Performance improvement of GaN-based light-emitting diode with a p-InAlGaN hole injection layer*

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The characteristics of a blue light-emitting diode (LED) with a p-InAlGaN hole injection layer (HIL) is analyzed numerically. The simulation results indicate that the newly designed structure presents superior optical and electrical performance such as an increase in light output power, a reduction in current leakage and alleviation of efficiency droop. These improvements can be attributed to the p-InAlGaN serving as hole injection layers, which can alleviate the band bending induced by the polarization field, thereby improving both the hole injection efficiency and the electron blocking efficiency.

Keywords: InGaN light-emitting diodes (LEDs), p-InAlGaN hole injection layer (HIL), numerical simulation

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1. Introduction

InGaN/GaN-based high brightness light-emitting diodes (LEDs) are promising to replace the conventional incandescent and fluorescent lamps due to their inherent higher energy efficiencies and other advantages.[1–5] However, these devices are subjected to a rapid efficiency droop with the injection of an increased current,[6,7] many investigations have suggested that the polarization field is one of the main mechanisms of efficiency droop.[8–13] The polarization field leads to a severe reduction in electron-hole wave function overlap ($\Gamma_{\text{e_hh}}$), consequently resulting in a reduction in the radiative recombination rate and the internal quantum efficiency of the optoelectronic device. The existence of the polarization field also produces an electronic overshoot phenomenon. In order to prevent the electronic overshoot, the AlGaN electron blocking layer (EBL) between the active region and the p-type contact layer is introduced.[14–16] However, the piezoelectric polarization electric field caused by lattice mismatch at the interface between the AlGaN and the GaN, which leads to the AlGaN valence band bending, increases the effective height of the valence band and so hinders the hole injection.

To improve hole injection, P-GaN, AlGaN, InGaN, and InGaN/GaN superlattices were used as hole injection layers,[17–23] Shur *et al.*,[24] and Chitnis *et al.*[25] showed that an accumulation hole layer (AHL) can be created at AlGaN/GaN interface in AlGaN/GaN heterostructure by using polarization effect. In the present paper, we propose a p-type InAlGaN hole injection layer (HIL) which also acts as a stress release layer (SRL)[26] between the multiple quantum wells (MQW) and the AlGaN electron blocking layer (EBL) for InGaN/GaN blue light-emitting diode (LED), which probably enhances the hole injection without lowering the blocking capability of electrons and improves the radiation and luminous efficiency. The optical and electrical properties of the blue LED are investigated numerically with APSYS (Advance Physical Model of Semiconductor Devices) simulation software, which is capable of dealing with the physical properties of LEDs by solving Poisson's equation, current continuity equations, carrier transport equations, quantum mechanical wave equations and photon rate equations.

2. Structure and parameters

The original blue InGaN/GaN MQW LED (sample A) used in this paper as a reference consists of a *c*-plane 100-μm-thick sapphire substrate, a 50-nm-thick undoped GaN buffer layer, a 4-μm-thick n-GaN layer (n-doping = 5×10^{18} cm^{-3}), five 3-nm-thick undoped $In_{0.15}Ga_{0.85}N$ QWs separated by six 15-nm-thick undoped GaN barriers, a 20-nm-thick p-doped $Al_{0.18}Ga_{0.82}N$ EBL (p-doping = 5×10^{17} cm^{-3}), and a 150-nm-thick p-doped GaN (p-doping = 7×10^{17} cm^{-3}). In addition to the performance of the LED with proposed p-GaN hole injection layer (HIL) (sample B), the characteristics of the LED with p-$In_{0.06}Al_{0.45}Ga_{0.49}N$ (sample C) are also discussed and compared in this study. The p-GaN HIL and p-$In_{0.06}Al_{0.45}Ga_{0.49}N$ are 5-nm-thick layers with a p-doping concentration equal to that in EBL. The device geometry is 300 μm×300 μm in size. Schematic diagrams of the original structure and the structures with redesigned layers are depicted

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in Fig. 1. The operating temperature is assumed to be 300 K and the internal absorption within the light-emitting diode device is set to be 500 m^{-1}. Other parameters can be found in Ref. [27].

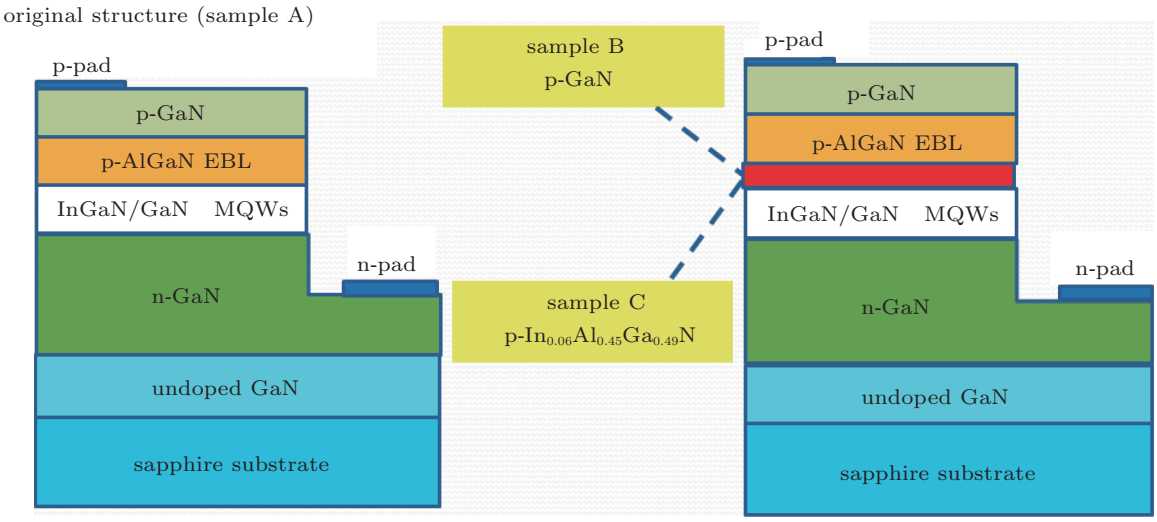


Fig. 1. (color online) Schematic of original LED (sample A), LED with a p-GaN HIL (sample B), and LED with a p-InAlGaN HIL (sample C).

3. Results and discussion

Figure 2 shows the plots of light output power and internal quantum efficiency (IQE) versus current for the three LED structures under study. It is evident that the light output power and IQE are more significantly enhanced in the LED with sample C than with sample A and sample B. The simulation result indicates that the LED with sample C has the highest light output power, about twice that of sample A and a relatively small efficiency droop at 200 mA. The best results of sample C can be attributed to relatively high electron and hole injection efficiency, lower current leakage and larger radiative recombination.

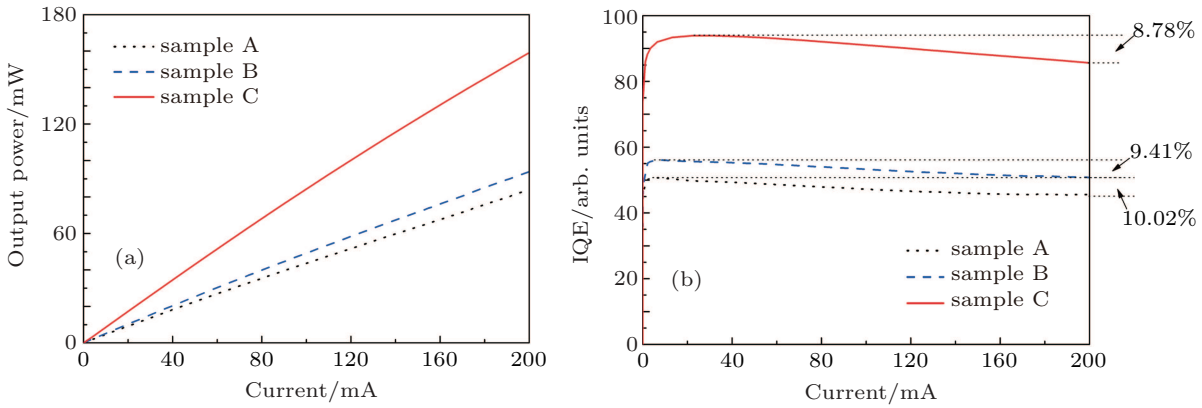


Fig. 2. (color online) Plots of (a) light output power and (b) IQE versus current for the three LED structures under study.

Figure 3 shows the energy band diagrams and carrier concentrations of the LEDs with sample A, sample B, and sample C at 200 mA. Figures 3(a)–3(c) show that the InGaN/GaN LED is subjected to a polarization field, which leads to serious tilting of the energy band. The lattice mismatch between GaN and AlGaN can generate a strong piezoelectric polarization field. As shown in Figs. 3(a) and 3(b), the effective potential barrier height for electrons in the conduction band of the EBL and p-GaN HIL is relatively low compared with that in p-InAlGaN HIL. As indicated in Fig. 3(c), for the structure with p-InAlGaN HIL, the higher potential height in the conduction band of 416 meV is beneficial to holding back electron overshoot into the p-type region. On the other hand, the crystal lattice constant of p-$In_{0.06}Al_{0.45}Ga_{0.09}N$ HIL is close to that of $Al_{0.18}Ga_{0.82}N$ EBL, which can reduce the lattice distortion in the AlGaN layer, weaken the piezoelectric polarization electric field at the interface between HIL and EBL, reduce the band bending and improve the hole injection efficiency. The electron and hole concentrations of the three structures at 200 mA are shown in Figs. 3(d)–3(f). It can be seen that the electron and the hole concentrations in the active

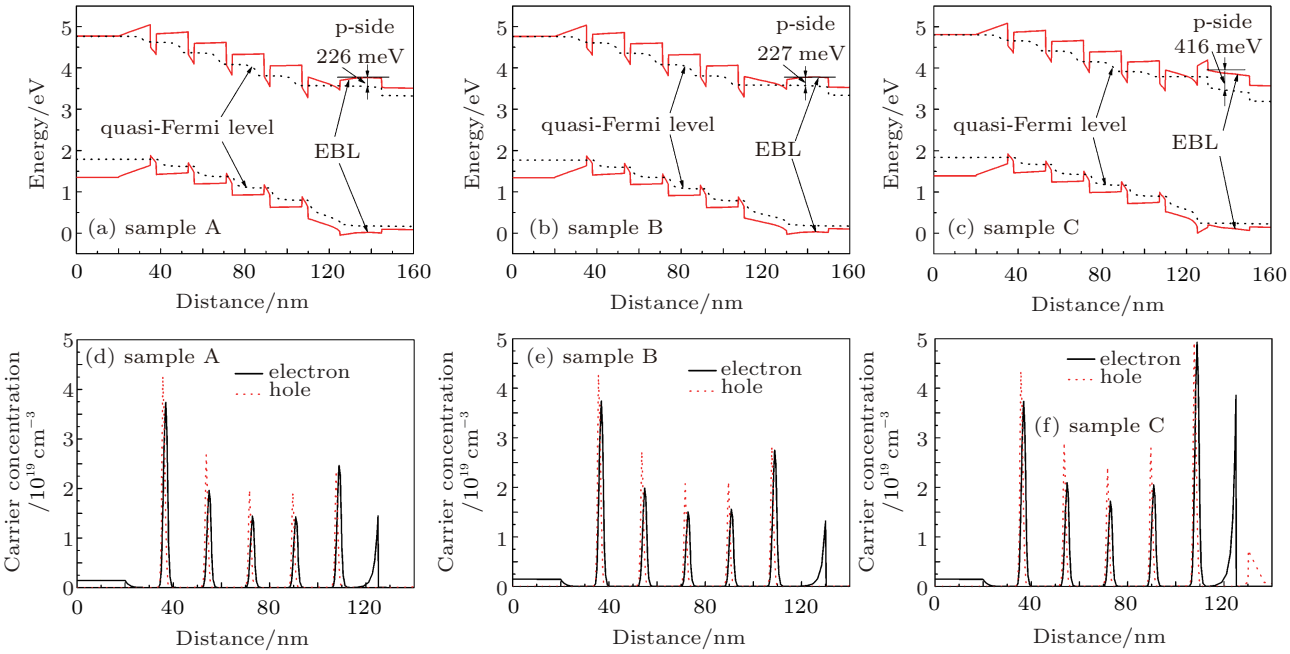


Fig. 3. (color online) (a)–(c) Energy band diagrams and (d)–(f) carrier concentrations of the LEDs with the three LED structures at 200 mA.

region of sample C are larger than those in sample A and sample B, especially in the last QW next to the p-type with a large number of carriers markedly accumulated, which is shown in Fig. 3(f). The larger electron and hole concentrations in the QW with sample C also demonstrate that the p-AlGaN HIL is conducive to enhancing electron blocking and hole injection efficiency. In addition, a larger carrier concentration in the structure with a p-InAlGaN HIL results in more radiative recombination in these QWs.

The electron current density distributions of the three structures under 200 mA are shown in Fig. 4. For sample C, due to a mass of electrons in the QWs adjacent to the p-side, which can also be seen in Fig. 3(f), the electrons

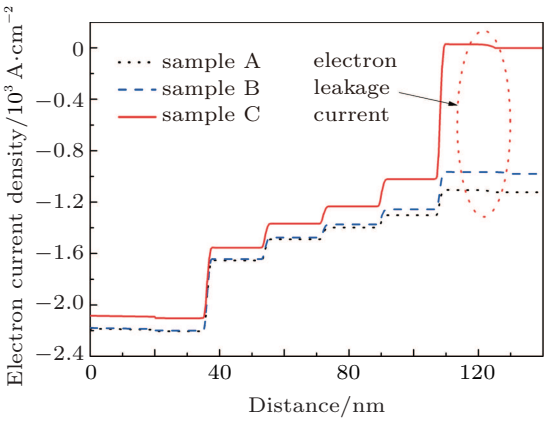


Fig. 4. (color online) Electron current densities throughout the three structures under 200 mA.

can be confined in QWs efficiently and the electron leakage can be neglected. Due to the large polarization field induced band bending between GaN and AlGaN, the EBL and p-GaN HIL can hardly block the electron overflowing from QWs to p-type layer, and thus severe electron leakage currents are observed in sample A and sample B. However, for the sample C structure, the inserted $In_{0.06}Al_{0.45}Ga_{0.49}N$ layer can reduce the lattice distortion of AlGaN, and thus alleviate the piezoelectric polarization field at the interface between HIL and EBL induced band bendings, concurrently the electrons can be efficiently confined in MQWs and finally the electron leakage current can be dramatically reduced.

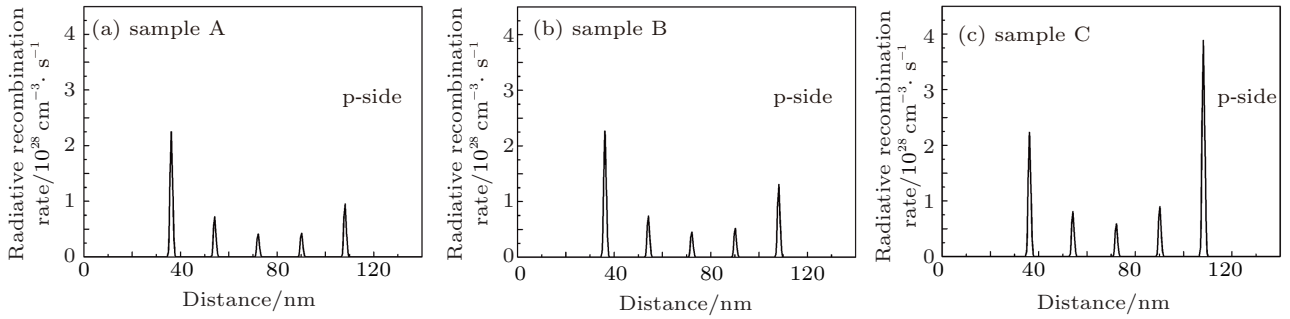


Fig. 5. Radiative recombination rates in MQWs of three structures at 200 mA.

The radiative recombination rates of the three structures are plotted in Fig. 5. It can be seen that the three structures show different characteristics in recombination rate distribution in the active region. For sample A and sample B the radiative recombination happens dominantly in QWs close to n-side, but for sample C, the radiative recombination occurs mainly in QWs adjacent to p-side. The total radiative recombination rate in MQWs with p-InAlGaN HIL is larger than that in the other two kinds of structures.

4. Conclusion

In this paper, InGaN-based LEDs with different p-type HILs are numerically investigated by using the APSYS simulation software. The simulation results show that the LED with a p-$In_{0.06}Al_{0.45}Ga_{0.49}N$ HIL has better performance than the LED with a p-GaN HIL. An improved light output power, a reduction in efficiency drop, a larger carrier concentration, lower current leakage and larger radiative recombination are observed in this structure. The physical origin for the performance improvement is due mainly to less band bending, induced by a smaller polarization field at the interface between the HIL and EBL, thereby enhancing both the hole injection efficiency and the electron blocking efficiency.

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