Advantages of Blue LEDs With Graded-Composition AlGaN/GaN Superlattice EBL

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***Abstract*— InGaN/GaN light-emitting diodes (LEDs) with graded-composition AlGaN/GaN superlattice (SL) electron blocking layer (EBL) were designed and grown by metal-organic chemical vapor deposition. The simulation results demonstrated that the LED with a graded-composition AlGaN/GaN SL EBL have superior hole injection efficiency and lower electron leakage over the LED with a conventional AlGaN EBL or normal AlGaN/GaN SL EBL. Therefore, the efficiency droop can be alleviated to be ∼20% from maximum at an injection current of 15–120 mA, which is smaller than that for conventional AlGaN EBL (30%). The corresponding experimental results also confirm that the use of a graded-composition AlGaN/GaN SL EBL can markedly enhance the light output power by 60%.**

***Index Terms*— Light-emitting diodes (LEDs), quantum well (QWs), superlattice (SL).**

I. Introduction

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 and the liquid crystal display (LCD) backlighting. However, as the efficiency of LEDs is improving, the upcoming challenge is the efficiency "droop" for high-brightness applications. The efficiency droop is the phenomenon that the efficiency reduces rapidly when a LED operates at high current density. The major cause of efficiency droop is still a huge controversy. In recent years, great efforts have been made to reduce the efficiency droop. Some of groups focus on increasing electron-hole wavefunction overlap by solving charge separation issue in the active region, such as using staggered InGaN quantum well and semipolar InGaN/GaN LEDs [1], [2]. To understand the mechanisms of droop, some theoretical investigations have been performed previously on the current injection efficiency [3]–[5], and additionally, several novel barrier designs to alleviate efficiency droop behavior have been reported [6], [7]. Electron overflow out of the active region as well as poor injection and transport of holes have also been identified as the major reasons for efficiency droop [8]. 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 [9]. To overcome this electron overflow problem, one solution is to introduce a multiple quantum barrier (MQB) superlattice (SL) into the p-type region adjacent to the active region of the device. The MQB SL consists of alternating layers of narrow and wide bandgap semiconductor materials. Similar electron blocking effect by applying distributed Bragg reflector had been previously employed in the fields of red-emitting laser diodes [10], [11]. In recent years, many scientists have employed the conventional AlGaN/GaN SL to obtain better performance of LEDs [12], [13]. However, Zhang *et al.* found that the performance improvement by the conventional AlGaN/GaN SL EBL is limited due to the severe band bending of the EBL caused by a strong electrostatic field generated by the lattice mismatch between the AlGaN and GaN interface [14]. Several suggestions about the special designs of EBL have been reported, including employing graded-composition EBL (GEBL) and adopting the polarization-matched AlGaInN EBL to relieve above issue [15], [16]. However, our simulated research found that performance enhancement by the conventional AlGaN/GaN SL EBL is superior compared to GEBL. The reason could be attributed to the improvement in electron confinement for conventional AlGaN/GaN SL EBL structure. In this letter, we designed and grew a LED structure with graded-composition AlGaN/GaN SL by using metal-organic chemical vapor deposition (MOCVD). Enhanced performance in such graded-composition designed AlGaN/GaN SL was demonstrated by both simulation and experiment.

II. Experiments and Structure Design

The reference sample in this letter is the so-called original structure which was grown on a c-plane sapphire

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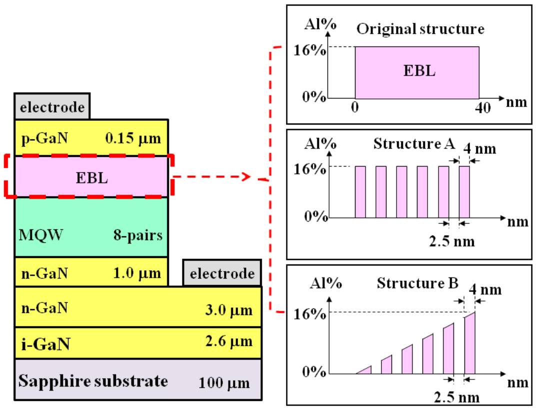

Fig. 1. Schematic diagrams of the original structure and the redesigned EBLs.

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 is 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. The growth temperature of conventional EBL and graded-composition SL EBL was the same (1010 °C). During the growth of AlGaN, we kept the flow rates of trimethylgallium (TMGa), ammonia (NH_3), and bis cyclopentadienyl magnesium (Cp_2Mg). Meanwhile, the flow rates of trimethylaluminium (TMAl) are graded increasingly. During the growth of GaN, we kept the flow rates of TMGa, NH_3, and Cp_2Mg. Fig. 1 shows the schematic diagrams of the original and proposed structures. The LED devices were measured under continuous wave condition at room temperature and the light output power was collected by integration sphere.

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. The simulated structures, such as layer thicknesses, doping concentrations, and aluminum composition are the same as the actual devices. Commonly accepted physical parameters were adopted to perform the simulations, the percentage of screening of 50%, the Shockley-Read-Hall recombination lifetime of 10 ns, and the Auger recombination coefficient in QWs with order of 10^{-31} cm^6/s, respectively. The material parameters used in the simulation are shown in Table I.

TABLE I
MATERIAL PARAMETERS USED IN THE SIMULATION

Parameter	GaN	InN
m_e/m_0	0.2	0.07
m_h/m_0	1.25	0.6
γ_e	1.0	1.0
$N_{g,e}$ (cm^{-3})	2×10^{17}	8×10^{18}
$\mu_{max,e}$ (cm^{2}V^{-1}s^{-1})	1000	1100
$\mu_{min,e}$ (cm^{2}V^{-1}s^{-1})	55	30
γ_h	2.0	2.0
$N_{g,h}$ (cm^{-3})	3×10^{17}	3×10^{17}
$\mu_{max,h}$ (cm^{2}V^{-1}s^{-1})	170	340
$\mu_{min,h}$ (cm^{2}V^{-1}s^{-1})	3	3

III. ANALYSIS AND DISCUSSION

Fig. 2 shows the energy band diagrams of these three LED structures at 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 due to the severe polarization fields at the interface between the last QB and the AlGaN EBL. This band bending will cause accumulation of electrons and then leads to severe electron leakage. On the p-type side, the EBL acts as a potential barrier for holes due to the polarization-induced band bending effect. Therefore, the holes are difficult to transport into multiple quantum wells (MQWs) and thus the radiative recombination is hindered. In our design, when the graded-composition AlGaN/GaN SL EBL is used, the interface of band bending is pushed away from the MQW active region, as shown in Fig. 2(c). In addition, a higher effective potential barrier height for electrons can be created due to the grade-composition AlGaN/GaN SL EBL.

These phenomenon discussed above can be readily checked via the calculation of the electron and hole concentration distributions within the active regions at 120 mA shown in Fig. 3. In Fig. 3(a), more severe electron accumulation at the last-QB/EBL interface caused by band bending can be found in original structure. However, the electron accumulation disappears in structure B. As shown in Fig. 2(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. 3(a) and (b). While both adapted SL EBL design, between structure A and B, some differences in terms of electron/hole transportation can still be perceived. Although structure A has smaller band bending around the last QB and the EBL due to the relation of the strain, its polarization field between the last QB and the SL EBL is still large enough to form an effective

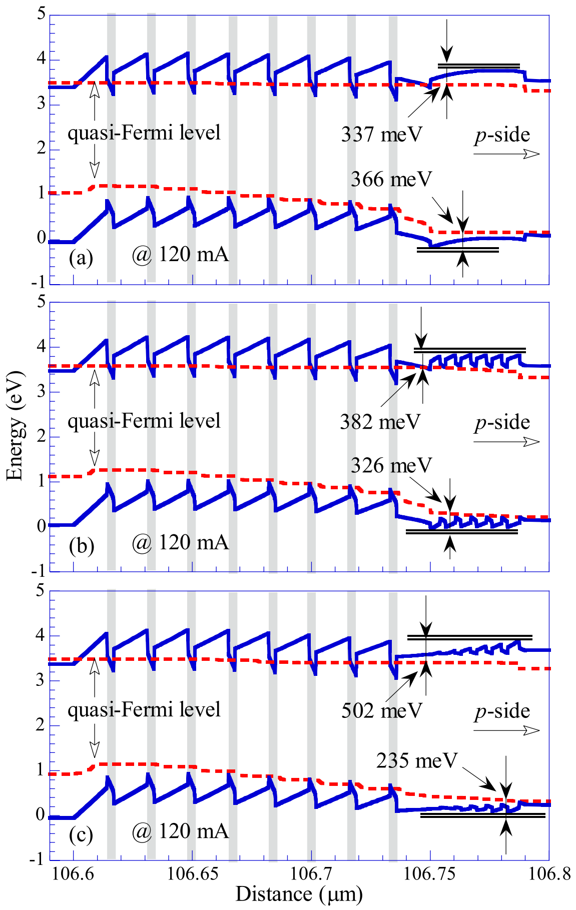

Fig. 2. Energy band diagrams of (a) original structure, (b) structure A, and (c) structure B at 120 mA.

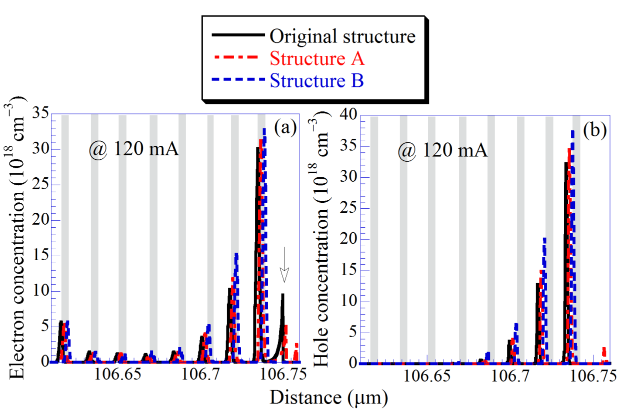

Fig. 3. (a) Electron and (b) hole concentration distributions within the active regions of these three LED structures at 120 mA.

potential height for holes of 326 meV. Meanwhile, structure B with a special designed graded-composition AlGaN/GaN SL has the slightest band bending due to the smallest polarization induced surface charge density in the last-QB/EBL interface. As shown in Fig. 2 (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

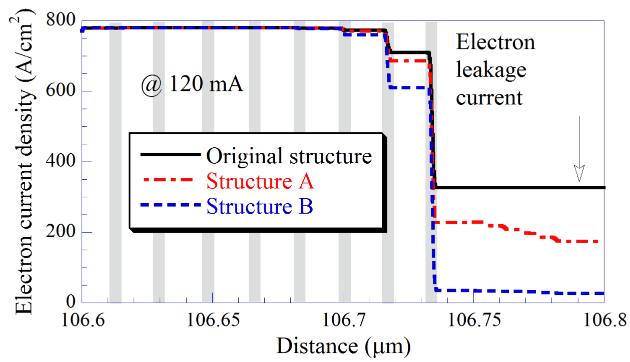

Fig. 4. Electron current density profiles near the active regions of these three LED structures at 120 mA.

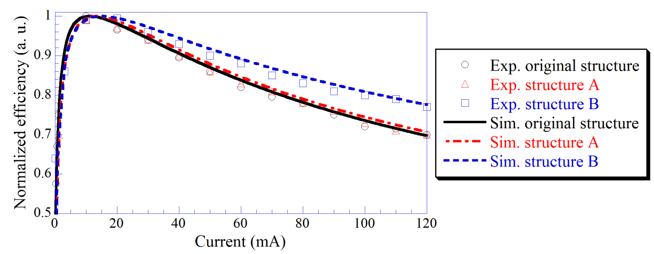

Fig. 5. Normalized efficiency performance curves of these three LED structures.

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. 3(a) and (b).

Fig. 4 shows the electron current density profiles near the active regions of these three LED structures at 120 mA. The electron current is injected from n-type layers into QWs and recombines with holes, which results in the decrease of electron current density. Electron current overflow across the EBL is considered as the leakage current. After replacing the conventional EBL with SL EBL in structure A, the electron overflow can be reduced significantly, and the electron leakage current can be further suppressed by employing the structure B. This result shows that the graded-composition AlGaN/GaN SL EBL structure is also an efficient electron blocker for InGaN/GaN LEDs.

In addition to simulation results, the three LED structures were grown by MOCVD to examine our theory. The much fewer electron leakage can be reflected upon the higher quantum efficiency, as shown in Fig. 5. The efficiency droop, defined as $(\eta_{\text{peak}}-\eta_{120\text{ mA}})/\eta_{\text{peak}}$, was reduced from 30% in original structure to 20% in structure B. This improvement could be mainly attributed to the enhancement of hole injection as well as electron confinement. The light output powers of the three LED structures were also investigated by experiment and simulation, as illustrated in Fig. 6, which shows good agreement between the experiment data and simulation results. 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. Compared with original structure, the light output powers of structure A and B are found to be enhanced by 17% and 60% at 120 mA, respectively. Structure B has higher light output

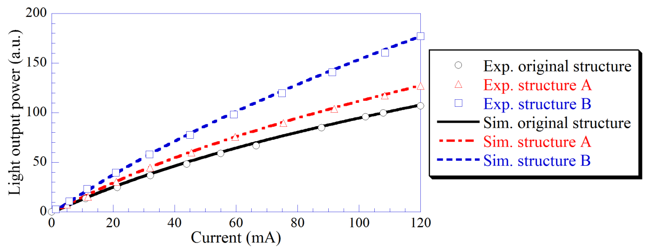

Fig. 6. Experiment and simulation light output power vs current (L-I) of these three LED structures.

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.

IV. Conclusion

The InGaN/GaN LEDs with a graded-composition AlGaN/GaN SL EBL were investigated both experimentally and numerically. The APSYS 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, and these phenomenon 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.

References

[1] H. Zhao, G. Liu, J. Zhang, J. D. Poplawsky, V. Dierolf, and N. Tansu, "Approaches for high internal quantum efficiency green InGaN light-emitting diodes with large overlap quantum wells," *Opt. Express*, vol. 19, no. S4, pp. A991–A1007, Jul. 2011.

[2] D. F. Feezell, J. S. Speck, S. P. DenBaars, and S. Nakamura, "Semipolar $(20\bar{2}\bar{1})$ InGaN/GaN light-emitting diodes for high-efficiency solid-state light," *IEEE J. Disp. Technol.*, vol. 9, no. 4, pp. 190–198, Apr. 2013.

[3] H. Zhao, G. Liu, R. A. Arif, and N. Tansu, "Current injection efficiency induced efficiency-droop in InGaN quantum well light-emitting diodes," *Solid-State Electron.*, vol. 54, no. 10, pp. 1119–1124, Oct. 2010.

[4] I. E. Titkov, D. A. Sannikov, Y.-M. Park, and J.-K. Son, "Blue light emitting diode internal and injection efficiency," *AIP Adv.*, vol. 2, pp. 032117-1–032117-4, Jul. 2012.

[5] H. Zhao, G. Liu, J. Zhang, R. A. Arif, and N. Tansu, "Analysis of internal quantum efficiency and current injection efficiency in III-nitride light-emitting diodes," *IEEE J. Display Technol.*, vol. 9, no. 4, pp. 212–225, Apr. 2013.

[6] S. Choi, *et al.*, "Efficiency droop due to electron spill-over and limited hole injection in III-nitride visible light-emitting diodes employing lattice-matched InAlN electron blocking layers," *Appl. Phys. Lett.*, vol. 101, pp. 161110-1–161110-5, Oct. 2012.

[7] G. Liu, J. Zhang, C.-K. Tan, and N. Tansu, "Efficiency-droop suppression by using large-bandgap AlGaInN thin barrier layers in InGaN quantum-well light-emitting diodes," *IEEE Photon. J.*, vol. 5, no. 2, pp. 2201011-1–2201011-12, Apr. 2013.

[8] K. J. Vampola, M. Iza, S. Keller, S. P. DenBaars, and S. Nakamura, "Measurement of electron overflow in 450 nm InGaN light-emitting diode structures," *Appl. Phys. Lett.*, vol. 94, no. 6, pp. 061116-1–061116-3, Feb. 2009.

[9] S.-H. Han, *et al.*, "Effect of electron blocking layer on efficiency droop in InGaN/GaN multiple quantum well light-emitting diodes," *Appl. Phys. Lett.*, vol. 94, no. 23, pp. 231123-1–231123-3, Jun. 2009.

[10] M. R. Brown, R. J. Cobley, K. S. Teng, P. Rees, and S. P. Wilks, "Modeling multiple quantum barrier effects and reduced electron leakage in red-emitting laser diodes," *J. Appl. Phys.*, vol. 100, no. 8, pp. 084509-1–084509-8, Oct. 2006.

[11] T. Takagi, F. Koyama, and K. Iga, "Design and photoluminescence study on a multiquantum barrier," *IEEE J. Quantum Electron.*, vol. 27, no. 6, pp. 1511–1519, Jun. 1991.

[12] P. Kozodoy, M. Hansen, S. P. DenBaars, and U. K. Mishra, "Enhanced Mg doping efficiency in $Al_{0.2}Ga_{0.8}N$/GaN superlattices," *Appl. Phys. Lett.*, vol. 74, no. 24, pp. 3681–3683, Apr. 1999.

[13] K. Kumakura and N. Kobayashi, "Increased electrical activity of Mg-acceptors in $Al_xGa_{1-x}N$ superlattices," *Jpn. J. Appl. Phys.*, vol. 38, pp. L1012–L1014, Jul. 1999.

[14] 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, pp. 221103-1–221103-3, Nov. 2011.

[15] C. H. Wang, *et al.*, "Hole injection and efficiency droop improvement in InGaN/GaN light-emitting diodes by band-engineered electron blocking layer," *Appl. Phys. Lett.*, vol. 97, pp. 261103-1–261103-3, Dec. 2010.

[16] Y.-K. Kuo, M.-C. Tsai, and S.-H. Yen, "Numerical simulation of blue InGaN light-emitting diodes with polarization-matched AlGaInN electron-blocking layer and barrier layer," *Opt. Commum.*, vol. 282, pp. 4252–4255, Jul. 2009.