Extended Abstracts of the 2015 International Conference on Solid State Devices and Materials, Sapporo, 2015, pp224-225

Performance Enhancement of Blue InGaN Light-Emitting Diodes with p-InGaN/GaN SPS Last Barrier and p-AlGaN/GaN SPS EBL

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Abstract

The blue InGaN light-emitting diodes (LEDs) with specific designs of p-InGaN/GaN superlattices (SLS) last barrier (LB) and p-AlGaN/GaN SLS electron blocking layer (EBL) are investigated numerically and experimentally. The simulation results show that the newly designed LEDs have a better performance over the original structure of blue InGaN LED which is attributed to the electrons overflow suppression, holes injection enhancement, and piezoelectric polarization effect improvement in active region.

1. Introduction

Several different energy band engineering designs on EBL also have been suggested like as the graded AlGaN EBL, the AlGaN/GaN SLS EBL [1] and the triangle shape AlGaN-GaN-AlGaN EBL [2] to reduce internal polarization between the LB and EBL that can increase the effective potential height for electrons at the conduction band and decrease he effective potential height for holes at the valence band near the LB and EBL, it's can effectively increase carriers pass to active region recombination. Finally, these different EBL designs enhance the internal quantum efficiency and reduce efficiency droop.

In this study, we propose a newly structure that integrates p-InGaN/GaN SPS LB and p-AlGaN/GaN SPS EBL from previously works. The result shows on ours the newly designed structure reducing polarization effect, increasing hole injection and decreasing the efficiency droop.

2. Experiment and Results

The properties of the LEDs with different structure designs were investigated numerically with the Advance Physical Model of Semiconductor Devices (APSYS) program developed by Crosslight Software Inc. [3] Fig. 1 shows the schematic diagrams of all LED structures. The structure of the conventional blue InGaN LED (donated as original structure) grown on c-plane sapphire substrate with a 3-μm thick n-type GaN. The active region is consisted of six $In_{0.2}Ga_{0.8}N$ quantum wells (QWs), sandwiched by seven GaN quantum barrier, followed by a 40-nm p-type bulk $Al_{0.15}Ga_{0.85}N$ EBL, and then a 80-nm thick p-type GaN cap layer were on top of the bulk EBL, the conventional structure is used in this paper as a reference and the device geometry is 300 × 300 μm^2. Another LED structure had similar original structure except for the LB which was replaced by an Mg-doped p-type GaN barrier (donated as Structure A). In the third structure (denoted as Structure B), the p-type LB was transformed p-type $In_{0.07}Ga_{0.93}N$/GaN SPS barrier from structure A, the p-SPS LB composition is 5 pairs 1-nm-thick $In_{0.07}Ga_{0.93}N$ and 1-nm-thick GaN. For the fourth structure (denoted as Structure C), the p-AlGaN bulk EBL was replaced by a 20 pairs p-$Al_{0.15}Ga_{0.85}N$/GaN SPS EBL from structure B, These thickness of the p-$Al_{0.15}Ga_{0.85}N$ and p-GaN both are 1 nm. Subsequently, the Mg-doped p-type GaN cap layer was on top of the SPS EBL. Finally, the newly design (Structure C) not only retains the p-InGaN/GaN SPS LB but also has p-AlGaN/GaN SPS EBL.

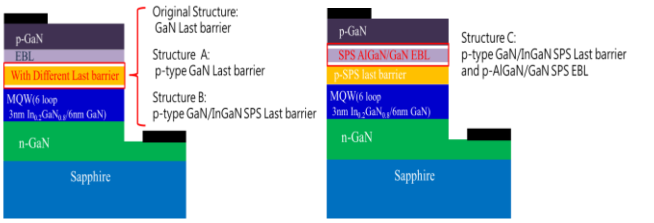

Fig. 1. Schematic diagrams of LEDs with a conventional LB (Original Structure), LEDs with a p-LB (Structure A), LEDs with a p-InGaN/GaN SPS LB (Structure B), LEDs with a p-InGaN/GaN SPS LB and p-AlGaN/GaN SPS EBL (Structure C).

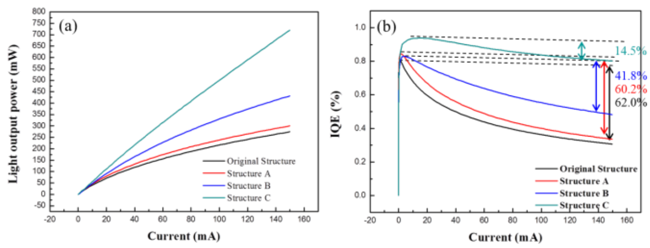

Fig. 2. (a) Light output power and (b) IQE for these four LEDs

Fig. 2 shows the light output power and IQE as functions of injection currents for the four LEDs. It is worth noting that the Structure C LEDs with p-InGaN/GaN SPS LB and p-AlGaN/GaN SPS EBL exhibit highest output power than other structures. The Structure C also has a highest IQE and a better droop behavior. The efficiency droop ratio (i.e. the reduction percentages from peak IQE to IQE at 150 mA) of Structure C was only 14.5% which was much better than the others. In order to further investigate the mechanism responsible for IQE of these fabricated LEDs regarding the above experimental results, the energy band diagrams, carrier distribution, and radiative recombination rate in active region of these LEDs were numerically simulated.

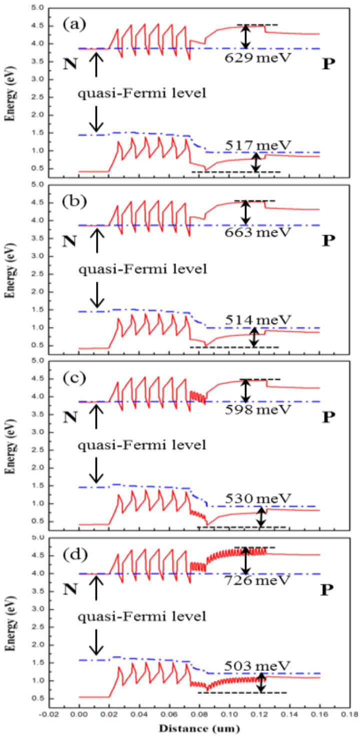

Fig. 3. Energy band diagrams of (a) original structure, (b) structure A, and(c) structure B (d) structure C at 150 mA.

Fig. 3 (a)-(d) shows the energy band diagrams of these four LED structures at 150 mA. As shown in Fig. 3(a), it can be seen the original structure has a strong band bending between the LB and the bulk EBL due to the severe polarization fields that lead to reduce ΔEc (629 meV) and elevate ΔEv (517 meV). Therefore, electrons leakage current overflowed from active region to p-GaN and holes were blocked by bulk EBL. In Fig. 3(b), it can be seen the doped p-type LB of Structure A has a higher ΔEc (663 meV) and smaller ΔEv (514 meV) than original structure. This is because p-type LB structure has a different p-n junction at equilibrium state. According to previously literature, the energy band gap of the p-type LB can effectively improve △Ec and △Ev to let electrons effectively be blocked and holes easily be injected into active region. Among these structures, the Structure C integrated superior performances of p-InGaN/GaN SPS LB and p-AlGaN/GaN SPS EBL that not only can more effectively block the electrons by highest △Ec (726 meV) but also improve the holes injection by lowest △Ev (503 meV). This is the reason why the light output power and IQE of Structure C can achieve the best performances. On the other hand, it was found the △Ec and the △Ev of Structure B were the worst in Fig. 3(c).

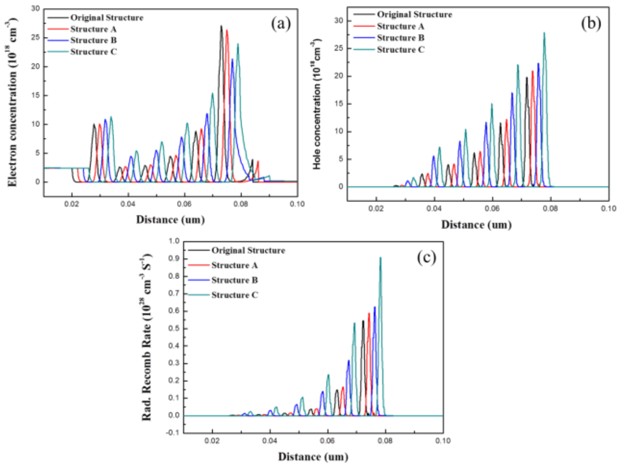

Fig. 4. (a) the electron concentrations (b) the hole concentrations (c) the radiative recombination rate for these four structures at 150 mA.

However, the carrier distribution of Structure B was better than original structure and Structure A that is attributed to the design of p-InGaN/GaN SPS LB which can reduce the polarization field effect in active region like as the function of “pre-strain” layer.

Fig. 4 shows the carrier concentrations and radiative recombination rate. That can be seen the distribution of electron and hole concentrations of the structure C were more uniform in active region that is better than others structure in Fig. 4(a) and (b). This is because the potential barrier height for electrons and holes were elevated at the conduction band and reduced at the valance band, respectively, by p-InGaN/GaN SPS LB and p-AlGaN/GaN SPS EBL which can not only more effectively suppress the electron overflow but also improve the hole injection. On the other hand, the polarization effect in active region of the structure C was also effectively improved. Therefore, the radiative recombination rate of the structure C is enhanced as shown in Fig. 4(c).

3. Conclusions

In conclusion, the p-AlGaN/GaN SPS EBL with p-InGaN/GaN SPS LB of the newly designed structure of blue LEDs is not only effectively enhance holes injection into the active region but also significantly increase electrons concentration due to effectively improve polarization effect. Therefore, the IQE and efficiency droop of this structure is markedly improved.

References

[1] Y. Y. Zhang, and Y. A. Yin ,“Performance enhancement of blue light-emitting diodes with a special designed AlGaN/GaN superlattice electron-blocking layer,”Appl. Phys. Lett., vol. 99, 221103 (2011).

[2] Chao Liu, Zhiwei Ren, Xin Chen, Bijun Zhao, Xingfu Wang, and Shuti Li “Reduced Droop Effect in Nitride Light Emitting Diodes With Taper-Shaped Electron Blocking Layer,” IEEE Photon. Technol. Lett. , vol. 26, no. 13, pp. 1368–1371, July. 2014.

[3] APSYS by Crosslight Software Inc. Burnaby, Canada [Online]. Available: http://www.crosslight.com