Effect of last barrier on efficiency improvement of blue InGaN/GaN light-emitting diodes

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***Abstract*-Effect of last barrier (LB) with different thicknesses and p-doping concentrations on efficiency improvement of blue InGaN/GaN multiple quantum well (MQW) light-emitting diodes (LEDs) is simulated by APSYS software. The simulation results show that thin LB has positive effect at low p-doping concentration while negative at high concentration and that p-doping is more effective for LEDs with thick LB to increase their efficiency.**

Ⅰ. INTRODUCTION

GaN-based multiple quantum well (MQW) light-emitting diodes (LEDs) are attracting great attention for applications in high-power and high-brightness solid-state lighting. Their radiative hardness properties [1] have promoted them to be very useful in space application [2]. However, the joule energy will reduce the life time and efficiency of LED due to the rising of junction temperature [3][4]. Moreover, it has been found that the efficiency of these LED devices is substantially reduced with increasing injection current [5][6]. This efficiency droop phenomenon has become a significant bottleneck to the development of high-power GaN-based LEDs. The physical mechanisms behind it have been proposed including Auger recombination [7], electron leakage [8] and poor hole injection efficiency [9], but are still under debate. Many methods have been used to improve the efficiency droop by decreasing the electron leakage and increasing the hole injection efficiency [10][11]12].

Due to the difficulty of hole injection from p-type layer into quantum wells (QWs), carriers tend to accumulate in the last QW next to the p-type layer leading to the dominant role of this well in the radiative recombination of GaN-based MQW LEDs [13][14]. This indicates that the last barrier (LB) plays an important role in the hole transport of this kind of devices. So p-doped [15] and thin [16] LB are used successfully to improve the hole transport and then the efficiency droop. However, the effect of the LB with different thicknesses and p-doping concentrations on efficiency improvement of GaN-based MQW LEDs has not been discussed in detail. In this paper, blue InGaN/GaN MQW LEDs with varying thickness and p-doping concentration for the LB are investigated numerically by APSYS simulation software [17]. The effect of the LB on the efficiency improvement of these LEDs is analyzed systematically.

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Ⅱ. THEORETICAL MODELS AND PARAMETERS

The APSYS simulation software is a finite-element based device simulator which self-consistently solves Poisson-Schrödinger equations, current continuity equations, heat transfer equations and hydrodynamic equations, including K·P models for MQW band structure, quantum tunneling model for heterojunction, heat flow model for self-heating, ray-tracing model for photon extraction, spontaneous and piezoelectric polarization models for built-in electric field, non-local QW transport model for carriers to directly fly over QWs without scattering, as well as Shockley-Read-Hall (SRH) recombination and Auger recombination of carriers.

In the simulation, the Auger recombination coefficient is set to be 2.0×10^{-30} cm^6s^{-1} [7]. The SRH lifetime within QWs is estimated to be 100 ns. The AlGaN band offset ratio is assumed to be 0.5 [18], The built-in interface charges are calculated by the methods developed by Fiorentini *et al.* [19], assuming 25% compensation by fixed defects and other interface charges.

Ⅲ. LED DEVICE STRUCTURE

The original blue InGaN/GaN MQW LED used as a reference consists of a 1.5-μm-thick GaN buffer layer, a 4-μm-thick n-type GaN:Si (3×10^{18} cm^{-3}), six periods of $In_{0.2}Ga_{0.8}N$(2 nm)/GaN(13 nm) MQW active regions, followed by a 20-nm-thick p-type $Al_{0.15}Ga_{0.85}N$:Mg (1×10^{18} cm^{-3}) EBL and a 0.2-μm-thick p-type GaN: Mg (1×10^{18} cm^{-3}) cap layer. The device geometry is 300 × 300 μm^2. Then the LB thickness was changed from 10 to 19 nm and the p-doping concentration in the LB was increased from 0 to 5 $\times10^{18}$ cm^{-3}.

Ⅳ. RESULTS AND DISCUSSIONS

Fig. 1 shows the calculated internal quantum efficiency (IQE) and output power of the LEDs with different LB thicknesses when the p-doping concentrations in LB are 0, 1 $\times10^{17}$ and 1 $\times10^{18}$ cm^{-3}. As shown in Figs. 1(a) and 1(d), good agreement between experimental data and simulated results is achieved for the original LED. Moreover, with the decease of LB thickness, the IQE and output power are increased due to the increase of the hole injection efficiency and decrease of electron leakage [16]. With the increase of p-doping concentration in LB as indicated in Figs. 1(b) and 1(e), the LED efficiency is still increased with the decrease of LB thickness. However, as presented in Figs. 1(c) and 1(f), when the p-doping concentration in LB is equal to 1 $\times10^{18}$ cm^{-3}, the LED efficiency decreases with the decrease of LB thickness. These results show that the positive effect of thin LB in helping

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to increase the hole injection is affected significantly by the p-doping concentration in it.

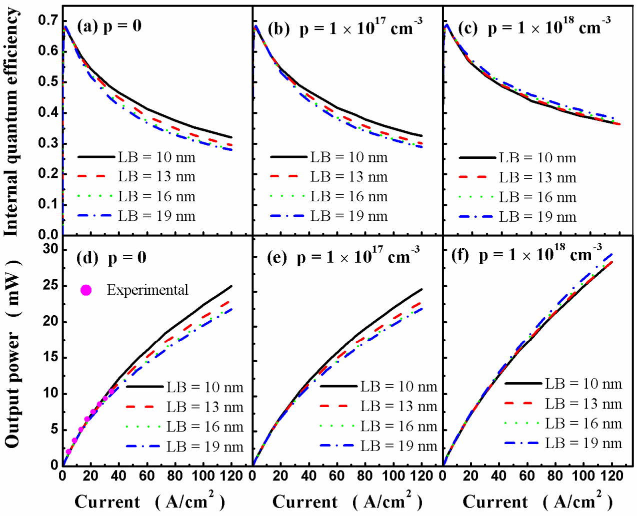

Fig. 1 Simulated IQE and output power for the LEDs with different LB thicknesses when the p-doping concentrations are 0, 1×10^{17} and 1×10^{18} cm^{-3} in LB

The simulated IQE and output power for the LEDs with different p-doping concentrations in LB when the thicknesses of LB are 10 and 19 nm are plotted in Fig. 2. It is apparent that the IQE and output power are all increased with the increase of p-doping concentration in LB regardless of the LB thickness since the increase of the hole injection efficiency [15]. But it also can be observed that the increase of the efficiency for the LED with thick LB is much faster than that for the LED with thin LB. This indicates that p-doping is more effective for the LEDs with thick LB to improve their efficiency droop.

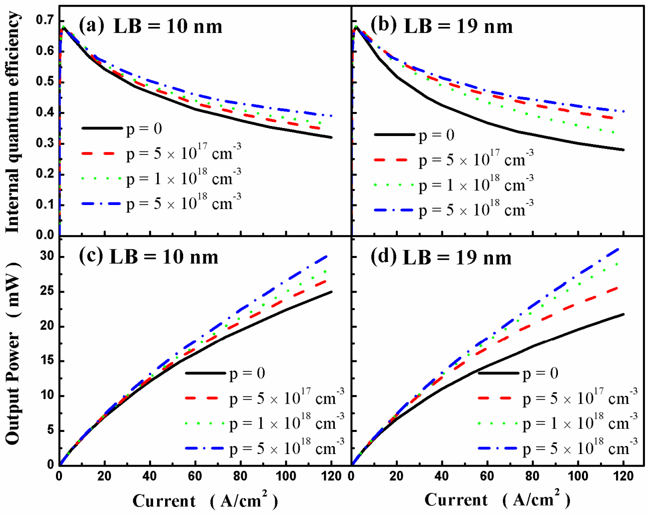

Fig. 2 Simulated IQE and output power for the LEDs with different p-doping concentrations in LB when the thicknesses of the LB are 10 and 19 nm

Fig. 3 illustrated the change of IQE as a function of p-doping concentration in LB for the LEDs with different LB thicknesses at 120 A/cm^2. As shown in Fig. 3, when the p-doping concentration in LB is less than 7×10^{17} cm^{-3}, thin LB plays positive role in the hole injection. But when it is greater than 1×10^{18} cm^{-3}, thick LB is more helpful to improve the efficiency droop of GaN-based LEDs than the thin one. It also can be found that when the p-doping concentration in LB is greater than 2×10^{18} cm^{-3}, the IQE tends to be saturated, which may be induced by the depletion of electrons.

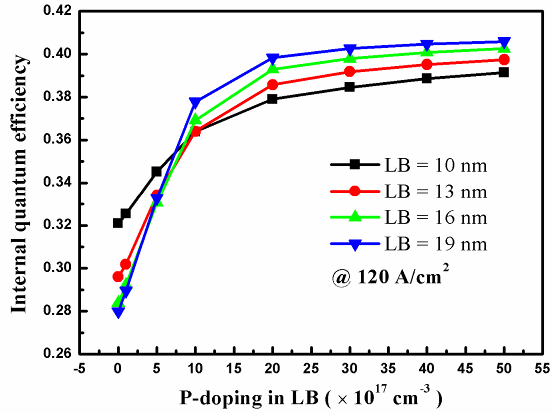

Fig. 3 IQE as a function of p-doping concentration in LB for the LEDs with different LB thicknesses at 120 A/cm^2

V. CONCLUSIONS

The effect of LB with different thicknesses and p-doping concentrations on the efficiency improvement of blue InGaN/GaN MQW LEDs has been investigated numerically. We found that thin LB is more beneficial to improve the efficiency droop at low p-doping concentration while at high p-doping concentration thick LB is much better, and that p-doping is more effective for the LEDs with thick LB to improve their efficiency. These results are very helpful for the design using LB to improve the efficiency droop of GaN-based MQW LEDs.

REFERENCES

[1] Y. L. Li, X. J. Wang, S. M. He, et al., J. Appl. Phys. **112**, 123515 (2012).
[2] W. Lu, T. Zhang, S. M. He, et al., Opt. Quant. Electron. **41**, 883 (2009).
[3] S. M. He, X. D. Luo, et al., Rev. Sci. Instrum. **82**, 123101 (2011).
[4] S. M. He, X. D. Luo, et al., Chin. Phys. Lett. **29**, 127802,(2012).
[5] T. Mukai, M. Yamada, et al., Jpn. J. Appl. Phys. Part 1 **38**, 3976 (1999).
[6] W. Sun, M. Shatalov, et al., Appl. Phys. Lett. **96**, 061102 (2010).
[7] Y. C. Shen, G. O. Mueller, et al., Appl. Phys. Lett. **91**, 141101 (2007).
[8] M. H. Kim, M. F. Schubert, et al., Appl. Phys. Lett. **91**, 183507 (2007).
[9] I. V. Rozhansky and D. A. Zakheim, Semiconductors **40**, 839 (2006).
[10] C. S. Xia, Z. M. S. Li, et al., J. Appl. Phys. **111**, 094503 (2012).
[11] C. H. Wang, C. C. Ke, et al., Appl. Phys. Lett. **97**, 261103 (2010).
[12] C. S. Xia, Z. M. S. Li, et al., Appl. Phys. Lett. **99**, 233501 (2011).
[13] A. David, M. J. Grundmann, et al., Appl. Phys. Lett. **92**, 053502 (2008).
[14] J. P. Liu, J.-H. Ryou, et al., Appl. Phys. Lett. **93**, 021102 (2008).
[15] Y. K. Kuo, M. C. Tsai, et al., IEEE J. Quantum Electron. **46**, 1214 (2010).
[16] S. H. Yen, et al., IEEE Photonics Technol. Lett. **22**, 1787 (2010)
[17] Crosslight Software Inc., Burnaby, Canada (http:// www. crosslight.com).
[18] J. Piprek and S. Li, Opt. Quant. Electron. **42**, 89 (2010).
[19] V. Fiorentini, F. Bernardini, et al., Appl. Phys. Lett. **80**, 1204 (2002).