Improvement of characteristics of an InGaN light-emitting diode by using a staggered AlGaN electron-blocking layer*

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The optical and physical properties of an InGaN light-emitting diode (LED) with a specific design of a staggered AlGaN electron-blocking layer (EBL) are investigated numerically in detail. The electrostatic field distribution, energy band, carrier concentration, electroluminescence (EL) intensity, internal quantum efficiency (IQE), and the output power are simulated. The results reveal that this specific design has a remarkable improvement in optical performance compared with the design of a conventional LED. The lower electron leakage current, higher hole injection efficiency, and consequently mitigated efficiency droop are achieved. The significant decrease of electrostatic field at the interface between the last barrier and the EBL of the LED could be one of the main reasons for these improvements.

Keywords: electron-blocking layer, light-emitting diodes, efficiency droop

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1. Introduction

Light-emitting diodes (LEDs) are investigated widely and deeply due to their great application prospect in lighting, backlighting of liquid crystal display, full colour display,[1–5] etc. The adjustability of In composition in InGaN materials makes the InGaN-based LED radiation wavelength range cover the full visible light region and part of the ultraviolet light region. However, the strong electrostatic fields which are generated by the piezoelectric polarization and spontaneous polarization around the InGaN quantum well (QW) active region and the electron-blocking layer (EBL) of the LED lead to the serious downward band bending problem.[6] It causes severe electron leakage current and low hole injection efficiency. Meanwhile, a conventional AlGaN layer used as an EBL cannot prevent the electrons from spilling over from the p layer effectively and even acts as a potential barrier for holes. As a result, the issue of internal quantum efficiency (IQE) droop cannot be improved effectively. Recently, various LED structures have been suggested to improve the confinement of carriers and enhance the optical performance, such as the p-doped last barrier,[7] the staggered QWs or delta-QWs,[8,9] the InAlN or the polarization-doped p-type AlGaN EBL,[10,11] the InGaN, AlGaN or InAlGaN barriers,[12–14] graded barrier,[15] etc.

In the present paper, a specific design of the EBL with a staggered AlGaN layer in an InGaN-based LED is investigated. The mechanisms of carrier transportation, the electrostatic fields distribution, and the radiative recombination rate are also discussed.

2. Structure and parameters

The conventional LED is used as a reference in this paper, and the schematic (structure A) is shown in Fig. 1. The epitaxial material is grown on a c-plane sapphire substrate with metal-organic chemical vapour deposition (MOCVD), followed by depositing a 50-nm undoped GaN nucleation layer, and then a 4.5-μm n-type GaN layer (n doping is 5×10^{18} cm^{-3}) in sequence. The active region consists of four-pairs of undoped $In_{0.1}Ga_{0.9}N$/GaN multiple quantum wells (MQWs) with four 2.2-nm wells and 15-nm barriers. On the top of the active region are a 0.03-μm p-type $Al_{0.18}Ga_{0.82}N$ EBL and a 0.2-μm p-type GaN cap layer (p doping is 7×10^{17} cm^{-3}). The area of the device geometry is 300×300 μm^2. For the improvement of the hole injection and the performance of the LED, an epitaxial structure (structure B) shown in Fig. 1 is designed, which is the same as structure A except that the conventional $Al_{0.18}Ga_{0.82}N$ EBL is replaced by a staggered $Al_xGa_{1-x}N$ structure. This staggered EBL contains three step-graded layers, and the Al mole content values of layers x are set to be 0.04, 0.09, and 0.18 sequentially. The thickness of each step-graded AlGaN layer is 0.01 μm so that the total thickness of the designed EBL is the same as that of the conventional EBL.

The physical and optical properties of the LED are investigated numerically with the advanced physical models of semiconductor devices (APSYS) simulation software.[16] In the simulation, the light extraction efficiency is assumed to be 0.78, and the band offset ratio is assumed to be 0.7/0.3.[17]

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Note that the surface charges could be screened due to the defects inside the device and their quantity obtained from the experimental measurement is usually smaller than those obtained from theoretical calculation for InGaN materials.[18] 40 percent of the calculated surface charge density is assumed in our simulation to be close to the experimental result. The epitaxial material parameters are chosen to be the same as those in Ref. [19]. The other simulation parameters are set to be the same as those in Ref. [20].

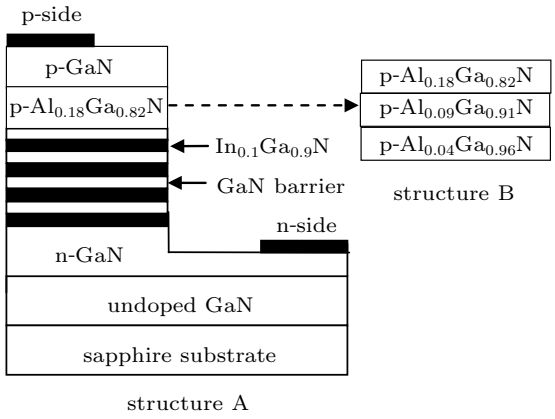


Fig. 1. Schematics of conventional LED (structure A) and our designed LED structure with staggered AlGaN EBL (structure B).

3. Results and discussion

Figure 2 illustrates the electrostatic fields which are generated by the piezoelectric polarization and spontaneous polarization around the active region and the EBL of the LEDs. Note that the horizontal positions in the plots are appropriately adjusted only for easy comparison. It can be seen that the electrostatic field at the interface between the last GaN barrier and the EBL in the conventional LED (structure A) is quite large. The strong piezoelectric polarization effect appears due to the serious lattice mismatch between the last GaN barrier and the AlGaN EBL, and the lattice mismatch becomes even more serious with the increase of Al mole composition in AlGaN material. The strong electrostatic field at the interface between the last barrier and the EBL can cause the downward band bending and the ineffectiveness of the EBL. This will deteriorate the optical performance of the conventional LED. However, when the staggered AlGaN layer is used as an EBL in an LED (structure B), the electrostatic field (short dot line) is much lower than that of the conventional EBL (solid line) at the interface between the last barrier and the EBL denoted as a rectangular box (short dash dot line) in the figure. The band bending is expected to be mitigated with the specific design.

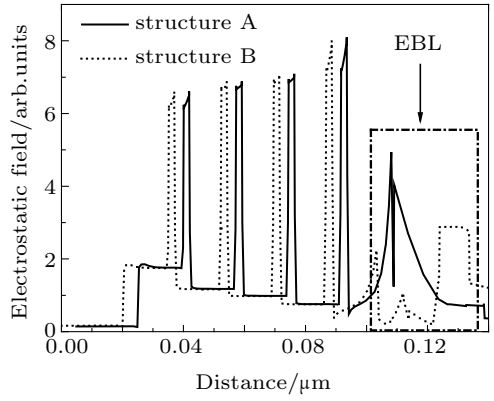


Fig. 2. Electrostatic fields of LEDs with the conventional EBL and the staggered AlGaN EBL at 150 mA. Note that the horizontal positions in the plots are appropriately adjusted only for the sake of easy comparison.

In the conventional InGaN-based LED, the strong polarization field is usually generated at the interface between the last barrier and the EBL due to the large lattice mismatch between the GaN material and the AlGaN material. The strong polarization field will seriously pull down the conduction band, and hence lead to a serious band bending problem. As shown in Fig. 3(a), the severe band bending of the conduction band makes the effective barrier height for electrons (311 meV) of the AlGaN EBL reduce significantly, and fails to confine the carriers. Moreover, as reported in Ref. [21], the conventional EBL also acts as a high potential barrier for holes because of the strong electrostatic field, which can block hole injection from the p layer dramatically. The effective potential height for holes (594 meV) is extremely high and leads to a very low efficiency of hole injection, as shown in Fig. 3(a). However, when using the staggered AlGaN layer as an EBL, the strong polarization field between the last barrier and the EBL has a great decrease. The smaller polarization field will mitigate the severe band bending, and will also raise the effective potential height for electrons (414 meV) and reduce the effective potential height for holes (318 meV), as shown in Fig. 3(b). Hence, the efficiency of hole injection from the p layer is enhanced, and the electron leakage current is reduced in our specific design compared with that in the conventional design.

Figure 4 shows the carrier concentration distributions of LEDs with conventional EBL and staggered AlGaN EBL at 150-mA injection current. It can be seen that the electron leakage current in the conventional EBL LED is two orders of magnitude higher than that of our specific design. Because of the lower effective potential height for electrons in the conventional design, more electrons spill over from the p layer, which causes the electron leakage current. While in the specific design, the effective potential height for electrons is higher, thus the electrons can be confined in the active region and the electron leakage current can be suppressed to a lower level. Comparing the hole concentrations in these two designs, it is found that the average hole concentration in the specific design is two orders of magnitude larger than that in the conventional one. That means that the specific design with a staggered AlGaN EBL can enhance the efficiency of hole injection due to the lower effective potential height for holes.

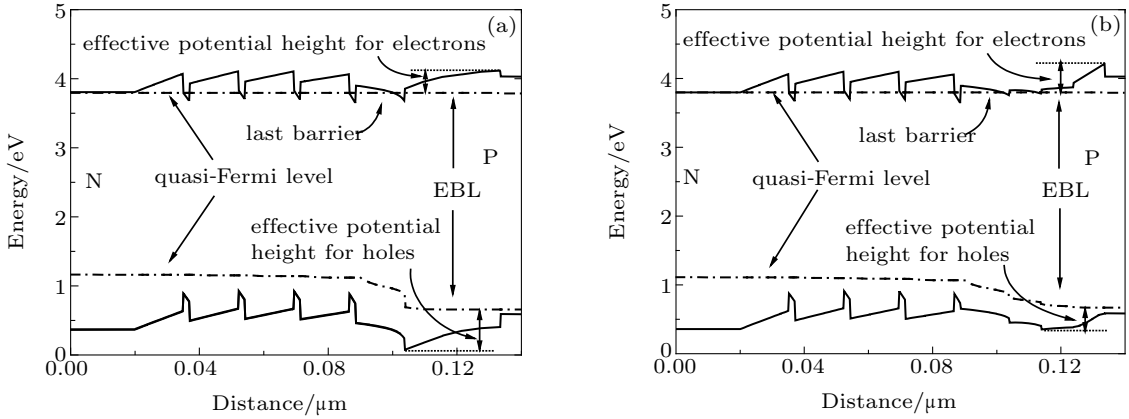


Fig. 3. Energy band diagrams of LEDs with (a) conventional EBL and (b) step-graded AlGaN EBL at 150 mA.

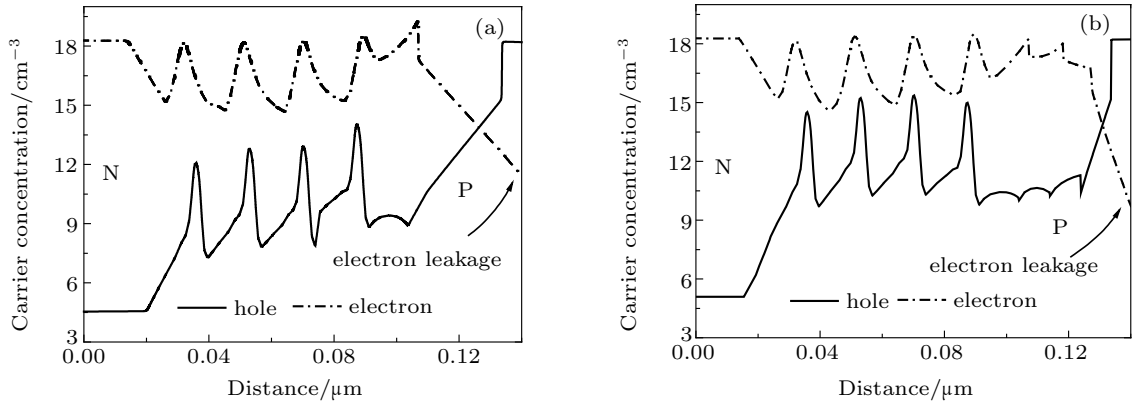


Fig. 4. Carrier concentration distributions of LEDs with (a) conventional EBL and (b) step-graded AlGaN EBL at 150 mA.

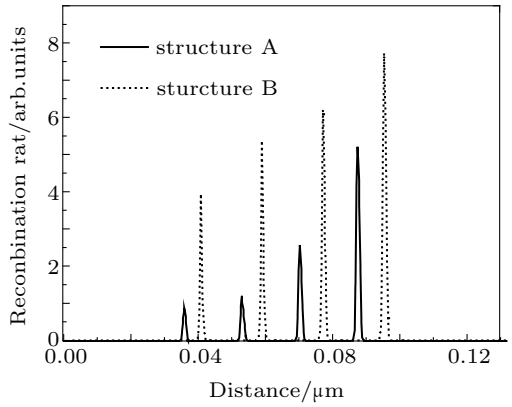


Fig. 5. The radiative recombination rates of two structures near the active region at 150 mA. Note that the horizontal positions in the plots are appropriately adjusted only for the sake of easy comparison.

Figure 5 shows the radiative recombination rates around the active region in two LED structures at 150-mA injection current. It is obvious that the radiative recombination rate is enhanced remarkably in structure B with the staggered AlGaN EBL. Because of the higher effective potential height for electrons in structure B (see Fig. 3), more electrons can be confined in the active region and participate in the recombination with holes. The lower effective potential height for holes also allows more holes to be injected into the active region. It makes the radiative recombination rate in structure B much greater than in structure A.

Figure 6 shows the optical properties of two LED structures, i.e., electroluminescence (EL) spectra, IQEs, and output powers. The spectrum intensity of structure B is almost twice as strong as that of structure A, as shown in Fig. 6(a). The better radiative recombination rate in structure B prominently enhances the luminescence of the LED. From the IQE curves in Fig. 6(b), we can see that efficiency droop appears in both structures with the increase of injection current. However, structure B has a slight efficiency droop of 18.9% compared with the 66.9% droop in structure A, and the efficiency droop is improved obviously when the staggered AlGaN structure is used as an EBL. It is shown that the output power of structure B keeps the increasing trend and strong intensity even at the large injection current situation, while the increase of output power in structure A is slow and the intensity is small under the same condition. It shows that a remarkable improvement of output power in the LED can be realized by using structure B.

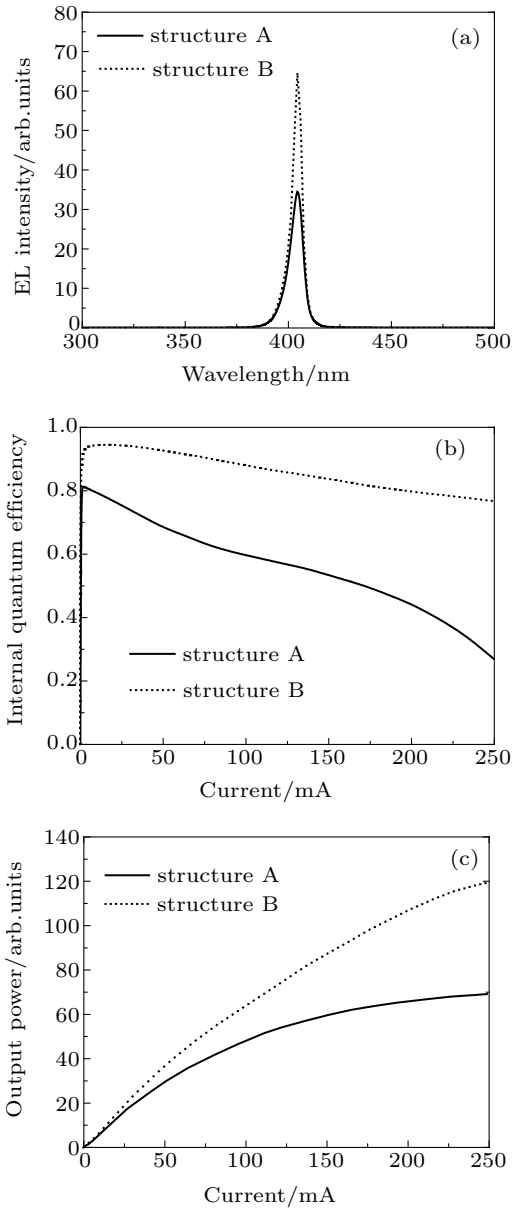


Fig. 6. (a) Spectra at 150 mA, (b) internal quantum efficiency, and (c) output power versus injection current of the LED with the conventional EBL and step-graded AlGaN EBL.

4. Conclusions

In the present paper, the optical and physical properties of the LEDs with a conventional EBL and a staggered AlGaN EBL are investigated numerically. The staggered AlGaN EBL LED performs better than the conventional one. The electrostatic field between the last barrier and the EBL can be significantly reduced in the LED. Stronger spectrum intensity, higher IQE and output power can be realized with the new structure. The efficiency droop at the large injection current is also markedly improved. The physical mechanism behind all of these improvements could be the enhancement of electron confinement and the promotion of the hole injection due to the staggered AlGaN EBL structure.

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