AZIMUTHALLY CONCENTRATED IRRADIANCE OF GaN-BASED LIGHT-EMITTING DIODES WITH Si_3N_4 MICROSTRUCTURE ARRAYS

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Abstract: *The Si_3N_4 microstructure array has been applied to the p-GaN surface of LED for modulating the light pattern concentrated with a cone of 50 degrees. Light extraction efficiencies are improved by about 20% in simulation and by 15% in EL measurement .*

1. Introduction

GaN-based light-emitting diodes (LEDs) are becoming more and more appealing in various applications from indicator lights to solid-state lighting due to their superior performances of energy efficiency, high reliability, and versatile colors. However, as considering LED lighting a replacement for fluorescent lighting, several characteristics such as brightness, color uniformity, and azimuthally concentrated irradiance should be taken into account. Several approaches have been proposed and demonstrated to improve the output efficiency of GaN-based LED chips [1-3]. A better color uniformity can be obtained in LED lamps or lighting modules by arranging the LED chips in certain sequences and patterns [4] or altering the form factor of phosphor-coating design [5, 6].

Several light-pattern modulation schemes have been reported, including theoretical demonstrations of etching photonic crystals [7] and photonic quasi-crystals [8] into the top emitting surfaces of LEDs or the experimental demonstration of monolithically integrated microstructure into sapphire substrates of LEDs [9]. Among these approaches, the ordered surface patterning of photonic (quasi-)crystals can be applied to design various azimuthally anisotropic irradiances from LEDs [7, 8]. Unfortunately, the dielectric microstructure on surface of LED to demonstrate azimuthally concentrated irradiances and maintain its electrical properties is not yet realized.

In this paper, the local modulation of photons within a micro-scaled region of MQWs just beneath the Si_3N_4 microstructure is proposed. We present the demonstration of the azimuthally concentrated irradiance from GaN-based LEDs.

2. Numerical simulation of GaN-based LEDs with Si_3N_4 microstructure arrays

In this analysis, an insulating Si_3N_4 layer is grown on the surface of p-GaN. We design a Si_3N_4-based microstructure to concentrate light emitted from the traditional planar LEDs. The proposed structure for the LED is grown on a sapphire substrate, as illustrated in Figure 1, including an n-GaN layer, multiple quantum wells (MQWs) targeted for emission at 450 nm, a p-GaN layer, and a Si_3N_4 film based microstructure on the top of the p-GaN layer. The parameters for microstructure arrays include, period $\Lambda = 0.5$ μm, filling factor $F = 0.5$, p-GaN layer thickness $h_{p\text{-}GaN} = 0.3$ μm, MQWs thickness $h_{MQWS} = 0.01$ μm, n-GaN layer thickness $h_{n\text{-}GaN} = 4$ μm, Si_3N_4 layer thickness $h_{Si3N4} = 0.65$μm, microstructure etching depth $h_{etch} = 0.3$ μm, and microstructure slanted angle $\theta = 75.6°$. The detail simulation model with FDTD analysis has been discussed in previous study [10].

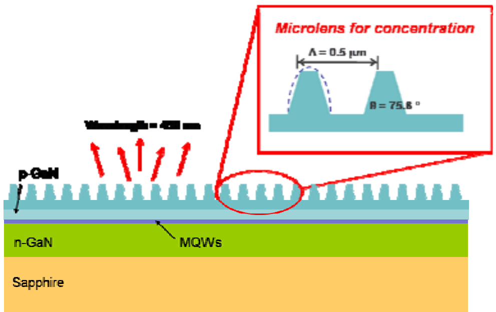

Fig. 1. Scheme of the designed LEDs with Si_3N_4 micro-structure arrays on the top of the p-GaN layer.

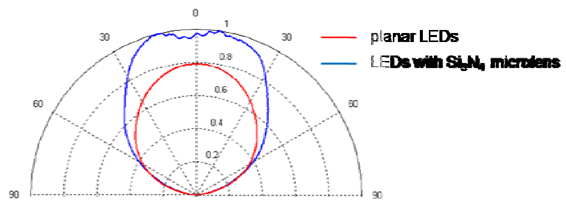

Fig. 2. The angular radiation patterns.

In Figure 2, the simulated angular radiation patterns emitting from the proposed LEDs with Si_3N_4 microstructure arrays and from the traditional LEDs with 650 nm-thick Si_3N_4 layer are shown by a blue line and a red line respectively. The light pattern can be modulated to the intensity variation less than 10% within the emitting angle of 50°. It implies that the Si_3N_4 microstructure arrays concentrates the light from MQWs effectively and also performs 20.7% enhancement in light extraction efficiency.

3. Experimental results

The proposed GaN-based LEDs with Si_3N_4 microstructures are fabricated with standard LEDs lithography. Figure 3 shows the fabricated microstructure observed by scanning electron microscope (SEM). It is observed with an average period close to 492 nm. The filling factor F corresponding to the average period is around 0.5. Figure 4 shows patterns of measured angular radiation emitting from the LED with proposed Si_3N_4 microstructure and LED with planar Si_3N_4 layer. The enhancement of light extraction efficiency and output beam patterns are similar to the predictions by the theoretical model in both LEDs. Light extraction efficiencies are improved by about 20% in simulation and by 15% in EL measurement (at input current of 20 mA as shown in Figure 5).

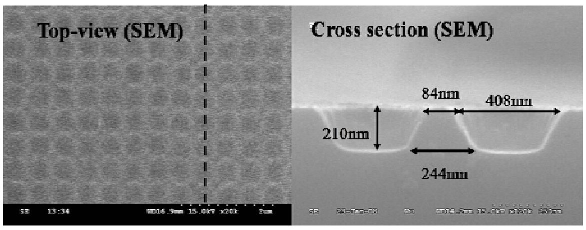

Fig. 3 SEM photographs of LEDs with Si_3N_4 microstructure arrays.

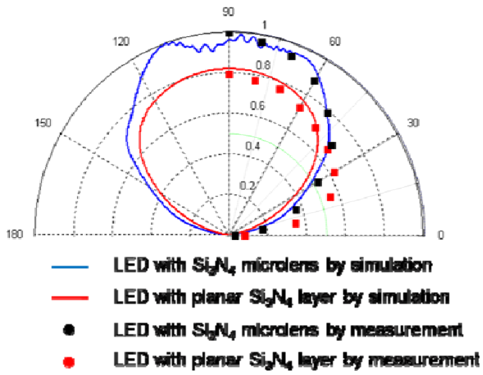

Fig. 4 Measured and simulated angular radiation patterns.

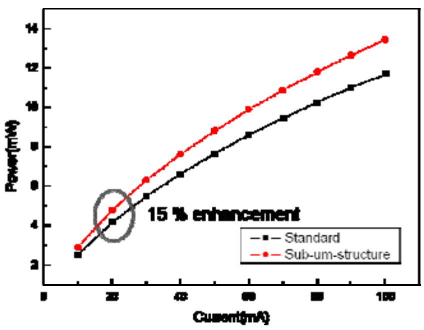

Fig. 5 L-I curves of the LEDs with Si_3N_4 microstructure array.

7. Conclusions

The Si_3N_4 microstructure array has been applied to the p-GaN surface of LED for modulating the light pattern concentrated with emitting cone of 50°. Through the analysis of FDTD and the measurement of PL angular-resolved, the modulation of proposed structure can be clear understood and confirmed. Light extraction efficiencies are improved by about 20% in simulation and by 15% in EL measurement. As a concluding remark, the proposed Si_3N_4 microstructure provides modulation for LEDs as a spatial intensity concentration device integrated with GaN-based LEDs structure.

Acknowledgement

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References

[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. Technol. 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] I. Moreno, U. Contreras, “Color distribution from multicolor LED arrays,” Opt. Express **15**, 3607-3618 (2007)

[5] A. Borbely, S. G. Johnson, “Performance of phosphor-coated light-emitting diode optics in ray-trace simulations,” Opt. Eng. **44**, 111308 (2005).

[6] C. Deller, G. Smith, J. Franklin, “Colour mixing LEDs with short microsphere doped acrylic rods,” Opt. Express **12**, 3327-3333 (2004)

[7] H. T. Hsueh, J. –F. T. Wang, C. H .Chao, W. Y. Yeh, C. F. Lai, H. C. Kuo, T. C. Lu, and S. C. Wang, “Azimuthal Anisotropy of Light Extraction from Photonic Crystal Light-emitting Diodes,” *in Conference on Lasers and Electro-Optics/Pacific Rim 2007*, (Optical Society of America, 2007), paper ThF1_4.

[8] M.D.B. Charlton, M.E. Zoorob, and T. Lee, “Photonic Quasi-Crystal LEDs Design, modeling, and optimization,” Proc. SPIE **6486**, 64860R-1-64860R-10 (2007).

[9] H. W. Choi, C. Liu, E. Gu, G. McConnell, J. M. Girkin, I. M. Watson, and M. D. Dawson, “GaN micro-Light Emitting Diode Arrays with Monolithically-integrated Sapphire micro-lenses,” Appl. Phys. Lett. **84**, (2004).

[10] Mount-Learn Wu, Yun-Chih Lee, Shih-Pu Yang, Po-Shen Lee and Jenq-Yang Chang, “Azimuthally isotropic irradiance of GaN-based light-emitting diodes with GaN microstructure arrays,” Opt. Express **17** (2009).