Greatly Improved Efficiency Droop for InGaN-Based Green Light Emitting Diodes by Quaternary Content Superlattice Electron Blocking Layer

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***Abstract*—We presented a low efficiency droop behavior green light emitting diodes (LEDs) with a quaternary content InAlGaN/GaN superlattice electron blocking layer (SL-EBL). The light output power shows a 57% enhancement and only 30% efficiency droop, which is attributed to a smooth band bending with a uniform carrier distribution.**

***Index Terms*—Green LEDs, Efficiency droop, Quaternary superlattice electron blocking layer**

I. INTRODUCTION

In recent years, solid-state lighting is blooming and thereby having a great achievement of saving energy and reduction of carbon. The InGaN-based light emitting diodes (LEDs) provide a potential to achieve the high brightness and high efficiency solid-state lighting system due to its widely tunable wavelength from ultraviolet to visible [1]. Despite the fact that white LED is performed well by using high transfer efficiency yellow phosphor and high brightness blue LED, the warm white efficacy of LEDs is essential to improve by high efficiency green LEDs.

The main challenge of high efficiency green LED is its low quantum efficiency. The strong built-in polarized field in InGaN-based materials, especially in high indium content of multiple quantum wells (MQWs) [2] would lead to a critical band bending and correspond to a serious drop of efficiency in high driving current density [3]. The main reason of efficiency droop behavior might come from the electrons overflow and insufficient injection for holes in LEDs.

The $Al_xGa_{1-x}N$ electron blocking layer (EBL) was adopted in general LED structures to overcome electron overflow. However, the electron overflow and hole injection cannot be improved effectively toward the general design of EBL. Several improved designs of EBL have been reported, including employing graded-composition EBL (GEBL) [1] and adopting the polarization-matched InAlGaN EBL [2]. However, Zhang *et al.* found that the performance improvement by the conventional AlGaN/GaN SL-EBL is limited due to the severe band bending would be caused by a strong electrostatic field through the lattice mismatch between the AlGaN and GaN interface [4].

In this study, a new approach of LED structure with InAlGaN/GaN SL-EBL structure has been designed and grown by metal organic chemical vapor deposition (MOCVD). It would reduce the polarization field in the last quantum barrier and further to improve the overflow for electrons as well as insufficient injection or transport for holes, hence, the reduction of efficiency droop behavior and light output power would be enhanced.

II. EXPERIMENT DETAILS

The reference sample in this letter is the so-called conventional LED which was grown on a 100-μm-thick c-plane sapphire substrate, followed by a 2-μm-thick undoped GaN layer and a 3-μm-thick *n*-type GaN layer (*n*-type doped [Si] = 5×10^{18} cm^{-3}). The active region is consisted of six pairs of 2.5-nm-thick $In_{0.27}Ga_{0.85}N$ multiple-quantum wells (MQWs), sandwiched by seven 10-nm-thick GaN barriers. Afterward, a 20-nm-thick *p*-type $Al_{0.15}Ga_{0.85}N$ EBL (*p*-typed doped [Mg] = 3×10^{17} cm^{-3}) and a 180-nm-thick *p*-type GaN capping layer (*p*-typed doped [Mg] = 5×10^{17} cm^{-3}). The contrasted LED structure (denoted as SL-EBL LED) had a same structure expect for the conventional AlGaN EBL, which was replaced by a 5 pairs $Al_{0.20}In_{0.03}Ga_{0.77}N$/GaN SL-EBL (*p*-typed doped [Mg] = 5×10^{17} cm^{-3}). The thickness for the $Al_{0.20}In_{0.03}Ga_{0.77}N$ and GaN in SL were both of 2 nm. Subsequently, the LED mesa with an area 300 × 300 μm^2 was defined by a standard LED process. The emission wavelengths of both LEDs were around 550 nm. Fig. 1 shows the schematic diagram for the conventional and proposed structures.

Based on our designs, the optical and electrical properties of the LEDs are calculated by APSYS simulation software, which was developed by Crosslight Software *Inc*.

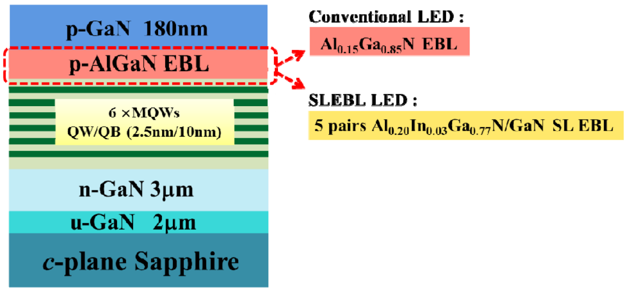

Fig. 1. Schematic diagrams of the conventional structure and SL-EBL LEDs.

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III. RESULTS AND DISCUSSION

Figure 2 shows the simulated electrostatic fields of conventional LED and SL-EBL LED near the active regions at 100 A/cm^2. As shown in the inset of Fig. 2, the electrostatic fields at GaN LB for conventional and SL-EBL LEDs are -3.7×10^5 and -2.3×10^5 V/m, respectively. The electrostatic field at the interface between LB and EBL was reduced during the InAlGaN/GaN SL-EBL is introduced, due to the lower lattice mismatch between GaN and $Al_{0.20}In_{0.03}Ga_{0.77}N$ layer.

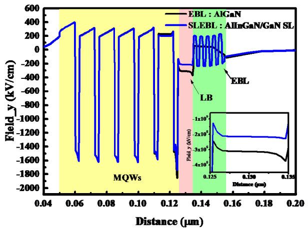

Fig. 2 The calculated electrostatic fields of conventional and SL-EBL LED at 100 A/cm^2.

Figure 3 shows the calculated energy band diagrams of these two LED structures at 100 A/cm^2. As shown in Fig. 3, as the electrostatics field at the interface between LB and EBL was reduced, the overall energy band will be pulled away from the MQW active region to improve the effective barrier height of EBL for the electrons and holes. As can be seen, the effective barrier height for electrons is increased from 228 meV to 327 meV, while the effective barrier height for holes is reduced from 245 meV to 196 meV. This result could suppress the electron overflow and improve the hole injection efficiency simultaneously.

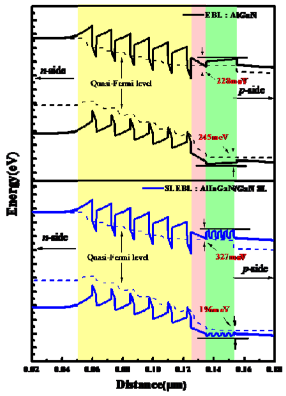

Fig. 3 Energy band diagrams of conventional and SL-EBL LED at 100 mA/cm^2.

The calculated electron and hole distributions within the active region for conventional and SL-EBL LEDs at 100 A/cm^2 are shown in Fig. 4 (a) and (b). We can find that the more electrons are confined in the well and no severe electron accumulation at the interface between the LB and EBL in SL-EBL LEDs. In addition, the more holes can inject into active region was obtained. Hence, the radiative recombination efficiency of SL-EBL LED is higher than conventional LED, as shown in Fig. 4 (c).

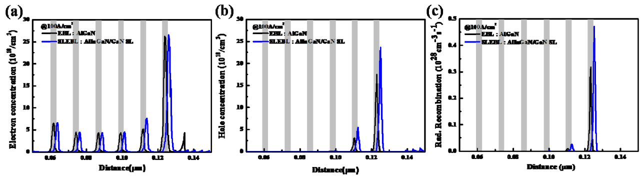

Fig. 4 (a) Electron distribution, (b) hole distribution and (c) radiative recombination efficiency within the active regions for conventional and SL-EBL LEDs at 100 mA/cm^2.

The light output power and external quantum efficiency (EQE) measurement as a function of injected current density for conventional and SL-EBL LED devices are shown in Fig. 5 (a) and (b), respectively. The light output power shows that the SL-EBL LED has a 57% enhancement at 100 A/cm^2 and only 30% droop behavior for SL-EBL LED. The significant improvements could be mainly attributed to the enhancement of hole injection as well as good electron confinement.

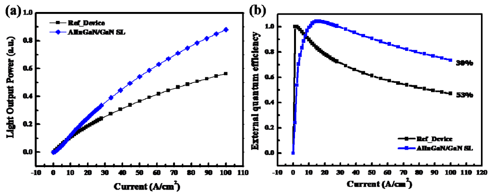

Fig. 5 (a) Light output of the both samples, (b) EQE as a function of current for two samples.

IV. CONCLUSION

In summary, the quaternary content InAlGaN/GaN SL-EBL for InGaN-based green LEDs is obtained. The electron field could be effectively reduced to pull up energy band in the GaN LB, further to improve the electron overflow and more enhanced a distribution for holes. The light output power of SL-EBL LED shows 57% enhancement at 100A/cm^2 as compared with conventional LED. In addition, the efficiency droop is reduced from 53% for conventional LED to 30% for SL-EBL LED.

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