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Enhancement of light power for blue light-emitting diodes by graded-composition AlGaN/GaN superlattice electron-blocker layer

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Abstract

InGaN/GaN light-emitting diodes (LEDs) with graded-composition AlGaN/GaN superlattice (SL) electron-blocking layer (EBL) was designed and grown by metal-organic chemical vapor deposition. The electrostatic fields, energy band diagrams, carrier concentrations, electron current density profiles, and light output powers were investigated. The simulation results demonstrated that the LED with a graded-composition AlGaN/GaN SL EBL was found to have superior hole injection efficiency and lower electron leakage over the LED with a conventional AlGaN EBL or with a normal AlGaN/GaN SL EBL. The experimental results also show that the use of a graded-composition AlGaN/GaN SL EBL can markedly enhance the light output power.

1. Introduction

Recently, the high-brightness InGaN/GaN light-emitting diodes (LEDs) have been investigated widely due to its potential applications in solid-state lighting industry, for example, the full-color displays, the liquid crystal display (LCD) backlighting, and the mobile platforms. However, as the efficiency of LEDs is improving, the upcoming challenge is the efficiency “droop” for high-brightness applications [1]. Electron overflow out of the active region as well as poor injection and transport of holes have been identified as the major reasons for efficiency droop [2]-[4]. Although a conventional p-type AlGaN electron blocking layer (EBL) is commonly employed in InGaN/GaN LEDs to create an energy barrier, the issue of electron overflow is still severe especially at high injection current densities. Furthermore, the polarization-field induced band bending and the valance band offset at the interfaces of last quantum barrier (QB) and EBL are considered to retard the injection of holes [1], [5]. In recent years, many scientists have employed the conventional AlGaN/GaN superlattice (SL) to obtain better performance of LEDs [6]. Several suggestions about the special designs of EBL have been reported, including employing graded-composition EBL and adopting the polarization-matched AlGaInN EBL to relieve above issue. In this research, we designed and grew a LED structure with graded composition AlGaN/GaN SL by using metal-organic chemical vapor deposition (MOCVD).

2. Experiments and results

The structure of the conventional LED (denoted as original structure) used in this paper as a reference was grown on a c-plane sapphire substrate, followed by a low temperature GaN nucleation layer, a 2.6-μm-thick undoped GaN layer, and a 4-μm-thick n-type GaN layer (n-doping = 1.5×10^{19} cm^{-3}). The active region consisted of eight 3-nm-thick $In_{0.19}Ga_{0.81}N$ quantum wells (QWs), sandwiched by nine 14-nm-thick n-type GaN barrier layers (n-doping = 1.3×10^{17} cm^{-3}). A 40-nm-thick p-$Al_{0.16}Ga_{0.84}N$ EBL (p-doping = 5×10^{17} cm^{-3}) and a 150-nm-thick p-type GaN cap layer (p-doping = 1×10^{18} cm^{-3}) were on top of the active region. Another LED structure (denoted as structure A) had similar layer structure except for the conventional AlGaN EBL, which was replaced by a 6 pairs p-$Al_{0.16}Ga_{0.84}N$/GaN SL EBL (p-doping = 5×10^{17} cm^{-3}). The thickness of the $Al_{0.16}Ga_{0.84}N$ SL barriers was 4 nm. The thickness of the GaN SL wells was 2.5 nm. For the third structure (denoted as structure B) with special designed graded-composition SL EBL, its structure was identical to structure A except for the six AlGaN SL barriers, whose compositions of aluminum are graded along the [0001] direction from 0% to 2.5%, 2.5% to 5%, 5% to 7.5%, 7.5% to 10%, 10% to 12.5%, and 12.5% to 16%, respectively.

Figure 1 shows the energy band diagrams of these three LED structures at current 120 mA. In original structure, the effective potential barrier height for electrons at the conduction band created by AlGaN EBL is substantially reduced by the strong band bending, which is induced by the severe polarization fields at the interface between the last QB and the AlGaN EBL. This band bending will cause electrons accumulating at this interface and then leads to severe electron leakage. Moreover, the EBL is found to act as a potential barrier also for holes due to the polarization-induced band bending effect. Therefore, the holes are difficult to transport into multiple quantum wells (MQWs). On the contrary, when the grade-composition AlGaN/GaN SL EBL is used, the interface of band bending is pushed away from the MQW active region, as shown in Fig. 1(c). In addition, a higher effective potential barrier height can be created due to the grade-composition

AlGaN/GaN SL EBL.

Figure 2 shows the electron and hole concentration distributions within the active regions of these three LED structures at current 120 mA. As shown in Fig. 1(a), the effective potential height for electrons at the conduction band near the last QB and the EBL of original structure (337 meV) is smaller than that of the other two structures, and its effective potential height for holes at the valance band (366 meV) is larger. As a result, the original structure has the worst electron confinement and hole injection efficiency. The electron and hole concentrations in the active regions of original structure are smaller than that of the other two structures, as shown in Fig. 2(a) and (b). As shown in Fig. 1 (c), the effective potential height for holes at the valance band of structure B (235 meV) is lower than those of the other two structures. Accordingly, the hole injection could be improved by using the structure B. In addition, the effective potential height for electrons at the conduction band of structure B (502 meV) becomes higher than that of the other two structures, which favors the confinement to electrons. Thus, structure B has the highest electron and hole concentrations in the MQWs, as shown in Fig. 2(a) and (b).

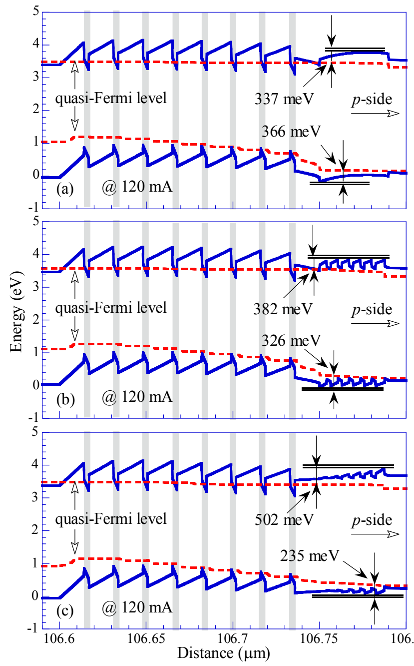

Fig. 1 Energy band diagrams of (a) original structure, (b) structure A, and (c) structure B at current 120 mA.

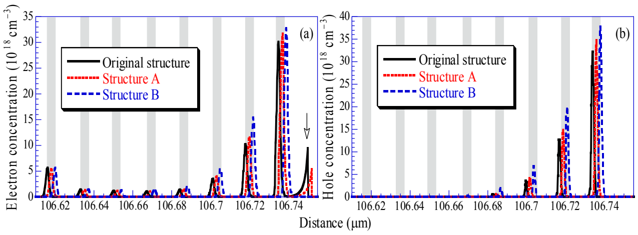

Fig. 2 (a) Electron and (b) hole concentration within the active regions of these three LED structures at current 120 mA.

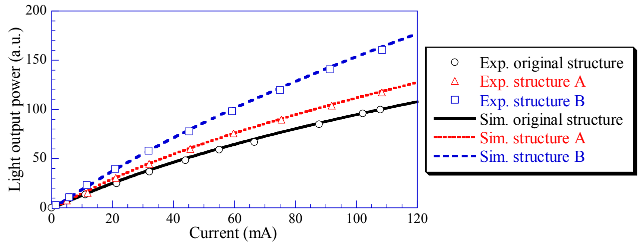

Fig. 3 Experiment and simulation light output power vs current (L-I) of these three LED structures.

The light output powers of the three LED structures were investigated by experiment and simulation, as illustrated in Fig. 3. It is noteworthy that the light output power can be improved by employing the SL EBL, especially for structure B with special designed graded-composition AlGaN/GaN SL EBL. Structure B has higher light output power than those of structure A with a normal AlGaN/GaN SL EBL because structure B benefits from better electron confinement capability and higher hole injection efficiency.

3. Conclusions

In conclusion, InGaN/GaN LEDs with a graded-composition AlGaN/GaN SL EBL were investigated both experimentally and numerically. The simulation results showed that when the conventional EBL is replaced by the graded-composition AlGaN/GaN SL EBL with aluminum composition increasing along the [0001] direction, the hole injection efficiency into the active regions is enhanced and the electron leakage current is reduced, which result in better electric and optical performance. Consistent with simulation results, an increase in the light output power of the InGaN/GaN LEDs with a graded-composition AlGaN/GaN SL EBL is confirmed through experimental measurement. given.

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