MECHANISM OF ENHANCED LIGHT EXTRACTION EFFICIENCY IN III-NITRIDE-BASED MICRO-ARRAY LIGHT-EMITTING DIODES

Jenq-Yang Chang, Yun-Chih Lee, Po-Shen Lee, Cheng-Huang Kuo and Mount-Learn Wu
Department of Optics and Photonics, National Central University, Taoyuan County 32001, Taiwan (R.O.C.)
Phone: 886-3-4227151ext 65283 and Fax: 886-3-4252897, and Email: jychang@dop.ncu.edu.tw

Abstract: *In this paper, the enhancement of light extraction efficiency in III-nitride-based light-emitting-diodes with microstructures is demonstrated numerically and experimentally. Multiple point sources are utilized in the finite-difference-time-domain analysis to model the behaviour of LED. The measured results of intensity–current characteristics and beam patterns also verify the numerical analysis.*

1. Introduction

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. Several approaches have been proposed and demonstrated to improve output efficiency of III-nitride-based LEDs, such as surface texturing [1-3], photonic crystals (PhCs) [4, 5], micrometer-scale LEDs (μ-LEDs) [6,7]. However, the random textured structure on the LED surface cannot control the photonic behavior in a predictable manner. The LEDs are light sources with broadband spectra, non-planar wavefronts, and random polarizations. These characteristics would result in the limited light extraction from LEDs with the surface integration of PhCs. The subwavelength PhC structure with a large surface-to-volume ratio is fabricated down to the p-GaN layer or even to quantum wells by using dry etching. The p-metal on the damaged side-facets of PhC structure would induce severe carrier loss due to surface recombination. LEDs with an array of microstructures are expected to enhance light extraction without deteriorating electrical properties. So far, however, no evaluation has been made of light extraction in LEDs with an array of microstructures. And there is a lack of clarity on the extraction of the microstructures, e.g., which fraction of the emitted light is expected to extract.

2. Simulated and experimental results

In this paper, 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 substrate. The structure parameters given in the following analysis include period of micro-hole Λ = 5 μm, micro-hole filling factor f = 0.5, the refractive index n_{ITO} = 1.8, $n_{pGaN} = n_{nGaN}$ = 2.5 and n_{MQW} = 2.4. Multiple point sources with TE and TM polarizations in the MQW region are utilized in the finite difference time domain (FDTD) analysis to model the behaviour of LEDs. The 22 point sources are uniformly arranged in the MQW structure of every microstructure. Due to the deep etching down to the n-type GaN layer, every microstucture on the proposed III-nitride based LED can be regarded as a μLED. Fig. 2 shows a diagram of simulated energy flux emitting from a single μLED on the proposed structure. The power penetrating into the n-type GaN layer converts to a guided mode and laterally extends in the layer up to a distance of ±25 μm. The neighbouring dummy microstructures would couple a partial power of the guided mode into the air. Since the period of microstructures is up to 5 μm, the momentum of escaping light from the dummy microstructures is almost the same as that of the guided mode. It means that the escaping light propagates in the air is the one with higher spatial frequencies. In order to study the mechanism of light extraction, the shallow etching of microstructures on the ITO p-contact is also fabricated.

Fig. 3 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. 4 shows measured and simulated angular radiation patterns of the LED with deep-etching microstructures down to the n-type GaN layer and the LED with shallow-etching microstructures on ITO. Both output beam patterns are measured at a dc driving current of 20 mA. 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. The omni-directional power penetrating into the n-type GaN layer converts to several guided modes and extends in the layer laterally. Power confined in guided modes can be effectively coupled into the air by the array of deep-etching microstructures. Since the absorption effect in GaN layers is neglected in simulation, the guided mode in the n-type GaN layer can be further extended in the lateral direction, the deviation between the experimental and simulated beam patterns of the LED with deep-etching microstructure occurs. 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.

3. Conclusion

In this paper, multiple point sources with TE and TM polarizations in the MQW region are utilized in the finite difference time domain (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.

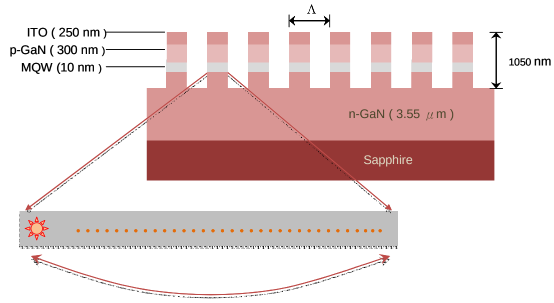

Fig. 1. Schematic diagram of the III-nitride-based LEDs with the deep etching of microstructures down to the n-type GaN layer.

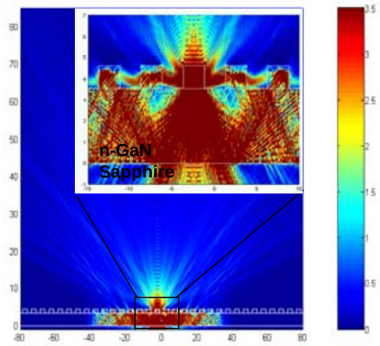

Fig. 2. Diagram of simulated energy flux emitting from a single μLED on the proposed structure.

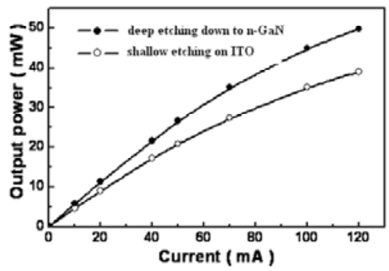

Fig. 3. Measured L-I curves of both LEDs with different microstructures, including the shallow etching of microstructures on the ITO p-contact (shallow etching on ITO) and the deep etching of microstructures down to the n-type GaN layer (deep etching down to n-GaN).

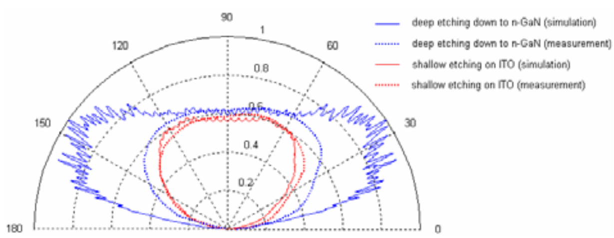

Fig. 4. Measured and simulated angular radiation patterns of LED with deep-etching microstructure (shallow etching on ITO) and the ITO microstructure LED (deep etching down to n-GaN).

Reference

[1] T. Fujii, Y. Gao, R. Sharma, E. L. Hu, S. P. DenBaars and S. Nakamura, "Increase in the extraction efficiency of GaN-based light-emitting diodes via surface roughening," Appl. Phys. Lett., **84**, 855-857 (2004).

[2] 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, "Selective wet etching of p-GaN for efficient GaN-based light-emitting diodes," IEEE Photon. Tech. Lett., **18**, 1512-1514 (2006).

[3] C. H. Kuo, C. C. Lin, S. J. Chang, Y. P. Hsu, J. M. Tsai, W. C. Lai and P. T. Wang, "Nitride-based light-emitting diodes with p-AlInGaN surface layers," IEEE Tran. Electron. Dev., **52**, 2346-2349 (2005).

[4] A. David, T. Fuji, R. Sharma, K. McGroddy, S. Nakamura, S. P. DenBaars, E. L. Hu, and C. Weisbuch, "Photonic-crystal GaN light-emitting diodes with tailored guided modes distribution," Appl. Phys. Lett., **88**, 061124-1-061124-3 (2006).

[5] C. H. Chao, S. L. Chung, and T. L. Wu, "Theoretical demonstration of enhancement of light extraction of flip-chip GaN light-emitting diodes with photonic crystals," Appl. Phys. Lett., **89**, 091116-1-091116-3 (2006).

[6] A. David, T. Fuji, B. Moran, S. Nakamura, S. P. DenBaars, R. Sharma, K. McGroddy, E. L. Hu, and C. Weisbuch, "Theoretical demonstration of enhancement of light extraction of flip-chip GaN light-emitting diodes with photonic crystals," Appl. Phys. Lett., **89**, 091116-1-091116-3 (2006).

[7] H. W. Choi, C. W. Jeon, and M. D. Dawson, "InGaN microring light-emitting diodes," IEEE Photon. Technol. Lett., **16**, 33–35 (2004).