High Output Power Near-Ultraviolet and Violet Light-Emitting Diodes Fabricated on Patterned Sapphire Substrates Using Metalorganic Vapor Phase Epitaxy

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Received February 20, 2003, Accepted August 22, 2003

ABSTRACT

Near-Ultraviolet (NUV) and violet light-emitting diodes (LEDs) with an InGaN multi-quantum-well (MQW) structure were fabricated on patterned-sapphire substrate (PSS) using a single growth process of metalorganic vapor phase epitaxy (MOVPE). The PSS with parallel grooves along the <1120> direction and the <1100> direction was fabricated by standard photolithography and subsequent reactive ion etching (RIE). In this study, the PSS with parallel grooves along the <1120> direction was used. The GaN layer grown by lateral epitaxy on a patterned substrate (LEPS) had dislocation density of $1.5 \times 10^8$ cm$^{-2}$. The LEPS-NUV (or violet)-LED chips were mounted on the Si bases in a flip-chip bonding arrangement. When the LEPS-NUV-LED (the emission peak wavelength $\lambda_p$: 382 nm) was operated at forward-bias current of 20 mA at room temperature, the output power ($P_o$) and the external quantum efficiency ($\eta_e$) were 15.6 mW and 24%, respectively. When the LEPS-violet-LED ($\lambda_p$: 405 nm) was operated at forward-bias current of 20 mA at room temperature, the output power and the external-quantum efficiency were 26.3 mW and 43%, respectively. The PSS is very effective in reducing the dislocation density and increasing the extraction efficiency in the LEDs because of the scattering of the emission light at the patterned GaN/sapphire interface.

KEYWORDS: patterned sapphire substrate, PSS, MOVPE, LED, UV, white LED, solid state lighting

1. Introduction

High-performance optical devices such as amber, green, blue, white and ultraviolet (UV) light-emitting diodes (LEDs) and laser diodes (LDs) have been developed using GaN, AlGaN and InGaN compound semiconductors. These GaN devices are usually fabricated on sapphire substrate, because there is no large substrate available for GaN homo-epitaxial growth. Due to the large differences in the lattice constant, thermal expansion coefficient and chemical characteristics between GaN and sapphire, numerous threading dislocations are induced in the InGaN active layers through the GaN or AlN buffer layer grown at low temperature on the sapphire substrate. The dislocation density has been reported to be of the order of $10^9 - 10^{10}$ cm$^{-2}$. Although high-brightness blue and green LEDs have been realized in spite of the high dislocation density, reduction in the dislocation density is desired in order to improve the performance and reliability of these devices. The epitaxial-lateral overgrowth (ELO) technique based on selective-area growth (SAG) has recently attracted considerable attention, since blue violet laser diodes that were fabricated on an ELO-GaN layer resulted in the achievement of a long lifetime of more than 10,000 hours. Several
intensive studies on SAG have revealed that ELO is effective in reducing the dislocation density\(^{3,7-9}\). Recently, new ELO techniques using patterned substrate have been developed to reduce the dislocation density\(^{10-15}\). Using these techniques, we can reduce the dislocation densities by a single growth process without any interruption and a SiO\(_2\) mask.

On the other hand, white LEDs with high luminous efficacy have come to be expected in solid-state lighting. Although high-brightness white LEDs fabricated by blue LEDs and yellow phosphor are available, white LEDs with high luminous efficacy, high general color-rendering index (CRI) and a variety of color temperature are desirable in order to realize new solid-state lighting. White LEDs fabricated by a combination of high power near ultraviolet (NUV) or violet LEDs and red/green/blue (RGB) phosphors are one of the hopeful methods to realize the solid-state lighting with the properties of high luminous efficacy and CRI.

In this study, we succeeded in fabricating the high output power multi-quantum-well (MQW) NUV and violet LEDs using the lateral epitaxy on a patterned substrate (LEPS) technique and described its electrical and electroluminescence (EL) properties.

2. Experiment

Epitaxial layers of NUV (or violet)-LED devices were grown on a patterned-sapphire substrate (PSS) by the metal-organic vapor phase epitaxy (MOVPE) technique under atmospheric pressure. The growth process was carried out without a mask, which is used in the conventional ELO process, and without any interruption. The PSS was e-face sapphire of 2-inch diameter with parallel grooves along the \(<1120>_{\text{GaN}}\) direction or \(<1100>_{\text{GaN}}\) direction. The PSS was fabricated by standard photolithography and subsequent reactive ion etching (RIE), in which Cl\(_2\) gas was used. The dimensions of the structure were as follows: the widths of the ridges and grooves and the depth of grooves were 3 \(\mu\) m, 3 \(\mu\) m and 1.5 \(\mu\) m, respectively.

![Image](image.png)

Fig. 1 Cross-sectional SEM micrographs of LEPS-GaN grown on the PSS aligned along the \(<1120>_{\text{GaN}}\) direction at the growth time of 40 min (a), at the growth time of 100 min (b), LEPS-GaN grown on the PSS aligned along the \(<1100>_{\text{GaN}}\) direction at the growth time of 30 min (c), at the growth time of 60 min (d).
Figure 1 (a) and (b) show the cross-sectional scanning-electron microscope (SEM) micrographs of LEPS-GaN grown on the PSS aligned along the $<1120>_{\text{GaN}}$ direction at the growth time of 40 min (a), and at the growth time of 100 min (b). The GaN layer is grown on the bottom of the grooves and the top of the ridges with a $\{1101\}$ facet structure (along the $<1120>_{\text{GaN}}$ direction). As a result, the GaN layer buried these grooves completely as shown in Figure 1 (b). On the other hand, Figure 1 (c) and (d) show the cross-sectional SEM micrographs of LEPS-GaN grown on the PSS aligned along the $<1100>_{\text{GaN}}$ direction at the growth time of 30 min (c), and at the growth time of 60 min (d). The GaN layer, which was grown from the top of the ridges, extended over the grooves. As a result, a flat GaN layer with an air gap over the grooves was formed. In this study, the PSS aligned along the $<1120>_{\text{GaN}}$ direction was used for the substrate of the LEDs because of the superior EL characteristics in the LEDs.

Figure 2 depicts a schematic diagram of the NUV (or violet)-LED consisting of the PSS, a 27-nm-thick GaN buffer layer grown at low temperature, 6-$\mu$m-thick n-GaN:Si, 50-nm-thick n-Al$_{0.1}$Ga$_{0.9}$N:Si, a MQW structure with four 3-nm-thick InGaN wells sandwiched between 10-nm-thick GaN barriers, 50-nm-thick p-Al$_{0.1}$Ga$_{0.9}$N:Mg and 100-nm-thick p-GaN:Mg. In this study, we fabricated three types of LED with the various In composition of InGaN wells. At room temperature (RT), the emission peak wavelengths of the sample A, sample B and sample C were 382 nm, 390 nm and 405 nm, respectively.

The LED chip was fabricated as follows. First, a p-type electrode with high reflectance was deposited on the p-GaN surface. Next, a partial p-GaN area was etched to 800 nm depth, until the n-GaN contact layer was revealed. A n-type electrode was deposited on the n-GaN-revealed surface for ohmic contact. SiO$_2$ film was deposited for the isolation and protection of the surface. Next, the sapphire was lapped and polished until the total thickness was 100 $\mu$m. The wafer was cut into a rectangular shape (350 $\mu$m x 350 $\mu$m). These LED chips were then mounted on the Si bases using Au-Sn alloy in a flip-chip bonding arrangement. The flip-chip LEDs were placed on lead frames, and then encapsulated by epoxy resin. The properties of the encapsulated LEDs were measured at RT.

3. Results and Discussion

Figure 3 shows the cross-sectional transmission-electron microscope (TEM) micrograph of LEPS-GaN grown on the PSS aligned along the $<1120>_{\text{GaN}}$ direction. The bending of the threading dislocation toward the lateral growth direction along the $<1100>_{\text{GaN}}$ is observed. The facet structure during the growth of the LEPS-GaN shown in Figure 1 (a) was estimated to be effective to bend the dislocation and reduce the dislocation density$^{10}$. It is considered the bending of the dislocation at the inclined facet results from a stress field formed by the dislocation$^{15}$. A lot of dislocations bend toward the lateral direction, and are terminated at the coalescence region. Therefore, the dislocation density can be reduced. The dislocation density of these samples was measured by the cathode luminescence (CL). The distribution and density of the dislocation measured by CL are as follows. The dislocation is random in the LEPS-GaN layer grown on the PSS aligned along the $<1120>_{\text{GaN}}$ direction. The dislocation density of the LEPS-GaN estimated to be approximately $1.5 \times 10^6$ cm$^{-2}$. On the other hand, the dislocation density of GaN layer grown on a conventional sapphire substrate (CSS) was estimated to be approximately $4 \times 10^6$ cm$^{-2}$.

Figure 4 shows the typical EL spectra of the LEPS-NUV-LED obtained at RT under various forward-bias currents. The peak wavelength and the full-
**Fig. 4** EL spectra of the LEPS-NUV-LED (Sample A) obtained at RT under various forward-bias currents.

**Table 1** Characteristics of the LEPS-LEDs.

<table>
<thead>
<tr>
<th></th>
<th>Sample A</th>
<th>Sample B</th>
<th>Sample C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Substrate</strong></td>
<td>PSS &lt;1120&gt;\text{GaAs}</td>
<td>PSS &lt;1120&gt;\text{GaAs}</td>
<td>PSS &lt;1120&gt;\text{GaAs}</td>
</tr>
<tr>
<td><strong>Dislocation density</strong></td>
<td>$1.5 \times 10^8 \text{ cm}^{-2}$</td>
<td>$1.5 \times 10^8 \text{ cm}^{-2}$</td>
<td>$1.5 \times 10^8 \text{ cm}^{-2}$</td>
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<tr>
<td><strong>Output power $P_0$</strong> @ 20 mA</td>
<td>15.6 mW</td>
<td>19.2 mW</td>
<td>26.3 mW</td>
</tr>
<tr>
<td><strong>External quantum efficiency $\eta_e$</strong> @ 20 mA</td>
<td>24%</td>
<td>31%</td>
<td>43%</td>
</tr>
<tr>
<td><strong>Peak Emission Wavelength</strong></td>
<td>382 nm</td>
<td>399 nm</td>
<td>405 nm</td>
</tr>
<tr>
<td><strong>Operating voltage</strong> @ 20 mA</td>
<td>3.4 V</td>
<td>3.4 V</td>
<td>3.4 V</td>
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**Fig. 5** Output power ($P$) of the LEPS-LEDs (Sample A, B and C) as a function of the forward-bias current.

**Fig. 6** External quantum efficiency ($\eta_e$) of LEPS-LEDs (Sample A, B and C) as a function of the forward-bias current.
width at half maximum (FWHM) at 20 mA were estimated to be 382 nm and 100 meV, respectively. With increasing current, the emission peak wavelength is constant below the injection current of 20 mA, slight red shift was observed above 20 mA, which may be due to heat generation caused by current injection. However, blue shift resulting from the piezoelectric field was not observed.

The output powers ($P_o$) and the external-quantum efficiencies (EQE, $\eta_e$) of three samples (A, B and C) at 20 mA are summarized in Table 1. At forward-bias current of 20 mA, the output powers and EQE of these samples (A, B and C) were 15.6 mW, 24%, 19.2 mW, 31%, 26.3 mW and 43%, respectively. Figure 5 shows the output power of the LEPS-LEDs (sample A, B and C) as a function of the forward-bias current. Figure 6 shows EQE of these samples as a function of the forward current. From these figures, it is evident that EQE of the LEPS-InGaN-LEDs are constant above 1 mA, and the output powers increase linearly up to 50 mA. We obtained output powers of approximately 37 mW, 45 mW and 61 mW at 50 mA, respectively. It is also evident that EQE of sample C at low injection current is higher than those of the others. It means that the increasing of the In composition at the NVU region decrease the effect of non-radiative recombination.

The ratio of output power of LEPS-LED to that of CSS-LED is approximately 130 - 140%. This is due to the decrease of non-radiative recombination centers, i.e., dislocations and point defects, of the LEPS-LED and due to increase the extraction efficiency because of the scattering of the emission light at the patterned GaN/sapphire interface. EQE of InGaN-LED fabricated on sapphire is limited by the internal-quantum efficiency and the extraction efficiency. The critical angle of total internal reflection at the interface of GaN ($\alpha=2.54$, @410 nm)/sapphire ($\alpha=1.79$, @410 nm) is 44.8° by Snell's Law. This means that 70% of the light generated in the MQW is confined in GaN-epitaxial layer and is absorbed by the electrode and MQW. The patterned GaN/sapphire interface scatters the confined light, and changes the angle of propagation. The scattered light has a chance to escape from the GaN layer again. Therefore, the extraction efficiency is increased.

4. Conclusions

We have demonstrated the characteristics of high-power LEPS-NUV (or violet)-LEDs with an InGaN-MQW fabricated on the PSS. The optimum growth condition, under which the facet structures are controlled during the growth, can reduce the dislocation density to be approximately $1.5\times10^4$ cm$^{-2}$. The optical output power and the EQE of LEPS-violet-LED (the emission peak wavelength: 405 nm) at forward-bias current of 20 mA were estimated to be 26.3 mW and 43%, respectively.

Acknowledgements

The authors are grateful to Mr. T. Jyouchi for the technical support in the sample preparation. This work was financially supported by “The light for the 21st Century” of the National project of METI/NEDO/JRCM in Japan.

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