Efficiency enhancement of InGaN based blue light emitting diodes with InGaN/GaN multilayer barriers*

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The advantages of InGaN based light-emitting diodes with InGaN/GaN multilayer barriers are studied. It is found that the structure with InGaN/GaN multilayer barriers shows improved light output power, lower current leakage, and less efficiency droop over its conventional InGaN/GaN counterparts. Based on the numerical simulation and analysis, these improvements on the electrical and the optical characteristics are mainly attributed to the alleviation of the electrostatic field in the quantum wells (QWs) when the InGaN/GaN multilayer barriers are used.

Keywords: GaN based light-emitting diode, InGaN/GaN multilayer barriers, electrostatic field

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1. Introduction

In recent years, the InGaN alloy system has attracted a great deal of attention as the composing material for high-brightness blue and green light-emitting diodes (LEDs), since it owns a great potential of band gap tunability in single and multiple quantum wells (QWs).[1−3] The key problem of high-power light-emitting diodes is the efficiency droop on the increase of the current density to above $j = 0.4$–4 A/cm^2.[4] Several mechanisms have been suggested to explain this effect, including insufficient hole injection into the InGaN/GaN MQWs,[5,6] electron overflow above the QW,[7,8] current leakage via structural defects,[9] non-radiative recombination,[10] and the effect of built-in piezoelectric fields in the QW.[11−13] However, the origin of the droop is still not clearly understood.

For the III-nitride system, the electrostatic field within the active region is a critical factor causing poor lighting characteristics. As we have illustrated before,[13] the lattice mismatch between the heterostructures can generate a piezoelectric polarization charge on the interface and lead to a strong electrostatic field. The strong electrostatic field in the active region will lead to band bending and a poor overlap of electron and hole wave functions, and hence, reduce the radiative recombination rate. To minimize the piezoelectric effect in the blue InGaN LEDs, several specific structure designs, such as heavy Si-doping in quantum barriers (QBs),[14−16] nonpolar (a- and m-planes) quantum wells grown on r-plane sapphire and r-LiAlO2,[17] semipolar GaN grown on m-plane sapphire,[18,19] polarization matched AlGaInN layers,[20] and dip-shaped QW structures, have been proposed.[21,22] Kuo *et al.*[23] proposed to use the InGaN barrier to replace the conventional GaN barriers. However, under this circumstance, the potential height for the carrier confinement may be reduced due to the relatively small energy band gap of InGaN. Recently, Chung *et al.*[24] proposed to use the GaN/InGaN multilayer barriers. In their experimental study, the additional GaN layer inserted into the InGaN barrier would prevent the formation of additional defects in the active layers and reduce the polarization matching effect. However, many of the fundamental properties of such InGaN based light-emitting diodes are not illustrated yet. In this work, we theoretically study the InGaN based LEDs with InGaN/GaN multilayer barriers using the APSYS (advanced physical models of semiconductor devices)[25] simulation program. The distinguishing

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feature of the structure is the barriers consisting of 3 nm-$In_{0.05}Ga_{0.95}N$/4 nm-GaN/3 nm-$In_{0.05}Ga_{0.95}N$. The barriers of the structure are referred to as multilayer barriers, since each barrier has three-layer $In_{0.05}Ga_{0.95}N$/GaN/$In_{0.05}Ga_{0.95}N$. Through our simulation, the critical physical mechanisms behind the improvement of the optical performance are presented.

2. Structure and parameters

The schematic diagrams of our proposed LED structures are shown in Fig. 1. The device geometry is designed to have a rectangular shape of 300 μm×300 μm. The conventional LED is composed of a 2.5 μm undoped GaN layer, a 2 μm Si-doped n-type GaN layer (n doping concentration = 5×10^{18} cm^{-3}), a MQWs active region, a 20 nm p-type $Al_{0.1}Ga_{0.9}N$ electron blocking layer (EBL, p doping concentration = 5×10^{17} cm^{-3}), and a 170 nm Mg-doped GaN cap layer (p doping concentration=1×10^{18} cm^{-3}). The active region is consisted of six 3.0-nm-thick $In_{0.16}Ga_{0.84}N$ quantum wells separated by seven 10-nm-thick GaN barriers. Another LED epitaxial structure (denoted as a multilayer barriers LED) has a similar layer structure except that the conventional GaN barriers are replaced by 3 nm-$In_{0.05}Ga_{0.95}N$/4 nm-GaN/3 nm-$In_{0.05}Ga_{0.95}N$.

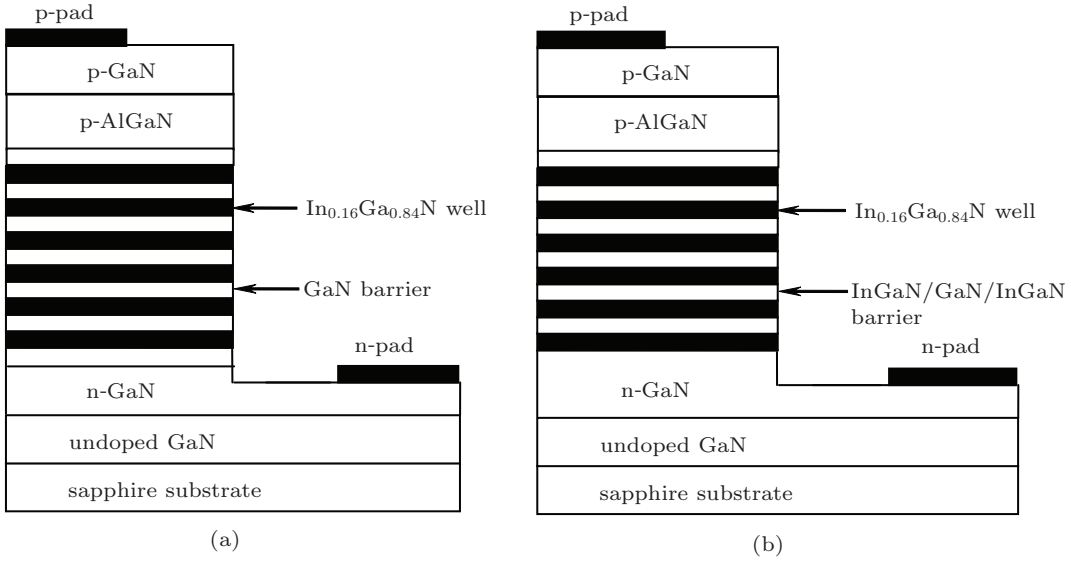


Fig. 1. Schematic diagrams of GaN-based LED structures with (a) GaN barriers and (b) InGaN/GaN multilayer barriers.

The band gaps of InGaN and AlGaN ternary alloys can be expressed respectively as[26]

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

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

where E_g(InN), E_g(AlN), and E_g(GaN) are the band gaps of InN, AlN, and GaN, and are 0.78 eV, 6.25 eV, and 3.51 eV, respectively. The internal absorption within the LED device is assumed to be 500 m^{-1}, and the operating temperature is assumed to be 300 K. The other material parameters of the semiconductors used in the simulation can be found in Ref. [27].

3. Results and discussion

The simulated electrostatic fields throughout the two LED structures at 200 mA are shown in Fig. 2. The electrostatic field in the conventional LED QWs is about 1.1 MV/cm, which is stronger than 0.9 MV/cm in the multilayer barriers LED QWs. The electrostatic field is apparently suppressed in the multilayer barriers LED QWs, which is because the multilayer barriers include three layers, that is, two 3-nm thick $In_{0.05}Ga_{0.95}N$ layers around a 4-nm-GaN layer. Because the lattice mismatch between $In_{0.05}Ga_{0.95}N$ and $In_{0.16}Ga_{0.84}N$ is smaller compared with that between GaN and $In_{0.16}Ga_{0.84}N$ at the QW and QB interfaces, the polarization field with the QWs can be greatly reduced.

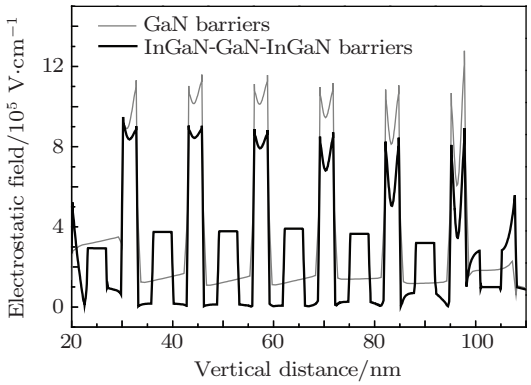


Fig. 2. Simulated electrostatic fields throughout the two LED structures under a 200 mA forward current.

Figure 3 illustrates the electron–hole wave function overlap ($\Gamma_{\mathrm{e-h}}$). By using the InGaN/GaN mutilayer barriers, the electrostatic field in the active region can be effectively suppressed, hence, the overlap between electron and hole wave functions and the probability of radiative recombination can be markedly enhanced. The overlaps between the electron and hole wave functions are 30.94% and 36.88% for the conventional and the multilayer barrier LEDs, respectively. The increase of the overlap between electron and hole wave functions results in more electrons contributing to the radiative recombination. Therefore, the electron leakage is diminished accordingly.

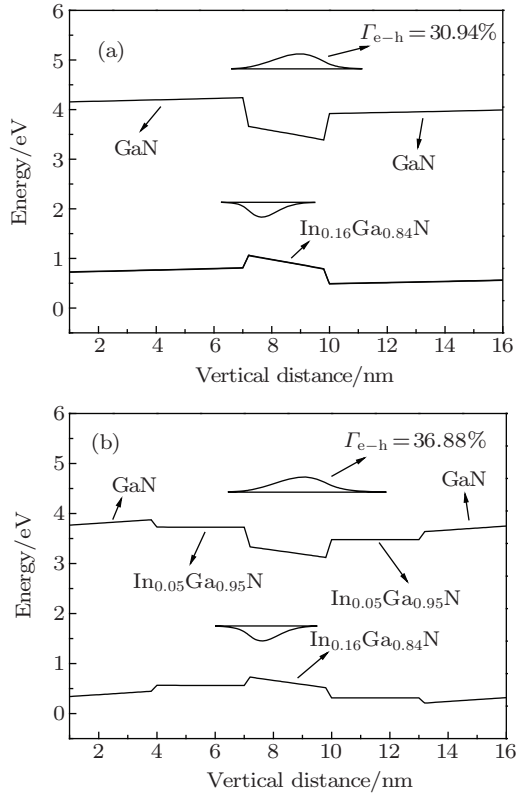


Fig. 3. Calculated band diagrams with ground-state electron and hole wave functions of (a) conventional QWs and (b) multilayer barriers LED QWs.

Figure 4 shows the electron current distributions of the two structures at 200 mA. As can be seen from Fig. 4, the electron leakage in the multilayer barriers LED is remarkedly reduced compare to that of the conventional LED. This can be explained as follows. The large polarization field induces a band bending in the active region, the QB and the EBL can hardly block the electron overflow from the QWs to the p-type layer, and thus a severe electron current leakage occurs in the conventional structure with GaN barriers. However, for the multilayer barriers LED, the inserted $In_{0.05}Ga_{0.95}N$ layer can reduce the lattice mismatch between the QW and the QB, and thus alleviates the polarization field that induces the band bending, hence the electrons can be efficiently confined in the MQWs, so the electron leakage current can be dramatically reduced.

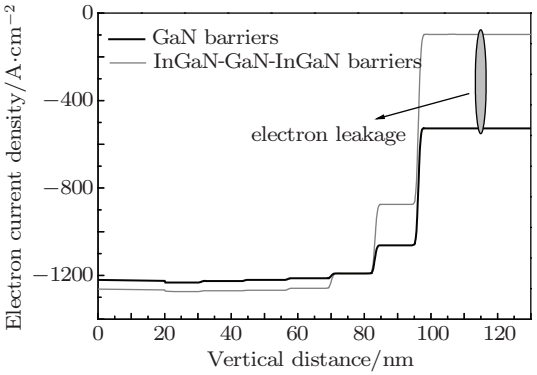


Fig. 4. Simulated electron current densities throughout the two LED structures under a 200-mA forward current.

Figure 5 shows the carrier concentrations near the active regions of the two LED structures under study at 200 mA. The result indicates that in the proposed structure with InGaN/GaN mutilayer barriers, more electrons and holes transport into the active region and contribute to the radiative recombination. The enhancement of electron concentration is due to the reduction of electron leakage current, as discussed earlier. In addition, because less holes are recombined by the leakage electrons in the p-layers, more holes can survive and transport into the active region.

The radiative recombination rates of the two structures are plotted in Fig. 6. Due to the enhanced electron-hole wave function overlap and the increased carrier concentration in the QWs, the total radiative recombination rate is improved about 62.5% when the InGaN/GaN mutilayer barriers are used.

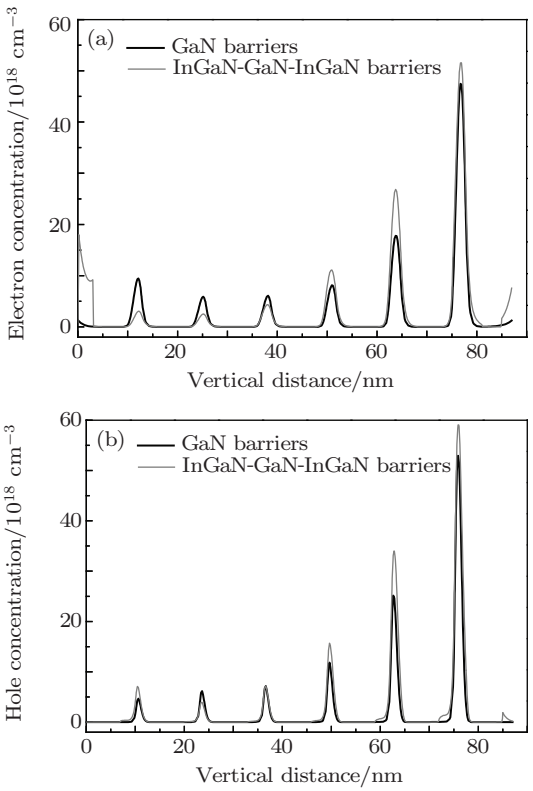


Fig. 5. (a) Electron and (b) hole concentration distributions in MQWs at a 200-mA forward current.

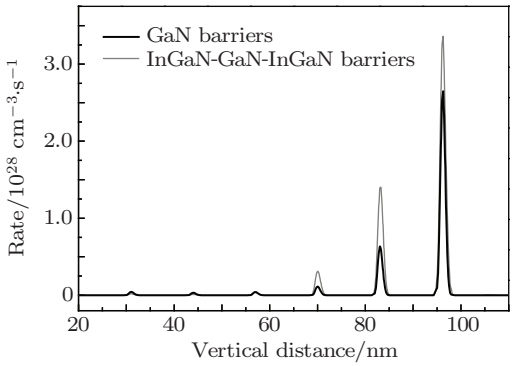


Fig. 6. Calculated radiative recombination rates in MQWs of the two structures at a 200-mA forward current.

Because of the advantages illustrated above, the performance of the multilayer barriers LED is expected to be superior to that of the conventional InGaN/GaN LED. Figure 7 shows the internal quantum efficiency (IQE) and the light output power each as a function of current for the two LED structures under study, which indicates that the multilayer barriers LED with InGaN/GaN mutilayer barriers has a better lighting efficiency, especially at a high current. It is noteworthy that there is almost no efficiency droop for the LED with InGaN/GaN mutilayer barriers.

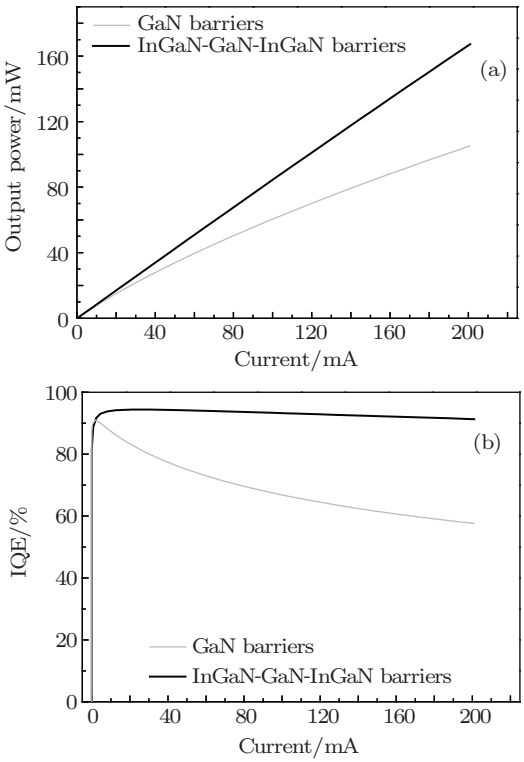


Fig. 7. (a) Output power and (b) IQE versus current for the two LED structures under study.

4. Conclusion

In this paper, InGaN-based LEDs with traditional GaN barriers and InGaN/GaN mutilayer barriers are numerically investigated using the APSYS simulation software. It is found that the conventional structure with GaN barriers has severe electron leakage, shows inferior light output power, and has a dramatic efficiency droop. In contrast, the LED with InGaN/GaN mutilayer barriers provides improved light output power, lower current leakage, and less efficiency droop. Our simulation shows that these improvements on electrical and optical characteristics are attributed mainly to the alleviation of the electrostatic field in the InGaN/GaN MQWs by using the InGaN/GaN mutilayer barriers.

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