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High Extraction Efficiency of GaN-Based Vertical-Injection Light-Emitting Diodes Using Distinctive Indium–Tin-Oxide Nanorod by Glancing-Angle Deposition

Min-An Tsai, Hsun-Wen Wang, Peichen Yu[1], Hao-Chung Kuo[1], and Shiuan-Huei Lin*

Department of Electrophysics, National Chiao-Tung University, Hsinchu 30010, Taiwan, R.O.C.
[1] *Department of Photonics and Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu 30010, Taiwan, R.O.C.*

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The enhanced light extraction and reduced forward voltage of a GaN-based vertical injection light emitting diode (VI-LED) with an indium–tin-oxide (ITO) nanorod array were demonstrated. The ITO nanorod array was fabricated by the glancing-angle deposition method. The employment of ITO nanostructures amplified not only the broadband transmission but also the current spreading. The optical output power of GaN-based VI-LEDs with ITO nanorods was enhanced by 50% compared with a conventional VI-LED at an injection current of 350 mA. The extraction efficiency was dramatically raised from 62 to 93% by the surface ITO nanorods. We also optimized the extraction efficiency of the GaN-based VI-LED with an ITO nanorod array by tuning the thickness of the n-GaN top layer via three-dimensional finite difference time domain (3D-FDTD) simulation.

1. Introduction

High-brightness GaN-based light-emitting diodes (LEDs) have attracted much attention for optoelectronics applications such as displays, traffic signals, backlights for cell phones, and exterior automotive lighting.[1)] To increase the luminous efficiency of LEDs, it is necessary to improve the external quantum efficiency, which is defined as the product of the internal quantum efficiency and extraction efficiency. Several methods, including the use of surface roughening techniques,[2–5)] inclined side-wall etching,[6,7)] patterned sapphire substrates,[8,9)] and highly reflective omnidirectional reflectors (ODRs),[10)] have shown improved light extraction efficiencies. Surface roughening is one of the most efficient methods to provide large enhancement for the extraction efficiency owing to the random scattering factors on the roughened surfaces. However, some of the proposed techniques could deteriorate the electrical properties of conventional LEDs owing to the thin-film structure of the top layer, which limits the surface texture depth about 200 nm.[11)]

In this work, we proposed a novel GaN-based vertical-injection LED (VI-LED) with a distinctive indium–tin-oxide (ITO) nanorod array by utilizing the glancing-angle deposition method.[12)] ITO is usually used as a transparent contact layer (TCL) for LEDs to improve the current spreading of the p-GaN layer owing to the high electrical conductivity (about $1.7 \times 10\,\Omega^{-1}\,\mathrm{cm}^{-1}$) and the high transparency ($>90\%$ at 465 nm) of ITO films. The excellent light extraction properties in the short wavelengths ($\lambda = 465$ nm) made it possible to achieve high-efficiency GaN-based LEDs with a large emission area. Therefore, it is advantageous to fabricate surface nanostructures with the same material as the TCL, to enhance both the transmission and the carrier injection simultaneously.

Compared with the conventional methods, the GaN-based VI-LED was fabricated by the techniques of wafer bonding and laser lift-off (LLO). Through these techniques, we are able to fabricate a tunable thickness of the n-GaN top layer with excellent electrical conductivity for current spreading.

The ITO nanorod array not only serves as an omnidirectional TCL for LEDs, but also shows enhanced broadband transmittance ($T > 90\%$) ranging from 450 to 900 nm.[13)] The electrical and optical properties of the VI-LED with a distinctive ITO nanorod arrays were fully investigated in this study.

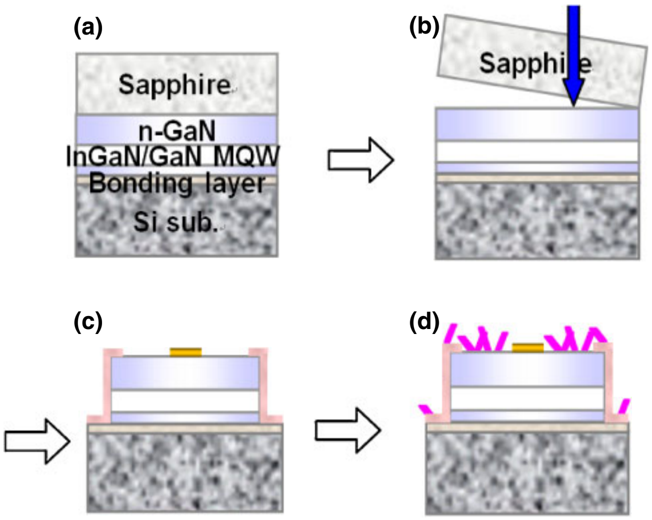

Fig. 1. (Color online) Fabrication process of GaN-based VI-LEDs with ITO nanorod array utilizing the glancing-angle deposition method: (a) wafer bonding, (b) laser lift-off, (c) mesa and passivation, and (d) ITO nanorod array.

2. Experimental Procedure

The fabrication process of the VI-LED used in this work is illustrated in Fig. 1. First, a conventional LED structure was grown on a *c*-plane sapphire substrate by metal organic chemical vapor deposition (MOCVD). The epitaxial LED structure consisted of a 30-nm-thick, low-temperature-grown GaN buffer layer, a 1.5-µm-thick, undoped GaN, a 1.2-µm-thick heavily doped n-type GaN, 12 pairs of InGaN/GaN multiple quantum wells (MQWs) with a total thickness of 0.2 µm, and a 0.2-µm-thick p-type GaN layer, and an ITO with a thickness of 240 nm was then deposited on the p-GaN. Moreover, the contact layer Ni/Ag/Pt and bonding layer Ti/Au were deposited on the surface of a Si wafer and a p-GaN layer, respectively. A silicon substrate was prepared with a highly reflective ohmic contact layer of Ni/Ag/Pt and a Ti/Au bonding layer on the p-GaN [Fig. 1(a)]. After the sapphire-based LED was bonded to the Si wafer, the wafer-

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*E-mail address: lin@cc.nctu.edu.tw

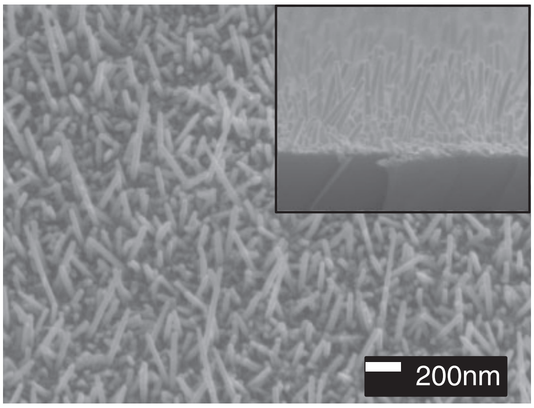

Fig. 2. Scanning electron microscopy (SEM) images of ITO nanorod array viewed from 45°. The inset image shows the cross-sectional view.

bonded sample was then subjected to the LLO process. A KrF excimer laser of wavelength 248 nm with a pulse width of 25 ns was used to remove the sapphire substrate. The laser was incident from the polished backside of the sapphire substrate onto the sapphire/GaN interface to decompose GaN into gallium and nitride atoms. The details of the LLO process are described in refs. 14 and 15. After the sapphire substrate removal [Fig. 1(b)], the undoped GaN was also removed to expose the n-GaN layer by the inductively coupled plasma reactive ion etching (ICP-RIE). Subsequently, the mesa with an area of $1 \times 1\,\mathrm{mm}^2$ was defined by using standard photolithography and dry etching. The sidewall was then passivated with SiNx and a bonding pad comprised of Cr/Pt/Au was deposited on both the top and bottom sides of the device as electrodes [Fig. 1(c)]. Finally, the ITO nanorod array was deposited by glancing-angle deposition, as shown in Fig. 1(d), which is described in ref. 12.

3. Results and Discussion

Figure 2 shows scanning electron microscopy (SEM) images of the ITO nanorods on a VI-LED surface with dimensions of ~30 nm in diameter and 300 to 800 nm in height. The density of this ITO nanorod array is $\sim 5 \times 10^9\,\mathrm{cm}^{-2}$ with an excellent uniformity across the entire surface. The light–current–voltage characteristics of GaN-based VI-LEDs with and without an ITO nanorod array were measured at room temperature, as shown in Fig. 3. The operation voltage was 3.39 and 3.47 V for VI-LEDs with and without an ITO nanorod array at an injection current of 350 mA, respectively. The slightly reduced voltage at 350 mA could be attributed to the conductive ITO nanorod array. Moreover, Fig. 3 also shows the light output power versus forward current characteristics. At an injection current of 350 mA, the light output power of the VI-LED with an ITO nanorod array was 378 mW, approximately enhanced by 50% compared with that of the VI-LED without an ITO nanorod array, 252 mW. Therefore, the ITO nanorod array not only increased the light output power, but also resulted in better current spreading than only the n-GaN top layer. Since the VI-LED with an ITO nanorod array has a smaller voltage at the same current injection condition, the enhancement of light output could be attributed to deterioration of the total internal reflection at the GaN/air interface by the nanorod array. The random ITO nanorod array could be regarded as the layers with gradient refractive indices, which serve as excellent antireflective layers for sufficient light extraction.

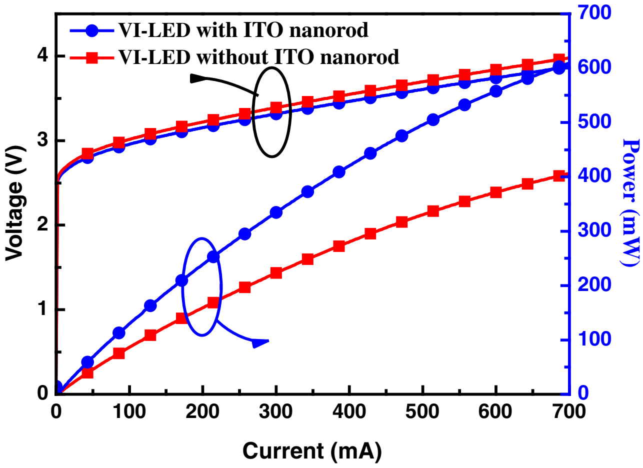

Fig. 3. (Color online) Light–current–voltage characteristics of the VI-LEDs with and without the ITO nanorod array, showing an enhancement factor of 50% for the output power at an injection current of 350 mA.

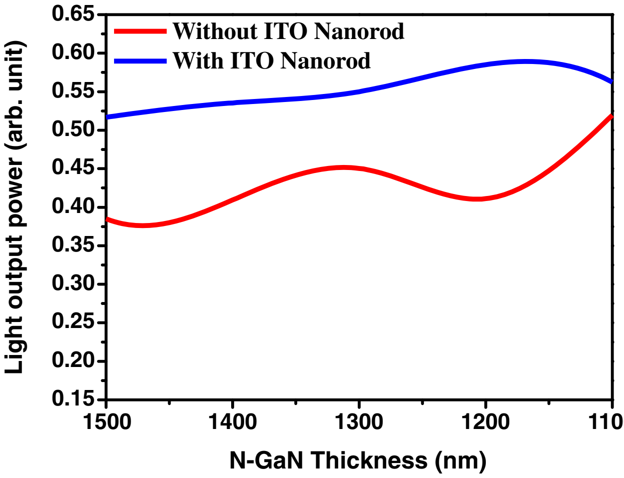

Fig. 4. (Color online) Calculated enhancement of light output power for GaN-based VI-LEDs with the ITO nanorod arrays compared with the VI-LEDs without the ITO nanorod array versus the thickness of the top n-GaN layer by using a 3D-FDTD method.

We further investigate extraction efficiency with respect to the thickness of the n-GaN top layer with and without the ITO nanorod array using the three dimensional finite-difference time-domain (3D-FDTD) method.[16] The details of the procedure used can be found in the literature.[13] The calculated results are illustrated in Fig. 4. The VI-LED without the ITO nanorod array shows an oscillatory dependence of light output power on the thickness of the n-GaN top layer owing to the Fabry–Perot effect. For the VI-LEDs with the ITO nanorod array, the enhancement of light extraction varies with the thickness of the n-GaN top layer and has a maximum value at the thickness of 1.2 µm. The light output power of the VI-LED with the ITO nanorod array revealed high light extraction and reduction of the

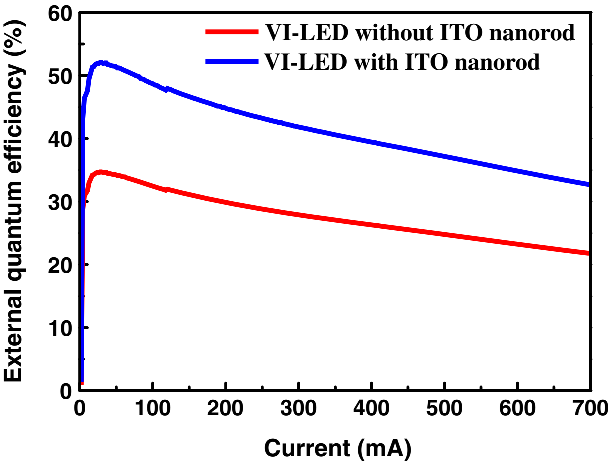

Fig. 5. (Color online) External quantum efficiency of the VI-LED with and without the ITO nanorod array varies with injected current.

Fabry–Perrot effect. However, the enhancement factor of the light output power by simulation has a maximum value of 42%, as shown in the inset image of Fig. 4. The experimental results showed a better value of 50% owing to the ITO nanorod array providing higher current spreading effect than that without an ITO nanorod array.

Further important information for quantifying the total light extraction in the VI-LED is the extraction efficiency, defined as $\eta_{\text{ext}} = \text{EQE}/\text{IQE}$,(17) where EQE and IQE are the external and internal quantum efficiencies, respectively. The EQE as a function of injection current was determined from the measurement of the total light output power of the VI-LED by using an integrating sphere, as shown in Fig. 5. The peak IQE of the VI-LED was estimated to be ~62%(18) using power- and temperature-dependence photoluminescence (PL) measurement. The extraction efficiency of the VI-LED with the ITO nanorod array was then estimated to be ~85%. If taking into account the shadow region of front pad (~4%) and the loss of the back reflection by the metal (~5%), an estimated extraction efficiency of the VI-LED with ITO nanorod array of 93% can be achieved.

4. Conclusions

In summary, the GaN-based VI-LED with the ITO nanorod array was successfully demonstrated by utilizing the glancing-angle deposition method. The ITO nanorod array revealed the effect of enhanced broadband transmission. For the GaN-based VI-LED, the deposited ITO nanorod array not only enhanced broadband transmission but also provided better electrical properties by reducing the forward voltage compared with conventional VI-LEDs. The light output power of the GaN-based VI-LED with the ITO nanorod array improved by 50% at an injection current of 350 mA. The extraction efficiency was dramatically raised from 62 to 93% by utilizing ITO nanorods. The 3D-FDTD simulated results suggested that the ITO nanorod array improved the light output power by behaving as a gradient-index layer.

Acknowledgments

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