Enhanced light output power in InGaN/GaN light-emitting diodes with a high reflective current blocking layer

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Abstract: The light output power of an InGaN/GaN light-emitting diode is improved by using a SiO_2/TiO_2 distributed Bragg reflector (DBR) and an Al mirror as a hybrid reflective current blocking layer (CBL). Such a hybrid reflective CBL not only plays the role of the CBL by enhancing current spreading but also plays the role of a reflector by preventing photons near the p-electrode pad from being absorbed by a metal electrode. At a wavelength of 455 nm, a 1.5-pair of SiO_2/TiO_2 DBR and an Al mirror (i.e. 1.5-pair DBR+Al) deposited on a p-GaN layer showed a normal-incidence reflectivity as high as 97.8%. With 20 mA current injection, it was found that the output power was 25.26, 24.45, 23.58 and 22.45 mW for the LED with a 1.5-pair DBR+Al CBL, a 3-pair DBR CBL, SiO_2 CBL and without a CBL, respectively.

Key words: distributed Bragg reflector; Al; current blocking layer; light-emitting diode
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1. Introduction

GaN-based light-emitting diodes (LEDs) have been widely used for outdoor full-color displays, traffic signals, exterior automotive lighting and liquid crystal display (LCD) backlight units due to their substantial advantages in brightness, power, life-time, and reliability. The essential requirements for an LED are high brightness and high efficiency. The external quantum efficiency of an LED can be expressed by the product of the internal quantum and extraction efficiency. Internal absorption and blocking of the light by metal electrodes are the most important factors responsible for light loss and low light extraction efficiency. It is well known that photons generated by spontaneous emission from the active region of LED are emitted in all directions. As a result, partial photons being emitted to the p-electrode pad could be absorbed inevitably by metal electrodes with low reflectivity. Thus, if the photons emitted to the p-electrode pad could be effectively reflected, the light extraction efficiency will be enhanced significantly. Many efforts have been made to improve light extraction efficiency[1−5]. Recently, a Ag or Al metallic mirror was inserted between the electrode pad and the transparent conductive layer to reduce the light absorption by the metal electrodes and to improve the light extraction efficiency[3]. However, high carrier density near the p-electrode pad caused a current crowding effect, which will decrease the uniformity and stability of the far-field emission[6]. Kao *et al.*[5] have used a five-pair SiO_2/TiO_2 DBR as a reflective CBL to alleviate the current crowding and photon absorption near the p-electrode pad. As we know, highly reflective DBRs are formed by a repeated periodic stack of alternating high and low refractive index layers. However, to increase reflectivity, the thickness of each layer should be precisely controlled and the number of pairs of the DBR should also be increased, which will be material and time consuming[7]. If we can combine the advantages of a DBR and a metallic mirror to acquire a highly reflective CBL, the number of DBR pairs can be reduced and thus the process time can also be shortened.

In this paper, we report on the enhancement of the light output power of an InGaN/GaN LED with a hybrid reflective CBL combining a SiO_2/TiO_2 DBR and an Al mirror. The hybrid reflective CBL, which had high reflectivity and fewer DBRs, reduced the current crowding effect and enhanced the light output power since photons near the p-electrode pad were reflected effectively instead of being absorbed by the metal electrode. Detailed fabrication process and the performance of the fabricated LED are described.

2. Experiments

The InGaN/GaN MQW LED epitaxial layers used in this study were all grown by metalorganic chemical vapor deposition (MOCVD) on c-face 2-inch sapphire (Al_2O_3) substrates. The epitaxial layers consist of a GaN nucleation layer, a Si-doped n-GaN buffer layer, a ten-period InGaN/GaN multiple quantum-well (MQW) active region and a Mg-doped p-GaN layer. The samples were then annealed at 700 ℃ for 60 s in a N_2 ambient using a rapid thermal annealing process to activate the Mg in the p-type layers[8]. A 1.5-pair SiO_2/TiO_2 DBR and an Al mirror or a 3-pair SiO_2/TiO_2 DBR or a SiO_2 structure was deposited on the top of the p-GaN layer by electron beam evaporation, to serve as the CBL. Then, the CBL was defined by photolithography and a wet-etching process. An ITO (indium tin oxide) layer (230 nm) was deposited onto the p-GaN top layer and CBL as the transparent conductive layer, and then annealed at 500 ℃ for 20 min in N_2 to form an ohmic contact. Cr/Pt/Au metal pads were deposited to form the p-type and n-type metal electrode. Finally, the sapphire substrate was thinned to 100 μm and softly polished to remove any stress. Then 220 × 540 μm^2 LED chips were obtained by a scrib-

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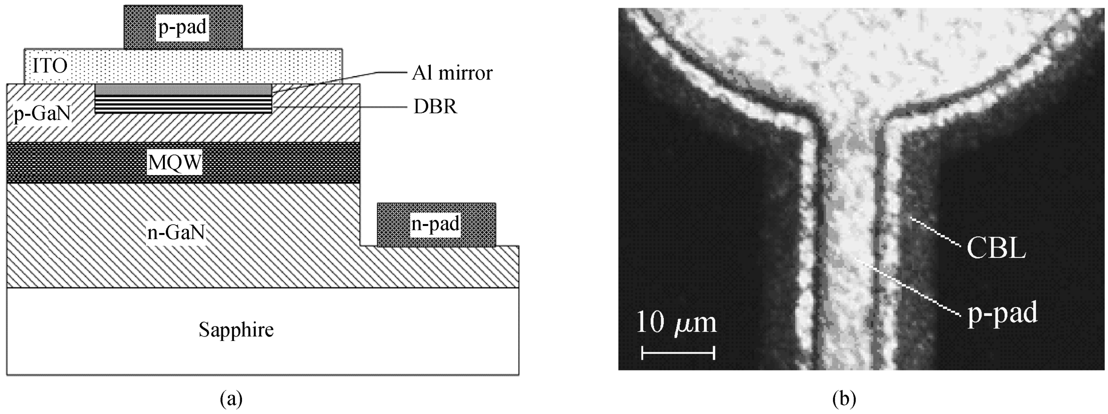

Fig. 1. (a) Schematic diagram and (b) top view photograph of the LED with the hybrid reflective CBL.

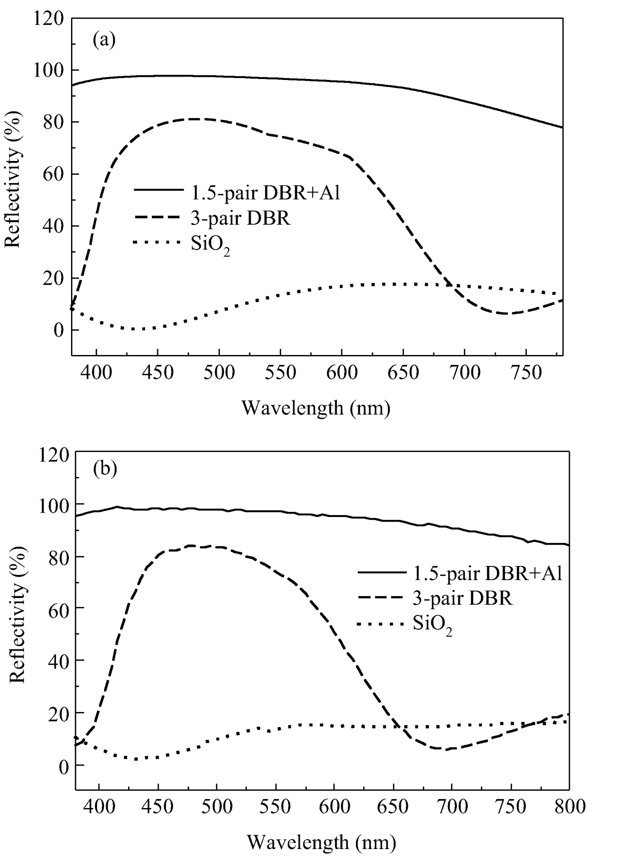

Fig. 2. The (a) calculated and (b) measured reflection spectra for the 1.5-pair DBR+Al, 3-pair DBR and SiO_2 structures with normal incidence.

ing and breaking process. The coverage of reflective CBL in a LED is approximately 12.6%. A schematic diagram and a top view photograph of the LED with the hybrid reflective CBL are shown in Fig. 1.

The forward current–voltage (I–V) curves and light intensity–current (L–I) measurements of the fabricated LEDs were performed by using a Keithley 2400 and an integrated sphere. The light intensity profiles distribution images of the LEDs were measured using a beam profiler.

Table 1. Simulated parameters of each layer in the LED structure.

Simulated parameter	SiO_2 in DBR	TiO_2 in DBR	Al	p-GaN	SiO_2
Refractive index, n	1.47	2.45	1.30	2.48	1.47
Thickness (nm)	77.4	45.9	100	200	220

3. Results and discussion

TFCalc optical simulated software was used to simulate the reflection spectra of the 1.5-pair DBR+Al, the 3-pair DBR and SiO_2. The simulated parameters of each layer used in the calculation are given in Table 1. Figure 2(a) shows the calculated reflection spectra of the 1.5-pair DBR+Al, 3-pair DBR and SiO_2 structure with normal incidence. It was found that reflectivity can reach 98.3%, 82.5% and 1.4 % at 455 nm, respectively. Figure 2(b) shows the normal-incidence reflection spectra of the 1.5-pair DBR+Al, the 3-pair DBR and the SiO_2 structure measured using a PMS-80 UV-VIS-near IR spectrophotocolorimeter. It can be seen that reflectivity can reach 97.8%, 81.6% and 3.6% at the same wavelength under three different situations. The calculated and measured reflectivities also were summarized in Table 2. The results in Table 2 indicate that SiO_2 CBL has very low reflectivity in the blue wavelength region, which probably results in partial photons transmitting through the SiO_2 CBL layer and being absorbed by the metal electrode. It can be seen that the reflectivity of the 1.5-pair DBR+Al is higher than that of the 3-pair DBR by a factor of 16.2% at 455 nm. Hence, the hybrid reflector with high reflectivity and fewer DBRs can be used to prevent the light from transmitting through the CBL and being absorbed by the metal electrode.

It should be noted that the measured reflection spectra shown in Fig. 2(b) is slightly lower and narrower than calculated spectra shown in Fig. 2(a). This is probably due to the thickness deviation between the designated SiO_2/TiO_2 layers and the actual deposited SiO_2/TiO_2 layers.

Figure 3 shows the forward I–V characteristics of the LEDs with 1.5-pair DBR+Al, 3-pair DBR, SiO_2 and without CBL, respectively. The forward voltages measured at 20 mA are 3.12, 3.15, 3.10 and 3.09 V for the LED with a 1.5-pair DBR+Al, a 3-pair DBR, SiO_2 and without a CBL, respec-

Table 2. Simulated and measured reflectivity (%) of different CBLs at 455 nm.

Reflectivity	1.5-pair DBR+Al	3-pair DBR	SiO_2
Simulated	98.3	82.5	1.4
Measured	97.8	81.6	3.6

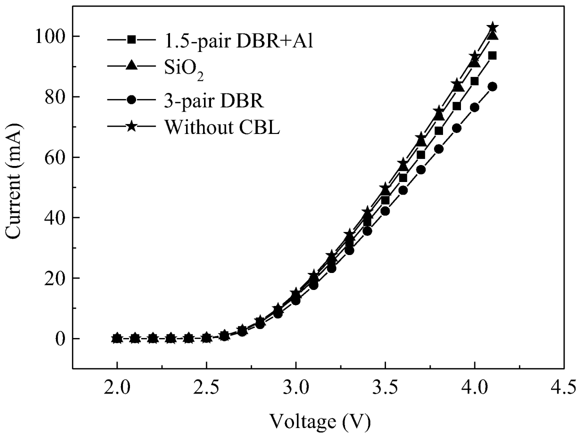

Fig. 3. Forward I–V characteristics of the LED with a 1.5-pair DBR+Al CBL, a 3-pair DBR CBL, SiO_2 CBL and without a CBL, respectively.

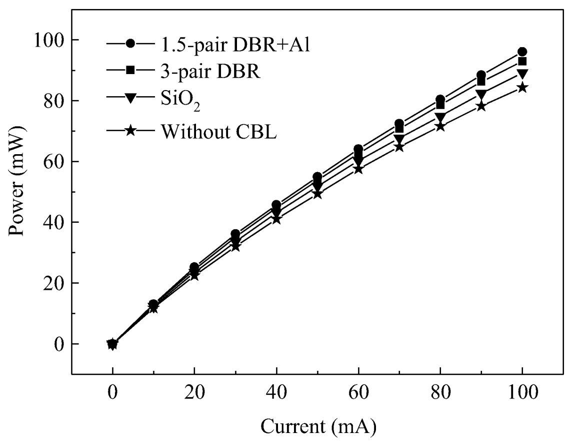

Fig. 4. Optical output power versus injection current of the LED with a 1.5-pair DBR+Al CBL, a 3-pair DBR CBL, a SiO_2 CBL and without a CBL, respectively.

tively. The slightly increased forward voltage for the LED with a CBL is attributed to the CBL structure, which forces the injected current to spread out from the p-electrode pad, giving rise to slight increase of current path and series resistance. However, the thicker CBL also results in a forward-voltage increase. The samples were then packaged into LED lamps.

The L–I characteristics of the LED with a 1.5-pair DBR+Al, a 3-pair DBR, SiO_2 and without a CBL are shown in Fig. 4. It can be seen that the output power of these LED lamps increases with the injection current. At an injection current of 20 mA, it was found that the optical output power is 25.26, 24.45, 23.58 and 22.45 mW for the LED with a 1.5-pair DBR+Al, a 3-pair DBR, SiO_2 and without a CBL, respectively. In other words, the output power of the LED with a 1.5-pair DBR+Al CBL was increased by 3.3%, 7.1%, 12.5% as compared to the LEDs with a 3-pair DBR CBL, a SiO_2 CBL and without a CBL. Such an enhancement should be mainly attributed to the reduction of the current crowding effect and the absorption of photons near the p-pad by the metal electrode. From Fig. 4 it can be found that the output power of the LED with the 1.5-pair DBR+Al is the largest, which should also be attributed to the highest reflectivity.

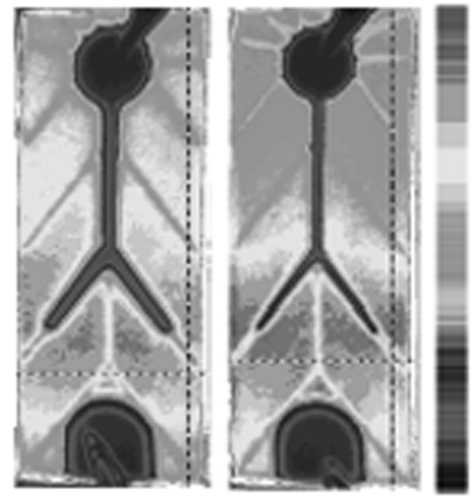

Fig. 5. Light intensity profiles distribution images of the LED (a) with and (b) without a 1.5-pair DBR+Al CBL measured with a 20 mA injection current.

Figure 5 shows light intensity profiles distribution images of the LED with and without a 1.5-pair DBR+Al CBL measured with a 20 mA injection current. Compared with the LED without a CBL, it was found that the light output power is distributed more uniformly in the LED with a 1.5-pair DBR+Al CBL. Such a result indicates that the inserted hybrid reflective CBL can effectively enhance current spreading.

4. Conclusion

In summary, we report the enhanced light output power of an InGaN/GaN LED with a hybrid reflective CBL combining a SiO_2/TiO_2 DBR and an Al mirror. At the wavelength of 455 nm, a 1.5-pair SiO_2/TiO_2 DBR and an Al mirror deposited on the p-GaN layer showed a normal-incidence reflectivity as high as 97.8%. With 20 mA current injection, it was found that the output power was 25.26, 24.45, 23.58 and 22.45 mW for the LED with a 1.5-pair DBR+Al CBL, a 3-pair DBR CBL, a SiO_2 CBL and without a CBL, respectively. Therefore, a hybrid reflective CBL with high reflectivity and fewer DBRs can be applied to improve the output power of GaN-based LEDs.

References

[1] Lee C M, Chuo C C, Liu Y C, et al. InGaN/GaN MQW LEDs with current blocking layer formed by selective activation. IEEE Electron Device Lett, 2004, 25(6): 384

[2] Chang S J, Shen C F, Chen W S, et al. Nitride-Based LEDs with an insulating SiO_2 layer underneath p-pad electrodes. Elec-

trochem Solid-State Lett, 2007, 10(6): H175
[3] Sheu J K, Hung I H, Lai W C, et al. Enhancement in output power of blue gallium nitride-based light-emitting diodes with omnidirectional metal reflector under electrode pads. Appl Phys Lett, 2008, 93: 103507
[4] Chiou Y Z, Chiang T H, Kuo D S, et al. The reliability analysis of GaN-based light-emitting diodes with different current-blocking layers. Semicond Sci Technol, 2011, 26(8): 085005
[5] Kao C C, Su Y K, Lin C L. Enhancement of light output power of GaN-based light-emitting diodes by a reflective current blocking layer. IEEE Photonics Technol Lett, 2011, 23: 986
[6] Huh C, Lee J M, Kim D J, et al. Improvement in light-output efficiency of InGaN/GaN multiple-quantum well light-emitting diodes by current blocking layer. J Appl Phys, 2002, 92: 2248
[7] Chang C S, Chang S J, Su Y K, et al. Nitride based power chip with indium-tin-oxide p-contact and Al back-side reflector. Jpn J Appl Phys, 2005, 44: 2462
[8] Ran Junxue, Wang Xiaoliang, Hu Guoxin, et al. Study on MOCVD-grown Mg doped GaN by annealing treatment. Chinese Journal of Semiconductors, 2005, 26(3): 494