Theoretical and experimental demonstration of enhanced light extraction efficiency in III-nitride-based micro-array light-emitting diodes

Po-Shen Lee, Yun-Chih Lee, Cheng-Huang Kuo, Jenq-Yang Chang, Mount-Learn Wu
Department of Optics and Photonics, National Central University, Taiwan

Abstract: The mechanism of enhanced light extraction efficiency in III-nitride-based light-emitting diodes (LEDs) with microstructures is demonstrated numerically and experimentally. The analysis of the mechanism is aimed at the photonic behavior to enhance light extraction effectively.
© 2008 OEST & OSJ
Keywords: *micro-array light-emitting diode, light extraction efficiency, finite difference time domain (FDTD)*

1. Introduction

The III-nitride-based compounds such as AlGaN and InGaN have been successfully applied to develop light-emitting diodes (LEDs) from ultraviolet to blue and green spectral regions [1,2]. And the invention of III-nitride-based LEDs is one of the key technological breakthroughs for solid state lighting. However, the high refractive index of GaN prohibits light beyond a critical angle from being extracted due to the total internal reflection. A large fraction of the generated light is trapped inside an LED and absorbed by the non-radiation absorption centers. Several approaches have been proposed and demonstrated to improve output efficiency of III-nitride-based LEDs, such as surface texturing [3-5], photonic crystals (PhCs) [6, 7], micrometer-scale LEDs (μ-LEDs) [8, 9]. Surface texturing deteriorates the total internal reflection effect, but the random textured structure on the LED surface cannot control the photonic behavior in a predictable manner. LEDs with the surface integration of PhCs may be limitedly effective, because LEDs are light sources with broadband spectra, non-planar wavefronts, and random polarizations. LEDs with an array of microstructures are expected to enhance light extraction without deteriorating electrical properties. However, there is a lack of clarity on the extraction of the microstructures, e.g., which fraction of the emitted light is expected to extract. FDTD is utilized in this study to clarify the mechanism of light extraction in III-nitride-based micro-array light-emitting diodes.

2. Numerical anaylsis with FDTD method in μ-LED

In this study, the numerical and experimental demonstrations for the enhancement of light extraction efficiency in III-nitride-based LEDs with an array of microstructures are proposed. As shown in Fig. 1, a schematic diagram of the III-nitride-based LEDs with the deep etching of microstructures through the InGaN/GaN MQW active structure and down to the n-type GaN layer are fabricated on a sapphire (Al_2O_3) substrate. As illustrated in this figure, the structure parameters given in the following analysis include period of micro-hole Λ = 10 μm, micro-hole filling factor f = 0.5. Multiple point sources with TE and TM polarizations in the MQW region are utilized in the FDTD analysis to model the behaviour of LEDs. Point sources are uniformly arranged in the MQW structure of every microstructure. It means the interval between two point sources is around 300 nm. Due to the microstructures can be regarded as an μLED with a hole-array. The numerical analyses of microstructures are considered in the same period with different filling factors as shown in fig. 2. Multiple light sources are arranged similarly with the characteristics of LEDs such as non-planar wavefronts and random polarizations.

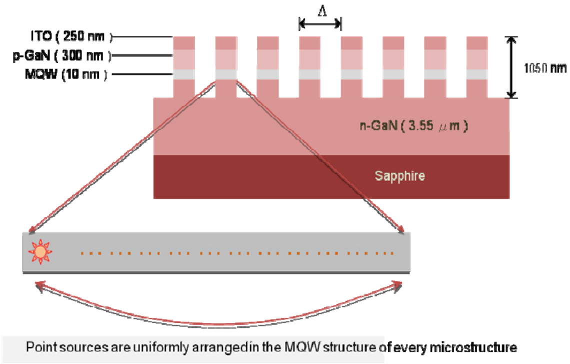

Fig. 1

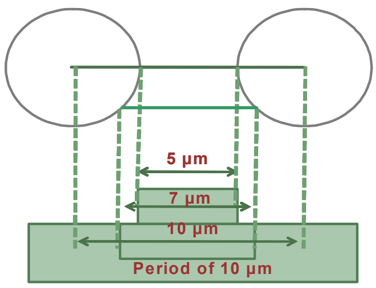

Fig. 2

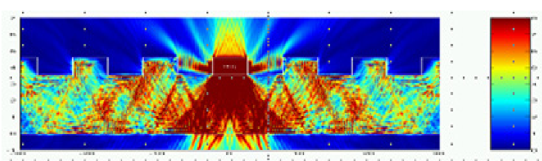

Fig. 3

Fig. 3 shows a diagram of simulated energy flux emitting from a single μLED on the proposed structure. LEDs with an array of these rectangular microstructures enhance light extraction mainly attributed to the scattering of light from the etched sidewall surfaces of each μLED. Also, this rectangular microstructure makes the light that penetrates into the n-type GaN layer scatter in a range of degree as an optical aperture with a special NA depends on the etching depth and the width of this structure. Besides, these neighbouring microstructures play roles as gratings to couple a partial power from the GaN layer into the air.

3. Numerical and experimental demonstration of LEDs with microstructures

The n-UV InGaN/GaN MQW LEDs used in this study were all grown on c-face sapphire substrates in a metalorganic chemical vapor deposition (MOCVD) system. The epitaxial structure consists of a 4-μm-thick Si-doped GaN n-cladding layer, an InGaN/GaN MQW active region and a 0.25-μm-thick Mg-doped GaN layer. After the growth, the surfaces of the samples are partially etched until the n-type GaN layers are exposed. Then a 250-nm-thick ITO film is deposited onto the LED surfaces by e-beam evaporation to serve as the p-contacts. The standard photolithography and dry etching are subsequently used to form microstructure pattern of the epitaxial structure. The etching depth of the epitaxial layers is controlled at 800 nm which is more than the total p-layer thickness and MQW-layer thickness. Fig. 4 shows top view photograph for the meshed LED and enlarged photograph of area A in the inlet. In order to study the mechanism of light extraction, the shallow etching of microstructures on the ITO p-contact is also fabricated.

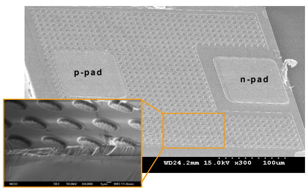

Fig. 4

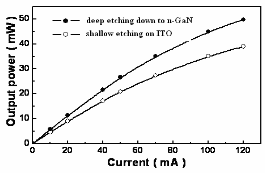

Fig. 5

Fig. 5 shows measured L-I curves of both LEDs with different microstructures, including the shallow etching of microstructures on the ITO p-contact and the deep etching of micro-holes down to the n-type GaN layer. It is found that output power of LED with deep-etching microstructure is larger than that with shallow etching on ITO. Under an injection current of 20 mA, the output powers are 9.0 and 11.3 mW for the microstructure ITO LED and the LED with deep-etching microstructure, respectively. Although the active region of LED is reduced by 33% as compared with the microstructure ITO LED, an enhancement in the extraction efficiency of 25.5% is obtained.

Fig. 6 shows measured and simulated angular radiation patterns of the LED with these two structures. Compared with the LED with a shallow etching on ITO, it can be seen clearly that output beam pattern of the LED with a deep etching down to n-GaN is broader. It means that a great amount of light with high-frequency components emits from the LED with deep-etching microstructures. This phenomenon is the same as prediction in the simulation. Power confined in guided modes can be effectively coupled into the air by the array of deep-etching microstructures. However, only a minority of power in the GaN epi-layers beneath the shallow-etching ITO microstructures converts to the guided modes of higher orders. The ITO microstructure cannot effectively couple the guided mode of LED into the air. The angular radiation pattern of the LED with a shallow etching on ITO is almost a Lambertian pattern in simulation and measurement.

4. Conclusions

In this study, multiple point sources with TE and TM polarizations in the MQW region are utilized in the FDTD analysis to demonstrate the mechanism of enhanced light extraction efficiency in III-nitride-based LED with deep-etching microstructure. The simulation successfully explains the broad beam pattern observed in LEDs with deep-etching microstructures. It is verified that a great amount of light with high-frequency components coupled from the guided light to the deep-etching microstructures is the mechanism of enhancement in light output of III-nitride-based micro-array LEDs.

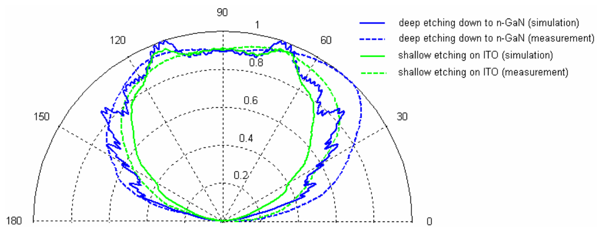

Fig. 6

6. References

[1] T. Mukai, M. Yamada and S. Nakamura : Jpn. J. Appl. Phys., **38** (1999).
[2] T. Mukai, M. Yamada and S. Nakamura : Jpn. J. Appl. Phys., **37**, pp. 1358-1361 (1998).
[3] T. Fujii, Y. Gao, R. Sharma, E. L. Hu, S. P. DenBaars and S. Nakamura: Appl. Phys. Lett., **84** (2004).
[4] S. I. Na, G. Y. Ha, D. S. Han, S. S. Kim, J. Y. Kim, J. H. Lim, D. J. Kim, K. I. Min and S. J. Park: IEEE Photon. Tech. Lett., **18** (2006).
[5] C. H. Kuo, C. C. Lin, S. J. Chang, Y. P. Hsu, J. M. Tsai, W. C. Lai and P. T. Wang, : IEEE Tran. Electron. Dev., **52** (2005).
[6] A. David, T. Fuji, R. Sharma, K. McGroddy, S. Nakamura, S. P. DenBaars, E. L. Hu, and C. Weisbuch : Appl. Phys. Lett., **88** (2006).
[7] C. H. Chao, S. L. Chung, and T. L. Wu: Appl. Phys. Lett., **89** (2006).
[8] A. David, T. Fuji, B. Moran, S. Nakamura, S. P. DenBaars, R. Sharma, K. McGroddy, E. L. Hu, and C. Weisbuch: Appl. Phys. Lett., **89** (2006).
[9] H. W. Choi, C. W. Jeon, and M. D. Dawson: IEEE Photon. Technol. Lett., **16** (2004).