Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp264-265

Light Extraction Improvement of Flip Chip Light Emitting Diodes Using Diffused Nanorod Reflector

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1. Introduction

With the increasing technology development, solid-state-lighting sources have been played a dispensable role in our life. To meet the requirement of high luminance and efficiency, various methods, such as photonic crystal [1], die shaping [2], reflector [3], flip-chip (FC) [4], surface roughness [5], and diffused reflector [6], were investigated to enhance the performances. Among those methods, the reflector possesses the advantages including low cost, simple process, and outstanding light extraction improvement of light-emitting-diodes (LEDs). In this work, the novel structure combined the reflector and the diffused nanorod was designed to further improve the light extraction efficiency. The diffused nanorod reflector exhibited a lower reflectivity caused from the air void among nanorod [7]. In this study, we discussed and analyzed the processes and performances of the FCLEDs with diffused nanorod reflector which led to diffused light and lower refractive index layer.

2. Experimental procedure

Figure 1(a), (b) and (c) shows the schematic configuration of the conventional FCLEDs, the FCLEDs with flat reflector, and the FCLEDs with diffused nanorod reflector, respectively. The epitaxy layers of the GaN-based LEDs were grown on c-plane sapphire substrates using a metal organic chemical vapor deposition (MOCVD) system. The structure composed of a 50-nm-thick GaN buffer layer, a 3-μm-thick Si-doped GaN layer ($n = 3\times10^{17}cm^{-3}$), an undoped InGaN-GaN multiple quantum wells (MQWs) active layer, a 50-nm-thick Mg-doped GaN layer ($p = 1 \times 10^{17}$ cm^{-3}), and a 300-nm-thick Mg-doped GaN layer ($p = 3 \times 10^{17}$ cm^{-3}). The InGaN-GaN MQW active layer consisted of ten periods of 3-nm-thick $In_{0.23}Ga_{0.77}N$ well and 7-nm-thick GaN barrier. To active the Mg-doped GaN layers, the grown samples were then annealed at 750 ℃ for 30 min in a N_2 ambient. Mesa etching was performed until the Si-doped GaN layer by a reactive ion etching system. After the etching process, the Ti/Al/Pt/Au (25/100/50/150 nm) *n*-electrode was deposited by an electron-beam evaporator and then annealed to form ohmic contact at 850 ℃ for 2 min in a pure N_2 ambient. The thin Ni/Au (2.5/2.5 nm) metals were deposited on *p*-GaN worked as current spreading layer. The thick Ni/Au (20/100 nm) deposited as *p*-electrode was annealed at 500 ℃ for 10 min in an air ambient. These fabricated devices were referred as the conventional FCLEDs. Fiqure 1(b) shows the FCLEDs with flat reflector. It was fabricated by directly depositing a 700-nm-thick metal reflector on the conventional FCLEDs.

Figure 1(c) shows the novel designed structure of the FCLEDs with diffused nanorod reflector. After fabricating the conventional LEDs, a 100-nm-thick Al-doped ZnO (AZO) film was deposited on the LEDs worked as a seed layer. A 500-nm-long ZnO nanorod array was then grown by hydro-thermal method. The growth solution and growth temperature were HMT (0.025 M), $Zn(NO)_3 \cdot 6H_2O$ (0.025 M) and 90 ℃, respectively. A 700-nm-thick Al was followed to deposit on the ZnO nanorod array using an electron-beam evaporator. To examine the roughened surface of the diffused nanorod reflector, it was observed by the scanning electron microscope (SEM). The inset of Fig. 2 shows the cross section of the diffused nanorod reflector. The roughened metal surface could be clearly found by the morphology of the nanorod array. In addition to the roughened metal surface caused by the ZnO nanorod array, the reflector let the reflection become the lambertian source for diffusion, called diffused nanorod reflector.

3. Experimental results and discussion

To analyze the diffusion ability of the nanorod array in the diffused nanorod reflector, the dependence of the reflection intensity on the angle was measured. The reflected light intensity was detected along the angle from −90° to 90°, when a He-Ne laser illuminated the samples with flat reflector and diffused nanorod reflector at an incident angle of 15°, respectively. As shown in Fig. 2, the reflected light intensity of the samples with diffused nanorod reflectors was stronger than that with flat reflector, when the reflection angle was not equal to the incident angle. This reflection improvement was attributed to the effect of diffused light resulted from the roughened interface. Therefore, it was deduced that the FCLEDs with diffused nanorod reflector could further enhance the light output power. The higher reflection was attributed to the higher possibility that light escaped from inner to air at the roughened interface of the diffused nanorod reflector.

Figure 3 shows the current-voltage characteristic of the three kinds of FCLEDs measured by Agilent 4156C semiconductor parameter analyzer. The forward voltage of the conventional FCLEDs, the FCLEDs with flat reflector and the FCLEDs with diffused 500-nm-long ZnO nanorod reflector was 3.5 V, 3.51 V, and 3.52 V, respectively. It could be found that the forward voltage of the three kinds of FCLEDs was kept at a similar voltage. As showed in the inset of Fig. 3, the associated light output power at an injection current of 200mA measured by an integral sphere was 17.54 mW, 24.59 mW and 27.47 mW, respectively. The light output power of the FCLEDs with 500-nm-long ZnO nanorod diffused reflector exactly was enhanced by 56.6% in comparison with the conventional FCLEDs. Furthermore, it was enhanced by 11.7% in comparison to the FCLEDs with flat reflector. These results exhibited that the light output power was significantly enhanced when the diffused nanorod reflector was employed on the conventional FCLEDs. To examine the output light distribution of the three kinds of FCLEDs, the light output diverse angle measurement was shown in Fig. 4. The result highlighted the difference from FCLEDs with and without diffused nanorod reflector. The light intensity distribution from 60° to 120° for the FCLEDs with diffused nanorod reflector was smoother than that of the FCLEDs without diffused nanorod reflector because the emitted photons of former one were scattered in a wider angle [8].

4. Conclusions

In this work, the novel designed structure with the diffused nanorod reflector was designed and used to enhance the light output performance of the FCLEDs. The diffused nanorod reflector composed of the Al metal with high reflectivity and the ZnO nanorod array with texture and low refractive index which provided the naturally roughened interface. According to the experimental results, the performances of the FCLEDs with the diffused nanorod reflector were better than that of the FCLEDs without the diffused nanorod reflector. This phenomenon was attributed to the high reflectivity roughened metal and the lower refractive index layer caused by the diffused nanorod reflector. Consequently, the FCLEDs with diffused nanorod reflector can enhance light output power not only by 56.6 % in comparison to the conventional FCLEDs but also by 11.7 % in comparison to the FCLEDs with flat reflector.

Acknowledgement

This work was supported by the Industrial Technology Research Institute, the Advanced Optoelectronic Technology Center, National Cheng Kung University and the National Science Council of Taiwan, Republic of China under the contract number NSC-99-2221-E-006-208-MY3.

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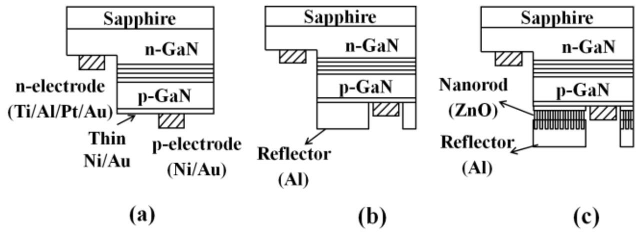

Fig. 1 Structures of (a) conventional FCLEDs, (b) FCLEDs with flat reflector, and (c) FCLEDs with diffused nanorod reflector.

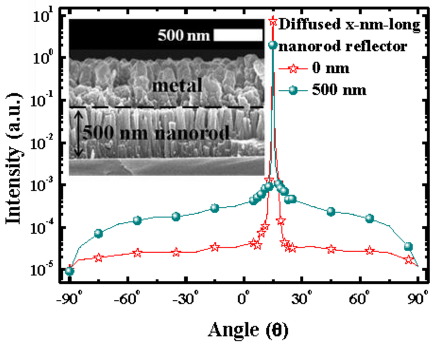

Fig. 2 Light output intensity of reflection along the angle and SEM images of diffused nanorod with 500-nm-long ZnO nanorods.

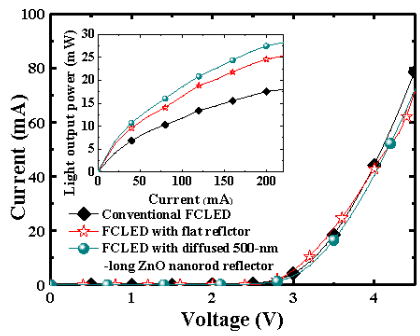

Fig. 3 Light output power and current-voltage characteristics of LEDs with and without diffused nanorod reflector.

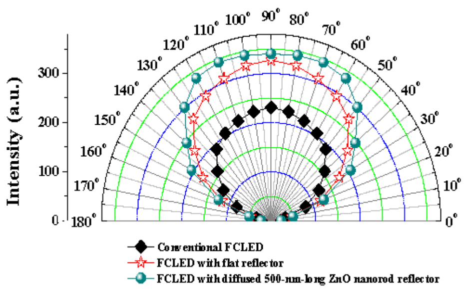

Fig. 4 Light output diverse angle of various FCLEDs