment. This suggests that the dielectric thickness and constant were not altered by the plasma treatment.

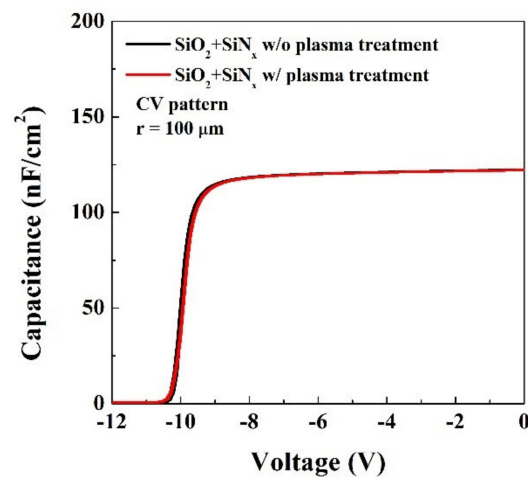


Figure 4. C-V characteristics of SiO₂/in situ SiN_x/AlGaIn/GaN MOS capacitor measured at 1 MHz.

Pulsed I-V measurement is a useful tool in analyzing gate lag or drain lag phenomenon caused by the trapping effect [13]. Gate lag characteristics have a strong correlation with RF output performance, which can be improved significantly by minimizing gate lag, i.e., the dispersion between DC and pulsed I-V characteristics [14]. The virtual gate effect, proposed by Vetury et al. [15], is well-known as an origin of the dispersion. Gate lag measurement was performed to investigate the effect of plasma treatment on the trapping phenomenon observed in GaN-based HEMTs by using the Accent DiVA D265 Dynamic analyzer. Quiescent bias points for the two pulsed measurements were $V_G = V_D = 0$ V and $V_G = -12$, $V_D = 0$ V. The pulse width was 1 μ s with 1 ms of the pulse period. $V_{GQ} = -12$ V was chosen to ensure that the DUT was completely pinched off and electrons were easily injected from the gate into the traps nearby. Figure 5 shows the pulsed and static I-V characteristics and the difference between static and pulsed I-V. ($V_G = V_D = 0$ V) resulted from the self-heating effect. As shown in Figure 5, the MOSHEMT without oxygen plasma treatment exhibited a larger I-V dispersion between the two measurement conditions. Although 38% dispersion was observed in the plasma-treated device, the untreated device showed 58% dispersion at $V_D = 15$ V. This result suggests a more serious virtual gate effect [15] and the ineffectiveness of the suppression of current collapse in the devices without plasma treatment.

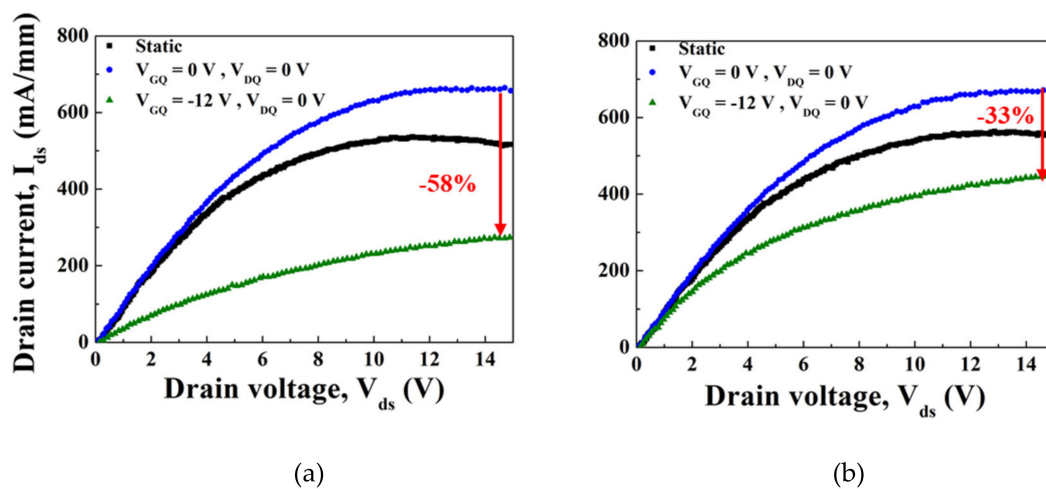


Figure 5. Pulsed I-V (gate lag) characteristics measured with 1 μ s-VG pulsed width in a 0.1 % duty cycle. (a) Without plasma treatment (b) With plasma treatment.

4. Discussion

When AlGaIn/GaN MOS-HEMTs were treated by oxygen plasma before SiO₂ dielectric deposition, they did not show any changes in DC I-V and C-V characteristics, such as pinch-off voltage, transconductance and C_{max}, indicating 2DEG property was not altered. Channel and Gate leakage characteristics were not degraded, either.

However, pulsed I-V measurement revealed that gate lag was aggravated if the surface of in situ SiN was not exposed to oxygen plasma before SiO₂ deposition. To investigate how the trap states of a SiO₂/SiN/AlGaIn MOS structure can be modified by oxygen plasma treatment, the devices were submitted to a short-term stress test and ΔV_{th} was monitored. The ΔV_{th} value can easily be translated into an interface trap density using the oxide capacitance [16]. In Figure 6, a plasma-treated device showed ΔV_{th} less than that of an untreated one during the bias stress, with the same electric field and time, suggesting that the interface trap density was decreased by plasma treatment.

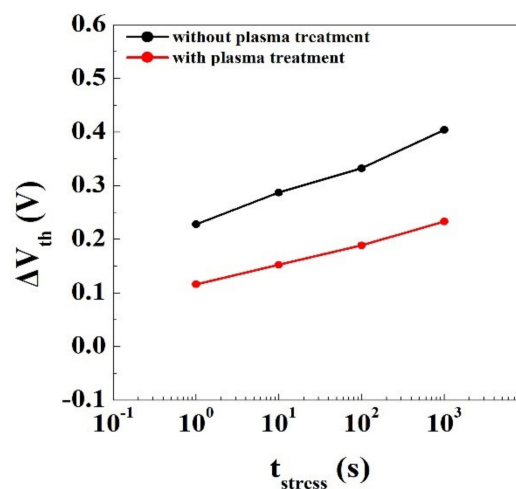


Figure 6. ΔV_{th} induced by a short-term gate bias stress measured from the plasma-treated and non-treated device.

We carried out further analysis of the SiO₂/SiN/AlGaIn MOS structure to understand the origin of the reduced trapping observed from the oxygen-plasma treated device. To quantify the oxygen composition in the SiO₂ film, x-ray photoelectron spectroscopy (XPS) measurements with sputter etch treatment was performed with the thetaprobe XPS system from Thermo Fisher Scientific at Analytical Instrumentation Center of Hanyang University, Seoul, Korea. A monochromatic Al K α X-ray source with 1486.6 eV and sputtering ion gun with Ar⁺ at 2 keV were used for analysis. At the top surface with no sputter etching, Si 2p and O 1s peak positions (not shown in Figure) are determined to be 103.08 and 532.58 eV for the untreated sample, respectively. Only a little change in binding energy was observed in the plasma-treated sample, showing each peak at 103.48 and 532.98 eV. Figure 7 also presents Si 2p and O 1s peaks, with 150 s of sputter etch time which is suggested to give a depth near the interface between ex-situ SiO₂ and in situ SiN. No significant changes in the XPS spectrum were observed. However, the XPS depth profile of each element in Figure 8 reveals that SiO₂ on in-situ SiN with oxygen-plasma treatment has an O/Si ratio close to the theoretical value (2:1). This suggests that oxygen-plasma treatment modified the surface of in-situ SiN in favor of the following SiO₂ deposition. Plasma oxidation of PECVD and LPCVD nitride has been already demonstrated to produce oxynitride films [17,18] Oxygen-plasma was also applied to convert the surface of silicon nitride into oxide [19]. Bui et al. proposed that this conversion was due to a loss of nitrogen into the plasma caused by the bonding instability of nitrogen at the surface of the dielectric [20]. Several reports proposed similar mechanisms that weakly bind nitrogen at the surface of silicon nitride can be replaced by oxygen [19,21].

The oxidized surface of silicon nitride by oxygen plasma can probably provide better conditions for ex-situ deposition of SiO_2 .

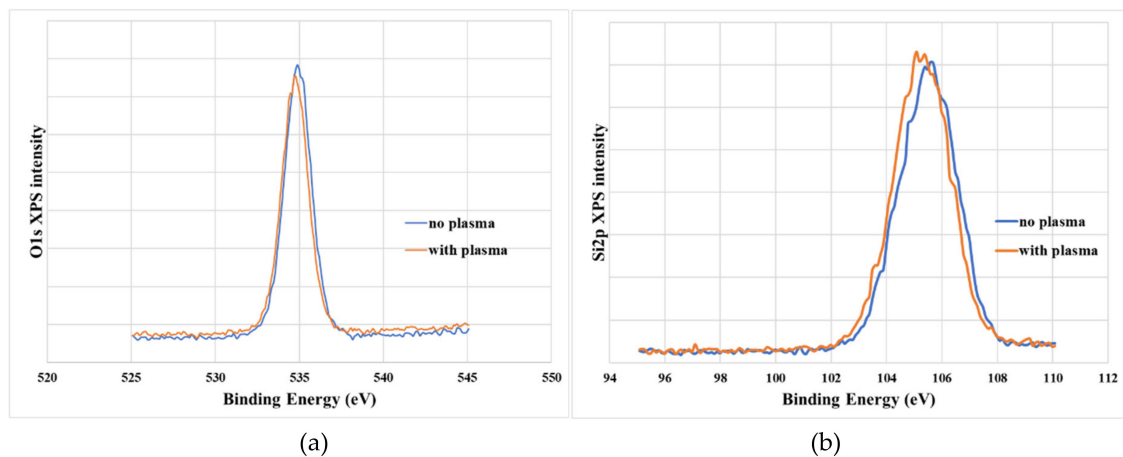


Figure 7. XPS spectrum of O1s and Si2p in the vicinity of the SiO_2/SiN interface. Sputter etching for 150 s. (a) O1s (b) Si2p.

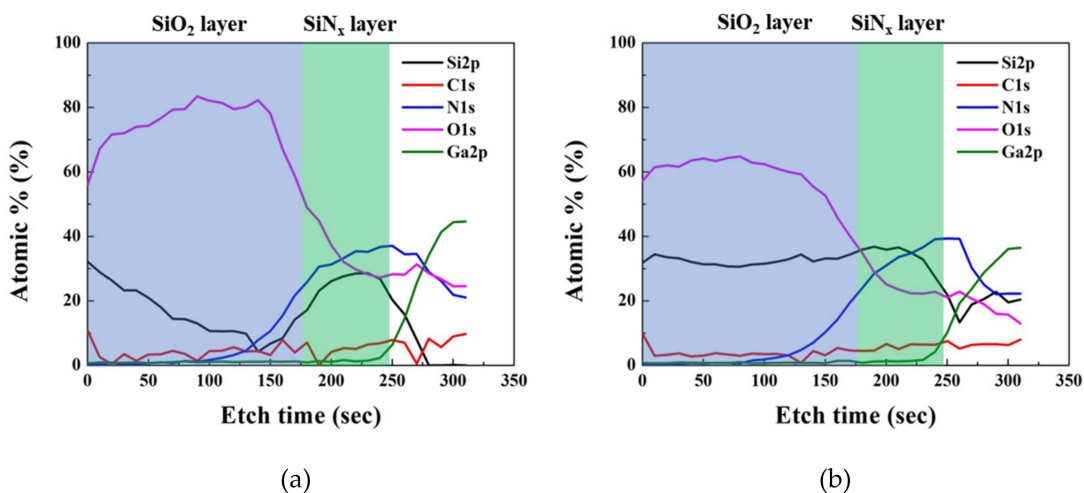


Figure 8. Atomic percent ratio vs. sputter time $\text{SiO}_2/\text{in situ SiN/AlGaN}$ MOS structure. (a) Without plasma treatment (b) With plasma treatment.

The current work is aimed at optimizing the treatment process with varying power and oxygen flow to further improve the SiO_2/SiN interface property. A more detailed characterization of the plasma-treated surface before SiO_2 deposition is now in progress. Besides, the effects of plasma treatment on the chemical bonding and morphology of the dielectrics will accompany this.

5. Conclusions

We investigate the effect of oxygen-plasma treatment on in-situ SiN on AlGaN/GaN heterojunction for MOS gate devices. Oxygen-plasma treatment was performed before a SiO_2 gate insulator was deposited on in situ SiN by PECVD. Oxygen-plasma treatment did not change DC I-V characteristics. However, the dispersion between DC and pulsed I-V characteristics was significantly alleviated by the plasma treatment. Accordingly, the plasma-treated device exhibited a smaller V_{th} shift than the untreated one, suggesting that the trapping into the interface states was mitigated. The XPS result revealed that the SiO_2 layer on the plasma-treated sample exhibited an O/Si ratio much closer to the theoretical value than the untreated one. In cases where a SiO_2 layer is employed as a gate insulator on

an AlGa_N/Ga_N-on-Si platform with an in situ Si_N capping layer, oxygen plasma treatment on the in situ Si_N layer can improve the quality of SiO₂ significantly.

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Conflicts of Interest: The authors declare no conflict of interest.

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