The advantage of blue InGaN multiple quantum wells light-emitting diodes with p-AlInN electron blocking layer*

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InGaN based light-emitting diodes (LEDs) with different electron blocking layers have been numerically investigated using the APSYS simulation software. It is found that the structure with a p-AlInN electron blocking layer showes improved light output power, lower current leakage, and smaller efficiency droop. Based on numerical simulation and analysis, these improvements of the electrical and optical characteristics are mainly attributed to the efficient electron blocking in the InGaN/GaN multiple quantum wells (MQWs).

Keywords: GaN-based light-emitting diodes, electron blocking layer, AlInN

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1. Introduction

InGaN/GaN based high-brightness light-emitting diodes (LEDs) have attracted much attention because of their applications in signage, back lighting, and general illumination. The phenomenon referred to as the efficiency droop is that the quantum efficiency monotonically decreases as the injection current increases. The efficiency droop is a severe problem for further applications of the high power GaN based light emitting diodes. There are many reports about the mechanism of the efficiency droop. Mechanisms, such as electron leakage,[1,2] the Auger recombination,[3] junction heating,[4] polarization field,[1,2] filling of localized states,[5] injection efficiency,[6,7] dislocation density,[8] and quantum confined stark effect (QCSE),[9] have been discussed. Much work has been done to alleviate the severe problem. Recently, Choi's experimental results showed that an LED with its lattice matched to the $In_{0.18}Al_{0.82}N$ electron blocking layer (EBL) could give superior light output power and superior electroluminescence (EL) intensity compared to the conventional LED.[10] For blue InGaN LEDs, the carrier injection in the active region and the electron leakage in the p-type layer may be the key issues.

2. Structure and parameters

In this paper, the conventional InGaN/GaN multiple quantum wells (MQWs) LEDs with p-AlGaN EBLs and the newly designed LEDs with lattice matched p-$Al_{0.82}In_{0.18}N$ EBLs are investigated numerically with the APSYS simulation program, which is developed by the Crosslight Software Inc.[11] The optical and the electrical properties are discussed. The blue InGaN based LED was grown on a *c*-plane sapphire substrate. The structure 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 2.8 nm-thick $In_{0.16}Ga_{0.84}N$ quantum wells (QWs) separated by six 10 nm-thick GaN barriers. On the top of the last quantum barrier (QB), there was a 20 nm-thick p-$Al_{0.1}Ga_{0.9}N$ (p doping = 5×10^{17} cm^{-3}) EBL or a 20 nm-thick lattice matched p-$Al_{0.82}In_{0.18}N$ (p doping = 5×10^{17} cm^{-3}) EBL. A 170 nm-thick p-GaN (p doping = 1×10^{18} cm^{-3}) was deposited at last. The device geometry was designed to be a 300 μm× 300 μm square. The device structure is shown in Fig. 1.

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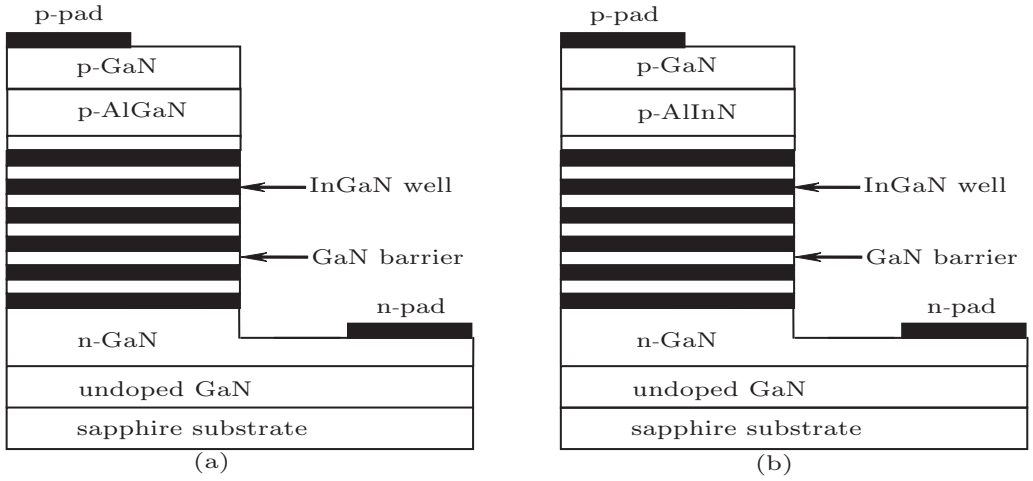


Fig. 1. Schematic diagrams of GaN-based LED structures with (a) a p-AlGaN EBL and (b) a p-AlInN EBL.

The band gaps of InGaN, AlInN, and AlGaN ternary alloys can be expressed as[12]

$$E_{\rm g}({\rm In}_x{\rm Ga}_{1-x}{\rm N}) = x \cdot E_{\rm g}({\rm InN}) + (1-x) \cdot E_{\rm g}({\rm GaN}) - 1.4x \cdot (1-x), \quad (1)$$

$$E_{\rm g}({\rm Al}_x{\rm In}_{1-x}{\rm N}) = x \cdot E_{\rm g}({\rm AlN}) + (1-x) \cdot E_{\rm g}({\rm InN}) - 3.4x \cdot (1-x), \quad (2)$$

$$E_{\rm g}({\rm Al}_x{\rm Ga}_{1-x}{\rm N}) = x \cdot E_{\rm g}({\rm AlN}) + (1-x) \cdot E_{\rm g}({\rm GaN}) - 0.7x \cdot (1-x), \quad (3)$$

where $E_{\rm g}$(InN), $E_{\rm g}$(AlN), and $E_{\rm g}$(GaN) are the band gaps of InN, AlN, and GaN with values of 0.78 eV, 6.25 eV, and 3.51 eV, respectively.[12] The internal absorption within the LED device is assumed to be 500 $\rm m^{-1}$, and the operating temperature is assumed to be 300 K. To simplify the simulation, the light extraction efficiency is assumed to be 0.78. Other material parameters of the semiconductors used in the simulation can be found in Ref. [13].

3. Results and discussion

The simulated light–current ($L-I$) performance curves of the two samples are plotted in Fig. 2. It can be seen that the performance difference between the two structures is very small at low injection current. With the increase in injection current, the performance difference between the two LEDs enlarges. The output power of the p-AlInN LED increases linearly with the increasing forward current. For the p-AlGaN LED, however, the output power only slowly increases. The light output power of the p-AlInN LED is about twice as large as that of the p-AlGaN LED at 200 mA.

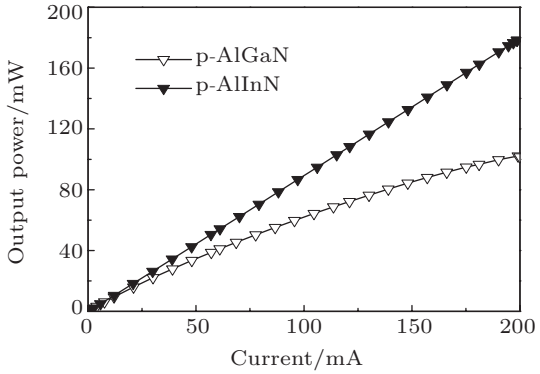


Fig. 2. Simulated L–I characteristics of the two samples.

In order to explain the above phenomenon, the energy band diagram of the p-AlGaN LED is plotted in Fig. 3(a). The polarization field induced sloped triangular barriers will hinder the transportation of electrons and cause the conduction band on the n-side to be higher than that on the p-side, which is similar to Park's results[1,2] and thus results in a large electron leakage current. Electrons in GaN based materials have a relatively smaller effective mass and therefore have a very high mobility compared to holes. Electrons can overflow across the p-AlGaN electron blocking layer potential very easily, which indicates insufficient electron blocking. The enlarged conduction band near the p-AlGaN is showed in Fig. 3(b). Due to the polarization field induced sloped triangular barriers, the barrier height of the p-AlGaN is about 36 meV, and the electrons can easily cross the potential, which

leads to the heavy electron overflow in the p-type region.

The energy band diagram of the p-AlInN LED is plotted in Fig. 4(a). Unlike that of the p-AlGaN LED, the energy band of the p-AlInN LED is not badly sloped. This is because the $Al_{0.82}In_{0.18}N$ layer is lattice matched with GaN, and thus the polarization field is greatly reduced. The enlarged conduction band near the p-AlInN is shown in Fig. 4(b). The potential between the last QB and the EBL is about 304 meV, which is much larger than that in the LED with the p-AlGaN EBL. Thus the electrons can hardly cross the potential, and the electron overflow in the p-type region is greatly reduced.

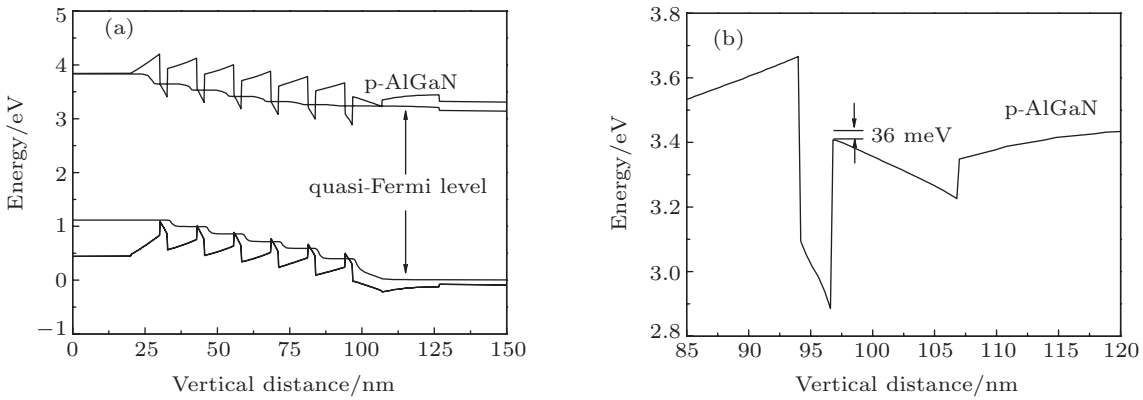


Fig. 3. (a) Calculated band diagram of p-AlGaN LED. (b) Enlarged conduction band near the EBL under 200 mA forward current.

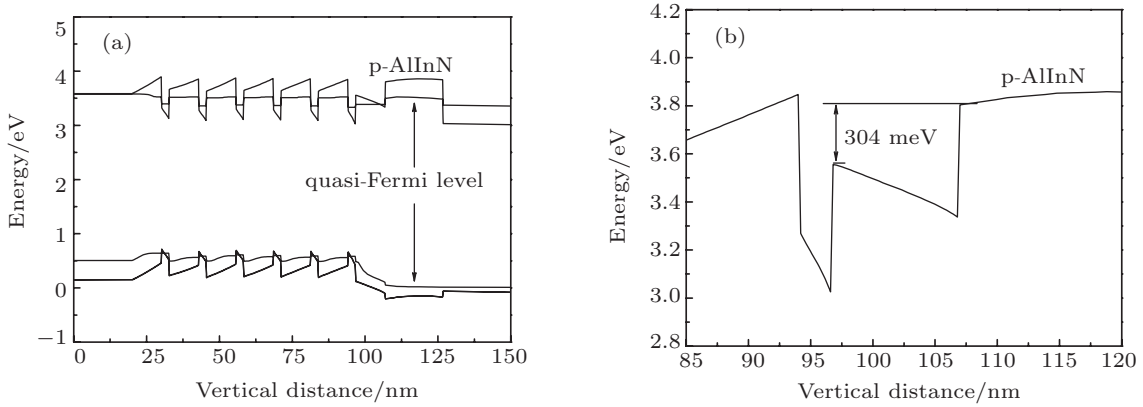


Fig. 4. (a) Calculated band diagram of p-AlInN LED. (b) Enlarged conduction band near the EBL under 200 mA forward current.

The electron current distributions of the two structures under 200 mA are shown in Fig. 5. The electron current leakage of the p-AlGaN LED is very severe, while for the p-AlInN LED, the electron overflow can be neglected. The electrons that escaped from the MQW active region can recombine with holes in the p-type region, which thereby lowers the LED efficiency. This reveals that the electron leakage current due to the polarization fields is one of the dominant mechanisms that result in the efficiency droop.

The dependence of the internal quantum efficiency (IQE) on the forward current is presented in Fig. 6. As the forward current increases, the two LED structures show different characteristics. Due to the severe electron overflow, an obvious efficiency droop in the IQE of the AlGaN LED is observed. While for the p-AlInN LED, the IQE barely decreases. This can be explained by the improved barrier potential between the last quantum barrier and the EBL, which leads to the efficient electron blocking and the reduced electron recombination with hole in the p-type region.

Our theoretical calculation indicates that the p-AlInN has many advantages over the p-AlGaN, and Choi's experimental results also demonstrated that the p-AlInN EBL can improve the LED characteristics. Then, to improve the performance of the LED, growing a high quality p-AlInN is a key issue. However, there have been technical challenges in growing

high-quality AlInN layers due to the inherent differences between the binaries (AlN, InN) associated with the lattice parameters,[14] the bonding energies, and the very different optimum growth temperature and pressure conditions for InN and AlN. In particular, the phase separation, the band gap fluctuations, the InN segregation, and the relaxation processes[15] should be considered. Lattice matched p-type AlInN samples were obtained in our previous work,[16] however, further research on the growth of the AlInN layer is needed for the improvement of the LED performance.

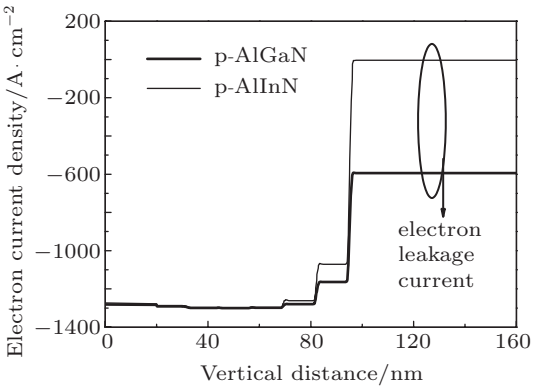


Fig. 5. Simulated electron current densities throughout the two LED structures under 200 mA forward current.

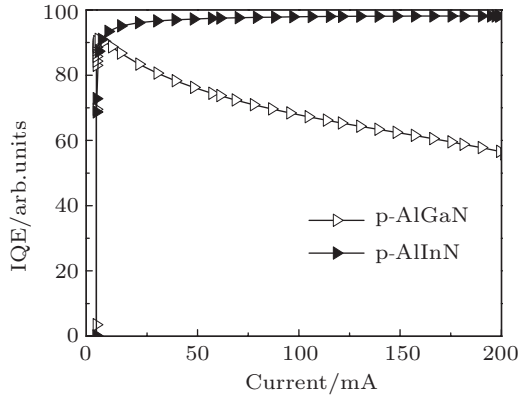


Fig. 6. IQE as a function of current for the two LED structures under study.

4. Conclusion

In this paper, InGaN based LEDs with different electron blocking layers have been numerically investigated by using the APSYS simulation software. It was found that the conventional structure with a p-AlGaN electron blocking layer had a severe electron leakage, and showed inferior light output power and dramatic efficiency droop. In contrast to the p-AlGaN LED, the LED with p-AlInN EBL showed improved light output power, lower current leakage, and smaller efficiency droop. Based on numerical simulation and analysis, these improvements of the electrical and optical characteristics were mainly attributed to the efficient electron blocking in the InGaN/GaN MQWs by the lattice matched p-AlInN EBL.

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