Efficiency and droop improvement in a blue InGaN-based light emitting diode with a p-InGaN layer inserted in the GaN barriers

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The advantages of a blue InGaN-based light-emitting diode with a p-InGaN layer inserted in the GaN barriers is studied. The carrier concentration in the quantum well, radiative recombination rate in the active region, output power, and internal quantum efficiency are investigated. The simulation results show that the InGaN-based light-emitting diode with a p-InGaN layer inserted in the barriers has better performance over its conventional counterpart and the light emitting diode with p-GaN inserted in the barriers. The improvement is due to enhanced Mg acceptor activation and enhanced hole injection into the quantum wells.

Keywords: GaN-based light-emitting diodes, p-InGaN layers, Mg acceptor

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1. Introduction

InGaN light-emitting diodes (LEDs) have found tremendous applications in illumination, liquid crystal display (LCD) back-lighting devices, and projection displays. However, the LED efficiency usually reaches a maximum value at low current density and then droops with the current density further increasing, which is referred to as "efficiency droop". The efficiency droop is caused by a non-radiative carrier loss mechanism that becomes dominant as the injection current increases.[1] Electron leakage,[1–3] lack of hole injection,[4–7] carrier delocalization,[8,9] Auger recombination,[10,11] defects,[12] and junction heating[13] have been suggested as possible causes. Nevertheless, the physical origin of efficiency droop is still under research and some investigations have shown that insufficient hole injection to the quantum well (QW) is a critical factor causing poor optical characteristic and efficiency droop. When an LED is used for a high power application, the hole injection and electron current leakage become very important. A hole has a relatively high effective mass and therefore a very low mobility in a GaN-based device, which makes it difficult for holes to transport from a p-type layer to an active region. Furthermore, the sloped down electron blocking layer (EBL) is found to act as a potential barrier for hole transportation.[14] In contrast to the hole, electrons have a small effective mass and therefore high mobility. Electrons can overflow across quantum barriers (QBs) and EBL potential easily, which gives rise to insufficient electron blocking. Furthermore, the leakage current into the p-type region can recombine with holes, thus reducing the hole injection efficiency and the quantum efficiency.

Many methods have been proposed to increase the hole concentration in QWs. Among them, Kim *et al.*[15] proposed using p-type ZnO as the hole injection layer to enhance the hole concentration, Kuo *et al.*[16] have shown that a p-type last barrier can effectively increase hole injection efficiency. In our previous study, a p-type InGaN hole reservoir layer HRL was designed and incorporated into a GaN based LED to enhance hole injection efficiency and alleviate efficiency droop.[17] Recently, Han *et al.*[18] experimentally showed that the hole injection efficiency can be improved by inserting Mg-doped GaN between two undoped GaN layers. In the present study, we theoretically illustrate the effect of inserting a Mg-doped InGaN layer between two undoped GaN layers. The electrical and optical properties of the conventional and newly designed LED are investigated numerically with the APSYS simulation program, which was developed by Crosslight Software Inc. Most of the parameters used in this paper are the same as in Ref. [19]. Other material parameters of the semiconductors used in the simulation can be found in Ref. [20].

2. Structure and parameters

The InGaN-based blue LEDs were grown on a c-plane sapphire substrate. The conventional LED (denoted as structure A) consisted of a 2.0-μm thick undoped GaN layer and a 2.0-μm thick n-GaN layer (n-doping = 5×10^{18} cm^{-3}). The active region consisted of six 3-nm-thick $In_{0.16}Ga_{0.84}N$ QWs, separated by six 10-nm-thick undoped GaN QBs. On the top of the last QB was a 20-nm thick p-$Al_{0.1}Ga_{0.9}N$ (p-doping = 5×10^{17} cm^{-3}) EBL and a 170-nm thick p-GaN (p-doping = 1×10^{18} cm^{-3}) layer. The device geometry was designed as a

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rectangular shape of 300 μm × 300 μm. LED chips were fabricated using a conventional mesa structure method. Another LED structure (denoted as structure B) had a similar layer structure except for the undoped GaN barriers. In LED B, barrier layers were Mg-doped with a doping concentration of 5×10^{17} cm^{-3} in the center of the barrier layer. The Mg-doped layer was sandwiched between two undoped GaN layers to prevent Mg from diffusing into the well layer during the subsequent high-temperature growth of the p-AlGaN EBL. The thickness of the barrier layer composed of u-GaN/Mg-doped GaN/u-GaN was 2 nm/6 nm/2 nm. LED C had a similar structure to that of LED B, except for the Mg-doped GaN that was replaced by Mg-doped InGaN. Thus, the barrier layers can be depicted as u-GaN/ Mg-doped InGaN/ u-GaN. These structures are shown in Fig. 1 and Table 1.

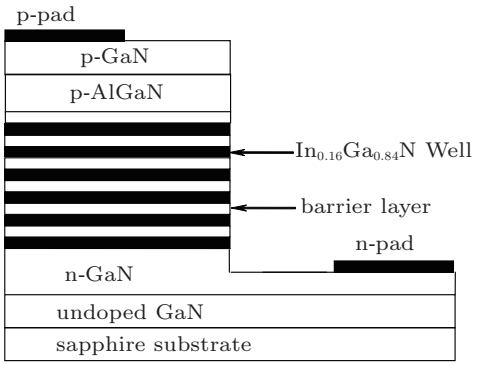


Fig. 1. Structures of the three LEDs.

Table 1. Barrier layers and thicknesses of the three structures.

Structures	Barrier layers	Thickness/nm
LED A	u-GaN	10
LED B	u-GaN/ p-GaN/ u-GaN	2/6/2
LED C	u-GaN/ p-InGaN/ u-GaN	2/6/2

The internal absorption within the LED device is set to be 500 m^{-1}, and the light extraction efficiency is assumed to be 0.78. The built-in interface charges due to spontaneous and piezoelectric polarization are calculated by using the methods developed by Fiorentini *et al.*[20] Theoretically, about 40% of the calculated interface charges are used to compensate for the fixed defects and other interface charges

3. Results and discussion

The hole concentrations of LEDs A, B, and C in the active region at 22 A/cm^2 (20 mA) are shown in Fig. 2. Usually, it is difficult for the holes to transport into the active region, owing to the relatively large effective mass and low mobility of holes in a blue InGaN LED. Under this circumstance, for a conventional InGaN LED, a large number of holes tend to accumulate in the QW next to the p-layer, as indicated in Fig. 2. It is also evident that by sandwiching a Mg-doped GaN in the barriers, the hole concentration in structure B is enhanced as compared with structure A. However, the activation energy of the Mg acceptor in GaN is as high as 166 meV and only a small portion of the Mg is ionized; the advantage of inserting a Mg-doped GaN layer is limited. According to Ref. [16], the activation energies of the Mg-doped group-III nitride-based semiconductors decrease with band-gap energy decreasing. The activation energy of Mg in $In_{0.05}GaN_{0.95}N$ is about 144 meV, which is much smaller than that in GaN.

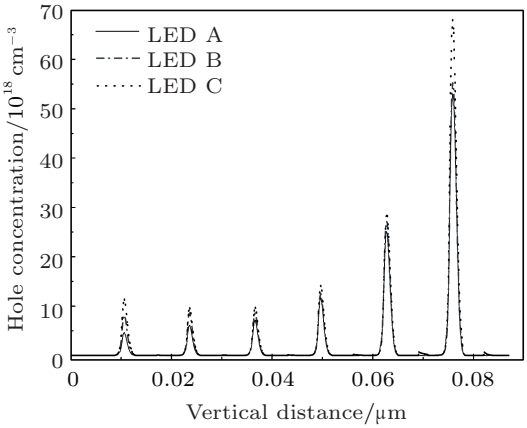


Fig. 2. Hole concentrations of the three LEDs at 20 mA.

Furthermore, due to the lattice mismatch between GaN and p-InGaN, there are strong polarization field in the p-InGaN. The strain-induced piezoelectric field and the spontaneous polarization field in the p-InGaN lead to the formation of a two-dimensional hole gas (2DHG).[21,22] As a result, the percentage of ionized Mg is greatly increased. On the other hand, as is well known, the valence band discontinuity within the GaN-InGaN-GaN barriers creates periodic oscillation of the valence band edge, while the built-in electric fields due to a spontaneous and piezoelectric polarization effect strengthen the oscillation. The periodic oscillation leads to spatial separation of free holes and ionized acceptors, and results in the enhancement of the ionization of the acceptors.[23,24] Thus, a larger proportion of Mg acceptors can be ionized in InGaN. In LED C, the hole concentration is greatly enhanced. The total hole concentration in LED C is increased by about 16.4% compared with LED B, and 17.22% compared with LED A.

Figure 3 shows the corresponding radiative recombination rates. Note that for LED A, the radiative recombination emanates mainly from the QW near the p-side layer because of the nonuniform distribution of holes as indicated in Fig. 2. For structures B and C, the hole concentration in the active region is enhanced, which in turn results in the increase of the radiative recombination rate. Our calculation indicates that the total radiative recombination rates inside the QWs of structure C at 20 mA are improved by a factor of 1.2 and 1.14 compared with those of structures A and B.

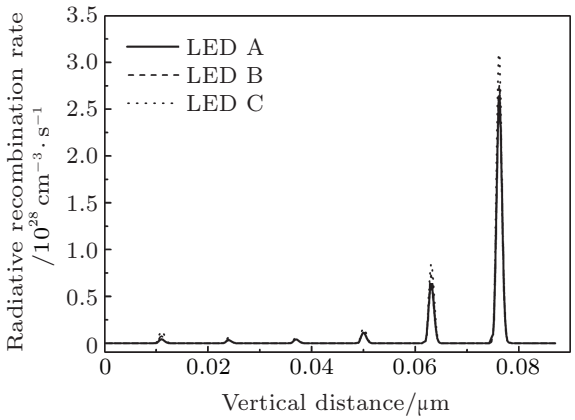


Fig. 3. Calculated radiative recombination rates of the three structures at 20 mA.

As shown in Fig. 4, the electron current of LED C in the p-type region is greatly reduced compared with those in LEDs A and B. This is due to the increased hole injection into QWs in LED C, more electrons can recombine with holes in the active region, thus the electron leakage into the p-type region is reduced. The escaped electrons from the MQW active region can recombine with holes in the p-type region, thereby lowering the LED efficiency. This reveals that the electron leakage is one of the dominant mechanisms that result in efficiency droop. For the LED with p-type InGaN inserted in the GaN barriers, hole injection can be enhanced and furthermore, the electron leakage out of the active region can be reduced.

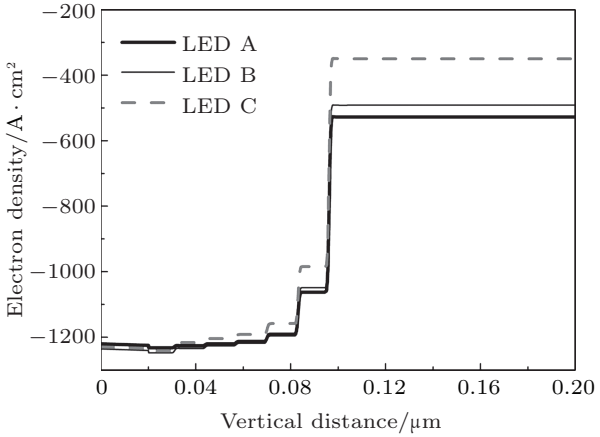


Fig. 4. Electron currents through the three LED structures at 20 mA.

Due to the improved hole injection, the superior performance of LED C is anticipated, compared with those of LEDs A and B. Figure 5 shows the IQE and light output power each as a function of current for the two LED structures under study, which indicates that LED C has better lighting efficiency, especially at high current.

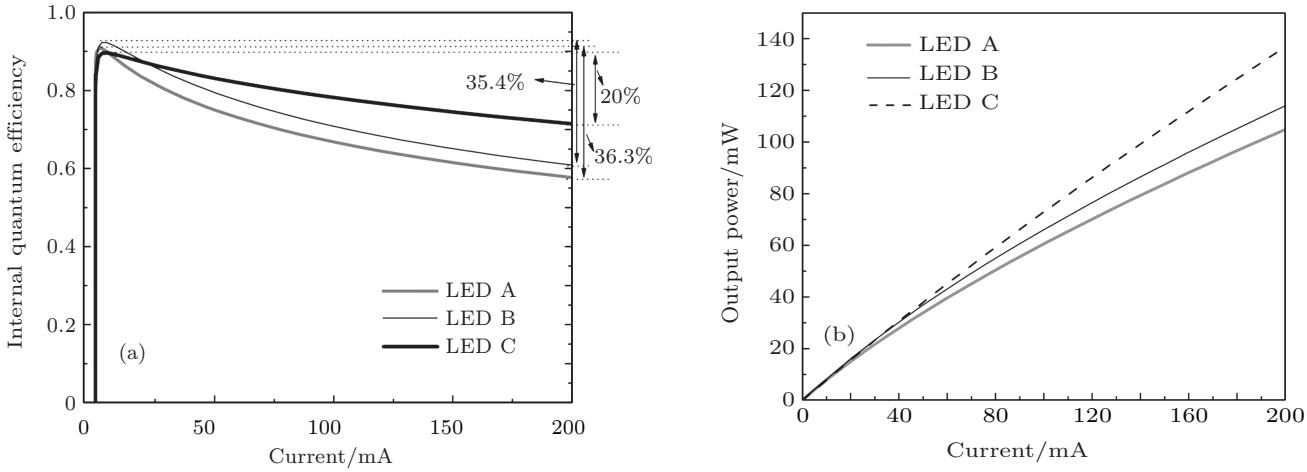


Fig. 5. (a) IQE and (b) light output power as functions of the current for the three LED structures.

4. Conclusions

In this paper, InGaN-based LEDs with p-doped barriers have been numerically investigated by using the APSYS simulation software. The simulation results show that the LEDs with p-InGaN sandwiched in the barriers have better performances than the LEDs without or with p-doped GaN barriers. This improvement can be attributed to the reduced activation energy of the Mg acceptor in InGaN and the enhanced hole injection into the QWs.

References

[1] Kim M H, Schubert M F, Dai Q, Kim J K, Schubert E F, Piprek J and Park Y 2007 *Appl. Phys. Lett.* **91** 183507

[2] Schubert M F, Chhajed S, Kim J K, Schubert E, Koleske F, Crawford M H, Lee S R, Fischer A J, Thaler G and Banas M A 2007 *Appl.Phys. Lett.* **91** 231114

[3] Schubert M F, Xu J, Kim J K, Schubert E F, Kim M H, Yoon S, Lee S M, Sone C, Sakong T and Park Y 2008 *Appl. Phys. Lett.* **93** 041102

[4] Pope I A, Smowton P M, Blood P, Thomson J D, Kappers M J and Humphreys C J 2003 *Appl. Phys. Lett.* **82** 2755

[5] Xie J, Ni X, Fan Q, Shimada R, Ozgur U and Morkoc H 2008 *Appl. Phys. Lett.* **93** 121107

[6] Rozhansky I V and Zakheim D A 2006 *Phys. Status Solidi C* **3** 2160

[7] Rozhansky I V and Zakheim D A 2007 *Phys. Status Solidi A* **204** 227

[8] Kim A Y, Götz W, Steigerwald D A, Wierer J J, Gardner N F, Sun J, Stockman S A, Martin P S, Krames M R, Kern R S and Steranka F M 2001 *Phys. Status Solidi A* **188** 15
[9] Chichibu S F, Azuhata T, Sugiyama M, Kitamura T, Washida Y, Okumurac H, Nakanwashi H, Sota T and Mukai T 2001 *J. Vac. Sci. Technol. B* **19** 2177
[10] Shen Y C, Müller G O, Watanabe S, Gardner N F, Munkholm A and Krames M R 2007 *Appl. Phys. Lett.* **91** 141101
[11] Gardner N F, Müller G O, Shen Y C, Chen G, Watanabe S, Götz W and Krames M R 2007 *Appl. Phys. Lett.* **91** 243506
[12] Monemar B and Sernelius E B 2007 *Appl. Phys. Lett.* **91** 181103
[13] Efremov A A, Bochkwereva N I, Gorbunov R I, Larinovich D A, Rebane Y T, Tarkhin D V and Shreter Y G 2006 *Semiconductors* **40** 605
[14] Han S H, Lee D Y, Lee S J, Cho C Y, Kwon M K, Lee S P, Noh D Y, Kim D J, Kim Y C and Park S J 2009 *Appl. Phys. Lett.* **94** 231123
[15] Kim B J, Ryu Y R, Lee T S and White H W 2009 *Appl. Phys. Lett.* **94** 103506
[16] Kuo Y K, Tsai M C, Yen S H, Hsu T C and Shen Y J 2010 *IEEE J. Quantum Electron.* **46** 8
[17] Lu T P, Li S T, Zhang K, Liu C, Xu Y Q, Tong J H, Wu L J, Wang H L, Yang X D, Yin Y A, Xiao G W and Zhou Y G 2012 *Appl. Phys. Lett.* **100** 141106
[18] Han S H, Cho C Y, Lee S J, Park T Y, Kim T H, Park S H, Kang S W, Kim J W, Kim Y C and Park S J 2010 *Appl. Phys. Lett.* **96** 051113
[19] Kumakura K, Makimoto T and Kobayashi N 2000 *Jpn. J. Appl. Phys.* **39** 337
[20] Fiorentini V, Bernardini F and Ambacher O 2002 *Appl. Phys. Lett.* **80** 1204
[21] Waldron E L, Graff J W and Schubert E F 2001 *Appl. Phys. Lett.* **79** 2737
[22] Gessmann T, Li Y L, Waldron E L, Graff J W, Schubert E F and Sheu J K 2002 *Appl. Phys. Lett.* **80** 986
[23] Zheng Q H, Yin Y A, Zhu L H, Huang J, Li X Y and Liu B L 2009 *Appl. Phys. Lett.* **94** 222104
[24] Waldron E L, Graff J W and Schubert E F 2001 *Appl. Phys. Lett.* **79** 2737