Enhancing extraction efficiency from GaN-based LED by using an omni-directional reflector and photonic crystal*

XU Qing-tao(许庆涛), **LI Kang**(李康)**, **KONG Fan-min**(孔凡敏), **and LIU Qian**(刘倩)
School of Information Science and Engineering, Shandong University, Jinan 250100, China

(Received 13 June 2009)

To enhance the light extraction efficiency of traditional light-emitting diodes (LEDs) by reducing the total internal reflection, an omni-directional reflector (ODR) and photonic crystal are adopted in the paper. The structures of photonic crystal and the ODR are designed by diffraction theory and finite difference time domain (FDTD) method. The photonic crystal is employed in the p-GaN layer and the ODR composed of TiO_2/SiO_2 is designed between the active region and substrate. The simulation results indicate that the light extraction of LEDs can be enhanced by 11.6 times, and the external quantum efficiency of LEDs will be effectively improved.

Document code: A **Article ID:** 1673-1905(2009)06-0405-4
DOI 10.1007/s11801-009-9119-2

The development of LEDs is limited because of their low output power. Hence, it is a crucial issue to improve the quantum efficiency of LEDs. This can be achieved by improving internal quantum efficiency or light extraction efficiency. The internal quantum efficiency has been greatly enhanced owing to high quality materials[1] and crystal growth[2] technology. Therefore, how to improve light extraction has been one of the hotspots at home and abroad recently.

There are two reasons to explain the low light extraction efficiency of traditional LEDs. First, because of the total internal reflection at the interface between the outer medium and semiconductor, most light forms guided modes in the active region rather than radiation modes[3]. Second, the substrate of LEDs is generally thick, so a large part of energy radiated into the substrate will be absorbed. Generally the light extraction efficiency is only 4%[4].

Aiming at the former, there are many methods to increase the efficiency[5-8]. Among them, photonic crystal is considered as a potential structure because of its large enhancement of light efficiency[4]. Currently, the feasible fabrication of photonic crystal incorporated in GaN-based LEDs has been investigated and implemented.

For the latter, an ODR employed between the substrate and active region reflects the downward light to reduce energy loss in the substrate. The efficiency could be effectively increased by the ODR[3]. Lin et al.[9] have proved that the ODR composed of TiO_2/SiO_2 does have better performance than a metallic ODR.

The simulation methods adopted in the paper are diffraction theory and FDTD. Photonic crystal is designed on the top surface to extract the guided mode, while a composite distributed Bragg reflector (DBR) as an ODR is employed between quantum wells and the substrate to reflect the downward light. Simulation results indicate that the designed structure can enhance the light extraction by 11.6 times, which effectively increases the external quantum efficiency of LEDs.

Fig.1 shows the LED structure with photonic crystal and a composite DBR. The structure consists of a 5 μm-thick substrate, two DBRs with different parameters as an ODR, a 3.5 μm-thick n-GaN layer, a multiple quantum-well (MQW) which is composed of five periods of 3 nm/7 nm-thick InGaN-GaN well, and a 0.2 μm p-GaN layer. The photonic crystal is designed in the p-GaN layer. The light wavelength emitted from the blue GaN-based LED is 460 nm.

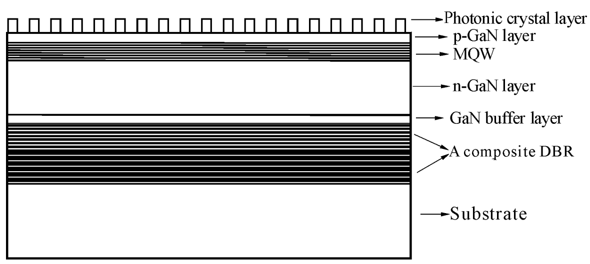

Fig.1 Schematic structure of the designed LED

* This work has been supported by the National Natural Science Foundation of China (No. 60877018), and the National Basic Research Development Program of China (Nos.2009CB930503,2009CB930501and 2007CB613203)

** E-mail:kangli@sdu.edu.cn

The reflectivity of a DBR is proportional to periods of the DBR and the refractive index discrepancy between two materials. Some reports have also demonstrated that the DBR composed of TiO_2/SiO_2 can obviously increase light extraction of LEDs[3, 6].

The refractive indices of TiO_2 and SiO_2 are respectively 1.48 and 2.52. Fig.2 shows the reflection spectrum of the first DBR by rigorous coupled wave analysis (RCWA) method. And the thicknesses of TiO_2 and SiO_2 are 78 nm and 46 nm. As shown in Fig.2, the central wavelength of reflection spectrum is about 460 nm, and its reflectivity is close to 1. Because the incident angle is 90^o, the DBR can ideally reflect blue light with a small incident angle. Fig.3 illustrates the relationship between the reflectivity of the first DBR and incident angle. When the angle is very small or quite large, the DBR can reflect incident light very well. If the incident angle is between 30^o and 50^o, the curve vibrates acutely, which degenerates the reflection effect of the DBR. Consequently, two DBRs are introduced into LED structure as an ODR to ameliorate the reflectivity for an arbitrary incident angle.

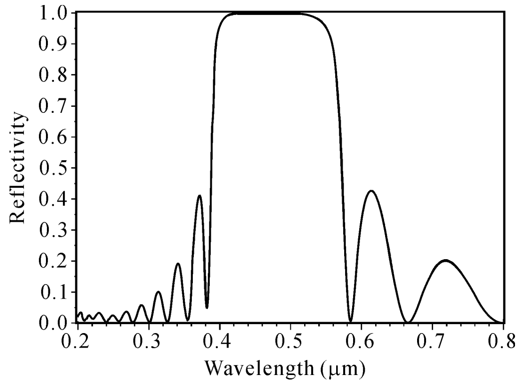

Fig.2 Reflection spectrum of the first DBR (normal incidence)

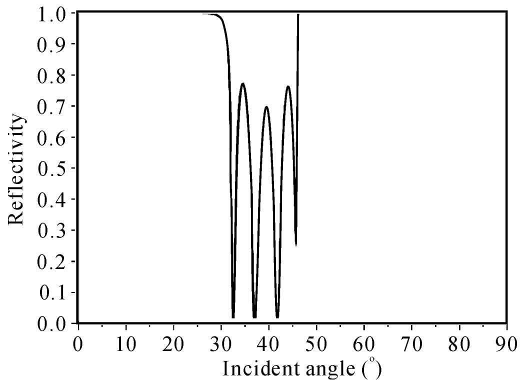

Fig.3 Relationship between the reflectivity of the first DBR and incident angle

After simulations, for the second DBR, the reasonable thicknesses of TiO_2 and SiO_2 are 116 nm and 69 nm respectively to reflect light with incident angle between 30^o and 50^o. Fig.4 shows the relationship between its reflectivity and incident angle. When the incident angle is larger than 22^o, the DBR can effectively reflect the incident light.

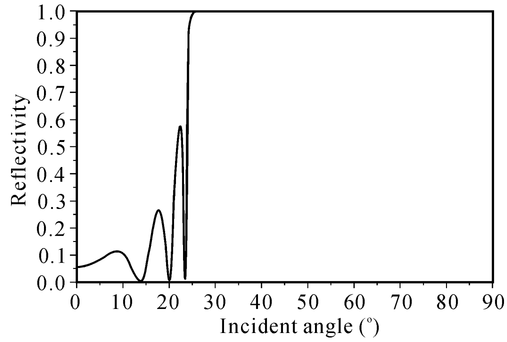

Fig.4 Relationship between the reflectivity of the second DBR and incident angle

At last, we combine the two DBRs together. The relationship between the reflectivity of the composite DBR and incident angle is shown in Fig.5. The curve slightly fluctuates with small incident angles, but the reflectivity is still larger than 0.99, and it is close to 1 at other angles. That is to say, the composite DBR can effectively reflect light with an arbitrary incident angle. The structure can excellently act as an ODR which reflects the downward light to prevent propagating into the substrate.

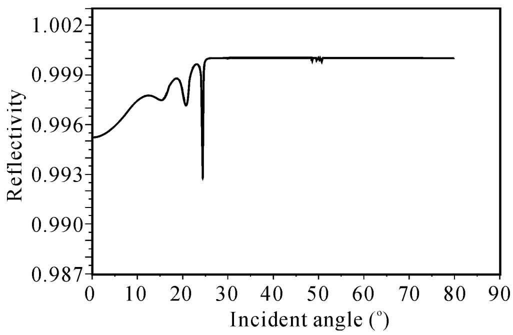

Fig.5 Relationship between the reflectivity of the composite DBR and incident angle

In simulations, the extracted electric-field intensity of planar LEDs, in which there is no photonic crystals, will be normalized. The light extraction efficiency of LEDs with photonic crystals depends on the parameters of photonic crystals, such as the lattice constant (a) and the depth of photonic crystals.

In Fig.6, we find that the electric-field intensity can mostly increase to 1.2-2.2 times of that without photonic crystals. And the intensity can be enhanced to 2.1 when the lattice constant is 0.8 μm and the depth equals to 0.18 μm. Fig.7

describes the relationship between the transmittivity and incident angle for photonic crystal LED and planar LED. The transmittivity of the planar LED is basically zero when incident angle is greater than the critical angle, but it can be significantly increased by the photonic crystal. When the incident angle is smaller than the critical one, the transmittivity of the photonic crystal LED is smaller than that of the planar LED. But it can be generally improved obviously by photonic crystal, because of light from LEDs emitted randomly.

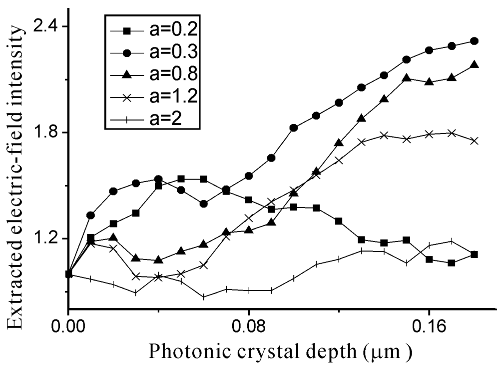

Fig.6 Relationship between the extracted electric-field intensity and photonic crystal depth

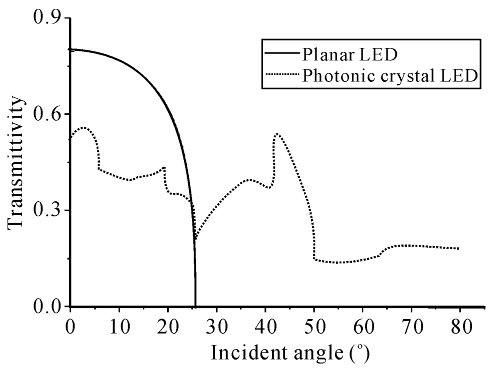

Fig.7 Relationship between the transmittivity and incident angle for planar LED and photonic crystal LED

Fig.8 illustrates the relationship between the extracted electric-field intensity and photonic crystal lattice constant when its depth equals to 0.18 μm. If the lattice constant is smaller than 0.2 μm, the intensity is fairly slight. It can be enhanced to 1.2-1.7 for other lattice constants, and the peaks, 2.3 and 2.1, come out when the lattice constant equals to 0.3 μm and 0.8 μm. Hence the intensity can be close to 2.1 when the lattice constant and depth of photonic crystal equal to 0. 8 μm and 0.18 μm respectively.

There are three structures to be simulated: the photonic crystal LED, that with a single DBR and that with a composite DBR. The lattice constant is 0.8 μm. In Fig.9, because the

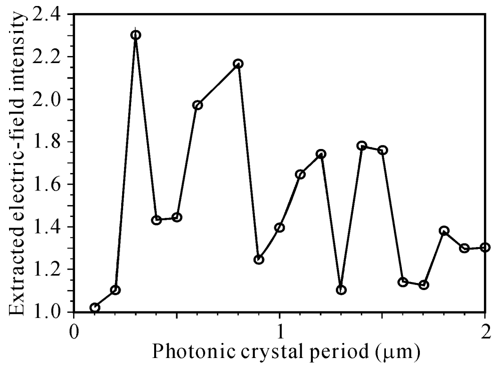

Fig.8 Relationship between the extracted electric-field intensity and photonic crystal period

downward light is radiated into the substrate which reduces the light extraction, the maximal intensity of photonic crystal LED is only about 2.1. The DBR can solve the problem. However one DBR only can reflect light with some certain incident angles, while the composite DBR can reflect light with any angles. As shown in Fig.9, the peak appears when the depth of photonic crystal equals to 0.18 μm. In the case, the extracted electric-field intensity of photonic crystal LED with a single DBR is about 3, while it comes up to 3.4 with a composite DBR. That is to say, the light extraction of power can be enhanced by 11.6 times.

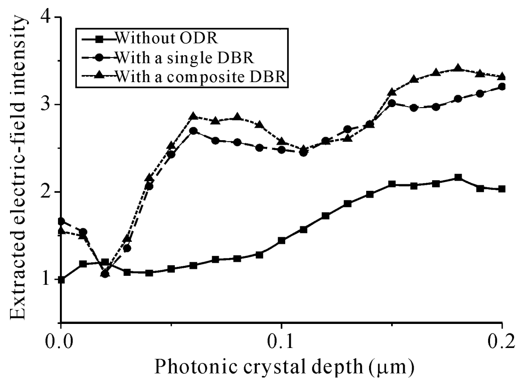

Fig.9 Relationship between the extracted electric-field intensity and photonic crystal depth for different structures

In Fig.8, when the lattice constant is smaller than 0.3 μm, the enhancement is very small, because the photonic crystal can not diffract the light with 460 nm wavelength. However the light extraction is effectively enhanced by the diffraction of photonic crystal when lattice constant is larger than 0.2 μm. The relationship between the extraction enhancement and the bandgap of photonic crystal is investigated in Ref. [1]. There is a bandgap when the ratio of the lattice constant to the light wavelength equals to 0.6. Therefore, the light can not propagate along the horizontal direction, while there is no limitation in the vertical direction. In conclusion, the extraction enhancement is due to the bandgap, diffraction of the photonic crystal and reflection of the composite DBR.

By using the photonic crystal structure and the composite DBR, light extraction of power can be enhanced by 11.6 times. The structure and materials of LEDs can be investigated to improve the light extraction in the next work, for example, the thin film LED structure. Furthermore, duty ratio of the photonic crystal will be considered.

References

[1] J. Y. Kim, M. K. Kwon and K. S. Lee, Appl. Phys. Lett., **91** (2007), 181109.

[2] K.Orita, S. Tamura and T. Takizawa, Jpn. J. Appl. Phys., **43** (2004), 5809.

[3] C. H. Lin, H. H. Yen and C. F. Lai, IEEE Photon. Technol. Lett., **20** (2008), 836.

[4] J. Park, J. K. Oh and K. W. Kwon, IEEE Photon. Technol. Lett., **20** (2008), 321.

[5] H. W. Huang, H. C. Kuo and C. F. Lai, IEEE Photon. Technol. Lett., **19** (2007), 565.

[6] K. Bao, X. N. Kang and B. Zhang, Appl. Phys. Lett., **92** (2008), 141104.

[7] Z. F. Xu, L. C. Cao and Q. F. Tan, Opt. Comm., **278** (2007), 211.

[8] H. Y. Hu, X. S. Xu and L. Lu, Journal of Optoelectronics • Laser, **19** (2008), 569.(in Chinese).

[9] C. H. Lin, C. F. Lai and T. S. Ko, IEEE Photon. Technol. Lett., **18** (2006), 2050.