Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp250-251

Highly Light-Collection Efficiency Based on Multi-Beam Diffractions from GaN-Based Micro-Cavity Light-Emitting Diodes with Photonic Crystals

Ying-Chien Chu[1,4], Yan-Kuin Su[1,2,3], Chia-Hsin Chao[4], Ming-Hsien Wu[4], and Wen-Yung Yeh[4]

[1] Institute of Microelectronics, and Department of Electrical Engineering, National Cheng Kung University
No. 1, University Rd., Tainan 70101, Taiwan, R.O.C.
Phone: +886-6-275-7575 #62382 E-mail: yksu@mail.ncku.edu.tw
[2] Advanced Optoelectronic Technology Center, National Cheng Kung University
No. 1, University Rd., Tainan 70101, Taiwan, R.O.C.
[3] Department of Electrical Engineering, Kun-Shan University
No. 949, Dawan Rd., Yongkang Dist., Tainan 710, Taiwan, R.O.C.
[4] Electronics and Optoelectronics Research Laboratories, Industrial Technology Research Institute
No. 195, Sec. 4, Chung Hsing Rd., Chutung, Hsinchu 31040, Taiwan, R.O.C.

1. Introduction

Developing the prospect of light-emitting diodes (LEDs) in the next generation microprojectors, higher radiation intensity and the directionality of extracted light will be the critical points. Rather than commercial projectors, microLED (μLED) array as projection imager is self-luminous and lower power consuming, hence it possesses higher luminous intensity and micromation for the handheld projector. In order to reduce the optical crosstalk and enhance the projection efficiency, further improvements of light extraction and directionality are required [1]. Photonic crystal (PhC) has been reported for improved light extraction efficiency (LEE) from GaN-based LEDs and for controlling the polarization properties of the extracted light [2-4]. However, there has been little investigation in ultrathin microcavity and microsized light-emitting diodes which are essential for microprojectors.

In this study, GaN-based microcavity LEDs (mcLEDs) which chip size is around tens of micrometer with two dimensional photonic crystals based on the near-Γ multi-diffractions are demonstrated. Rather than the highly-directional light extraction from pure Γ diffraction with single guided mode, the near-Γ multi-diffraction points of PhC are overlapped to equalize the far-field profile within a small extraction cone as shown in Fig. 1. This will result in the best light-collection efficiency with a ±15^{o} cone compared with previous pure Γ diffraction research [5].

2. Experiment

The wafers used in this experiment were grown by metal-organic chemical vapor deposition (MOCVD) with the emission peak of 450 nm. After growth, the epitaxial wafer was bonded onto another substrate and the original sapphire substrate was removed. The resulting structure was thinned down to a 3λ GaN effective cavity. PhCs with a square lattice of circular holes were then fabricated on the n-GaN surface with a lattice constant, a=370 nm and depth, t~80 nm. After the mesa definition, 30 x 30 μm^2, and passivation deposition by plasma-enhanced chemical vapor deposition (PECVD), a meshed Ti/Al/Ti/Au was deposited onto the n-GaN as the n-type contact layer. The resulting SEM images of the PhC microcavity LED is shown in Fig. 2(a). After the process, the dies were chipped and mounted on transistor outline (TO) package without epoxy encapsulation.

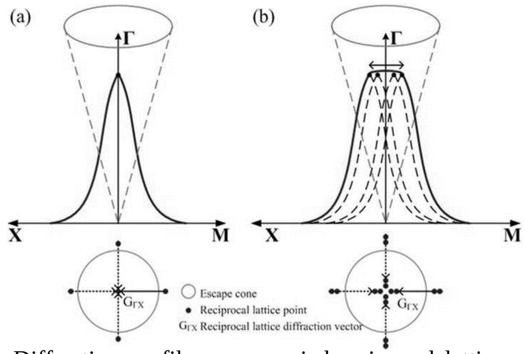

Fig. 1 Diffraction profile accompanied reciprocal lattice of PhC with (a) Γ- point and (b) near-Γ points.

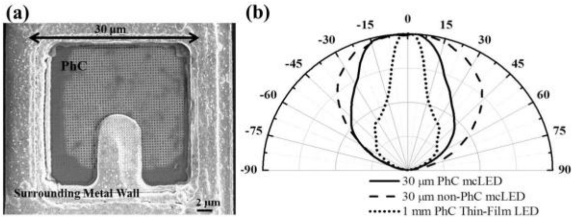

Fig. 2 (a) GaN-based 30 μm mcLED with 2D square lattice of circular PhC holes of a=370 nm, and t=80 nm PhCs, and (b) far-field emission distributions of devices as well as the prior study in deep-PhC (t=250 nm) thin-film LED with chip size as 1mm x 1mm.

3. Results and discussion

We measured the far-field emission distribution of the PhC mcLEDs to study the collimating properties and to assess how the waveguided light is diffracted by the PhC reciprocal wave vectors related to PhC. From the angular distribution radiation of mcLED with and without PhC measured under 20 mA, normalized with peak intensity, as shown in Fig. 2(b), the far-field pattern at half intensity of the non-PhC mcLED was 118^o that is close to the conventional Lambertian cone 120^o. The far-field angle at half intensity of the PhC mcLED was 92^o which was much less than the non-PhC device since the PhC enhances guided modes which will be diffracted by the reciprocal wave vectors and furthermore, the microcavity design enhances the interaction between PhCs and guided modes. We also compare the far-field property with the prior study [5] which demonstrated a deep-PhC pure Γ diffraction LED operating at normalized frequency (a/λ=0.82) and chip size of 1 x 1 mm, as shown in Fig. 2(b). The total light output power emitted into specific extraction cones can be calculated by integrating the intensity over the specific angles. Although the prior work presented a highly-directional emission pattern with the angle at half intensity as 30.7^o since deep PhC (t=250 nm) featured nearly a single guided mode, the light-collection efficiency within a ±15^o extraction cone, calculated as azimuthal etendue over total light output power was 10.2%. In comparison, the 30 x 30 μm^2 mcLED with PhC provided 10.8% within this cone. This result is much better than non-PhC mcLED of 6.57%. The light-collection enhancement of our near-Γ device is about 1.6 times the non-PhC device and the collection enhancement is better than the highly-directional device over the targeted extraction cone. These improvements are attributed to the near-Γ multi-beam diffractions associated with frequency (a/λ=0.84) of PhC. This would be proved through the angular-spectra- resolved EL measurement as shown in Fig. 3. The multi-beam diffractions equalized the light distribution within the ±15^o extraction cone, and therefore improved the light-collection efficiency compared with pure Γ single-beam diffraction of prior highly-directional device.

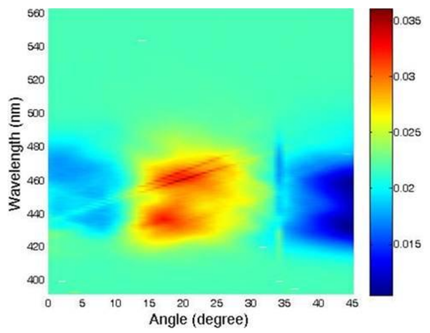

Fig. 3 Angular-resolved spectra without polarizer for 30 μm PhC mcLED.

The characteristics of the total absolute light output power-current-voltage (LIV) were measured by an integration sphere. The measured forward voltage for the PhC mcLEDs as shown in Fig. 4 slightly increased due to the etching damage on n-GaN and the worse current spreading of PhC holes, resulting in a little higher resistivity, nevertherless, the PhC mcLED showed an absolute light output power enhancement by 293%, compared with non-PhC mcLED under 15 mA due to the better light extraction of guided mode by periodic PhC.

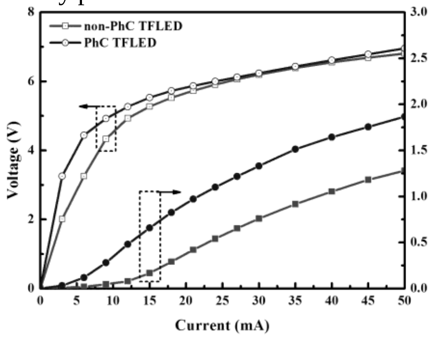

Fig. 4 The output power-current-voltage characteristics of mcLED with and without PhC.

4. Conclusion

A GaN-based mcLED with PhC multi-diffractions for highly light-collection efficiency has been demonstrated. At a driving current of 15 mA, the absolute light output power of the PhC mcLED was improved by 293% compared with the regular non-PhC mTFLED. The far-field measurements of PhC mcLED with near-Γ multi-diffractions showed a far-field angle at half intensity near ±46^o and presented a better light-collection efficiency of 10.79% within a ±15^o extraction cone improved over a prior highly-directional device (10.22%) with nearly single guided mode as well as over regular mcLED (6.57%). These results contribute to develop the prospect of LED microprojectors meeting a high luminance output under the etendue limitation.

Acknowledgements

The authors would like to thank the National Science Council and Bureau of Energy, Ministry of Economic Affairs of Taiwan, R.O.C. for the financial support under Contract No. NSC 99-2221-E-006-084-MY3, 100-2221-E-006-040-MY2 and 101-D0204-6, and the LED Lighting Research Center of NCKU for the assistance of device characterization. In addition, the authors also wish to thank the Technology Development Program, Ministry of Economic Affairs of Taiwan, R.O.C. for the financial support under Project No. B301AR1D10 and B351A41200 in ITRI.

References

[1] H.C. Lee, J.B. Park, J.W. Bae, P. T. T. Thuy, M.C. Yoo, and G.Y. Yeom, Solid-State Electron. **52** (2008) 1193.

[2] E. Matioli and C. Weisbuch, J. Phys. D: Appl. Phys. **43** (2010) 354005.

[3] C. F. Lai, J. Y. Chi, H. C. Kuo, C. H. Chao, H. T. Hsueh, J. F. T. Wang, and W. Y. Yeh, Opt. Express **16** (2008) 7285.

[4] Y. Xu, X. J. Chen, S. Lan, Q. F. Dai, Q. Guo, and L. J. Wu, Opt. Express **17** (2009) 4903.

[5] C. F. Lai, H. C. Kuo, P. Yu, T. C. Lu, C. H. Chao, H. H. Yen, and W. Y. Yeh, Appl. Phys. Lett. **97** (2010) 013108.