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Defect reduction and efficiency improvement of near-ultraviolet emitters via laterally overgrown GaN on a GaN/patterned sapphire template

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An approach to improve the defect density and internal quantum efficiency of near-ultraviolet emitters was proposed using a combination of epitaxial lateral overgrowth (ELOG) and patterned sapphire substrate (PSS) techniques. Especially, a complementary dot array pattern corresponding to the underlying PSS was used for the ELOG-SiO2 mask design. Based on the transmission-electron-microscopy and etch-pit-density results, the ELOG/SiO2/GaN/PSS structure can reduce the defect density to a level of 10^6 cm^-2. The internal quantum efficiency of the InGaN-based ELOG-PSS light-emitting diode (LED) sample showed three times in magnitude as compared with that of the conventional GaN/sapphire one. Under a 20 mA injection current, the output powers of ELOG-PSS, PSS, and conventional LED samples were measured to be 3.3, 2.9, and 2.5 mW, respectively. The enhanced output power could be due to a combination of the reduction in dislocation density (by ELOG) and improved light extraction efficiency (by PSS).

Unlike the previous double ELOG approaches, the presented ELOG-PSS structure needs only one regrowth process and will have high potential in future high-quality ultraviolet emitters, even blue/green laser diode applications. © 2006 American Institute of Physics.

The great potential of wide-band-gap group III nitrides has been limited in many applications by the very high density (10^9–10^11 cm^-2) of threading dislocations (TDs) that form when the nitride materials are grown on lattice-mismatched substrates. Recently, different growth approaches have been proposed for TD reduction. Epitaxial lateral overgrowth (ELOG) is a commonly used technique utilizing metal organic chemical vapor deposition (MOCVD) to reduce the TD density. In the ELOG method, a GaN film with several micrometers in thickness is first grown onto a sapphire substrate. Subsequently, a SiN or SiO2 stripe-type mask is produced, followed by epitaxial growth. Several groups have demonstrated direct lateral epitaxy growth onto a stripe-type patterned sapphire substrates (PSSs). A double ELOG technique where a second-layer SiO2 mask offsets over the window regions was utilized to enable a very low defect density (<10^6 cm^-2) GaN structure. However, this structure needs twice MOCVD regrowth process. In our previous studies, a considerably improved output power of near-ultraviolet (UV) InGaN light-emitting diodes (LEDs) on a PSS with a periodic hole pattern was obtained. In this work, we propose an approach to improve the defect density and internal quantum efficiency of UV emitters using a combination of PSS and ELOG techniques. Especially, a complementary dot array pattern corresponding to the underlying PSS was used for the ELOG-SiO2 mask design. This structure needs only single MOCVD regrowth process. Details of the electrical and optical properties of the ELOG/SiO2/GaN/PSS LED will be described.

The LED samples (chip size: 365×365 μm²) used in this study were all grown over 2 in. (0001) sapphire substrates by MOCVD. The wet-etched PSS was prepared using a periodic hole pattern (diameter: 3 μm; spacing: 3 μm) with an etching depth of 1.5 μm. The fabrication process of the crystallographic pyramidal patterns for the wet-etched PSS sample has been reported previously. The MOCVD GaN template with an initial thickness of ~3 μm was then grown on the wet-etched PSS. In the following, a dielectric SiO2 mask (~100 nm thick) was deposited on the GaN/PSS template where a dot array pattern offset over the underlying PSS was developed. Finally, the InGaN LED structure was grown upon the SiO2/GaN/PSS template via the ELOG process.

Figure 1(a) shows cross-sectional transmission-electron-microscopy (TEM) micrograph of the InGaN ELOG/SiO2/GaN/PSS LED structure. The multi-quantum-well (MQW) active region of the LED heterostructure is also shown in the inset of Fig. 1(b). It was found that the pyramidal pattern was not fully filled with the epilayer, where the GaN coalesced and laterally extended to from cantilever on the top of the pyramidal hole. Hence, freestanding laterally grown GaN epilayer was achieved on the pyramidal PSS with small voids. For the GaN-on-PSS sample, above these voids the dislocations do seldom observed. These voids could be associated with the relaxed morphologies of the GaN film side faces and usually led to TD bending in the direction of these voids. Furthermore, it can be seen clearly that a large number of extended TDs propagate throughout the GaN film, originating from the GaN/sapphire interface. The generation of these dislocations is caused by the large lattice mismatch between GaN and sapphire. Fortunately,
these TDs can be terminated by the SiO2 mask pattern (offset over the underlying PSS). In some active regions, there are almost free of TDs. The behavior is very similar to the previously ELOG works. A schematic diagram of the present TD reduction mechanism can be briefly illustrated in Fig. 1(b).

A prime concern about the ELOG/SiO2/GaN/PSS samples is their defect reduction revealed by the etch-pit-density (EPD) measurement. The etching process was carried out in a H2SO4 and H3PO4 mixture solution with a 1:3 ratio at 250 °C for 10 min. Hexagonal shaped pits were observed on the etched GaN surface. The scanning-electron-microscopy (SEM) micrographs of the EPD of the GaN/sapphire and ELOG-PSS samples are shown in Figs. 2(a) and 2(b), respectively. The total GaN thickness in each sample was kept at 6 μm. Hansen et al. have suggested that the origins of the large size pits were both pure edge and edge-screw mixed dislocations. The small pits were open-core dislocations (or nanopipes). These etch pits might be produced by the TDs propagating to the top surface of the GaN, which originates from the underlying GaN/sapphire interface. Thus the dislocation density of the ELOG-PSS sample can be estimated to be approximately of 6 × 10^5 cm^−2, which is much less than that of the control sample (2 × 10^9 cm^−2). The improvements in crystalline and optical quality of GaN using ELOG and PSS techniques are summarized in Table I, where the EPD, double-crystal x-ray diffractometry (DCXRD), and photoluminescence (PL) data were tabulated. It has been reported that the densities of screw dislocations including screw component of mixed dislocation and edge dislocation including edge component of mixed dislocation correspond to the DCXRD full widths at half maximum (FWHMs) of (002) and (102) planes, respectively. Moreover, the PL integrated ratios of the near-band-edge emission to the yellow luminescence band (I_{BE}/I_{YL}) and the room-temperature FWHM of PL emission represent the optical quality of the GaN epilayer. In brief, among the three structures, the ELOG-PSS sample has the strongest I_{BE}/I_{YL} emission ratio, the narrowest DCXRD, and PL FWHMs. These indicate that the improvements in the crystalline and optical quality of the ELOG/SiO2/GaN/PSS structure can be due to the efficient defect reduction.

To clarify the influence of dislocation reduction on the LED quality, we estimated the internal quantum efficiency (η_int) of the InGaN LED sample roughly using the temperature dependence of the integrated PL intensity. The luminescence thermal quench of an ideal InGaN MQW is mainly due to the thermal emission of carriers out of the MQW states into the barrier states, which can be attributed to the thermal barrier to escape from localized states and/or to capture at nonradiative recombination centers in the MQW. In general, the η_int value at low temperatures (∼10 K) can be regarded as 100% when neglecting the nonradiative recombination process. As shown in Fig. 3, the integrated PL intensities of

![FIG. 1. (a) Cross-sectional TEM micrograph of near-UV InGaN ELOG-PSS LED heterostructure, and (b) schematic diagram of the reduction mechanism of threading dislocations in the ELOG-PSS structure. The MQW active region of this LED heterostructure is shown in the inset of this figure.](image1)

![FIG. 2. Typical plane-view SEM micrographs of etch pit density in the wet-etched GaN surface for (a) ELOG-PSS and (b) conventional GaN/sapphire sample. The total GaN thickness in both samples was about 6 μm. An enlarged etching pit shape is also illustrated in the inset of this figure.](image2)

### TABLE I. Structure and optical performance of InGaN/AlGaN MQW LEDs grown on ELOG-PSS, PSS, and conventional sapphire templates.

<table>
<thead>
<tr>
<th>Sample</th>
<th>(002)</th>
<th>(102)</th>
<th>Etch pit density (cm^−2)</th>
<th>PL intensity (a.u.)</th>
<th>PL (FWHM) (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELOG-PSS</td>
<td>210</td>
<td>240</td>
<td>6 × 10^5</td>
<td>3.4</td>
<td>72</td>
</tr>
<tr>
<td>PSS</td>
<td>230</td>
<td>280</td>
<td>2 × 10^8</td>
<td>2.7</td>
<td>79</td>
</tr>
<tr>
<td>Sapphire</td>
<td>240</td>
<td>300</td>
<td>2 × 10^9</td>
<td>2.1</td>
<td>83</td>
</tr>
</tbody>
</table>
both the conventional (GaN/sapphire) and ELOG-PSS LEDs were nearly constant below 100 K and declined gradually with a further increase in temperature. At room temperature, the $\eta_{\text{int}}$ values (at 20 mA) were about 4.3% and 13.8% for the conventional and ELOG-PSS LEDs, respectively. The significant reduction in defect density could contribute the present evident improvements in the $\eta_{\text{int}}$ value.

Figure 4 shows the light output power versus injection current ($L-I$) characteristics of these LED samples. Here the LED chips were encapsulated in conventional epoxy lamp form (5 mm in diameter). These EL peak positions were located at 388 nm. The output power of the LED lamp was measured using an integrated sphere detector and the measured deviation was around 5%. It was found that the output intensity of these LED samples was linearly increased with the increase of the injection forward current until 60 mA and then saturated near 70 mA owing to the thermal heating effect. Under a 20 mA forward injection current, the output powers of ELOG-PSS, PSS, and conventional LED samples were estimated to be 3.3, 2.9, and 2.54 mW, respectively. A 30% enhancement in output power can be achieved in the ELOG-PSS LED sample as compared with that of the conventional GaN/sapphire LED sample. The improvement can be attributed to the reduction of nonradiative recombination centers from a reduced dislocation density ($\sim 10^5$ cm$^{-2}$) in the active layer. In view of the fact that there only needs single MOCVD regrowth process, the presented ELOG-PSS structure can be used as a suitable growth template for high-quality UV emitters and has high potential for blue/green laser diode applications.

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![Figure 3](image3.png)

**FIG. 3.** Temperature dependence of the Arrhenius plots for InGaN/AlGaN MQW LEDs grown on ELOG-PSS and conventional sapphire templates.

![Figure 4](image4.png)

**FIG. 4.** Room-temperature $L-I$ characteristics of InGaN/AlGaN MQW LEDs grown on ELOG-PSS, PSS, and conventional sapphire templates.