Comparison of nitride-based dual-wavelength light-emitting diodes with an InAlN electron-blocking layer and with p-type doped barriers*

Zhang Yun-Yan(张运炎) and Fan Guang-Han(范广涵)†

Institute of Opto-Electronic Materials and Technology, South China Normal University, Guangzhou 510631, *China*

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The advantages of nitride-based dual-wavelength light-emitting diodes (LEDs) with an InAlN electron blocking layer (EBL) are studied. The emission spectra, carrier concentration in the quantum wells (QWs), energy band and internal quantum efficiency (IQE) are investigated. The simulation results indicate that an LED with an InAlN EBL performs better over a conventional LED with an AlGaN EBL and an LED with p-type-doped QW barriers. All of the advantages are due to the enhancement of carrier confinement and the lower electron leakage current. The simulation results also show that the efficiency droop is markedly improved and the luminous intensity is greatly enhanced when an InAlN EBL is used.

Keywords: InAlN electron-blocking layer, p-type doped barriers, numerical simulation, dual-wavelength LED

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1. Introduction

The nitride-based light-emitting diode (LED) has attracted much attention due to its high efficiency, energy saving, small size and long lifetime. This solid lighting source will replace conventional incandescent and fluorescent lamps for general lighting in the future. The nitride-based dual-wavelength LED is composed of two kinds of quantum well (QW) that can emit light of different wavelengths. By adjusting the spectrum intensity, white light can be obtained. Therefore, a dual-wavelength LED is a phosphor-free white-light LED and will have perform better in solid-state white-light lighting areas.

Dual-wavelength LEDs, the same as the conventional single-wavelength LEDs, have several serious restrictions in their applications. One is known as efficiency droop.[1−3] A large number of scientists have tried to solve this problem.[4−6] The electron leakage current is widely regarded as one of the main causes that leads to efficiency droop. The electrons in nitride-based materials each have a relatively low effective mass than holes and their mobilities are very large. Because of this, the electrons can easily flow over to the p-type layer. An AlGaN layer is inserted between the active region and the p-type hole-injection layer in order that this wide band gap material layer can act as an electron-blocking layer to suppress escape of electrons out of the active region. However, recent studies show that electron confinement by a conventional AlGaN electron blacking layer (EBL) is not sufficiently effective to solve the efficiency droop problem because the effective barrier height of the EBL is not big enough. In addition, the lattice mismatch between AlGaN and GaN generates a piezoelectric polarization field which pulls down the conduction band at the AlGaN/GaN interface.

In this paper, two effective methods are presented to relieve the above issues. The advantages and disadvantages of these two methods will be discussed. One method is to use InAlN as an EBL. $In_xAl_{1-x}N$ has many attractive characteristics as an EBL, including the ability to form lattice-match GaN and $In_xGa_{1-x}N$, a wider energy band gap, a larger conduction-band offset relative to GaN, and a relatively low growth temperature. It has been widely used in semiconductor devices such as vertical-cavity surface-emitting lasers, in which InAlN acts as the low-index material component of a distributed Bragg reflector. The other method is to use p-type doped GaN as a QW barrier

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†Corresponding author. E-mail: gfan@scnu.edu.cn

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in the active region. Electrons are harder to move into the p-type doped GaN barrier than into the n-type doped GaN barrier. Therefore, the p-type doped GaN barrier can preclude some of the electrons from spilling over the active region.

2. Experiment

There are three kinds of structures discussed in this paper. The original structure is the conventional LED with an AlGaN EBL and n-type doped QW GaN barriers; the second structure is that with an AlGaN EBL and p-type doped QW GaN barriers; the third structure is one with an InAlN EBL and n-type doped QW GaN barriers. The optical and electrical properties of the three kinds of LEDs are investigated numerically with APSYS (Advance Physical Model of Semiconductor Devices)[7] simulation software, which was developed by the Crosslight Software Inc. APSYS software is capable of dealing with the physical properties of LEDs by solving Poisson's equation, the current continuity equation, the carrier transport equation, the quantum mechanical wave equation and the photon rate equation.

The original dual-wavelength LED used in this paper is grown on a *c*-plane sapphire substrate, followed by a 50-nm-thick undoped GaN layer and a 4.5-μm-thick n-GaN layer (n-doping=5×10^{18} cm^3). The active region consists of four 2-nm-thick InGaN QWs, separated by five 13-nm-thick n-GaN barriers (n-doping=7×10^{17} cm^3). The component of the two QWs which are closer to the p-type hole-injection layer is $In_{0.1}Ga_{0.9}N$; while the component of the other two QWs which are closer to the n-type electron-injection layer is $In_{0.2}Ga_{0.8}N$. On top of the active region are a 30-nm-thick p-$Al_{0.2}Ga_{0.8}N$ and a 0.15-μm-thick p-GaN cap layer (p-doping=7×10^{17} cm^3). The device geometry is designed into a rectangular shape of 300 μm×300 μm in size. The operating temperature is assumed to be 300 K. The light extraction efficiency is assumed to be 0.78. The second structure is the same as the original structure but for the five n-GaN barriers, which are replaced by p-GaN barriers (p-doping=7×10^{17} cm^3) here in the structure. The third structure is the same as the original structure but for the $Al_{0.2}Ga_{0.8}N$ EBL, which is replaced by $In_{0.18}Al_{0.82}N$ EBL here in the structure. The detailed structure of the LEDs can be seen from the following tables (Tables 1–3). Most of the parameters in this paper are the same as those in Ref. [2]. Other material parameters of the devices used in the simulation can be found in Ref. [3]. In Ref. [8] Kuo *et al.* studied the advantages of blue InGaN LEDs with InGaN barriers using these parameters and the same software. Their experimental data and simulations are shown to be in good agreement with each other.

Table 1. Schematic structure of the original LED.

p-GaN, 0.15 μm, 7×10^{17} cm^{-3}
p-$Al_{0.2}Ga_{0.8}N$, 0.03 μm, 7×10^{17} cm^{-3}
active layer (ii) $In_{0.1}Ga_{0.9}N$/ n-GaN (1×10^{18} cm^{-3})
active layer (i) $In_{0.2}Ga_{0.8}N$/ n-GaN (1×10^{18} cm^{-3})
n-GaN, 4.5 μm, 5×10^{18} cm^{-3}

Table 2. Schematic structure of the LED with p-type doped barriers.

p-GaN, 0.15 μm, 7×10^{17} cm^{-3}
p-$Al_{0.2}Ga_{0.8}N$, 0.03 μm, 7×10^{17} cm^{-3}
active layer (ii) $In_{0.1}Ga_{0.9}N$/ p-GaN (7×10^{17} cm^{-3})
active layer (i) $In_{0.2}Ga_{0.8}N$/ p-GaN (7×10^{17} cm^{-3})
n-GaN, 4.5 μm, 5×10^{18} cm^{-3}

Table 3. Schematic structure of LED with $In_{0.18}Al_{0.82}N$ EBL.

p-GaN, 0.15 μm, 7×10^{17} cm^{-3}
p-$In_{0.18}Al_{0.82}N$, 0.03 μm, 7×10^{17} cm^{-3}
active layer (ii) $In_{0.1}Ga_{0.9}N$/ n-GaN (1×10^{18} cm^{-3})
active layer (i) $In_{0.2}Ga_{0.8}N$/ n-GaN (1×10^{18} cm^{-3})
n-GaN, 4.5 μm, 5×10^{18} cm^{-3}

3. Results and discussion

As shown in Fig. 1(a), the luminous intensity of the LED with an InAlN EBL is much stronger than that with an AlGaN EBL. It can be seen from Fig. 1(b) that the original LED has the lowest IQE and a severe efficiency droop. The LED with an InAlN EBL has a high IQE in the whole range of injection current under study. The LED with an AlGaN EBL shows good performance at a low-injection current. However, it shows a rapid efficiency drop with the increase of injection current density, which suggests a severe carrier loss by spill-over. It also is very apparent in Fig. 1(c) that the LED with an InAlN EBL has the biggest output power and keeps a strong and increasing momentum. The output powers of the original LED and the LED with p-type doped barriers are much lower than the output power of the LED with an InAlN EBL and drops off rapidly with the increase of the injection current beyond the peak output power. Therefore, it can be found that the optical and electrical perfor-

mances of the InAlN EBL structure are much better than those of the other two structures.

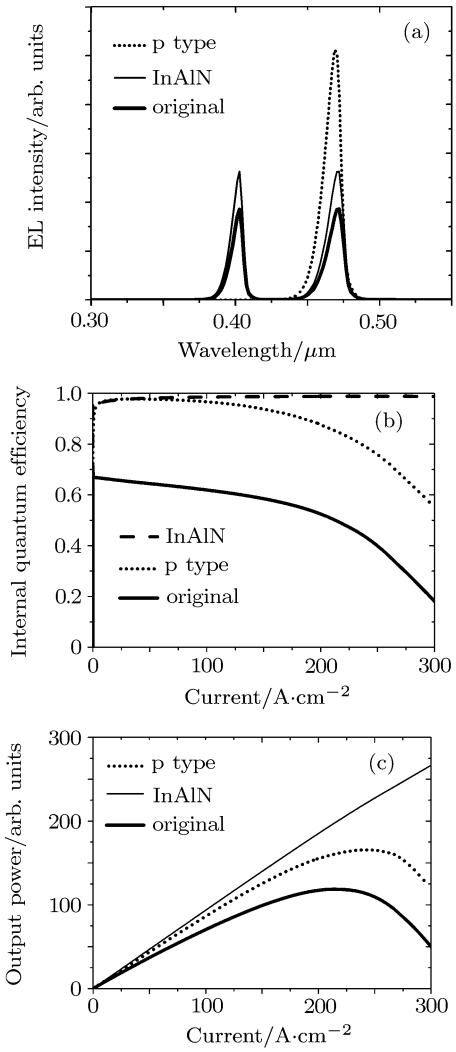


Fig. 1. (a) Spectra at 150 mA, (b) IQE and (c) output power versus injection current of LEDs with an InAlN EBL, p-type doped QW barriers and of original structure LED separately.

In Figs. 2(a) and 2(b), I and II are the effective potential barrier heights for electrons that are formed by EBL. InAlN material has a much wider energy band gap and a larger conduction-band offset relative to those of GaN. As can be seen in the figure, II is much bigger than I. The effective barrier height of the AlGaN EBL can be augmented by increasing the Al composition. However, the layer crystalline quality of the AlGaN layer will be degraded by strain-induced defects generated by the incorporation of a high Al mole fraction into the EBL. In addition, its high optimum growth temperature can produce significant thermal damage in the active region, thereby degrading its luminescence characteristics. Besides, the lattice mismatch between AlGaN and GaN will become worse with the increase of Al composition and the lattice mismatch will generate a piezoelectric polarization field, which will pull down the conduction band at the AlGaN/GaN interface. As a result, the effective barrier height of the EBL will be reduced and the leakage of the carriers will not be effectively suppressed. On the contrary, InAlN with an indium composition of 0.18 can grow lattice-matched to GaN. The piezoelectric polarization field between InAlN and GaN is much smaller than that between AlGaN and GaN and the pulling down of the conduction band at the InAlN/GaN interface is greatly mitigated.

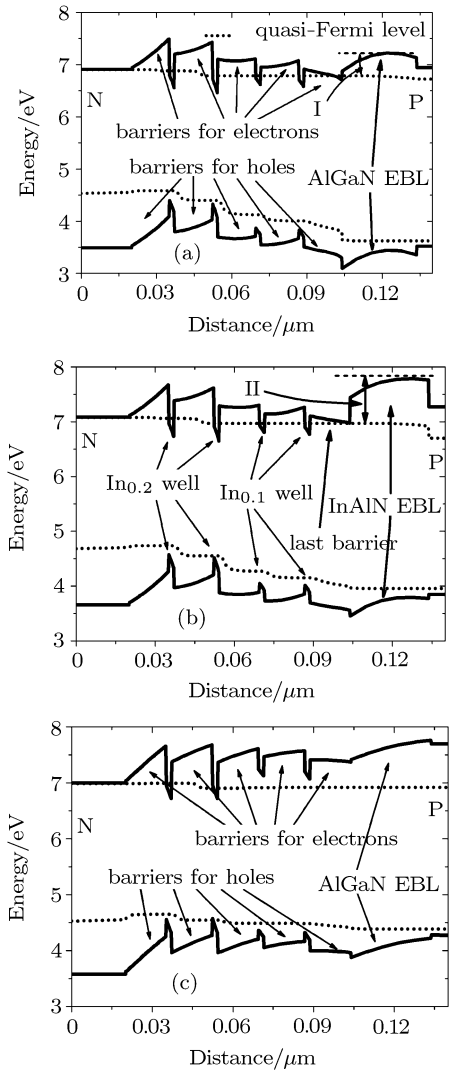


Fig. 2. Energy band diagrams of LEDs with (a) an AlGaN EBL, (b) an InAlN EBL and (c) p-type doped barriers at 150 mA separately.

Figure 3 shows the electrostatic fields of the LEDs with an AlGaN EBL and an InAlN EBL. It can be seen that the electrostatic field of the LED with an InAlN EBL near the last QW barrier and EBL is much smaller than that with an AlGaN EBL because InAlN

can grow lattice-matched to GaN. The band bending of InAlN EBL is smaller than that of AlGaN EBL which can be seen in Figs. 2(a) and 2(b).

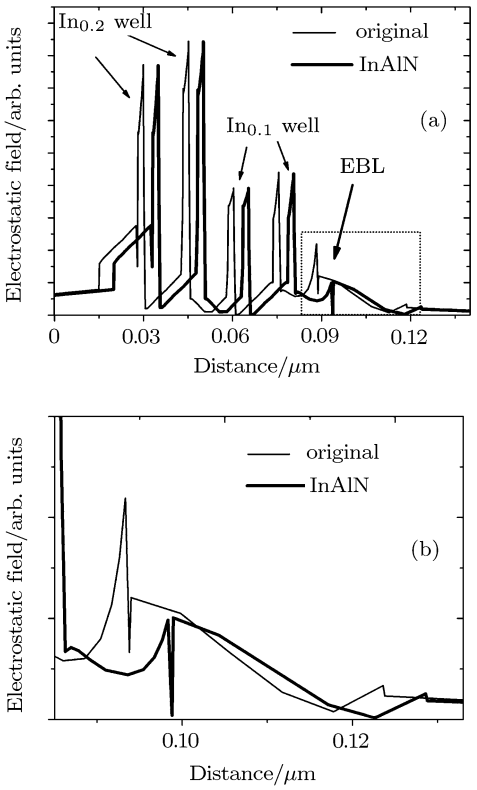


Fig. 3. (a) Electrostatic fields of the LED with an AlGaN and an InAlN EBL separately and (b) the magnifications of the fields near last QW barrier and EBL.

The InAlN EBL is more able to suppress the escape of the electrons out of the active region than the AlGaN EBL due to the much higher effective potential barrier height for electrons. Consequently, more electrons can stay in the QWs and recombine with holes. A comparison between Fig. 4(a) and Fig. 4(b) shows that the electron leakage of the structure with an InAlN EBL is much smaller. It is apparent in Fig. 4(d) that the radiative recombination rate of the structure with an InAlN EBL is much bigger than that of the structure with AlGaN EBL. That is why the structure with an InAlN EBL has the best performance as shown in Fig. 1.

A comparison between Fig. 2(a) and Fig. 2(c) indicates that the effective potential barrier heights of the QW barriers for holes are much lower when the barriers are p-type doped. The holes are easier to move into the p-type doped GaN QW barriers and the hole concentration in the QWs is much bigger, which can be seen in Fig. 4.

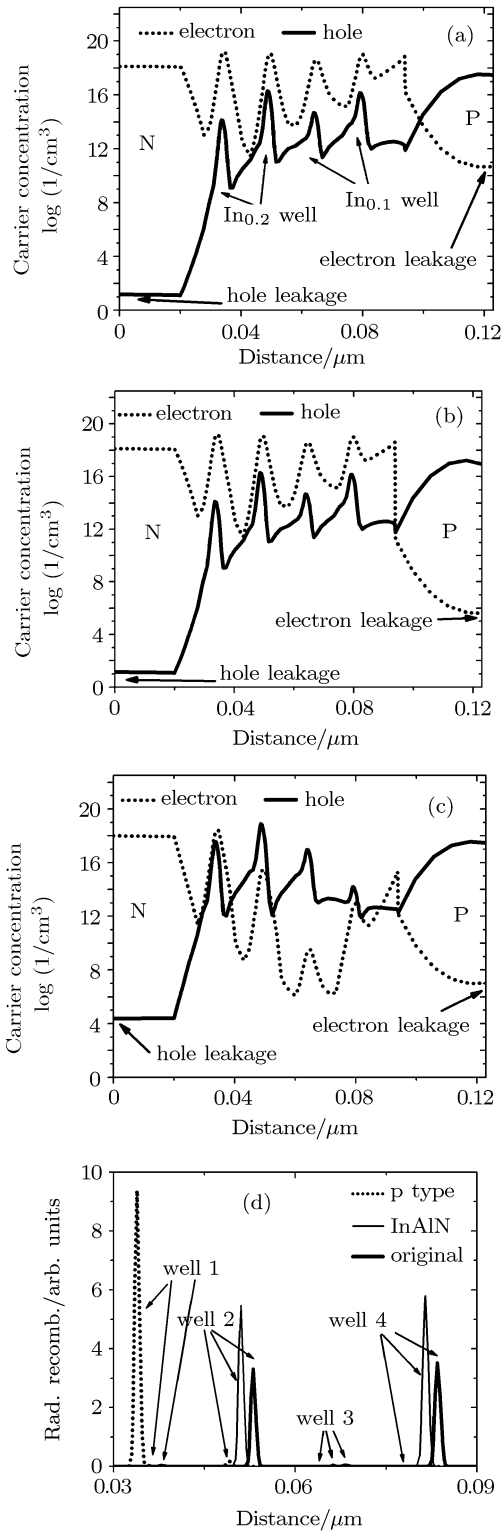


Fig. 4. Carrier distributions of (a) original structure with an AlGaN EBL, (b) structure with an InAlN EBL, (c) the structure with p-type doped barriers and the radiative recombination rates of the three structures near active region at 150 mA (there are small location shifts on horizontal axis for better observation in panel (d)).

However, that also causes an increase of the hole leakage current in Fig. 4(c) and leads to the efficiency

droop in Fig. 1(b). The effective potential barrier heights of the QW barriers for electrons are much higher in the LED with p-type doped barriers than those with n-type doped barriers. The p-type doped QW barriers impede the transportation of electrons in the active region. Thus, fewer electrons will escape outside the active region and overflow into the p-type layers. The electron current leakage can accordingly be greatly reduced, but the electron leakage current will rapidly increase when the injection current intensity is bigger than 200 A/cm^2, which leads to a severe efficiency droop, which can be seen in Fig. 1(b). Therefore, the p-type doped GaN QW barriers cannot effectively prevent the electron from overflowing into the p-type layers at a big injection current.

Although the p-type doped GaN QW barriers will help to increase hole concentration in the QWs, the concentration of holes in Fig. 4(c) is still quite small and non-uniform because the holes each have a relatively large effective mass and are very difficult to move in nitride-based materials. In addition, because the p-type doped QW barriers interfere with the flow of the electron current, the QW which is furthest away from the n-type electron-injection layer has lower electron concentration. Thus the electrons are not uniformly distributed in the QWs. Because of the uneven distributions of holes and electrons, only one QW which is next to the n-type electron-injection layer contributes to the radiative recombination in the active region which can be seen in Fig. 4(d). That seriously affects the electroluminescence spectrum and there is only one peak in the spectrum.

4. Conclusion

Nitride-based dual-wavelength LEDs with p-type doped QW barriers can reduce the electron leakage current but increase the hole leakage current and cause an uneven distribution of carriers, which results in efficiency droop and a low output power relative to those of LEDs with InAlN EBL. What is worse is that it will seriously affect the electroluminescence spectrum. However, LEDs have better electrical and optical performances when the conventional AlGaN EBL is replaced by an InAlN EBL. The new structure with an InAlN EBL has much higher IQE and stronger luminous intensity. Furthermore, the efficiency droop is markedly improved. All the advantages are mainly due to the better confinement of the carriers and smaller electron current leakage.

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