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Light output enhancement of GaN-based light-emitting diodes with oblique indium-tin oxide nanorod array

Chih-Chien Lin[1], Hsin-Ying Lee[2] and Ching-Ting Lee[1]*

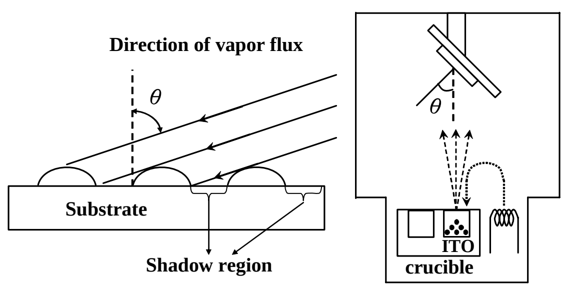
[1]Institute of Microelectronics, Department of Electrical Engineering
National Cheng Kung University, Tainan, Taiwan, Republic of China
*Tel: 886-6-2379582 Fax: 886-6-2362303 E-mail: ctlee@ee.ncku.edu.tw
[2]Department of Electro-Optical Engineering
National Cheng Kung University, Tainan, Taiwan, Republic of China

1. Introduction

Recently, III-V nitride semiconductors have been widely used in electronic devices [1-2] and optoelectronic devices [3-4]. The GaN-based light-emitting diodes (LEDs) have been applied in displays, backlights, and light sources. However, the external quantum efficiency of LEDs is seriously limited by the obstacle of light extraction. It is essential to study a promising method to increase the external quantum efficiency of LEDs. In general, to increase the extraction efficiency [5], dry etching methods, such as inductively coupled plasma (ICP) and reactive ion etching (RIE), are used to etch and roughen the top surface of GaN-based LEDs successfully. Unfortunately, dry etching methods would induce damages on p-GaN surface and degrade resultant electrical performances. Oblique deposition method is a promising and simple method for growing nanorods on the top surface of LEDs and enhance the light output intensity.

2. Experimental procedure and results

In this study, oblique deposition method [6] is used to deposit ITO nanorods array on the top surface of epitaxial structure of conventional GaN-based LEDs [7]. The schematic of oblique deposition configuration is shown in Fig. 1(a). Oblique ITO nanorods array deposition process consists of two steps. The first step is to deposit a thin ITO film on the p-GaN top layer of LEDs to form a shadow region for avoiding the incident vapor flux. The second step is to change the holder's angle and a nonshadow region. Therefore, the ITO nanorods can be simply deposited.



(a) (b)

Fig. 1 (a) Schematic of oblique deposition and (b) Oblique e-beam deposition system.

The oblique-angle e-beam deposition system is shown in Fig. 1(b). Pure ITO granules are used as the evaporation source. The tile angle θ is an incident angle between incident vapor flux and sample.The deposition rate and chamber temperature are 0.3Å/s and 300^{o}C, respectively. Figure 2 shows the schematic structure of GaN-based LEDs with oblique ITO nanorods array.

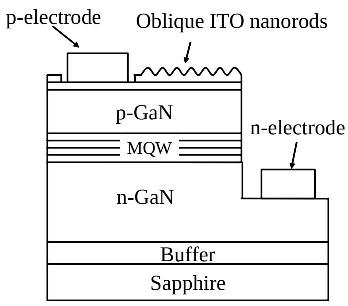


Fig. 2 Structure of ITO LEDs with oblique ITO nnanorods.

3. Results and Discussion

Figure 3 shows the dependence of the refractive index on the oblique-angle θ. The refractive index reduces with the increase of oblique-angle. According to this experimental result, the matched refractive index n_{ITO} of ITO nanorods between air and p-GaN for increasing light output is described:

$$n_{ITO} = \sqrt{n_{Air} \times n_{GaN}} = \sqrt{1 \times 2.5} \cong 1.6 ,$$

where n_{Air} and n_{GaN} are the refraction index of air and GaN at wavelength of 450nm, respectively. As the result shown in Fig. 3, the matched refractive index can be obtained using the oblique-angle of 45^{o}. Atomic force microscopy (AFM) images of the oblique ITO nanorods array is shown in Fig. 4. The roughness of the ITO nanorods array is about 10.7nm, which is larger than that of ITO film. Figure 5 shows the current-voltage characteristics of LEDs with and without the oblique ITO nanorods array deposited with oblique-angle of 45^{o}. The associated forward voltage of LEDs at 20mA is 3.4V and 3.3V, respectively. A similar electrical performance of the LEDs was found. Figure 6 shows the light output characteristics of LEDs with and without oblique ITO nanorods array deposited with 45^{o}. The light output (at 100mA) of the LEDs with oblique ITO nanorods array increases by 36% compared with that of conventional LEDs. This improvement of light output power is deduced from the matched refractive index and the increase of the roughness induced by the ITO nanorods array deposited on the p-GaN of LEDs.

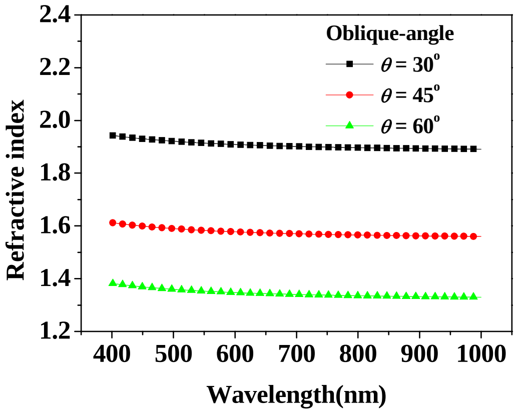


Fig. 3 The dependence of refractive index on oblique-angle θ.

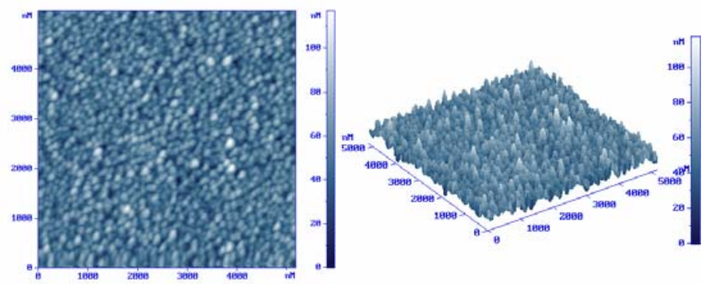


Fig. 4 AFM images of the oblique ITO nanorods array.

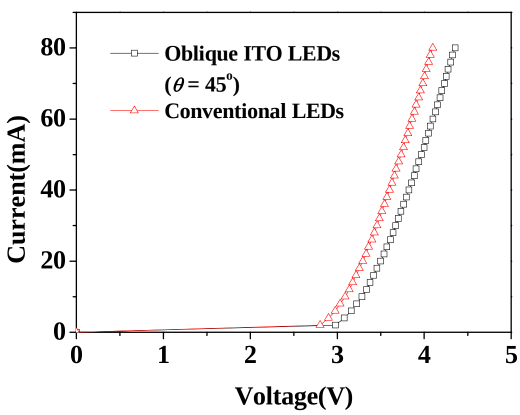


Fig. 5 Current-voltage characteristics of oblique ITO LEDs and conventional LEDs.

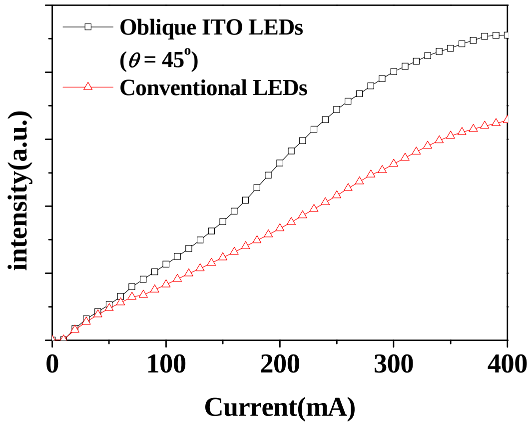


Fig. 6 Output light intensity of oblique ITO LEDs and conventional LEDs.

4. Conclusions

In this study, we used oblique e-beam deposition method to deposit oblique ITO nanorods array on the p-GaN of LEDs. The roughness of the deposited ITO nanorods is about 10.7nm and the refractive index of the ITO layer can be controlled from 2 to 1.35. Owing to the increase of roughness and the matched refractive index of the ITO nanorods deposited on the surface of p-GaN, the light output of light-emitting diodes (LEDs) increases by 36% compared with that of conventional LEDs. The forward voltage at 20mA of LEDs with ITO nanorods is 3.4V which was comparable with 3.3V of conventional LEDs. According to the experimental results, the simple oblique e-beam deposition method can be expected as a promising method to increase the extraction efficiency of GaN-based LEDs.

Acknowledgements

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