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Enhanced Light Extraction of GaN-Based Light Emitting Diodes Using Nanorod Arrays

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Using a self-shadowing nature, various indium tin oxide (ITO) nanorod arrays were deposited on the surface of GaN-based light emitting diodes (LEDs) by an electron-beam deposition system. The surface morphology and effective refractive index could be controlled by the oblique angle of the deposited ITO nanorod arrays. The surface morphology and the matching refractive index of 1.6 between air and p-GaN layer were obtained for the ITO nanorod arrays with an oblique angle of 45°. Comparing the conventional LEDs without ITO nanorod arrays, the light output power increase of 26.4% is attributed to the surface morphology and the matching refractive index obtained by the ITO nanorod arrays.

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Recently, III-V nitride-based light emitting diodes (LEDs) have aroused considerable interest in applications of displays, back lights, and light sources.[1,2] To obtain high performances, the improvement of both internal quantum efficiency and light-extraction efficiency of the LEDs is needed. In view of the achievement in epitaxial growth and structure, the internal quantum efficiency of the LEDs has been improved significantly. However, the high power and high efficiency of LEDs are still obstructed by light-extraction efficiency. To obtain high light-extraction efficiency, several methods can be used including flip-chip mounting,[3] surface roughness,[4] conductive omnidirectional reflectors (ODRs),[5] antireflection (AR) coating,[6] photonic crystal,[7] etc. The oblique-angle deposition technique was used in ODR and multi-AR coating fabrication to provide high reflection at the visible region and enhance the light output of LEDs, respectively.[5,6] In this work, a single indium tin oxide (ITO) nanorod layer with various surface morphology and refractive indexes was deposited using an electron-beam deposition system. The ITO nanorod arrays were deposited on the top surface of GaN-based LEDs for the improvement of light-extraction efficiency. To understand the mechanism of various ITO nanorod arrays, the dependences of the effective refractive index and volume fraction of ITO nanorod arrays on the oblique angle were measured and investigated.

Experimental Results and Discussion

Figure 1a shows the schematic configuration of the oblique-angle electron-beam deposition system. A 10 nm thick ITO film was deposited on the surface of LEDs to perform a self-shadow of the following deposition process.[8,9] By changing the angle of the substrate holder, various ITO nanorod arrays can be deposited by the assistance of the self-shadowing nature, as shown in Fig. 1b. The oblique angle θ is the incident angle between the incident vapor flux and the perpendicular direction of samples.

Figure 2 shows the scanning electron microscope (SEM) images of the deposited ITO nanorod arrays with oblique angles of 30, 45, and 60°. It indicates that the film surface morphology varies with the oblique angle θ used in deposition. For the oblique angle of 30° shown in Fig. 2a, deposited films were granular in nature and hardly any nanorod formation occurred. However, for the 45° oblique deposition, the deposited layer, as shown in Fig. 2b, clearly exhibited a surface morphology having the form of nanorod arrays. This can be qualitatively interpreted as follows. The layer grows with the grains in the primary granular layer as growth centers. Due to the larger oblique angle of the substrate surface with the evaporation flux, the grains cast shadows that cover a larger part of the gap between neighboring grains, where the ITO growth is suppressed. The preferential growth along the grain results in the deposited ITO layer in the form of nanorod arrays. Considering the fact that the primary granules distribute randomly on the substrate surface, with a further increase in oblique angle to 60°, the shadows become larger than the gap between some of the neighboring grains, making these neighboring grains grow into a single rod; hence, the effective number of growth centers decreases. Therefore, the formed ITO nanorod arrays have a smaller rod density but greater rod length and diameter compared with the one having a 45° oblique deposition angle.

The effective refractive index of the ITO nanorod arrays, measured by an ellipsometer, as a function of wavelength is shown in Fig. 3. The effective refractive index decreases with the increase in the oblique angle θ. Therefore, the effective refractive index of the ITO nanorod arrays can be controlled by changing the oblique angle. Using the Bruggemann effective medium approximation[10]

$$V_{\mathrm{air}}\left(\frac{n_{\mathrm{air}}^2 - n_{\mathrm{eff}}^2}{n_{\mathrm{air}}^2 + 2n_{\mathrm{eff}}^2}\right) + V_{\mathrm{ITO}}\left(\frac{n_{\mathrm{ITO}}^2 - n_{\mathrm{eff}}^2}{n_{\mathrm{ITO}}^2 + 2n_{\mathrm{eff}}^2}\right) = 0 \qquad [1]$$

the volume fraction of air and ITO in the film, V_{air} and V_{ITO} $(=1 - V_{\mathrm{air}})$, can be calculated. For the wavelength of 450 nm, the refractive index of air $n_{\mathrm{air}} = 1$, the refractive index of ITO $n_{\mathrm{ITO}} = 2.06$, and the measured effective refractive index n_{eff} of the nanorod layer, corresponding to oblique angles of 30, 45, and 60°, is 1.92, 1.6, and 1.36, respectively. By substituting these parameters into Eq. 1, the associated volume fraction of ITO is 87, 58, and 37.5%, respectively. The volume fraction of ITO decreases with the increase in oblique angle. This experimental result indicates that the decrease in the effective refractive index with the increase in oblique angle can be attributed to the decrease in the volume fraction of ITO.

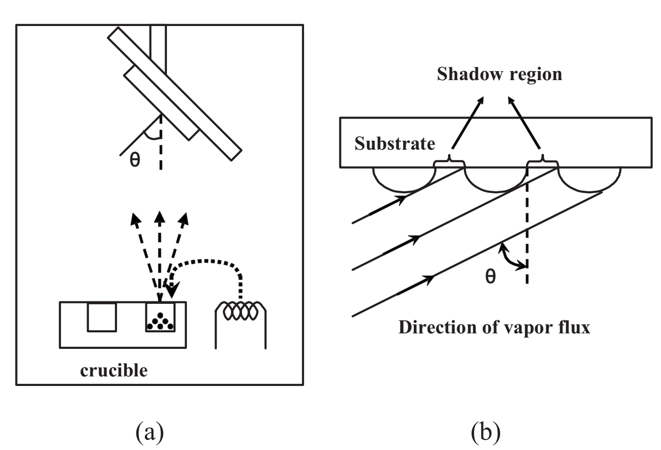

Figure 1. (a) Oblique-angle electron-beam deposition system and (b) schematic configuration of oblique-angle deposition.

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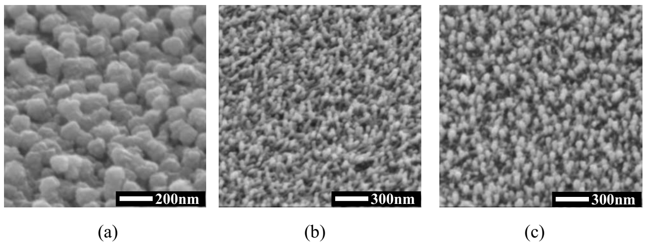

Figure 2. SEM images (tilt angle is 45°) of the ITO nanorod layer with different oblique angles θ: (a) θ = 30°, (b) θ = 45°, and (c) θ = 60°.

The epitaxial layers of the LEDs were grown on *c*-plane sapphire substrates using a metallorganic chemical vapor deposition system. The structure was composed of a 50 nm thick GaN buffer layer, a 3 μm thick Si-doped GaN layer (3×10^{17} cm^{-3}), an undoped InGaN/GaN multiple quantum well (MQW) active layer, a 50 nm thick Mg-doped $Al_{0.2}Ga_{0.8}N$ layer (1×10^{17} cm^{-3}), and a 300 nm thick Mg-doped GaN layer (3×10^{17} cm^{-3}). The InGaN/GaN MQW active layer consists of 10 periods of 3 nm thick $In_{0.23}Ga_{0.77}N$ well and 7 nm thick GaN barrier. The grown samples were then annealed at 750°C for 30 min in N_2 ambient for the activation of generating holes.

By using previously reported standard fabrication processes of LEDs,[11] the conventional LEDs were fabricated as shown in Fig. 4a. To study the function of ITO nanorod arrays, a 10 nm thick ITO film was deposited on the conventional LEDs and ITO nanorod arrays were then deposited using the electron-beam deposition system with oblique angles of 30, 45, and 60°. After depositing the ITO nanorods, the ITO nanorods on the top surface of the LEDs were protected by a photoresist and the other ITO nanorods existing at the sidewall were etched by dilute HCl, as shown in Fig. 4b. Therefore, the short circuit on the sidewalls of the LEDs could be avoided. The current–voltage (*I-V*) characteristics of the LEDs measured by an HP4145 semiconductor parameter analyzer are shown in the inset of Fig. 5. The conventional LEDs and the LEDs with various ITO nanorod arrays reveal similar *I-V* characteristics. The forward voltage of the LEDs operated at 20 mA is ~3.3 V. The measured peak wavelength of the fabricated LEDs is ~450 nm. Figure 5 shows the light output power of the conventional LEDs and the LEDs with various ITO nanorod arrays measured by LCS-100 sphere optics light measurement systems. Comparing with the conventional LEDs, the light output power of the LEDs, operated at 200 mA, with ITO nanorod arrays deposited with oblique angles of 30, 45, and 60°, increases by 7, 26.4, and 14.8%, respectively. The increase in light output power is attributed to the surface morphology performed by depositing the ITO nanorod arrays on the surface of LEDs. Among the three cases, the output enhancement with the oblique angles of 45 and 60° is larger than that with the oblique angle of 30°, which is clearly due to their better nanorod morphology. Furthermore, the best output performance for LEDs with ITO nanorod arrays deposited with an oblique angle of 45° can be attributed to its effective refractive index. The best matching refractive index of a layer sandwiched between the air of index $n_{air} = 1$ and the p-GaN layer of index $n_{GaN} = 2.5$ can be calculated by

$$(n_{air} \times n_{GaN})^{1/2} \cong 1.6 \quad [2]$$

According to the measured effective refractive index shown in Fig. 3, the effective refractive index of the ITO nanorod arrays with an oblique angle of 45° is 1.6, which is nearly equal to the best matching refractive index between air and the p-GaN layer. It indicates that the higher light-extraction efficiency of the LEDs with ITO nanorod arrays deposited with an oblique angle of 45° is deduced from the surface morphology and matching refractive index caused by the ITO nanorod arrays.

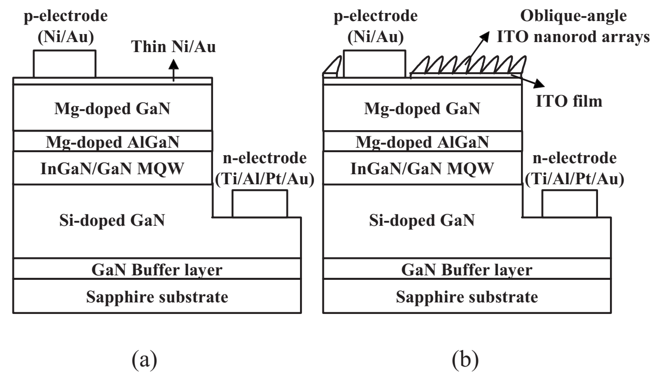

Figure 4. Structure of (a) conventional LEDs and (b) LEDs with ITO nanorod.

Conclusions

Using a self-shadowing nature, ITO nanorod arrays with various oblique angles can be deposited on the surface of GaN-based LEDs using an electron-beam deposition system. The surface morphology and effective refractive index of the ITO nanorod arrays can be

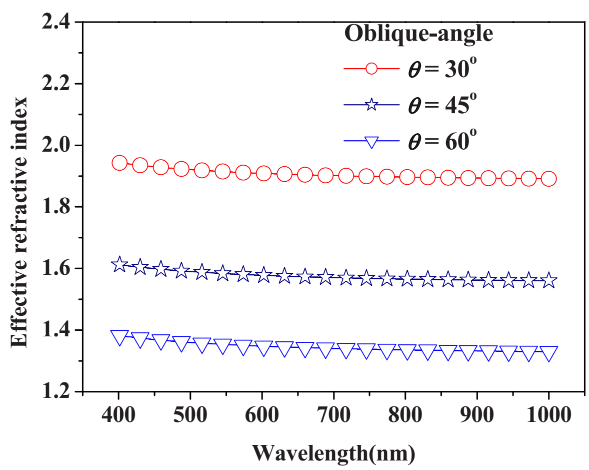

Figure 3. (Color online) The dependence of refractive index on oblique angle θ.

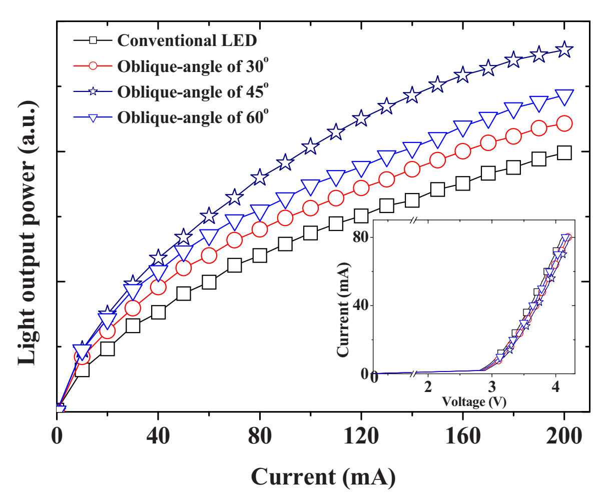

Figure 5. (Color online) *I-V* characteristics and light output characteristics of LEDs with and without the ITO nanorod arrays deposited with different oblique angles θ.

controlled by changing the oblique angle. For the ITO nanorod arrays with an oblique angle of 45°, the matching refractive index of 1.6 between air and the p-GaN layer is obtained. Comparing with the conventional LEDs, the light output power increase of 26.4% is attributed to the function of surface morphology and matching refractive index performed by the ITO nanorod arrays. According to the experimental results, the ITO nanorod arrays are expected to be a promising structure for improving the light-extraction efficiency of LEDs.

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