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 mΩcm$^2$ 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 mΩcm$^2$ 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$_{0.25}$Ga$_{0.75}$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 plasma lab 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
Surface morphologies with and without SF$_6$ plasma treatment were determined by AFM in terms of RMS roughness over a 4x4 $\mu$m$^2$ region, as shown in Fig. 2. The AFM images indicated that the surface morphologies improved with 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 $\mu$A/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.

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 $3.5 \times 10^7$ and the improved SS of 71 mV/dec.
In order to further investigate the interface and the surface related properties, the pulsed I-V measurements with increasing quiescent drain bias point (V<sub>DSQ</sub>) were performed. As shown in Fig. 5, the drain current collapse phenomena were improved with SF<sub>6</sub> treatment for 2 min. But larger current discrepancies were observed with longer SF<sub>6</sub> 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<sub>6</sub> 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<sub>6</sub> 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<sub>ON</sub>/I<sub>OFF</sub> ratio, and current discrepancy with SF<sub>6</sub> plasma treatment time were summarized in Table I.

![Fig. 5. Pulsed I-V characteristics of AlGaN/GaN HEMTs (W<sub>G</sub> = 2x50 µm) (a) without SF<sub>6</sub> treatment, (b) with SF<sub>6</sub> treatment for 2 min, and (c) with SF<sub>6</sub> treatment for 5 min. The pulses have 200 ns duration with 1 ms separation.](image)

### Table I
**The Characteristics of Gate Current, Subthreshold Slope, and Current Discrepancy with Various SF<sub>6</sub> Plasma Treatment Time**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ref. device</th>
<th>SF&lt;sub&gt;6&lt;/sub&gt; plasma treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>I&lt;sub&gt;DS&lt;/sub&gt; [mA/mm]</td>
<td>5.7×10&lt;sup&gt;-4&lt;/sup&gt;</td>
<td>1.2×10&lt;sup&gt;-4&lt;/sup&gt;</td>
</tr>
<tr>
<td>SBH [V]</td>
<td>0.71</td>
<td>0.70</td>
</tr>
<tr>
<td>IF</td>
<td>1.28</td>
<td>1.26</td>
</tr>
<tr>
<td>SS [mV/dec]</td>
<td>151</td>
<td>154</td>
</tr>
<tr>
<td>I&lt;sub&gt;ON&lt;/sub&gt;/I&lt;sub&gt;OFF&lt;/sub&gt;</td>
<td>1.4×10&lt;sup&gt;4&lt;/sup&gt;</td>
<td>1.1×10&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
<tr>
<td>Current discrepancy&lt;sup&gt;1&lt;/sup&gt;</td>
<td>30.8 %</td>
<td>27.3 %</td>
</tr>
</tbody>
</table>

<sup>1</sup>I<sub>DS</sub> was average value at V<sub>G</sub> = -100 V.

The measured breakdown voltage characteristics of the fabricated devices with and without SF<sub>6</sub> plasma treatment are shown in Fig. 6 (a). The drain leakage current and breakdown voltage were improved by applying SF<sub>6</sub> plasma treatment. We also measured breakdown voltage of the device with 2 min SF<sub>6</sub> 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<sup>2</sup> 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.](image)

![Fig. 7. Specific on-resistance versus breakdown voltage of AlGaN/GaN HEMTs with SF<sub>6</sub> plasma treatment for 2 min and reported state-of-the-art GaN HEMTs.](image)
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.

ACKNOWLEDGEMENTS

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REFERENCES


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