 Suppressing Leakage Current in InGaN/GaN Multiple-Quantum Well LEDs by N$_2$O Plasma Treatment

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The effect of N$_2$O plasma treatment on the reverse leakage currents in InGaN/GaN multiple-quantum-well (MQW) light-emitting diodes (LEDs) was investigated. The reverse leakage current of an MQW LED after an N$_2$O plasma treatment was decreased by two orders of magnitude compared to that of an untreated LED. This can be attributed to the passivation of surface and sidewall damage on the GaN, produced as a result of the dry etching process during fabrication of the LED for electrode formation. These results reveal that nonradiative defects can be reduced by N$_2$O plasma passivation and the reverse leakage current in an MQW LED can be substantially decreased, resulting in an improvement in the optical output of the MQW LED.

Results and Discussion

The effect of the N$_2$O plasma treatment on the performance of the LEDs was examined under plasma conditions of rf power ranging from 10 to 100 W at 300°C, pressure of 1 Torr, a flow rate of 500 sccm, and a plasma treatment time of 10 min. The reverse and forward electrical characteristics of LEDs treated by the N$_2$O plasma at various rf powers are shown in Table I. The LEDs treated with an N$_2$O plasma at an rf power of 20 W showed a decrease by around three orders of magnitude in reverse leakage current, with a slight increase in the turn-on voltage, which is attributed to a reduction in leakage current induced by the surface and sidewalls of the LEDs. However, for a plasma power above 30 W, the electrical characteristics of the LEDs become degraded, as shown in Table I. In a previous report on the activation of Mg acceptors in p-GaN by energetic ion bombardment employed. Therefore, the degradation in the electrical properties of the LED treated with an N$_2$O plasma above

<table>
<thead>
<tr>
<th>Sample</th>
<th>Power (W)</th>
<th>Operating voltage (V) at 20 mA</th>
<th>Reverse leakage current (nA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>−1 V</td>
<td>−2 V</td>
</tr>
<tr>
<td>Without plasma treatment</td>
<td>3.7</td>
<td>0.15</td>
<td>30</td>
</tr>
<tr>
<td>A</td>
<td>10</td>
<td>3.6</td>
<td>0.12</td>
</tr>
<tr>
<td>B</td>
<td>20</td>
<td>3.5</td>
<td>0.12</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>3.75</td>
<td>0.18</td>
</tr>
<tr>
<td>D</td>
<td>50</td>
<td>3.8</td>
<td>0.15</td>
</tr>
<tr>
<td>E</td>
<td>100</td>
<td>3.8</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Table I. Summary of electrical characteristics of 300 μm MQW LEDs treated with an N$_2$O plasma. The N$_2$O plasma treatment was performed at rf power level of 10-100 W, N$_2$O flow rate of 500 sccm, chamber pressure of 1 Torr, treatment time of 10 min, and substrate temperature of 300°C.

The MQW LEDs were grown on the sapphire (0001) substrates by a metalorganic chemical vapor deposition (MOCVD) system (Encore D125). The procedure for the growth of the epi layer structure of the MQW LED has been described elsewhere. After a rapid thermal annealing of the p-GaN contact layer on the MQW at 950°C, mesa-type LED structures (300 μm diam) were prepared using an inductively coupled plasma etching system (Oxford Plasma 100). Metal contacts were then formed using Ti/AI (30 nm/80 nm) as an n-electrode, Pt (8 nm) as a light transmitting p-electrode, and Ni/Au (30 nm/80 nm) as a top electrode pad. For Ohmic contacts, the LEDs were annealed at 450°C for 1 min under an N$_2$ ambient. To investigate the effect of surface passivation on the electrical properties of the LEDs, an N$_2$O plasma treatment was performed in a plasma-enhanced chemical vapor deposition (PECVD) chamber by varying the radio frequency (rf) power (10-100 W), a plasma treatment time of 10 min, and the sample holder temperature of 300°C at a fixed N$_2$O flow rate of 500 sccm. The current-voltage (I-V) curves of the LED sample were then measured at room temperature using a parameter analyzer (HP 4145A).

Experimental

Because GaN and related devices hold considerable promise for use in the areas of opto-electronic devices, high-power/high-temperature electronic devices, and ultra violet (UV) detectors, research efforts are currently focused on processes which are necessary to improve their performance. One approach to improve the reliability and performance of GaN devices involves reducing the leakage current in the devices. For example, the performance of photodiodes such as low-UV-light-intensity detectors can be significantly improved by reducing the extent of reverse leakage current. For GaN-based electronic devices, Adivaranah et al. reported that the reverse leakage currents is primarily the result of material defects caused by mesa etch and that surface recombination can be significantly reduced using SiO$_2$ surface passivation, resulting in an improved electrical performance of such devices. In our previous report, the reverse leakage current of InGaN/GaN multiple quantum well (MQW) light-emitting diodes (LEDs) resulting from surface and sidewall damage formed as the result of the dry etching process for an electrode pattern transfer was greatly reduced as a result of surface passivation by a wet chemical treatment. In this study, we show that a plasma treatment of LEDs using an N$_2$O plasma after the deposition of the contact metals leads to a dramatic decrease in the reverse leakage current of InGaN/GaN MQW LEDs. It was also found that the pathways for the leakage current at reverse voltages involve the surfaces and sidewalls of the GaN layers in LEDs.

an rf plasma power of 30 W is similar to that of an p-GaN film treated with an N₂ plasma. As a result, the deterioration in the electrical properties of the LED treated with an N₂O plasma can be attributed to plasma damage caused by the energetic ion bombardment of LEDs. Table I shows that optimal electrical properties of LEDs are achieved at an rf plasma power of 20 W.

Figure 1 shows the $I-V$ curves of LEDs treated with an N₂O plasma under the optimum plasma conditions (rf power of 20 W) and an untreated sample. The operating voltage of LED with an N₂O plasma passivation at 20 mA was reduced and also the slope of $I-V$ curve was steeper than that of the untreated LED, meaning that the series resistance of the LED was decreased by a plasma passivation. These results show that the N₂O plasma treatment of LEDs effectively reduces the reverse leakage current (Fig. 1a) with reducing the operating voltage at a current of 20 mA and series resistance of the LED (Fig. 1b) by passivating the etch damage which was produced on the surface and sidewalls of n- and p-GaN layers in LEDs. We also measured the optical power of these two LEDs with and without an N₂O plasma passivation (not shown). At a current of 20 mA, the optical power of LEDs with an N₂O plasma passivation was increased compared to that of LED without this passivation. Based on these results, it can be drawn a conclusion that the N₂O plasma passivation greatly influences the electrical and optical performance of LEDs.

It has been reported that the leakage current in photodiode or p-n junction devices flows through the mesa sidewalls formed by dry etching or through the bulk region of the device. In our previous work, it was shown that an N₂ plasma treatment of the etched n-GaN surface effectively removes the dry etch-induced defects and damage to the surface, leading to improved electrical and optical properties of the etched n-GaN surface. Therefore, in the N₂O plasma treatment of the LED, it appears to passivate the damaged GaN layer formed by dry etching for electrode pattern transfer and to reduce the leakage current flow in the surface and sidewalls of the LED. To identify the leakage current path of MQW LEDs at low reverse bias voltages, the reverse leakage currents were measured as a function of mesa diameter. Five mesa-type LEDs with device sizes

![Figure 1](image1.png)

(a) Reverse leakage currents and (b) $I-V$ characteristics of MQW LEDs treated and untreated by an N₂O plasma under optimal plasma condition (rf power of 20 W).
of 176-640 μm were fabricated. Figure 2 shows that the reverse leakage currents of the different sized LEDs increased with increasing LED diameter in a linear manner. These results suggest that the leakage current at a low reverse bias is dominated by leakage current on the etched surface and sidewalls of MQW LEDs. If the reverse leakage current is dominated by leakage current through the bulk region of the device, the leakage current would be expected to increase in proportion to $d^2$, where $d$ represents the diameter of the LED. As shown in Fig. 2, however, the reverse leakage currents increase linearly with increasing mesa size, indicating that the paths of the reverse leakage current at low reverse voltages are related not to the bulk region but to the surfaces and sidewalls of the LEDs.

The reverse leakage current for the untreated LED increased rapidly with applied voltages lower than $-1.5$ V as shown in Fig. 1a. The increase in the reverse leakage current of an untreated LED may lead to the breakdown of the LED, resulting in its failure. To investigate the effect of N$_2$O plasma treatment on the reverse leakage current of LEDs of various sizes, we measured the reverse leakage currents at $-2$ V as a function of mesa diameter. Figure 3 shows the reverse leakage currents for LEDs treated and untreated by an N$_2$O plasma as a function of mesa pattern size at a reverse voltage of $-2$ V. These results clearly show that the reverse leakage current of MQW LEDs can be drastically decreased by an N$_2$O plasma treatment of the LEDs after the pattern transfer process for n- and p-electrode formation.

**Conclusions**

This study shows that the treatment of LEDs with an N$_2$O plasma after dry etching for LED electrode formation leads to a drastic decrease in the reverse leakage current at reverse voltages. It was also found that the source of the reverse leakage current which flows in LEDs at reverse voltages is due to electrical damage to the surface and sidewalls of the mesa structures on the LEDs, produced during the dry etching for electrode pattern transfer. The passivation of nonradiative damage on the surface and sidewalls of LED by an N$_2$O plasma also greatly improved the forward $J$-$V$ curves and optical output power of the LEDs.

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**References**