Enhanced efficiency of GaN-based light-emitting diodes with periodic textured Ga-doped ZnO transparent contact layer

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(Received 22 May 2007; accepted 7 June 2007; published online 28 June 2007)

GaN-based light-emitting diodes (LEDs) with indium tin oxide (ITO)/Ga-doped ZnO (GZO) composite oxide films serving as a transparent contact layer (TCL) were demonstrated. In this study, the wall-plug efficiency of LEDs (LED-III) with textured ITO/GZO composite TCL can be markedly improved by 200% and 45% of magnitude as compared to conventional LEDs with Ni/Au TCL (LED-II) and planar ITO/GZO TCL (LED-I), respectively. Compared to LED-II, this enhancement is due to the enhanced light extraction efficiency of ITO/GZO composite TCL with high transparency. Compared to LED-I, ZnO-based TCL with a higher refractive index ($n \sim 2.0$) allows further enhancement of light extraction through the creation of a textured structure on transparent conductive oxide TCL deposited on the top surface of LEDs. In addition, the ITO/GZO composite TCL with a thickness of 550 nm is far larger than that of Ni/Au TCL with a thickness of approximately 15 nm. Therefore, in addition to the effect of high transparency, the thicker ITO/GZO TCL with low lateral resistance would also act as a current-spreading layer leading to an enhancement of light extraction. © 2007 American Institute of Physics. [DOI: 10.1063/1.2753110]

The development of high-efficiency InGaN light-emitting diodes (LEDs) is considered one of the most important topics in the area of solid-state lighting. However, the efficiency of LEDs is limited by several factors including the high resistivity of $p$-GaN; hence, the severe current crowding occurs under the $p$ electrode. For this reason, a thin Ni/Au layer with transparency below 70% in the visible region has been extensively investigated to serve as the transparent contact layer (TCL). Transparent conductive oxides (TCO), such as indium tin oxide (ITO), have high transparency in the visible region, allowing it to serve as the TCL in LEDs. ZnO-based TCO is a well-known wide gap material and an alternative substrate for a TCL in LEDs. It has similar electrical and optical properties to ITO, but it is a nontoxic material, which has high temperature stability and costs less to manufacture. Recent research demonstrated that using ZnO doped with gallium resulted in films both with low resistivity and high transmittance in the visible region.

The light extraction efficiency (LEE) of LED devices is mainly governed by the probability that a photon emitted from the active layer will escape from the high-refractive-index semiconductor material into the lower-refractive-index surrounding material, i.e., air or resin. To enhance the probability of escape for photons generated in the active layer of the LED, the angular randomization of photons can be achieved through surface scattering from the roughened top surface of the LED. In addition to high transparency, ZnO-based TCL with a higher refractive index ($n \sim 1.9–2.1$) allows further enhancement of light extraction through the creation of a textured structure on the ZnO-based TCL deposited on the top surface of LEDs. In this study, GaN-based LEDs with a periodic textured structure performed on the Ga-doped ZnO (GZO) TCL instead of the $p$-GaN layer were designed to further increase the LEE. Typically, ZnO-based TCO prepared by magnetron sputtering can achieve a refractive index of around 2 in the visible region. Therefore, GZO films with a textured surface were used as the TCL on InGaN blue LEDs to achieve a marked enhancement in light output power compared to LEDs with Ni/Au or planar GZO TCL.

The InGaN/GaN multiple-quantum-well LED wafers used in this study were grown on $c$-face sapphire (0001) substrates by metal organic vapor phase epitaxy. The detailed layer structure and growth procedure have been described in previous publication. For LEDs with planar ITO/GZO composite TCL (LED-I), a 30-nm-thick ITO film was first deposited onto the $p$-GaN layer using an electron beam evaporator, and then the GZO film with a 3% Ga content was deposited on the aforementioned samples using a magnetron sputtering method. The total thickness of the ITO/GZO composite TCL...
was 550 nm. ZnO and Ga₂O₃ targets were used as the sputtering sources during the cosputtering deposition of the GZO films. The samples were then annealed at 800 °C for 1 min in ambient N₂ in a rapid thermal annealing system. In this study, LEDs with Ni (5 nm)/Au (10 nm) TCL were also prepared for the purpose of comparison and were labeled as LED-II. For the fabrication of LED-III, after the deposition of Ni/Au, the samples were annealed at 550 °C in ambient air for 5 min. Periodic texture was performed on the GZO TCL by photolithography and a wet etching process using a dilute HCl solution (HCl:H₂O=1:4) to create a 5-μm-wide GZO strip, while the spacing between two GZO strips was kept at 10 μm. The etching depth of the GZO layer was around 370 nm. Figures 1(a) and 1b illustrate the schematic device structure with a cross-section view and a top-view graph of the InGaN/GaN LEDs with periodic texture on the GZO TCL, respectively. In this study, LEDs with textured GZO TCL were labeled as LED-III. In this study, all fabricated LEDs had a dominant emission wavelength of 460 nm.

The current-voltage characteristics of experimental LEDs were measured using the HP-4156C semiconductor parameter analyzer, and the output power of the LEDs was measured with a calibrated integrating sphere.

The forward voltages \( (V_f) \) measured at 20 mA were equal to 3.65, 3.3, and 3.75 V for the LED-I, LED-II, and LED-III, respectively, as shown in Fig. 2. It should be noted that LEDs with GZO directly deposited onto the p-GaN layer exhibit poor electrical properties with typical \( V_f \) values as high as 5 V. Similar results were also obtained for the GaN-based LEDs with Al-doped ZnO TCL. This can be attributed to the fact that the resistivity (electron concentration) of GZO is still not low (high) enough to form a low-resistivity Ohmic contact and may even result in a Schottky contact.

In other words, the GZO/p-GaN contact with a high Schottky barrier hinders the carrier from transporting through the interface. To further reduce the \( V_f \) of LEDs with GZO TCL, a thin ITO layer, which has resistivity as low as \( \sim 1 \times 10^{-4} \) Ω cm, was inserted between the GZO and p-type GaN. This scheme differs from previous reports using a thin Ni or NiO₅ layer, which has a lower transparency compared to ITO thin layer, to improve the electrical performance of GaN LEDs with TCO layers as the TCL. As depicted in Fig. 2, LED-I and LED-III exhibit a \( V_f \) of around 3.7 V when the low-resistivity ITO layer was inserted between the GZO and p-type GaN layer. This improvement could be attributed to the fact that an ITO with low resistivity can lead to an Ohmic contact rather than a Schottky contact, which was observed in the GZO/p-type GaN contact.

With an injection current of 20 mA, the light output powers are 4.5 and 2.08 mW for LED-I and LED-II, respectively, as shown in Fig. 2. Although the output power of LED-I was much higher than that of LED-II, we should note that the forward voltage of LED-I was also higher than the forward voltage of LED-II, as shown in Fig. 2. Therefore, to properly evaluate the overall efficiency of these LEDs, we have to estimate the wall-plug efficiency (WPE) based on electrical and optical characteristics, as shown in Fig. 2. When a forward current of 20 mA was applied, the WPEs of LED-I and LED-II were estimated to be around 6.2% and 3.1%, respectively. Clearly, the WPE of LED-I is around two times higher than that of LED-II. The increase of light output can be attributed to the increase of light transmittance in the ITO/GZO composite TCL. It should be noted that the ITO/GZO and Ni/Au films were also deposited on a sapphire substrate to determine the transparency by transmission spectroscopy. At a wavelength of 460 nm, the transparencies were around 92% and 60% for the ITO/GZO composite films and the Ni/Au films, respectively. The question of why the 50% increase in transmittance of TCL as compared with ITO/GZO and Ni/Au can lead to a 115% improvement of light output power at an injection current of 20 mA must be addressed. With the exception of absorption, light extraction efficiency in LEDs is mainly limited by critical angle loss and Fresnel loss. As mentioned above, the ITO/GZO composite TCL with total thickness of around 550 nm, which is a nine-quarter-wave antireflection optical film, could have the Fresnel loss below 5% in LED-I. This is far less than that of LED-II, which exhibits a Fresnel loss of approximately 15% if the refractive indexes of GaN and GZO were around 2.4 and 2.0, respectively. In addition, the 550-nm-thick ITO/
GZO composite TCL with lower lateral resistance as compared to Ni/Au thin TCL would play the role of a good current-spreading layer leading to an enhanced light extraction. In addition, GZO has a refractive index of around 2.0, which allows further enhancement of light extraction by creating a textured surface on the GZO layer. As shown in Fig. 2, the light output power of LED-III is even higher that of LED-I, exhibiting an output power of around 6.7 mW corresponding to a WPE of around 9% at an injection current of 20 mA. Table I shows the forward voltage, light output power, and wall-plug efficiency when the LEDs were driven at dc current of 20 mA. Comparing LED-III and LED-I, this marked enhancement of light output or WPE in the LED-III is due to the texture added to the GZO layer, as shown in Fig. 1(b). Two reasons account for the increased extraction of photons. First, in the LED-III, photon extraction can occur at the etched GZO sidewall, whereas LED-I has no such sidewall area due to the planar surface of the GZO in LED-I. Second, the etched GZO surface is rougher than that of the as-deposited GZO surface, as shown in the Fig. 1(c). The escape probability of photons generated in the active layer of the LED can be enhanced by increasing the angular randomization of photons at the roughened surface. In other words, the combination of the sidewall area and surface roughening on the etched GZO layer could effectively disperse the angular distribution of photons in the optical phase space, leading to a larger escape cone in the textured GZO layer over the planar structure. Considering the electrical properties of LED-III and LED-I, although the surface texture performed on the GZO layer should cause a reduction of lateral cross-section area and hence an increase of lateral resistance, only a slight increase in $V_f$ can be obtained indicating that the texture process would not significantly result in a degradation of the electrical property compared to those of GaN-based LEDs with planar GZO TCL. Although using ITO to serve as the TCL of LED is a well accepted technology, ZnO-based TCLs with high refractive index of around 2.0 would render another advantage when a roughening process is performed on the surface. In other words, since packaged LEDs are generally encapsulated using epoxy with a refractive index of around 1.5, further improvement in light extraction by means of surface roughening performed on ITO TCL would thus be minor because the typical refractive index of an ITO film prepared by our e-beam evaporator is around 1.7.

In conclusion, ITO/GZO and Ni/Au films were deposited on $p$-type GaN to serve as the TCL. Although the 20 mA forward voltage of LEDs with planar ITO/GZO composite TCL (LED-I) is slightly higher than LEDs with Ni/Au TCL (LED-II), the output power of the LED-I is far higher than LED-II. Therefore, the wall-plug efficiency was two times higher than that of LED-II. This improvement could be attributed to the fact that the ITO/GZO composite TCL has high transparency and a larger thickness as compared to thin Ni/Au TCL. The thick ITO/GZO TCL with low lateral resistance would also act as the current-spreading layer leading to an enhancement of light extraction. In addition, the thick ITO/GZO TCL with high refractive index could be partially etched away using a HCl solution to form a periodic texture on the GZO layer and thereby result in a further enhancement of light extraction efficiency.

<table>
<thead>
<tr>
<th>LED</th>
<th>Forward voltage (V)</th>
<th>Light output power (mW)</th>
<th>Wall-plug efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED-I</td>
<td>3.65</td>
<td>4.5</td>
<td>6.2</td>
</tr>
<tr>
<td>LED-II</td>
<td>3.3</td>
<td>2.08</td>
<td>3.1</td>
</tr>
<tr>
<td>LED-III</td>
<td>3.75</td>
<td>6.7</td>
<td>9</td>
</tr>
</tbody>
</table>

TABLE I. Forward voltage, light output power, and wall-plug efficiency when the LEDs were driven at dc current of 20 mA.