Efficiency enhancement of an InGaN light-emitting diode with a p-AlGaN/GaN superlattice last quantum barrier*

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(Received 6 March 2013; revised manuscript received 12 July 2013)

In this study, the efficiency droop of an InGaN light-emitting diode (LED) is reduced significantly by using a p-AlGaN/GaN superlattice last quantum barrier. The reduction in efficiency droop is mainly caused by the decrease of electron current leakage and the increase of hole injection efficiency, which is revealed by investigating the light currents, internal quantum efficiencies, energy band diagrams, carrier concentrations, carrier current densities, and radiative recombination efficiencies of three LED structures with the advanced physical model of semiconductor device (APSYS).

Keywords: light-emitting diodes, p-AlGaN/GaN superlattice, last quantum barrier, efficiency droop

PACS: 85.60.Jb, 73.61.Ey, 78.60.Fi, 87.15.A– **DOI:** 10.1088/1674-1056/22/11/118504

1. Introduction

In recent years, high-brightness InGaN light-emitting diodes (LEDs) have made great progress in applications, including general illumination, liquid-crystal display back lighting, full-color display, etc.[1–3] Nevertheless, many applications, like solid-state lighting, still have not been popularized due to the severe efficiency droop, i.e., the quantum efficiency monotonically decreases as the injection current increases. There are many reports about the possible physical mechanism of the efficiency droop, such as current injection efficiency,[4,5] electron leakage,[6] polarization effect,[7] current crowding effect of localized states,[8] carrier delocalization,[9] the quantum confined Stark effect (QCSE),[10] and the Auger recombination.[11] Among the numerous reports, it has been identified by Wang *et al.*[12] that the electron leakage as well as inefficient injection and transportation of holes is the main reason for the efficiency droop. The hole in a GaN based material has a relatively large effective mass and thus a very low mobility. Moreover, the electron blocking layer (EBL) in the conventional LED is also considered to act as a potential barrier for holes. So, it is very difficult for holes to inject into and transport in the active region. As for the electrons, because of their opposite characters to those of holes and the insufficient blocking efficiency of the EBL under polarization fields, they can transport easily in the active region and even spill over the EBL to the p-type region. What is worse, those leaked electrons recombine with holes in the p-type region and therefore the hole injection efficiency is further reduced. This is a common problem in the conventional LEDs. A large number of methods[13–15] have been proposed to restrain the efficiency droop. Especially, in these years, many people reduced the efficiency droop of InGaN light-emitting diode by adjusting the last quantum barrier.[16,17] The idea of p-doping in the last epitaxial barrier, based on the conventional LED structures, was proposed to improve the optical performance of InGaN LEDs by Kuo *et al.*[18] Recently, however, the research by Liu *et al.*[19] showed that a p-doped last quantum barrier cannot effectively reduce the electron current leakage or increase the hole injection efficiency. Therefore, in order to further reduce the efficiency droop, an InGaN light-emitting diode using p-AlGaN/GaN superlattice as the last quantum barrier is put forward and a numerical analysis is also carried out in this paper. The physical and optical properties of the InGaN LEDs are studied by analysing the light current, internal quantum efficiency, energy band diagram, carrier concentration, carrier current density, and radiative recombination efficiency.

2. Structure and parameters

The structure of the conventional LED (denoted as the original structure) used in this paper as a reference is grown on a *c*-plane sapphire substrate, followed by a 50-nm-thick

*Project supported by the National Natural Science Foundation of China (Grant No. 61176043), the Special Funds for Provincial Strategic and Emerging Industries Projects of Guangdong Province, China (Grant Nos. 2010A081002005, 2011A081301003, and 2012A080304016), the First Phase of Construction of Guangdong Research Institute of Semiconductor Lighting Industrial Technology, China (Grant No. 2010A081001001), the High Efficiency LED Epitaxy and Chip Structure and Key Technology for Industrialization, China (Grant No. 2012A080302002), and the Youth Funding of South China Normal University (Grant No. 2012KJ018).

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undoped GaN buffer layer and a 4.5-μm-thick n-GaN layer (n-doping = 5×10^{18} cm^{-3}). The active region consists of five 2.2-nm-thick $In_{0.11}Ga_{0.9}N$ quantum wells (QWs) sandwiched between six 15-nm-thick GaN barriers. A 20-nm-thick p-$Al_{0.15}Ga_{0.85}N$ EBL (p-doping = 5×10^{17} cm^{-3}) and a 0.17-μm-thick p-GaN cap layer (p-doping = 8×10^{17} cm^{-3}) are on the top of the active region. The device is designed to have a rectangular geometry of 300 μm × 300 μm. The other two LED structures have an identical layer structure to that of the original structure except for the last quantum barrier. In order to avoid the diffusion of magnesium into the QWs during crystal growth, the situation in which the p-doped last quantum barrier (LQB) accounts for 14 nm in the 15 nm-thick layer is also considered. Therefore, the last quantum barrier of one LED structure is replaced by a 1 nm undoped GaN layer and a 14 nm p-doped GaN layer (p-doping = 5×10^{17} cm^{-3}) (denoted as structure A); and the last quantum barrier of the other LED structure is replaced by a 1 nm undoped GaN layer and a 7-period p-$Al_{0.15}Ga_{0.85}N$/GaN (1 nm/1 nm, p-doping = 5×10^{17} cm^{-3}) superlattice (denoted as structure B), respectively. The schematic diagrams of the three structures are depicted in Fig. 1.

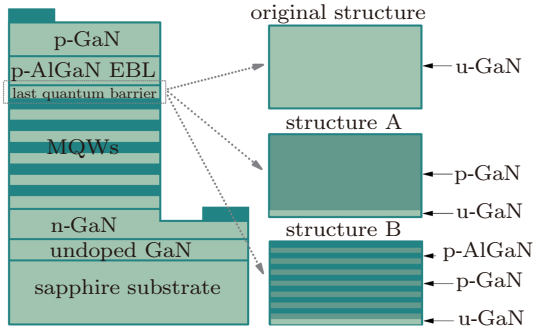


Fig. 1. (color online) Schematic diagram of InGaN LEDs with u-GaN LQB (original structure), p-GaN LQB (structure A), and p-AlGaN/GaN superlattice LQB (structure B).

The optical and electrical properties of the LEDs are investigated numerically with the advanced physical model of semiconductor devices (APSYS),[20] a simulation software developed by the Crosslight Software Inc. The APSYS software is capable of dealing with the physical properties of LEDs by solving the Poisson's equation, current continuity equations, carrier transport equation, quantum mechanical wave equation, and photon rate equation. The charge densities screened by the injected charge carriers are determined self-consistently at different levels of current injection. In this paper, in order to correspond to the experimental measurement, the interface charge density is assumed to be 50% of the calculated value. The charge densities shielded by the injected charge carriers are determined self-consistently at different levels of current injection. To simplify the simulation, the operating temperature and the internal absorption within the LED device are set to be 300 K and 2000 m^{-1}, respectively. In this simulation, the Auger recombination, the Shockley–Read–Hall recombination lifetime, and the radiative recombination coefficient are assumed to be 3.0×10^{-31} cm^6/s, 100 ns, and 2.0×10^{-11} cm^3/s, respectively. Most of the parameters used in this paper are similar to those employed in Ref. [21]. The other material parameters of the devices used in the simulation can be found in Ref. [18].

3. Simulation results and discussion

The output power and the internal quantum efficiency (IQE) versus the injection current for the three structures are shown in Fig. 2. It can be seen that the output powers of the two new designed LEDs are much higher than that of the original LED, and the output power is remarkably enhanced when the p-GaN last quantum barrier is replaced by the p-AlGaN/GaN superlattice (SL) last quantum barrier. The output power of structure B increases almost linearly over the whole injection current range, which could be attributed to the reduced efficiency droop as depicted in

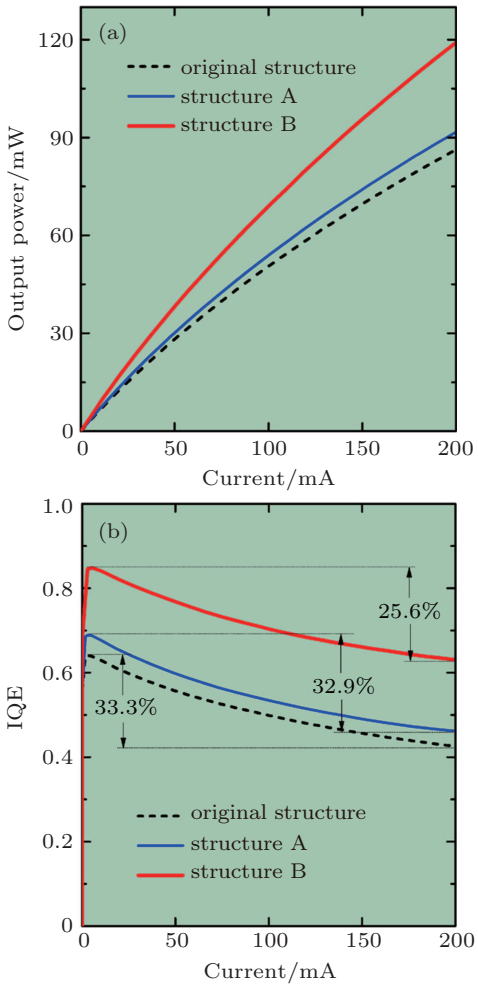


Fig. 2. (color online) (a) Light output power and (b) IQE versus injection current for the three structures.

Fig. 2(b). While for the original structure and structure A, the output powers increase sublinearly. Correspondingly, in Fig. 2(b), the IQE of the LED with p-AlGaN/GaN SL LQB is improved remarkably compared with that of the other two structures. At 200 mA, the IQEs of structure A and structure B are about 7.1% and 24.5% higher than that of the original LED, respectively. In the whole injection current range, the efficiency droop of the original LED is 33.3%, which is mainly caused by severe electron leakage and poor hole injection efficiency. While for the LED with p-AlGaN/GaN SL LQB, the degradation of the IQE is only about 25.6%, which can be explained by analyzing the following energy diagrams of the three structures.

The energy band diagrams and electrostatic fields of the three structures at 200 mA are plotted in Fig. 3. In the original structure, the energy band of the last quantum barrier is pulled down seriously by a strong electrostatic field shown in Fig. 3(d), which is caused by the compressive strain. As shown in Fig. 3(a), the effective potential height for electrons in the conduction band of the AlGaN EBL (269 meV) is much smaller than that of the other two structures, and the effective potential height for holes in the valence band at the same part (308 meV) is much larger than that of the other two structures. Meantime, there is no significant change in the band bending of the LED with p-GaN LQB. However, on the one hand, the lattice mismatch between the GaN layer and the AlGaN layer in the p-AlGaN/GaN superlattice of structure B can generate a strong piezoelectric polarization field, as shown in Fig. 3(f). This piezoelectric polarization field along with the spontaneous polarization field pulls down the GaN energy band and pulls up the AlGaN energy band, thus the overall energy band of the p-AlGaN/GaN superlattice last barrier is hardly bent. As a result, the effective potential barrier height for electrons in the conduction band of the EBL is enhanced and the electron leakage can be effectively suppressed. In the mean time, because of the decreased band bending effect caused by the polarization field, the EBL as a potential barrier for holes is reduced, which is beneficial to the injection of holes into the active region. On the other hand, the p-type doping last barrier is helpful for holes to transport across the EBL into the QWs near the n-type layer. In addition, the AlGaN/GaN superlattice in the actual LED can produce a valence-band edge oscillation by employing alloys at different valence-band edge positions. This can increase the overall hole concentration by allowing deep acceptors in the barriers to ionize into the valence band of the neighboring narrow-bandgap material and will partially overcome the low doping efficiency of deep acceptors.[22] Therefore, as can be verified in Fig. 4(c), structure B has the lowest electron leakage and the biggest hole concentration in the QWs due to the largest effective potential barrier height for electrons (314 meV) and the smallest effective potential barrier height for holes (273 meV).

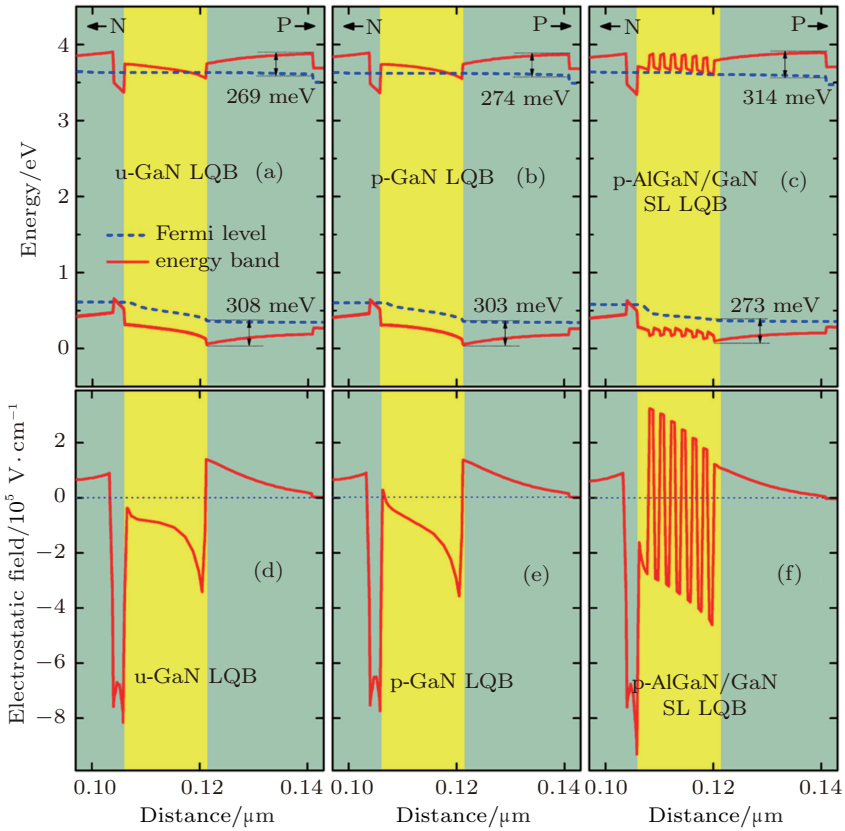


Fig. 3. (color online) (a)–(c) Energy band diagrams and (d)–(f) electrostatic fields of the three structures at 200 mA.

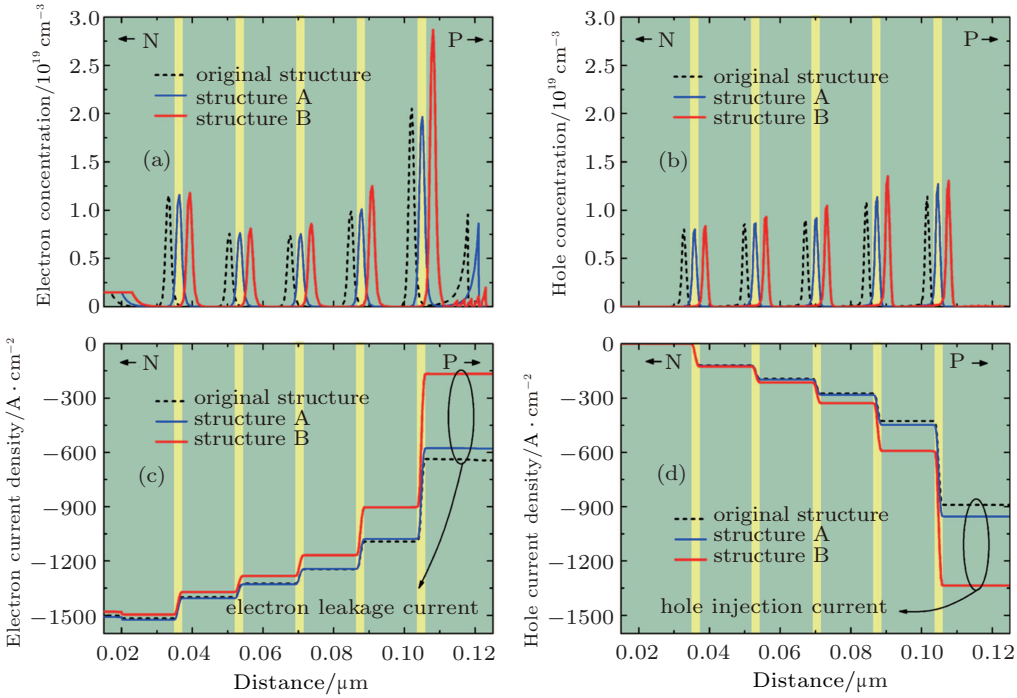


Fig. 4. (color online) (a), (b) Carrier concentrations and (c), (d) carrier current densities of the three structures at 200 mA.

Figure 4 shows the carrier concentrations and carrier current densities of the three structures at 200 mA. Note that the horizontal positions for the original structure and structure B are shifted slightly for better observation. It can be seen in Fig. 4(a) that the electron concentrations in these three structures increase gradually from n-type region to p-type region and tend to accumulate in the QWs close to the p-layers owing to the small effective mass and high mobility of electrons in group III nitride-based materials. Obviously, the electron concentration is remarkably improved in the active region of structure B, especially in the last few wells, which is caused by the greatest effective confinement for electrons in the three structures. Correspondingly, in Fig. 4(c), the electron current density, which is exhausted by holes transported from p-type region, decreases gradually, and the electrons overflow from the active region into the p-type region, which is viewed as the leakage current as seen in Fig. 4(a) in the last quantum barrier. As can be seen in the last quantum of Figs. 4(a) and 4(c), the LED with p-AlGaN/GaN SL LQB has the smallest leakage current, owing to the largest effective potential barrier height for electrons. Similarly, in Fig. 4(b), the hole concentration is lower than the electron concentration and decreases gradually from the QW near p-side to that near n-side because of the high effective mass and low mobility of holes in nitride based materials. We can find that the hole concentration in the active region of structure B is the largest among the three structures because the hole injection efficiency is effectively improved, as depicted in Fig. 4(d).

Figure 5 shows the radiative recombination rates of the three structures at 200 mA. The horizontal positions of the LEDs with undoped GaN LQB and p-AlGaN/GaN SL LQB have been shifted slightly for better observation. According to the above analyses, more electrons can stay in the active region to recombine with holes with the increase of the carrier concentration. As a result, more QWs can contribute to the radiative recombination and the efficiency droop is reduced, especially in the case with a big forward driver current. Therefore, in structure B, the radiative recombination rate is higher than that in the other two structures owing to the enhancement of electron confinement and hole injection efficiency.

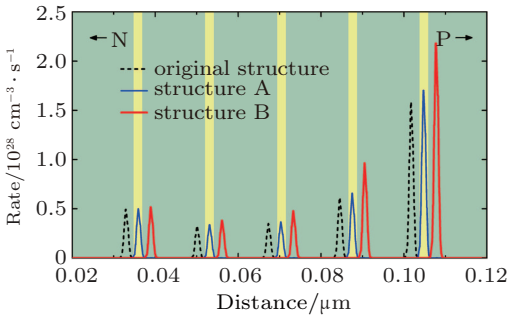


Fig. 5. (color online) Radiative recombination rates of the three structures at 200 mA.

4. Conclusion

To reduce the efficiency droop of InGaN LEDs, a newly designed LED is proposed with a p-AlGaN/GaN superlattice last quantum barrier. The simulation indicates that the optical and electrical properties of the proposed structure are markedly enhanced due to the increase of hole injection, the decrease of electron leakage, and the bigger radiative recombination of the QWs.

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