Simulation study of blue InGaN multiple quantum well light-emitting diodes with different hole injection layers*

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(Received 20 September 2011; revised manuscript received 23 November 2011)

InGaN-based light-emitting diodes with p-GaN and p-AlGaN hole injection layers are numerically studied using the APSYS simulation software. The simulation results indicate that light-emitting diodes with p-AlGaN hole injection layers show 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-AlGaN 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: GaN-based light-emitting diodes, hole injection layer, injection efficiency

PACS: 85.60.Jb, 87.15.A–, 78.60.Fi, 73.61.Ey **DOI:** 10.1088/1674-1056/21/6/068506

1. Introduction

InGaN/GaN-based high-brightness light-emitting diodes (LEDs) have attracted much attention because of their broad applications in signage, back lighting, and general illumination. However, the LED efficiency usually reaches a maximum value at low current density and then droops with the current density further increasing, which is termed as "efficiency droop". Many suggested mechanisms of the efficiency droop have been proposed.[1−9] Of all these suggestions, the most possible causes are electron leakage and poor hole injection efficiency. For GaN-based materials, a hole has a relatively high effective mass and therefore a very low mobility. Furthermore, the high activation energy of the Mg dopant leads to a low free hole concentration. Besides, the p-AlGaN electron-blocking layer (EBL) also retards the injection of holes.[10] Recently, Chang *et al.*'s[11] results showed that the use of n-AlGaN quantum barriers (QBs) led to more effective hole injection and electron blocking. Wang *et al.*[12] illustrated that graded-composition EBL (GEBL) was conducive to improving the hole injection efficiency. Chen *et al.*[13] exhibited that the employment of the p-type GaN last barrier in GaN LEDs resulted in superior light output power. In the present paper, p-GaN and p-$Al_{0.05}Ga_{0.95}N$ hole injection layers (HILs) are employed to improve hole injection efficiency.

2. Structure and parameters

The InGaN-based blue 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 3-nm-thick $In_{0.16}Ga_{0.84}N$ quantum wells (QWs), separated by six 10-nm-thick GaN QBs. On the top of the last QB was a 30-nm-thick p-GaN (p-doping = 5×10^{17} cm^{-3}) or p-$Al_{0.05}Ga_{0.95}N$ (p-doping = 5×10^{17} cm^{-3}) HIL, a 20-nm-thick p-$Al_{0.1}Ga_{0.9}N$ (p-doping = 5×10^{17} cm^{-3}) electron blocking layer (EBL), and a 170-nm-thick p-GaN (p-doping = 1×10^{18} cm^{-3}) layer was deposited finally. The device geometry was designed into a rectangular shape of 300 μm×300 μm, and the device structure is shown in Fig. 1. The optical and electrical performances of the two structures were investigated numerically with the APSYS simulation program, developed by Crosslight Software Inc.[14] The bandgap

*Project supported by the National Natural Science Foundation of China (Grant No. 50602018), the Science and Technology Program of Guangdong Province, China (Grant Nos. 2010B090400456, 2009B011100003, and 2010A081002002), and the Science and Technology Program of Guangzhou City, China (Grant No. 2010U1-D00191).

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energies of the InGaN and AlGaN ternary alloys can be expressed as[15]

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

$$E_{\rm g}({\rm Al}_x{\rm Ga}_{1-x}{\rm N}) = x \cdot E_{\rm g}({\rm AlN}) + (1-x) \cdot E_{\rm g}({\rm GaN}) - 0.7x \cdot (1-x), \quad (2)$$

where $E_{\rm g}$(InN), $E_{\rm g}$(AlN), and $E_{\rm g}$(GaN) are the bandgap energies of InN, AlN, and GaN, and their values are 0.78, 6.25, and 3.51 eV, respectively.[15] 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. The surface charges at the interface are calculated by the method developed by Fiorentini *et al.*[16] Considering the screening effects caused by defects, the surface charge densities are assumed to be 50% of the calculated values. 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. [17].

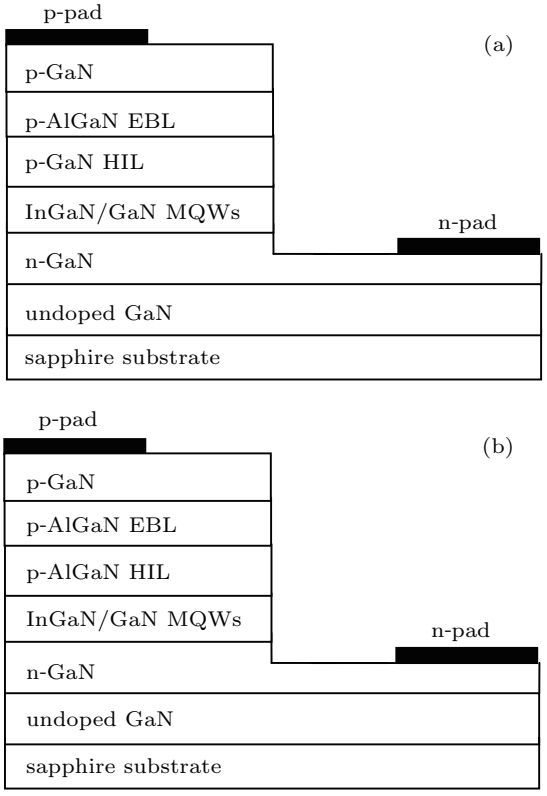


Fig. 1. Schematic diagram of GaN-based LED structures with a p-GaN HIL (a) and p-AlGaN HIL (b).

3. Results and discussion

The curves of the LED output intensity versus the injection current (L–I curves) of the two samples are plotted in Fig. 2. It can be seen that the light output powers of the two samples both increase as forward injection current increases. The difference in light output power between the two samples is enlarged at high forward current. The enhanced light output power is observed when the p-GaN HIL is replaced by a p-AlGaN HIL. The output power of the LED with a p-AlGaN HIL at 200 mA is 173 mW, while it is 133 mW for the LED with a p-GaN HIL.

The simulated electrostatic fields near the EBL of the two LED structures under 200 mA forward current are shown in Fig. 3. Due to smaller lattice mismatch between the p-$Al_{0.05}Ga_{0.95}N$ HIL and the p-$Al_{0.1}Ga_{0.9}N$ EBL, a weaker electrostatic field at the HIL/EBL interface is observed, but a larger electrostatic field exists at the last-QB/HIL interface in this structure. It should be noted that the electrostatic field is also mitigated in the EBL region. As is known, the EBL usually acts as the potential for both holes and electrons, and the downward band bending induced by the polarization can be alleviated by using a p-AlGaN HIL. The hole injection efficiency and the electron blocking efficiency can be improved in this structure.

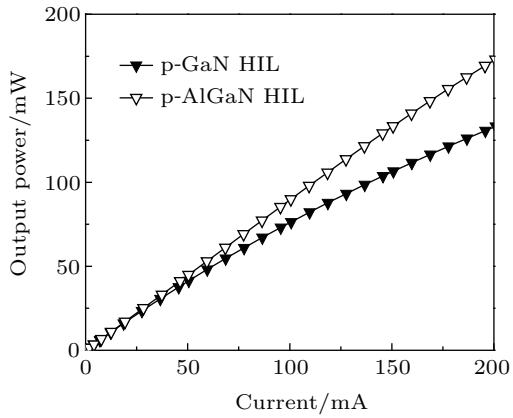


Fig. 2. The simulated L–I characteristics of two samples.

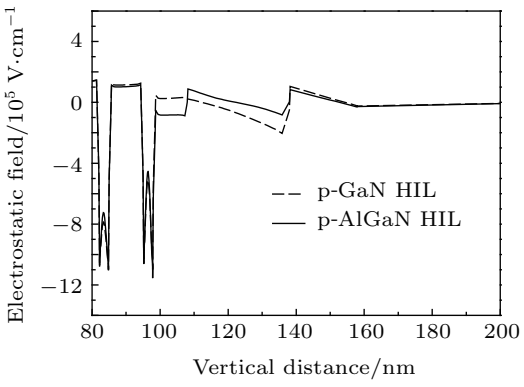


Fig. 3. Simulated electrostatic fields near the EBL of two structures under 200 mA forward current.

The enlarged energy band diagram near the EBL of the two structures is plotted in Fig. 4. The sloped triangular barriers and the band bending induced by the polarization fields are observed in both structures, especially in the HIL region. Due to a stronger polarization field induced by larger lattice mismatch, both the conduction band and the valence band bending of the structure with a p-GaN HIL are more serious than those of the structure with a p-AlGaN HIL. It should be noted that at the interface between the p-GaN HIL and p-AlGaN EBL, a relatively deep potential well is observed and a lot of electrons and holes are confined in this well. Due to relatively small effective mass and therefore a very high mobility, electrons can cross the small potential of the EBL and arouse insufficient electron blocking. Furthermore, the confined holes will reduce the hole injection efficiency. The LED with a p-AlGaN HIL has a relatively high potential barrier height for electron transport, and efficient electron blocking would be anticipated in this structure. On the other hand, the alleviated valence band bending will reduce the potential height for holes and enhance the capability of hole transportation. As a result, more holes can be injected into the active region.

The simulated carrier concentrations of the two samples in multiquantum wells (MQWs) cut from the n-side to the p-side at 200 mA are plotted in Fig. 5. It can be seen that the two structures show the same carrier concentration distribution, and a large number of carriers accumulate in the last QW next to the p-type. Both the electron concentration and the hole concentration in the active region of the LED with a p-AlGaN HIL are larger than those of the LED with a p-GaN HIL. Due to more severe band bending induced by a larger polarization field, a potential well exists at the interface between the p-GaN HIL and EBL, and a lot of electrons and holes accumulate in this well. Due to a relatively small effective mass and therefore a very high mobility, the electrons in this potential well can transport to the p-type region by doping and tunneling, and thus a larger electron concentration is observed in the p-GaN layer. However, due to relatively high effective mass and a very low mobility, holes trapped in this potential well can hardly move to the active region, so a lower hole concentration in the MQW is observed. The larger electron and hole concentration in the QW with a p-AlGaN HIL also demonstrates 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-AlGaN as the HIL indicates more radiative recombination in these QWs.

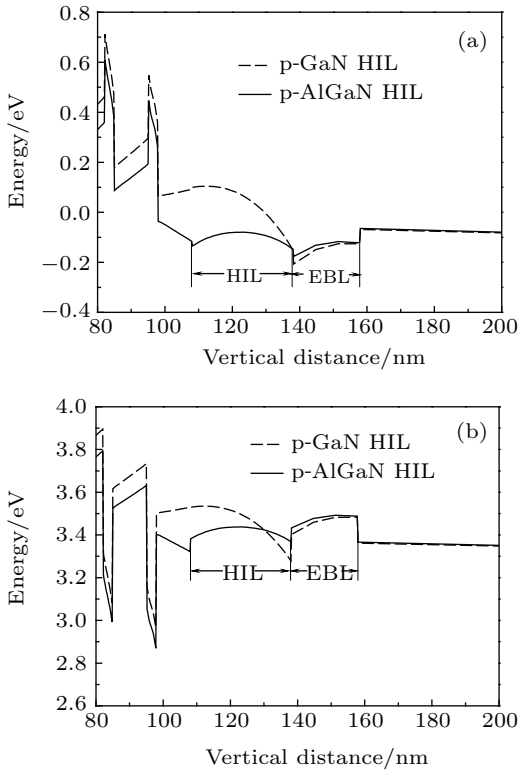


Fig. 4. The enlarged (a) valence band and (b) conduction band of the two structures at a 200-mA forward current.

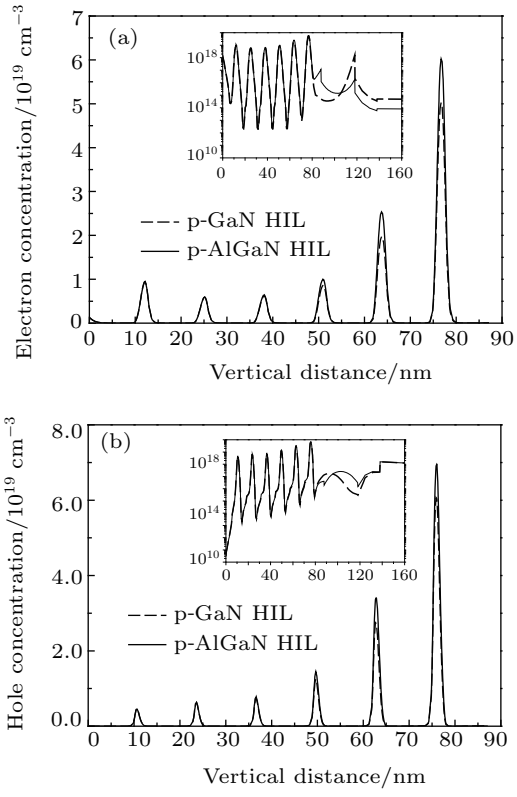


Fig. 5. (a) Electron and (b) hole concentration distributions in MQWs at a 200-mA forward current.

The electron current distributions of the two structures under 200 mA are shown in Fig. 6. A more severe electron leakage current is observed in the structure with a p-GaN HIL, which results from the diminished effective potential height for electrons by polarization-induced conduction band bending. But for the LED with a p-AlGaN HIL, the electron leakage current can be neglected, which can be attributed to the enhanced potential for electrons and thus efficient electron blocking by the reduced polarization field. The electrons that have escaped from the MQW active region can recombine with holes in the p-type region, thereby lowering the LED efficiency.

The dependence of internal quantum efficiency (IQE) on forward current is presented in Fig. 7. As forward current increases, the IQEs of the two LED structures show different variation trends. For the structure with a p-AlGaN HIL, efficiency droop is barely observed, while for the structure with a p-GaN HIL, an obvious efficiency droop is seen in this structure. The polarization-induced energy band bending can greatly influence carrier transport, and thus affect IQE. The alleviated efficiency droop can be explained by improved hole injection efficiency and electron blocking efficiency when the p-GaN HIL is replaced by a p-AlGaN HIL.

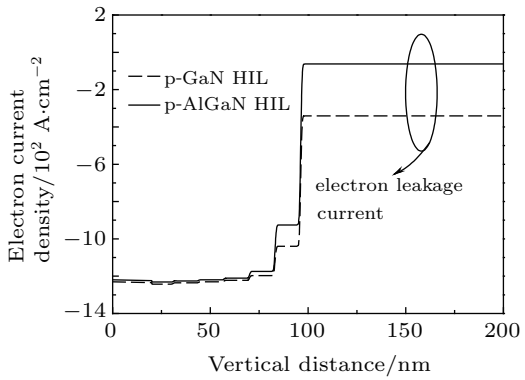


Fig. 6. Simulated electron current density throughout the two LED structures under a 200-mA forward current.

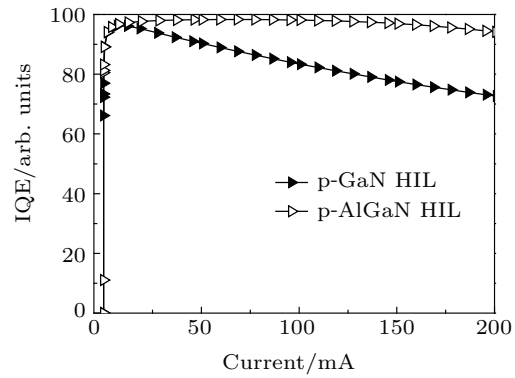


Fig. 7. IQEs versus current for the two LED structures under study.

The simulation results indicate that the LED with a p-AlGaN HIL shows superior optical and electrical performance, such as an increase in light output power, a reduction in current leakage and alleviation of efficiency droop. However, it is difficult to grow a p-AlGaN with a high hole concentration due to the relatively high ionization energy of Mg in AlGaN. On the other hand, in order to obtain a high-quality AlGaN layer, the AlGaN layer growth temperature is usually higher than 1050 °C, but the growth temperature of the Mg-doped AlGaN layer is usually lower than 1000 °C to avoid damaging the InGaN/GaN multiquantum layers in the LED structure, which leads to a low-quality p-AlGaN layer. Thus, the growth conditions of AlGaN need further optimization to improve the overall optical and electrical performance of LEDs.

4. Conclusions

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 LEDs with a p-AlGaN HIL have better performance than the LEDs with a p-GaN HIL. Improved light output power, lower current leakage, and a reduction in efficiency droop 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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