The Effects of SF_6 Plasma and *in-situ* N_2 Plasma Treatment on Gate Leakage, Subthreshold Slope, and Current Collapse in AlGaN/GaN HEMTs

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Abstract

We investigated the removal of SiN_x pre-passivation layer and the SiN_x re-deposition process with surface treatments. By using the optimized SF_6 plasma and *in-situ* N_2 plasma treatments, the gate leakage current was reduced to 67 nA/mm at the gate voltage of -100 V, and the subthreshold slope was improved to 71 mV/dec. The breakdown voltage of 220 V and the specific on-resistance of 0.52 mΩ·cm^2 were achieved for the gate-to-drain distance of 3 μm, and current collapse phenomena were also improved. For the gate-to-drain distance of 12 μm, the breakdown voltage of 1390 V and the specific on-resistance of 1.86 mΩ·cm^2 were achieved.

INTRODUCTION

Gallium nitride based HEMTs have shown great potential for high-frequency and high-power applications, because they have superior material properties such as electron mobility, carrier density, saturation velocity, band gap energy, and breakdown field [1]. However, surface related problems such as large reverse gate leakage currents through Schottky contacts and current collapse phenomena still need better solutions [2]. The subthreshold characteristics, which are dominated by gate leakage currents, have also become important for low dissipated power and good pinch-off [3].

Device processing involves various kinds of residues, etching steps, and junction formation steps, which may introduce defects on the processed GaN surface. In GaN-based materials, the surface is very sensitive to various influences on the surface potential, strongly affecting the characteristics of the fabricated device [4-5]. CF_4 plasma treatment has been widely used to reduce the reverse gate leakage current of AlGaN/GaN Schottky barrier diodes or HEMTs [6-7]. However, plasma induced damage due to the high bias voltage and undesirable carbon might be created on the surface. The reduction in the gate leakage current and the improvement in the subthreshold characteristics with O_2 plasma treatment have also been reported [3], but HEMTs with higher surface oxide content are more susceptible to the degradation in terms of their gate leakage and trapping characteristics [8].

In this work, we employed soft SF_6 plasma for the removal of high temperature ohmic annealed SiN_x pre-passivation layer and surface treatment on underlying GaN layer, subsequently. By using pure SF_6 gas with soft plasma condition and optimizing treatment time, we could reduce the possible plasma damage and prevent the carbon or oxygen contamination on the surface. To recover nitrogen-vacancy and suppress current collapse phenomena, N_2 plasma treatment was also employed after SF_6 plasma treatment. With SF_6 plasma and *in-situ* N_2 plasma treatment prior to SiN_x passivation (re-deposition), we could improve gate characteristics, subthreshold characteristics, and pulsed I-V characteristics.

DEVICE STRUCTURE AND FABRICATION

The epitaxial layers grown on Si substrate consisted of a 3 nm GaN capping layer, a 20 nm $Al_{0.23}Ga_{0.77}N$ barrier layer, a 100 nm i-GaN layer, and a 3.9 μm C-doped GaN buffer layer. The measured channel electron mobility and sheet resistance were 1740 cm^2/V·s and 528 Ω/sq. First, device isolation was carried out using low damage BCl_3/Cl_2 plasma etching. Then, cleaning with SPM and diluted HF (1:10) was performed for 10 min each before SiN_x pre-passivation. A 10 nm SiN_x pre-passivation layer was deposited at 350 °C using ICP-CVD with the intention of protecting the cleaned GaN surface during high temperature ohmic annealing. After that, drain and source ohmic contacts were formed by using a Si/Ti/Al/Mo/Au (5/20/80/35/50 nm) metal stack and annealed at 780 °C for 1 min in nitrogen ambient using RTA. The contact resistance was 0.52 Ω·mm.

Fig. 1 illustrates the process flow after ohmic contact formation. By applying SF_6 plasma with soft plasma conditions using Oxford plasmalab 80 plus RIE system, we removed the SiN_x pre-passivation layer and treated the GaN surface simultaneously. The SF_6 plasma treatment was performed with a SF_6 gas flow of 100 sccm, a chamber pressure of 100 mTorr, and a RF power of 10 W. The SF_6 plasma treatment time, varied with 1, 2, 3, and 5 min, included the etching time for 10 nm SiN_x (etch rate of SiN_x was about 20 nm/min). Thus, SF_6 plasma treatment time on bare GaN surface was actually 30 sec less than our experimental plasma time. For the reference sample, the 10

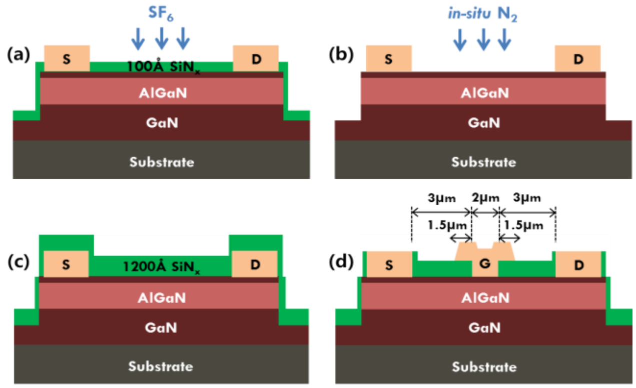

Fig. 1. Cross-sectional schematic of AlGaN/GaN HEMT fabrication flow after ohmic formation. 10 nm SiN$_x$ was removed and then surface treatments were carried out simultaneously by using SF$_6$ plasma before 120 nm SiN$_x$ re-deposition with *in-situ* N$_2$ plasma treatment.

nm SiN$_x$ layer was removed by BOE (1:7) for 2 min. After removing the SiN$_x$ pre-passivation layer with or without SF$_6$ plasma treatment, 120 nm ICP-CVD SiN$_x$ was re-deposited at 350 ℃ with 2 min *in-situ* N$_2$ plasma pre-treatment for all samples. The re-deposited SiN$_x$ passivation layer under the gate region was etched again with SF$_6$ soft plasma and then Ni/Au (20/180 nm) was evaporated as a Schottky gate metal. Additional 30 nm ICP-CVD SiN$_x$ was deposited for 2nd passivation and a 400 ℃ post-gate annealing was applied to stabilize the device characteristics.

RESULTS AND DISCUSSION

Surface morphologies with and without SF$_6$ plasma treatment were determined by AFM in terms of RMS roughness over a 4×4 μm^2 region, as shown in Fig. 2. The AFM images indicated that the surface morphologies improved with SF$_6$ plasma treatment.

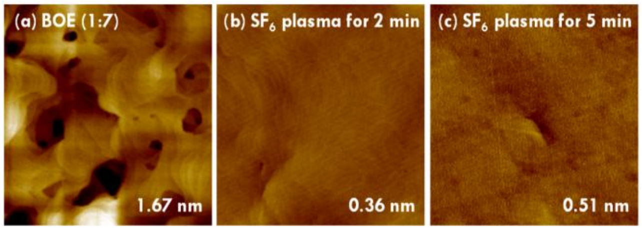

Fig. 2. AFM images showing GaN surface morphologies with and without SF$_6$ plasma treatment.

The improved surface could affect the electrical characteristics of AlGaN/GaN HEMTs. Fig. 3 (a) show the reverse gate leakage currents of the fabricated devices with and without SF$_6$ plasma treatment. With the optimum SF$_6$ plasma treatment for 2 min, the reverse gate leakage current was significantly reduced from 57 μA/mm to 67 nA/mm for the gate voltage of -100 V. The forward biased gate current characteristics of the devices with and without SF$_6$ plasma treatment were also plotted in Fig. 3 (b). SBHs and IFs were extracted from the measured forward gate currents. By applying SF$_6$ plasma treatment for 2 min, the SBH of AlGaN/GaN HEMT increased from 0.71 to 1.09 eV with negligible change of IF (1.28 and 1.29 for without and with SF$_6$ plasma treatment, respectively). The gate turn-on voltage for 1 mA/mm forward gate current increased to 1.06 V, enhancing the gate voltage swing limit. With SF$_6$ plasma time of 5 min, the IF and the reverse leakage currents were degraded, indicating the possible plasma damage.

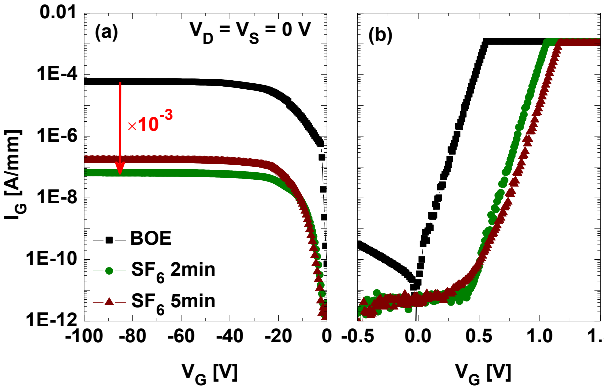

Fig. 3. (a) Reverse and (b) forward biased gate leakage currents of AlGaN/GaN HEMTs with and without SF$_6$ plasma treatment. The reduction of reverse biased leakage current with SF$_6$ plasma treatment for 2 min is about three orders of magnitude.

The transfer characteristics of devices with and without SF$_6$ plasma treatment were measured and shown in Fig. 4. The reduction of gate currents with SF$_6$ plasma treatment improved the SS and the on/off drain current ratio, because both drain leakage current and SS are dominated by reverse gate leakage current when the device is pinched off [3]. The maximum on/off drain current ratio was determined with $I_{D,ON}$ at V_{GS} = 1 V and minimum $I_{D,OFF}$. The device with SF$_6$ treatment for 2 min exhibited the excellent characteristics such as the maximum on/off drain current ratio of 3.5×10^7 and the improved SS of 71 mV/dec.

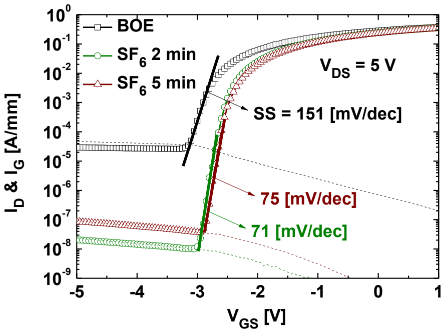

Fig. 4. Transfer characteristics with (symbol line) drain currents and (dashed line) gate currents of AlGaN/GaN HEMTs with and without SF$_6$ plasma treatment at V_{DS} = 5 V.

In order to further investigate the interface and the surface related properties, the pulsed I-V measurements with increasing quiescent drain bias point (V_{DSQ}) were performed. As shown in Fig. 5, the drain current collapse phenomena were improved with SF_6 treatment for 2 min. But larger current discrepancies were observed with longer SF_6 plasma exposures, which indicates that plasma-induced damage on GaN surface might have occurred with long plasma exposure time, although we employed soft plasma condition for SF_6 to reduce the possible plasma damage. It was reported that the regions responsible for the I-V dispersions were located close to the gate edges rather than under the gate [9]. Since we exposed soft SF_6 plasma all over the GaN surface, not only the gate region but also the gate edges were treated (gate to source and gate to drain region were also included). Therefore, the amount of adsorbates close to gate edges was reduced, thereby mitigating I-V dispersions. The variation of gate leakage current, SBH, IF, SS, I_{ON}/I_{OFF} ratio, and current discrepancy with SF_6 plasma treatment time were summarized in Table I.

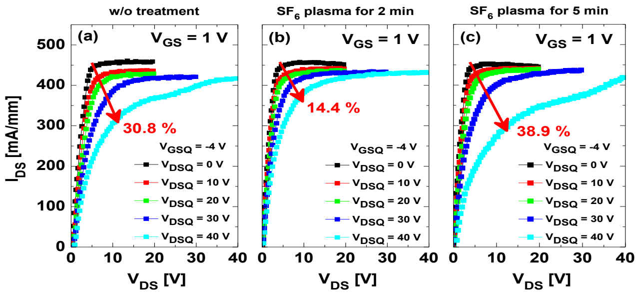

Fig. 5. Pulsed I-V characteristics of AlGaN/GaN HEMTs (W_G = 2×50 μm) (a) without SF_6 treatment, (b) with SF_6 treatment for 2 min, and (c) with SF_6 treatment for 5 min. The pulses have 200 ns duration with 1 ms separation.

TABLE I

THE CHARACTERISTICS OF GATE CURRENT, SUBTHRESHOLD SLOPE, AND CURRENT DISCREPANCY WITH VARIOUS SF_6 PLASMA TREATMENT TIME

	Ref. device	SF_6 plasma treatment			
		1 min	2 min	3 min	5 min
I_G[1] [A/mm]	5.7×10^{-5}	1.2×10^{-4}	6.7×10^{-8}	3.5×10^{-7}	1.5×10^{-7}
SBH	0.71	0.70	1.09	1.06	1.06
IF	1.28	1.26	1.29	1.33	1.39
SS [mV/dec]	151	154	71	72	75
I_{ON}/I_{OFF}[2]	1.4×10^{4}	1.1×10^{4}	3.5×10^{7}	6.3×10^{6}	9.2×10^{6}
Current discrepancy[3]	30.8 %	27.3 %	14.4%	34.6 %	38.9 %

[1] I_G was average value at V_G = -100 V.

[2] The on/off drain current ratio was determined with $I_{D,ON}$ when V_{GS} = 1 V and minimum $I_{D,OFF}$.

[3] Current discrepancy was defined between I_{DS} at V_{DS} = 5 V, V_{DSQ} = 0 V and I_{DS} at V_{DS} = 10 V, V_{DSQ} = 40 V (V_{GS} = 1 V, V_{GSQ} = -4 V).

The measured breakdown voltage characteristics of the fabricated devices with and without SF_6 plasma treatment are shown in Fig. 6 (a). The drain leakage current and breakdown voltage were improved by applying SF_6 plasma treatment. We also measured breakdown voltage of the device with 2 min SF_6 plasma treatment for large gate-to-drain distance. We achieved the breakdown voltage of 1390 V and the specific on-resistance of 1.86 mΩ·cm^2 for the gate-to-drain distance of 12 μm, as shown in Fig. 6 (b). The device performance of our HEMTs with optimized surface treatment is plotted in the specific on-resistance versus breakdown voltage benchmark and compared with state-of-the-art GaN-based HEMTs reported in the literature (see Fig. 7) [10].

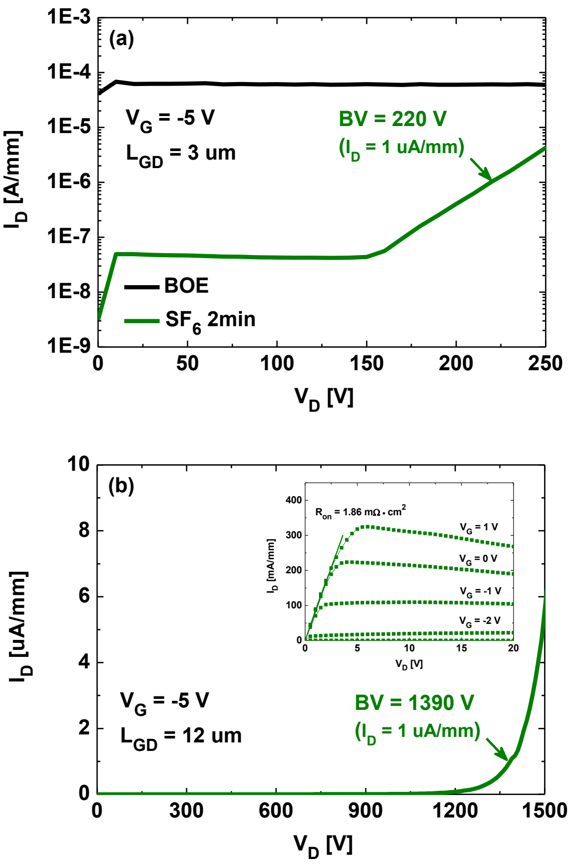

Fig. 6. Three terminal breakdown voltage characteristics for the gate-to-drain distance of (a) 3 μm and (b) 12 μm.

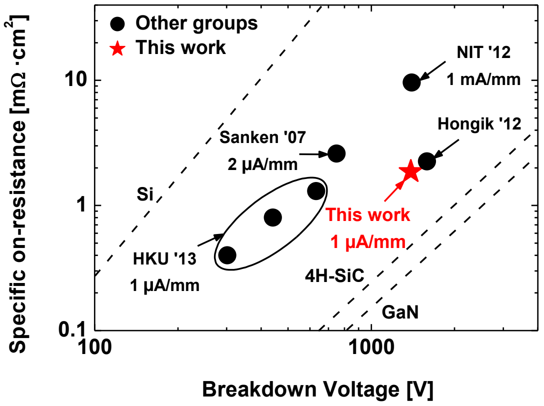

Fig. 7. Specific on-resistance versus breakdown voltage of AlGaN/GaN HEMTs with SF_6 plasma treatment for 2 min and reported state-of-the-art GaN HEMTs.

CONCLUSIONS

The removal of SiN_x pre-passivation layer and surface treatment with SF_6 plasma and SiN_x re-deposition with *in-situ* N_2 plasma were successfully employed. We achieved the reduction in the gate leakage current, the improvement in subthreshold characteristics and current collapse, and the enhancement in the breakdown voltage. With this study, we suggest the employment of soft SF_6 plasma and *in-situ* N_2 plasma treatment for the improved device performance of AlGaN/GaN HEMTs.

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ACRONYMS

HEMT: High-electron-mobility-transistor
I-V: Current-voltage
SPM: Sulfuric acid hydrogen peroxide mixture
ICP-CVD: Inductively coupled plasma chemical vapor deposition
RTA: Rapid thermal annealing
RIE: Reactive ion etching
BOE: Buffered oxide etchant
AFM: Atomic force microscopy
RMS: Root mean square
SBH: Schottky barrier height
IF: Ideality factor
SS: Subthreshold slope