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Improvement of light extraction for a target wavelength in InGaN/GaN LEDs with an indium tin oxide dual layer by oblique angle deposition

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GaN-based blue LEDs were fabricated and studied with porous, dense, and dual-layer indium tin oxide (ITO) structures as transparent top electrodes to enhance light extraction. The electroluminescence intensity of the LED with a thickness-optimized and refractive-index-tuned ITO dual layer at I = 20 mA was higher by 19.7% than that of the conventional LED with a 200 nm planar ITO. This study confirmed that an ITO dual layer can be made with a single material by optimizing the thickness and tuning the refractive index, which improves the power output without any electrical property degradation. © 2016 The Japan Society of Applied Physics

Indium gallium nitride (InGaN) is being studied increasingly as a prospective material for LEDs.1-3) Transparent top conductive layers such as indium tin oxide (ITO) are essential for LED fabrication, and various techniques have been studied in order to improve light extraction. One of the most employed methods to enhance the light extraction efficiency in LED fabrication is surface texturing, which can be formed on the N-face of GaN,2,4) on a p-GaN surface,5) and even on an ITO layer.6) However, because texturing by the direct etching of p-GaN induces plasma etching damage7) and degrades electrical properties, texturing has been studied widely on ITO layers.8,9) ITO texturing made by wet or dry etching was also revealed to increase the series resistance in ITO films.10) It is also important to optimize the ITO thickness in LED applications because reflectance fluctuates with ITO thickness variation, which improves light extraction at a target wavelength.11) Another way of enhancing light extraction is nanotexturing at a subwavelength scale to form a low reflectance in a broad wavelength range; however, for this approach, more complex fabrication procedures, such as the use of subwavelength structures (SWWs) obtained by laser hologram lithography,12) are required. In addition, for multilayer antireflection (AR) coating, it is difficult to select a material with an appropriate index while satisfying the optical transmittance and electrical conductivity. Moreover, when using heterogeneous materials, Fresnel reflection should also be considered. As a way to solve this problem, a graded-refractive-index (GRIN) AR coating method that includes oblique angle deposition is being used for tuning the refractive index.13) Oblique angle deposition is a well-known method that produces a low reflective index with a porous film by surface diffusion and self-shadowing effects.14-19) A reduced reflectivity in a broad wavelength range can be used for general purpose, but it is not exactly suitable for the optical performance of LEDs in comparison with inputting complex fabrication processes because the full width at half maximum (FWHM) of the emission is smaller than 50 nm in conventional blue and green LEDs.20,21)

In this study, we formed an ITO top conductive layer for a particular target wavelength (450 nm) using a dual layer that combined an ITO with a modified refractive index deposited by oblique angle deposition and a conventional ITO. Then, we developed a transparent conductive oxide (TCO) with a low reflectance at a specific wavelength without nanofabrication. We also eliminated the Fresnel reflection through GRIN AR coating by oblique angle deposition while using the same material. This was possible by combining refractive index tuning through oblique angle deposition and reducing the reflectivity at a target wavelength through destructive interference by the thickness control of the ITO dual layer.

The LED structure consisted of Si-doped 2.2 µm n-GaN on an undoped GaN/Al2O3 template, InGaN/GaN multiquantum wells (MQWs), and a Mg-doped 100 nm p-GaN layer. The LED structure consisted of Si-doped 2.2 µm n-GaN on an undoped GaN/Al2O3 template, InGaN/GaN multiquantum wells (MQWs), and a Mg-doped 100 nm p-GaN layer. The LED structure consisted of Si-doped 2.2 µm n-GaN on an undoped GaN/Al2O3 template, InGaN/GaN multiquantum wells (MQWs), and a Mg-doped 100 nm p-GaN layer. The LED structure consisted of Si-doped 2.2 µm n-GaN on an undoped GaN/Al2O3 template, InGaN/GaN multiquantum wells (MQWs), and a Mg-doped 100 nm p-GaN layer. The LED structure consisted of Si-doped 2.2 µm n-GaN on an undoped GaN/Al2O3 template, InGaN/GaN multiquantum wells (MQWs), and a Mg-doped 100 nm p-GaN layer.

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occurs between lights with different phases, which makes the reflectance fluctuation at the thin film dependent on the thickness of the dual layer between the $n_1$ and $n_2$ materials.

Figure 3 shows simulation results of the reflectance based on the refractive index variation in pITO in the range that can make a graded index on the basis of Eqs. (1)–(7). Figures 3(a)–3(c) show the reflectance results obtained when air was set to be the $n_0$ material ($n_0 \approx 1$) and pITO layers were obliquely deposited at angles of 80, 70, and 60°, respectively. We can see that the black area with a reflectance less than 0.5% is most widely distributed under 80° ($n_1 \approx 1.35$) conditions as in Fig. 3(a). Figures 3(d)–3(f) show another set of reflectance results when we set $n_0$ as $\sim 1.5$. Black areas represent regions with a reflectance lower than 0.5% in all contour plots.

Figure 4(a) shows the calculated reflectance at the target wavelength (450 nm) based on the thickness of the ITO layers on the GaN layer. The results confirm that the minimum and maximum reflectances are periodically repeated. Figure 4(b) shows the reflectance curves for the three minimum reflectance conditions indicated in Fig. 4(a) as P1, P2, and P3. We
can see that all three conditions represent the minimum reflectance exactly at the target wavelength, and that the P1 condition shows the lowest reflectance around the target wavelength. Therefore, we fabricated LEDs with the ITO dual layer and the P1 condition in order to confirm the concept of the dual ITO by investigating the electrical and optical properties.

From our simulation results, structures with an ITO dual layer were fabricated as shown in Fig. 5(a). Although dITO obtained by the conventional method had its own refractive index of 2.0, pITO obtained by the oblique angle deposition method had a tuned value \( n_{pITO} \approx 1.35 \) at 450 nm.23) Thus, a GRIN structure was formed from air \( (n_{air} = 1) \) to pITO \( (n_{pITO} \approx 1.35) \), dITO \( (n_{dITO} \approx 2.0) \), and GaN \( (n_{GaN} \approx 2.5) \) by depositing pITO (70 nm) on dITO (40 nm) in accordance with the results of the above simulation for the target wavelength (450 nm) as shown in Fig. 5(a).

Figure 5(b) shows the reflectivity of the fabricated ITO thin layers on the GaN film at normal incidence. The solid lines are the measured data, and the dotted lines are the simulated data obtained using the equations. The simulated reflectance fluctuation tendency is very close to the measured data and we consider that the small deviation comes from the surface morphology, absorption, and thickness variation by the E-beam evaporator. However, it clearly shows that the ITO dual layer has the lowest reflectance at the target wavelength (450 nm) and also over the entire wavelength range.

Then, to verify the enhancement through the reduced reflectance, LEDs were fabricated with the ITO layers shown in Fig. 5(b). Figure 6(a) shows the current versus voltage \((I-V)\) curves and Fig. 6(b) shows the electroluminescence (EL) of the four samples. Although the current at 3 V was determined to be 18.24 mA for the (3)-pITO 70 nm sample and 23.33 mA for the (2)-dITO 40 nm sample, the (4)-ITO dual layer and (1)-dITO 200 nm (ref.) sample had similar values (25.97 and 27.09 mA, respectively). We can see that the (2)-dITO 40 nm sample has a higher resistance than the
(1)-dITO 200 nm (ref.) sample and (4)-ITO dual layer, which we attributed to too thin a layer as shown in Fig. 5(a). The (3)-pITO 70 nm sample had the poorest electrical properties because of a lower conductivity due to a lower density than dITO. This also resulted in a highly reduced EL intensity as seen in Fig. 6(b).

The EL intensity of the ITO dual layer at \( I = 20 \text{ mA} \) was higher by 19.7% than that of the planar ITO 200 nm sample as shown in Fig. 6(b). The EL enhancement came from the reduced reflectance (~13.6%) through the destructive interference by the thickness-optimized ITO dual layer, resulting in a higher light extraction without electrical degradation. This result demonstrates that the refractive-index-tuned ITO dual layer can function very efficiently as a top electrode with a higher extraction efficiency in LEDs. Furthermore, normalized far-field radiation patterns were measured for four types of LEDs at an injection current of 20 mA as shown in the inset of Fig. 6(b). The output intensity of the LED with the (4)-ITO dual layer was higher than that of any other LED including the (1)-dITO 200 nm (ref.) sample in the entire angular range. Therefore, we could see that the ITO dual layer significantly increased the light extraction efficiency through far-field pattern investigation.

We fabricated GaN-based MQW LEDs and studied them with four different ITO structures as a transparent top electrode to increase the light extraction efficiency by reducing reflectivity. EL intensity was increased with a thickness-optimized and refractive-index-tuned ITO dual layer that reduced the reflectance. We confirmed from this study that an ITO dual layer can be made with a single material by thickness optimization and refractive index tuning, which improves the power output without degrading the electrical properties.  

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