Light extraction of GaN LEDs with 2-D photonic crystal structure

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Ultraviolet photo-lithography is employed to introduce two-dimensional (2D) photonic crystal (PC) structure on the top surface of GaN-based light emitting diode (LED). PC patterns are transferred to 460-nm-thick transparent indium tin oxide (ITO) electrode by inductively coupled plasma (ICP) etching. Light intensity of PC-LED can be enhanced by 38% comparing with the one without PC structure. Rigorous coupled wave analysis method is performed to calculate the light transmission spectrum of PC slab. Simulation results indicate that total internal reflect angle which modulated by PC structure has been increased by 7°, which means that the light extraction efficiency is enhanced outstandingly.

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GaN light emitting diode (LED) with high output-power is currently highly desirable for the applications such as flat panel displays, printers, traffic lights, and general lighting due to its compact size, high efficiency, and long lifetime. High-output-power operation requires the improvement in both the internal quantum efficiency and light emitting extraction efficiency of the LEDs.

With the improvement of semiconductor epitaxy technology, high quality GaN quantum well structure was successfully grown and the internal quantum efficiency of the device was evidently increased. However, only 4%($1/4n^2$, n is GaN refractive index) of total emission light can be extracted because of the total internal reflection confinement of the emitted light in the high refractive index[1]. Most of spontaneous emission was trapped in the active layer performing as guided modes and delocalized modes[2]. Various kinds of methods including surface roughness, flip chip[3,4], and substrate mirror[5,6] were used to enhance the light extraction efficiency. The introduction of two-dimensional (2D) photonic crystal (PC) structure on top surface of GaN LEDs is a novel method to increase light extraction efficiency. This method can effectively alter the radiation pattern as well as enhance the extraction efficiency of spontaneous emission, and has been widely used in LED[7−9] and organic LED (OLED)[10]. Normally the desired radius of air holes in PC structure on GaN LED are 100−300 nm, and thus electron beam lithography[9] or nanoimprint[2,10] is commonly used to define the PC patterns at the first fabrication step, which still needs to be further developed due to its low throughput and high mask cost.

In this letter, a low-cost ultraviolet photo-lithography technique is reported to fabricate GaN-based PC LEDs. Numerical simulation indicates that micron-scale PC structure modulates the transmission of indium tin oxide (ITO) layer on the top of GaN LED, thereby total internal reflection angle at the interface between top layer and air is increased and high extraction efficiency is obtained.

300-nm quantum well structure of GaN layer was grown on the sapphire substrate followed by p-doped GaN as contact layer. 460-nm-thick ITO transparent electrode was then deposited on the top of the GaN epitaxial layer by magnetron sputtering. Annealing process at 400 °C was applied to decrease the p-contact resistance.

Triangular PC patterns with 2-μm period and 500-nm radius air-hole was defined by ultraviolet photolithography. The patterns were transferred to transparent ITO electrode by inductively coupled plasma (ICP) etching. In order to avoid the degradation of GaN quantum well illuminant characteristic during dry etching process, PC pattern penetrated through only ITO layer and stopped at GaN-ITO interface. Figure 1 is the illustration of GaN PC-LED structure.

Figure 2 shows a scanning electron microscope (SEM) image of the PC-LED structure. The surface area of PC pattern is 350×350 (μm), which covers the LED luminous region. For comparison, GaN LEDs without PC were simultaneously fabricated onto the same GaN wafer.

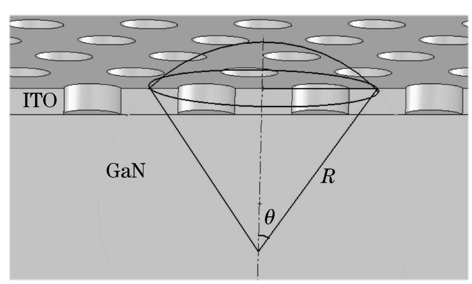

Fig. 1. Sketch of GaN slab and ITO layer with PC structure. The light emission area is defined by the total internal reflection angle θ.

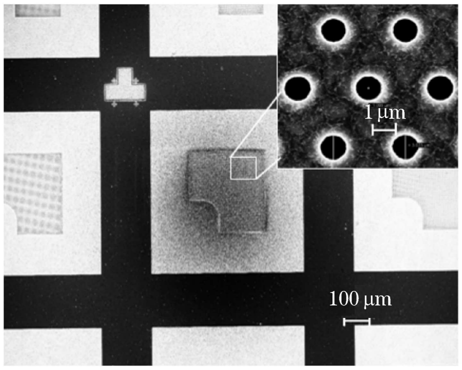

Fig. 2. SEM image of micron scale PC LED.

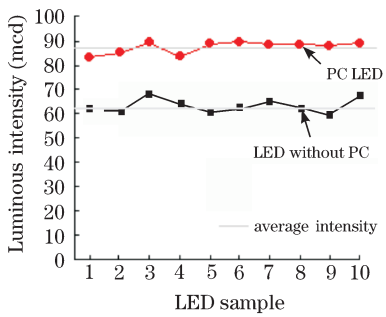

Fig. 3. Luminous intensity for the PC LED and LED without PC samples.

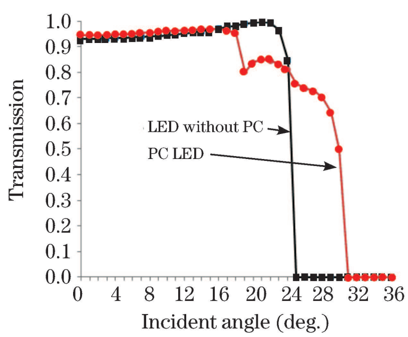

Fig. 4. Light transmission versus incident angle θ for PC LED and LED without PC.

The LED light output power was measured using integrated sphere detector. Figure 3 shows the luminous intensity of twenty LED samples, which were randomly chosen. The circles are luminous intensity for PC LED samples, while the rectangles are LEDs without PC structure. The gray lines show the averaged values, which are 87.3 and 63.2 mcd for LEDs with and without PC structure, respectively. From the measured results, it can be induced that a 38% enhancement of radiation intensity was achieved due to the introduction of the PC surface.

In order to study the characteristics of extraction effects with PCs theoretically, rigorous coupled wave analysis method was implemented. Device model is designed as ITO layer with PC structure on the top of GaN slab. The PC is arranged as matrix of air holes. For the periodic pattern, only one repeated cell in x-y dimension is required for the calculation of light transmission spectrum. The refractive indices of GaN and ITO layer are 2.4 and 2, respectively. The period is 2 μm and the radius of air holes is 0.5 μm. The depth of air-hole is 0.46 μm, which is the same as the thickness of ITO layer.

The light transmission as the function of incident angle θ in the x-z plane was simulated with TE polarized states at wavelength of 450 nm. The calculated results are shown in Fig. 4. The circle-dotted line is the transmission of PC LED and the rectangle-dotted line is that of LED without PC, respectively. If the incident light angle θ is larger than the total internal reflection angle, the efficiency decreases dramatically to zero. Comparing with LED without PC structure, the total internal reflection angle is increased by 7° for PC-patterned GaN LED due to modulation by PC in ITO layer. These modulations increase probabilities for trapped photon in high index layer to escape into the air.

The light extraction factor can be calculated by integrating angle dependent transmission efficiency at a fixed angle. For a light source in active layer, the light emission efficiency was limited by the total internal reflection angle. The emission power P_{out} of light cone can be expressed as

$$P_{\text{out}} = P_0 \cdot \int_0^{\pi/2} T(\theta) \cdot 2\pi R^2 \cdot \sin\theta \cdot \mathrm{d}\theta, \qquad (1)$$

where P_0 is the power of the light source, θ is the light incident angle, R is a unified radius for different incident angle, $T(\theta)$ is the light transmission of the GaN and ITO slab, as shown in Fig. 4.

The emission power P_{out} ratio between LEDs with and without PC structure shows that the emission power of PC-patterned LED is 40% more than the standard LED, which is coincident to the measured data of 38%. Hence we can conclude that the total internal reflection angle expansion plays an important role in light extraction.

In conclusion, PC GaN LED was fabricated by ultraviolet photo-lithography and ICP etching techniques. It indicates that light extraction is enhanced by introducing the micrometer-scale PC structure into ITO layer. The 38% light extracting enhancement was obtained. Rigorous coupled wave analysis method was used to study the extraction enhancement roughly, and further explanation will be given by using photonic band structure. The transmission spectra indicate that total internal reflection angle between ITO and air is increased by 7° The calculated light extraction enhancement factor is 40%, which is consistent well with experimental results (38%). It indicates that there is a flexible and efficient way to enhance light extract efficiency by introducing micron-scale PC patterns into ITO layer with active layer underneath.

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References

1. H. Benisty, H. De Neve, and C. Weisbuch, IEEE J. Quantum Electron. **34,** 1612 (1998).

2. F. S. Diana, A. David, I. Meinel, R. Sharma, C. Weisbuch, S. Nakamura, and P. M. Petroff, Nano Lett. **6,** 1116 (2006).
3. X. Jin, B. Zhang, T. Dai, W. Wei, X. Kang, G. Zhang, S. Trieu, and F. Wang, Chin. Opt. Lett. **6,** 788 (2008).
4. P. Niu, Y. Li, H. Liu, H. Hu, H. Jia, and H. Chen, Laser Optoelectron. Prog. (in Chinese) **44,** (9) 43 (2007).
5. H. Kuang, J. Liu, H. Cheng, and F. Jiang, Acta Opt. Sin. (in Chinese) **28,** 143 (2008).
6. C. Shen, H. Feng, Z. Xu, and S. Jin, Chin. Opt. Lett. **6,** 152 (2008).
7. S. Fan, P. R. Villeneuve, and J. D. Joannopoulos, Phys. Rev. Lett. **78,** 3294 (1997).
8. M.-K. Kwon, J.-Y. Kim, I.-K. Park, K. S. Kim, G.-Y. Jung, S.-J. Park, J. W. Kim, and Y. C. Kim, Appl. Phys. Lett. **92,** 251110 (2008).
9. B. Rong, H. W. M. Salemink, E. M. Roeling, R. van der Heijden, F. Karouta, and E. van der Drift, J. Vac. Sci. Technol. B **25,** 2632 (2007).
10. C. Liu, V. Kamaev, and Z. V. Vardeny, Appl. Phys. Lett. **86,** 143501 (2005).