Mechanism of Enhanced Light Extraction Efficiency in III-nitride-based Micro-array Light-emitting Diodes

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Abstract --- *In this study, the enhancement mechanism of light extraction efficiency in III-nitride-based light-emitting diodes (LEDs) with an array of microstructures is demonstrated numerically and experimentally. Multiple point sources in the MQW region are utilized in the finite difference time domain (FDTD) analysis to model the behaviour of deep etching microstructure down to the n-type GaN LED. The simulated beam patterns reveal that the microstructures act as coupler to extract modulated light in the n-type GaN layer. With analysis of the mechanism in light extraction, the photonic behavior of LEDs is able to be controlled and extracted effectively.*

Keywords --- LED, microstructure, mechanism, modulated, light extraction, FDTD

Introduction

The III-nitride-based compounds such as AlGaN and InGaN have been successfully applied to develop light-emitting diodes (LEDs) from ultraviolet (UV) to blue and green spectral regions [1, 2]. For example, III-nitride-based blue and green LEDs have already been extensively used in full-color displays and high efficient light source for traffic light lamps. Moreover, 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 a 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], proper substrate shaping [10], thin GaN structures [11], and flip-chip packaging [11]. 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.

Simulation Model and Mechanism

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 = 5 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. As shown in Fig. 1, 22 point sources are uniformly arranged in the MQW structure of every microstructure. It means the interval between two point sources is around 100 nm. 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. 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, and the great increase in the surface areas. 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. However, as fig. 2 illustrates, the optical power emitting into the n-type GaN layer is much larger than that escapes into the air. A part of this optical power, propagating in the GaN layer because of the total internal reflection effect, extends restrictedly in the lateral direction due to neighbouring microstructures of a single μLED as a reflecting wall. Besides, these neighbouring microstructures play roles as gratings to couple a partial power from the GaN layer into the air.

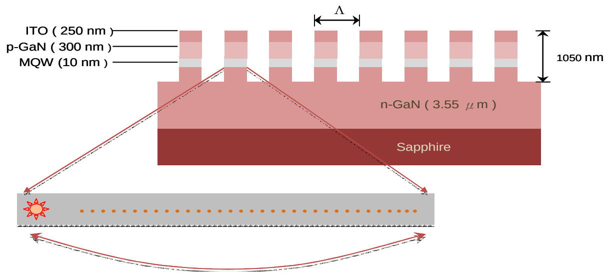

Fig.1 . Schematic diagram of the III-nitride-based LEDs with the deep etching of microstructures through the InGaN/GaN MQW active structure and down to the n-type GaN layer. fabricated on a sapphire (Al_2O_3) substrate.

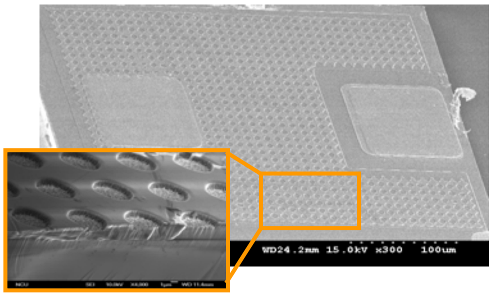

Fig. 3 . Scanning electron microscope image for the surface of LED with microstructures.

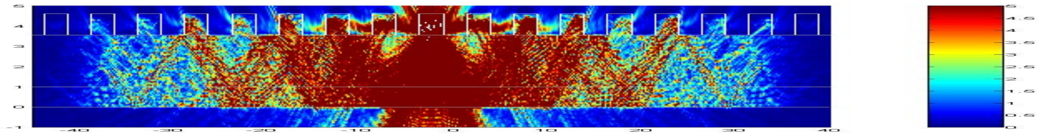

Fig. 2 . Diagram of simulated energy flux emitting from a single μLED on the proposed structure through FDTD method shows restrict effect of microstructures on light extension.

Experimental Demonstration of LED with Micro-array

The n-UV InGaN/GaN MQW LEDs used in this study were all grown on c-face (0001) 2-inch 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. 3 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 shows measured and simulated angular radiation patterns of the LED with deep-etching microstructures down to the n-type GaN layer (deep etching down to n-GaN) and the LED with shallow-etching microstructures on ITO (shallow etching 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-spatial frequency components emits from the LED with deep-etching microstructures. This phenomenon is the same as prediction in the simulation. The light with high-frequency components consists of the light from etching sidewalls and from neighbouring periodic structures of μLEDs. However, only a minority of power in the GaN epi-layers beneath the shallow-etching ITO microstructures escapes out to the air. The angular radiation pattern of the LED with a shallow etching on ITO is almost a Lambertian pattern in simulation and measurement.

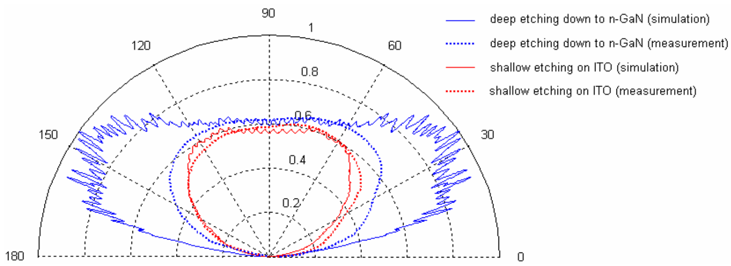

Fig. 4 . Measured and simulated angular radiation patterns of the LED with deep-etching microstructures down to the n-type GaN layer (deep etching down to n-GaN) and the LED with shallow-etching microstructures on ITO (shallow etching on ITO)

Optimization of Light Extraction

Shorter propagating distance of light in the GaN layer before escaping out to the air may enhance extraction when absorption effect is considered in the real case. An optimized microstructure as fig.5 is designed to achieve this objective. It makes energy flux in the GaN layer oscillate regularly in a small region by utilizing an arranged period of the μLEDs. The propagating light with the most power in the n-GaN layer become directional light by a spatial filter-like mechanism through the designed NA and the critical angle between the GaN layer and the sapphire layer. The arranged periodic microstructures, the μLEDs, play roles as walls that locate on the position, which is able to shorten the pathway and modulate the directional light in GaN. For effectively extract the modulated wave at a time, the oblique etching sidewalls are is necessary. As shown in Fig. 6, the oblique etching sidewalls help the energy flux couple into the air. As simulated angular radiation patterns of the LED with the rectangular microstructures (blue line) and with the trapezoid microstructures (green line) shown in fig.7, significant light with high-spatial frequency components is attribute to result of the oblique etching sidewalls and a relative enhancement of 15% compared to those structures with the rectangular shape of non-modulated light is obtained.

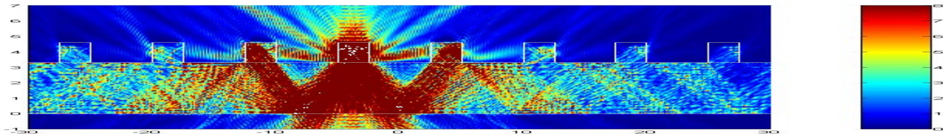

Fig. 5. Diagram of simulated energy flux shows a design that controls most power oscillating laterally in 17 μm.

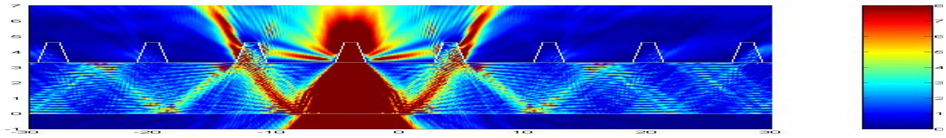

Fig. 6. Diagram of simulated energy flux shows light extraction from oblique etching sidewalls of optimized trapezoid microstructures.

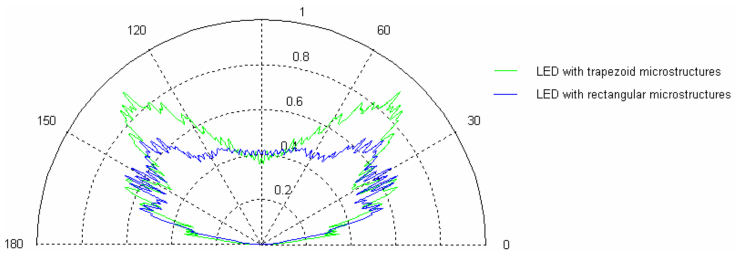

Fig. 7. Simulated angular radiation patterns of the LED with rectangular microstructures (blue line) and with trapezoid microstructures (green line). The relative enhancement is 15% compared to those structures with rectangular shape of non-modulated light in optics.

Conclusion

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. It is verified that amount of light with high-frequency components extracted directly from etching sidewalls and coupled by the neighbouring structures of μLEDs are the enhancement mechanisms of micro-array LEDs. Moreover, the light behaviour in the GaN epilayer can be modulated by the microstructures and FDTD analysis also provides the optimized structure with effective light extraction.

Reference

[1] T. Mukai, M. Yamada and S. Nakamura, “Characteristics of InGaN-based UV/blue/green/amber/red light-emitting diodes,” Jpn. J. Appl. Phys., **38**, pp. 3976-3981, 1999.

[2] T. Mukai, M. Yamada and S. Nakamura, “Current and temperature dependences of electroluminescence of InGaN-based UV/blue/green light-emitting diodes,” 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, “Increase in the extraction efficiency of GaN-based light-emitting diodes via surface roughening,” Appl. Phys. Lett., **84**, pp. 855-857, 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, “Selective wet etching of p-GaN for efficient GaN-based light-emitting diodes,” IEEE Photon. Tech. Lett., **18**, pp. 1512-1514, 2006.

[5] 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**, pp. 2346-2349, 2005.

[6] 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**, pp. 061124-1-061124-3, 2006.

[7] 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**, pp. 091116-1-091116-3, 2006.

[8] 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**, pp. 091116-1-091116-3, 2006.

[9] H. W. Choi, C. W. Jeon, and M. D. Dawson, “InGaN microring light-emitting diodes,” IEEE Photon. Technol. Lett., **16**, pp. 33–35, 2004.

[10] K. H. Kim, J. Li, S. X. Jin, J. Y. Lin, and H. X. Jiang, “III-nitride ultraviolet light-emitting diodes with delta doping,” Appl. Phys. Lett., **83**, pp. 566-568, 2003.

[11] M. Yamada, T. Mitani, Y. Narukawa, S. Shioji, I. Niki, S. Sonobe, K. Deguchi, M. Sano, and T. Mukai, “InGaN-based near-ultraviolet and blue-light-emitting diodes with high external quantum efficiency using a patterned sapphire substrate and a mesh electrode,” Jpn. J Appl. Phys., **41**, pp. 1431-1433,. 2002.