A GaN–AlGaN–InGaN last quantum barrier in an InGaN/GaN multiple-quantum-well blue LED*

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The advantages of a GaN–AlGaN–InGaN last quantum barrier (LQB) in an InGaN-based blue light-emitting diode are analyzed via numerical simulation. We found an improved light output power, lower current leakage, higher recombination rate, and less efficiency droop compared with conventional GaN LQBs. These improvements in the electrical and optical characteristics are attributed mainly to the specially designed GaN–AlGaN–InGaN LQB, which enhances electron confinement and improves hole injection efficiency.

Keywords: GaN-based light-emitting diode, efficiency droop, multilayer barrier, last quantum barrier

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1. Introduction

Light-emitting diodes (LEDs) have attracted much attention and have been investigated widely due to their energy-saving capability, high efficiency, small size, long lifetime, and high efficiency. These solid light sources have great application prospects in areas such as general illumination, the back lighting of liquid-crystal displays, and full-color displays.[1–4] Even though the luminous emission efficiency of LEDs has improved markedly in recent years, it remains a challenging issue, especially in that the quantum efficiency actually decreases with increasing current above tens of milliamps — a phenomenon called efficiency droop. This is particularly bad for high-brightness applications. Many theories have been proposed to explain this unique phenomenon, such as poor hole injection,[5,6] electron leakage,[7,8] carrier delocalization,[9] the polarization effect,[10] and Auger recombination.[11,12] Among these factors, the poor hole injection efficiency and insufficient electron confinement are believed to play key roles.[13–15]

Many researchers have reported that most carriers tend to be confined in the last quantum well (QW) next to the p-type layer, and more particularly, that this well plays a significant role in the radiative recombination of GaN-based multiple quantum well (MQW) LEDs.[16,17] This is mainly due to the difficulty in injecting holes from the p-type region into the QWs. Many ways to improve the droop have been proposed to avoid this problem, such as LEDs with a thin or p-type GaN last quantum barrier,[18,19] or a short-period superlattice (SPSL) structure.[20] In this paper, we propose a design with a 3 nm GaN/4 nm $Al_{0.05}Ga_{0.85}N$/3 nm $In_{0.05}Ga_{0.85}N$ multilayer last quantum barrier (LQB) to enhance the emission efficiency and reduce the efficiency droop of InGaN/GaN MQW blue LEDs at high injection currents. The optical and electrical properties of the conventional and designed LEDs are investigated numerically with the APSYS simulation program, which was developed by Crosslight Software, Inc.[21]

2. Structure and parameters

The two structures are shown in Fig. 1. The conventional blue InGaN/GaN LED used in this paper as a reference (denoted as structure A) is grown on a *c*-plane sapphire substrate, followed by a 4 μm-thick n-GaN layer (n-doping = 2×10^{18} cm^{-3}). The active region consists of six 2.5 nm-thick $In_{0.15}Ga_{0.85}$ QWs sandwiched by seven 10 nm-thick GaN barriers. On top of the active region are a 20 nm-thick $Al_{0.15}Ga_{0.85}N$ layer (p-doping = 5×10^{17} cm^{-3}) and a 0.2 μm-thick p-GaN cap layer (p-doping = 5×10^{17} cm^{-3}). The device geometry is designed as a rectangular 300 μm×300 μm shape. The other epitaxial LED structure (denoted as structure B) has a similar layer structure, except that the conventional 10 nm-thick GaN last quantum barrier is replaced by a multilayer barrier: 3 nm GaN/4 nm $Al_{0.05}Ga_{0.85}N$/3 nm $In_{0.05}Ga_{0.85}N$.

The band-gap energies of the InGaN and AlGaN ternary alloys can be expressed as[22]

$$E_g(In_xGa_{1-x}N) = xE_g(InN)+(1-x)E_g(GaN) - 1.4x(1-x), \quad (1)$$

$$E_g(Al_xGa_{1-x}N) = xE_g(AlN)+(1-x)E_g(GaN) - 0.7x(1-x), \quad (2)$$

where E_g(AlN), E_g(InN), and E_g(GaN) are the band-gap

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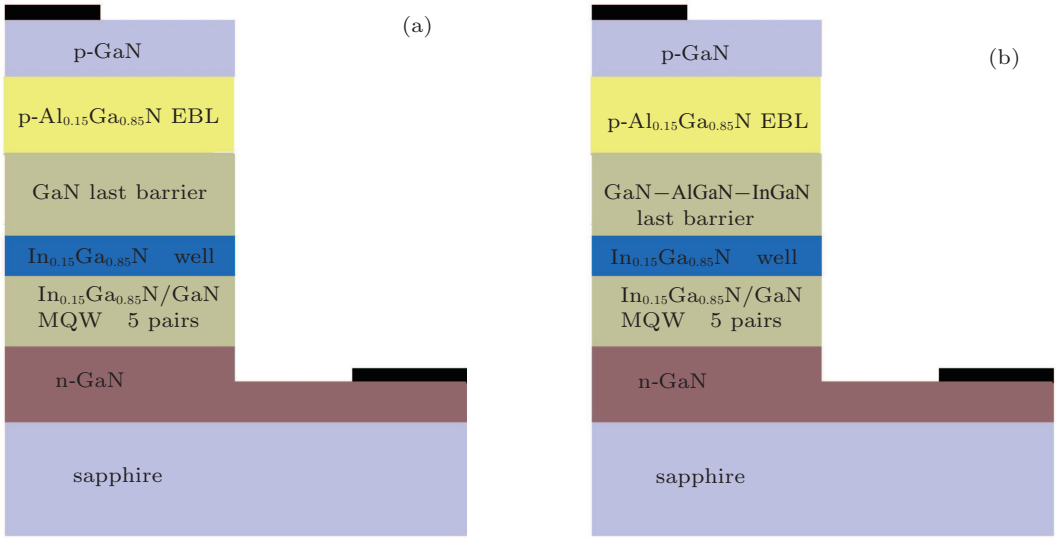


Fig. 1. (color online) Schematic diagrams of GaN-based LED structures with (a) GaN LQB or (b) GaN–AlGaN–InGaN multilayer barriers.

energies of AlN, InN, and GaN, respectively, with values of 6.25 V, 0.78 V, and 3.4 V. The operating temperature is assumed to be 300 K and the internal absorption within the LED device is set to be 500 m^{-1}, with the light extraction efficiency assumed to be 0.78.[23] Most of the parameters in this paper are the same as those in Ref. [24]. The other material parameters of the devices used in the simulations can be found in Ref. [25].

3. Results and discussion

As we can see in Fig. 2, the electrostatic fields are much stronger in the active region of the GaN LQB than in the GaN–AlGaN–InGaN LQB, especially for the last QW, which is near the p-side. The strong electrostatic fields in the active region lead to band bending and poor overlap of the hole and electron wave functions, and hence reduce the radiative recombination rate. Thus, the GaN–AlGaN–InGaN multilayer barrier has an obvious advantage over a conventional GaN barrier in radiative recombination due to the smaller electrostatic fields in the active region.

As is shown in Fig. 3, the piezoelectric and spontaneous polarization fields pull down the energy band at the last GaN quantum barrier and AlGaN electron blocking layer (EBL) interface due to the lattice mismatch. As a result, the effective potential barrier height for electrons in the conduction band of the EBL is reduced and the electron leakage cannot be effectively suppressed. Moreover, due to the poor electron confinement, many electrons overflow to the p-side and dramatically decrease the hole injection efficiency. In addition, the apparent sharp dip in the valence band in the energy band of the InGaN layer forms a tunneling effect, which strengthens the hole mobility to the active region and increases the hole concentration, although the effective potential barrier height for holes is almost the same. Figure 3 shows that the effective potential barrier height for electrons in the conduction band of structure A (668 meV) is much smaller than the value for structure B (907 meV). As a result, it can be seen in Fig. 4 that the LED of structure B has much lower electron leakage.

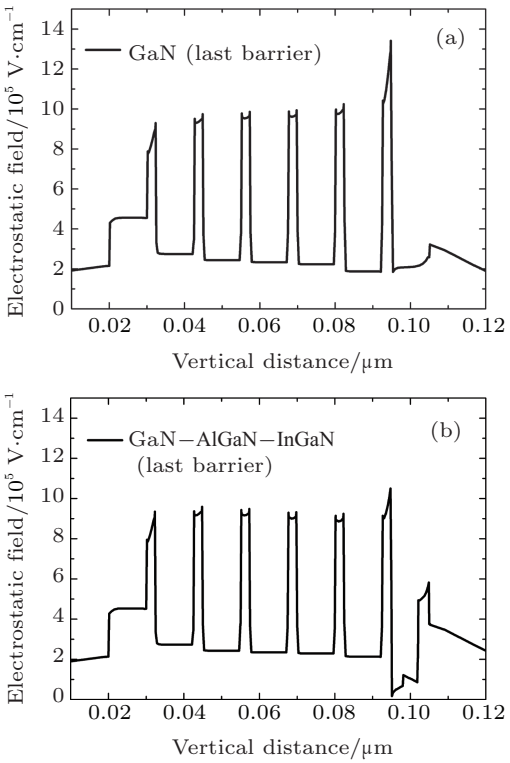


Fig. 2. Simulated electrostatic fields of structures A (a) and B (b) at 200 A/cm^2.

Figure 5 shows the carrier concentrations near the active regions of both types of LED structure under study at 200 A/cm^2. The result indicates that in the proposed structure B with the GaN–AlGaN–InGaN multilayer barrier, more electrons and holes are transported into the active

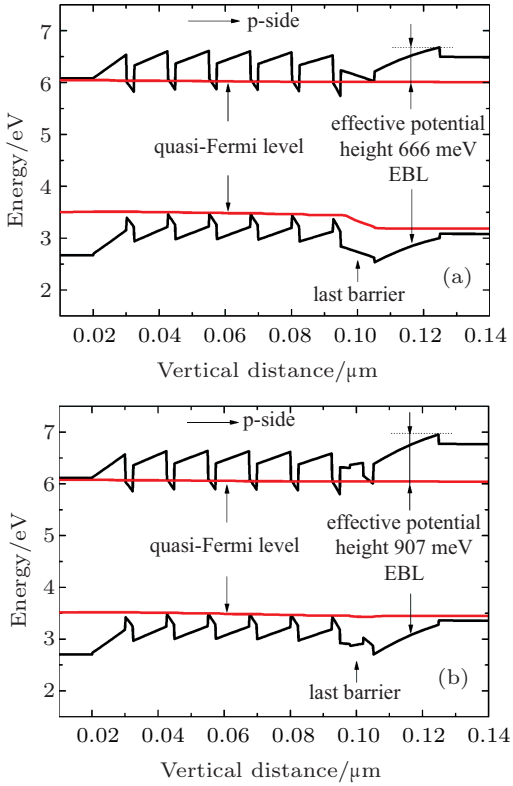


Fig. 3. (color online) Energy band diagrams of structures A (a) and B (b) at 200 A/cm^2.

region and contribute to the radiative recombination as shown in Fig. 6. The enhancement in electron concentration is due to the effective potential barrier height for electrons, which leads to a reduction in the electron leakage current. In addition, more holes can survive and be transported into the active region under lower electron leakage current, and as a result, the concentration of holes in the active regions is significantly improved.

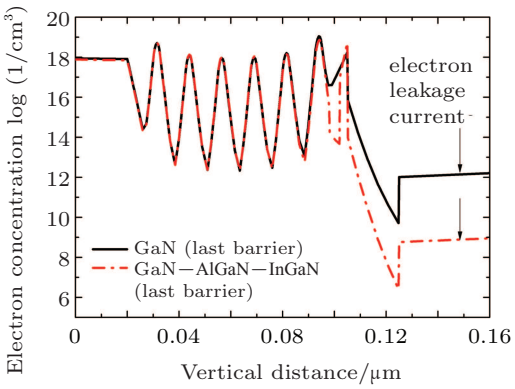


Fig. 4. (color online) The electron concentrations of structures A and B at 200 A/cm^2.

Considering the advantages illustrated above, the performance of the multilayer LQB LED is expected to be superior to that of the conventional InGaN/GaN LED. As is shown in Fig. 7, structure B shows a much higher emission efficiency and greater output power, and its efficiency droop ratio can be reduced down to 6.8% at 200 A/cm^2 compared with the value of 20.1% for structure A.

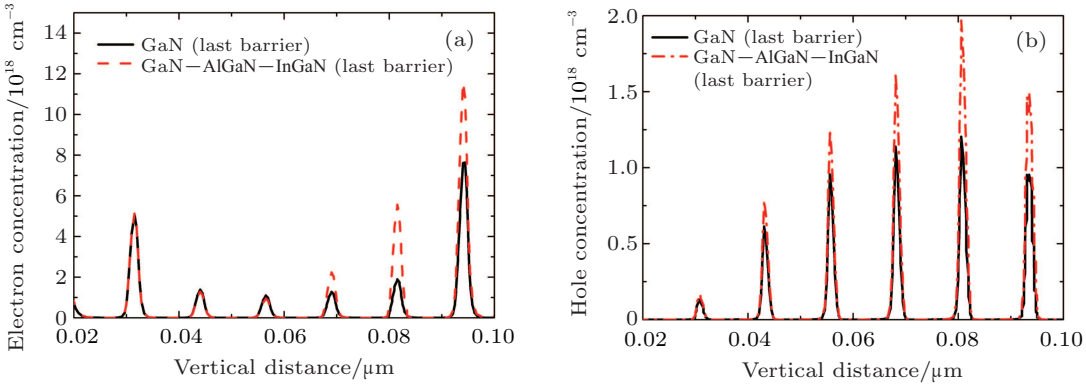


Fig. 5. (color online) The electron and hole concentration distributions in the MQWs of structures A (a) and B (b) at 200 A/cm^2.

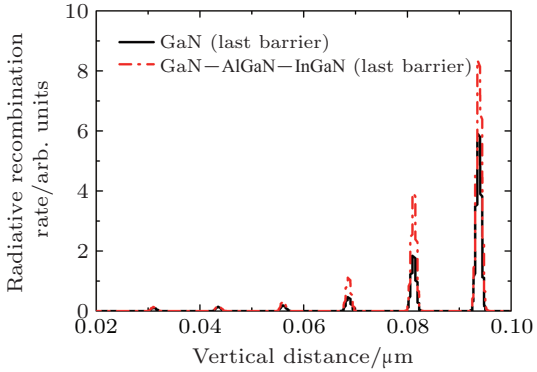


Fig. 6. (color online) The radiative recombination rates in the MQWs of structures A and B at 200 A/cm^2.

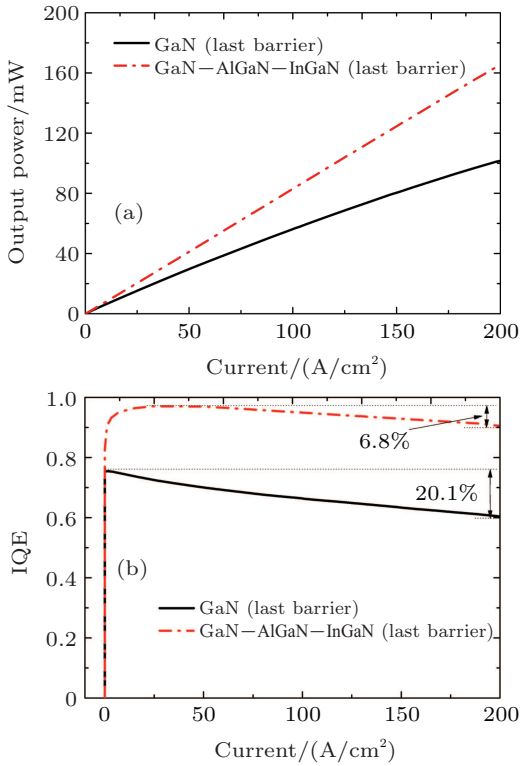


Fig. 7. (color online) The output power (a) and IQE (b) of structures A and B at 200 A/cm^2.

4. Conclusions

In conclusion, blue InGaN/GaN MQW LEDs with a conventional GaN LQB or multilayer LQB were investigated numerically using APSYS simulation software. When the last GaN barrier is replaced by a GaN-$Al_{0.05}Ga_{0.85}N$-$In_{0.05}Ga_{0.85}N$ multilayer barrier, a deep potential well is formed, which confines more electrons and increases the number of holes tunneling into the LQB from the p-type region. This effect provides the LEDs with a higher light output power, lower current leakage, higher emission efficiency, and less efficiency droop.

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