OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 4, No. 8, August 2010, p. 1106 - 1110

Effect of electron blocking layer on efficiency droop in blue InGaN/GaN based light-emitting diodes

S. SINGH*, D. ROBIDAS, N. ROHILA, S. PAL, C. DHANAVANTRI
Optoelectronics Devices Group Central Electronics Engineering Research Institute (CEERI), Council of Scientific &Industrial Research, Pilani-333031, India

Light emitting diodes (LEDs) based on GaN/InGaN material suffer from efficiency droop at high current injection levels. We investigate the effect of Electron Blocking Layer (EBL) on Internal Quantum Efficiency (IQE) in multiple quantum well (MQW) GaN/InGaN LEDs to reduce the efficiency droop. The simulation results reflect a significant improvement in the efficiency droop for the structure without any EBL.

(Received July 22, 2010; accepted August 12, 2010)

Keywords: Light-emitting diodes (LEDs), Multi quantum well (MQW), Efficiency droop, Electron blocking layer (EBL)

1. Introduction

In recent time, GaN/InGaN based LEDs have been commercialized for indoor and outdoor lighting and displays, however, they suffer from reduction in efficiency at relatively high injection current levels, which has been named as the "efficiency droop" [1]. The quantum efficiency reaches its peak at low current density and thereafter monotonically decreases for further increasing the drive current [2]. The radiative recombination rate and output power of the InGaN based LEDs are thus degraded accordingly [3].

Recently, the effect of the Auger recombination at high injection current has been reported, which leads to the efficiency droop [4]. The reason to the essential Auger recombination presented may come from the unusual Auger coefficient of the GaN-based material, which varies from 1×10^{-34} to 5.37×10^{-28} cm^6/s obtained from experimental measurements and theoretical estimations [5]. A double-heterostructure has therefore been proposed as an active layer to solve the problem [2]. However, the origin of efficiency droop is still under debate.

One of the approaches to improve the overall efficiency of III-nitride Blue LED is to reduce the electron overflowing problem [6] by optimizing the blue LED structure. The III-nitride compound semiconductors require relatively large injection currents (for their operation due to lower hole concentration), higher series resistance and lower material gain, ultimately making the electron overflowing problem more serious than other compound semiconductors. At present, incorporation of electron blocking layer (EBL) [7] is known to be one of the most effective approaches in reducing this problem. Moreover, it plays an important role in filling the pits, which are initially caused by the lattice mismatch between GaN and the sapphire substrate. The subsequent strained InGaN-GaN MQW that is grown at relatively lower temperature (750^0C) would further intensify density and/or size of the emerging pits [8]. To improve the efficiency of MQW LEDs, EBL plays an important role in confining electrons effectively in the MQW region [6]. The p-type AlGaN EBL is usually used in blue LEDs to reduce the electron leakage current. However, the p-type AlGaN layer also retards the injection of holes, which leads to the degradation of efficiency at higher current level. Sheng-Horng Yen et al [9] suggested to use n-type AlGaN layer below the active region for reduction of efficiency droop in InGaN/InGaN MQW LED.

In this study, we investigated the effect of EBL on efficiency droop in InGaN/GaN MQW LEDs. The optical and electrical properties of InGaN/GaN MQW LED are investigated with SiLENSe 4.2 software. Band diagrams of the LED structure as a function of bias, electron and hole transport inside a heterostructure, non-radiative and radiative carrier recombination have also been discussed.

2. Structure and parameters

A typical InGaN/GaN based blue LED structure grown on a *c*-plane sapphire substrate, with a 1.5 µm-thick undoped GaN layer, and a 4.5µm-thick n-GaN layer (n-doping=$5\times10^{18}cm^{-3}$) has been considered as a reference. The active region is consisting with five 2-nm thick undoped $In_{0.}$21Ga0.79N QWs sandwiched by six 10-nm thick undoped GaN barrier layers. On top of the active region, a 20-nm-thick p-Al0.15Ga0.85N electron blocking layer (EBL) (p-doping=1.2×1018cm-3) and subsequently a 0.5-µm-thick p-GaN cap layer (p-doping=$1.2x1018cm^{-3}$) were considered. Fig. 1 shows the basic LED structure which has been simulated in this work.

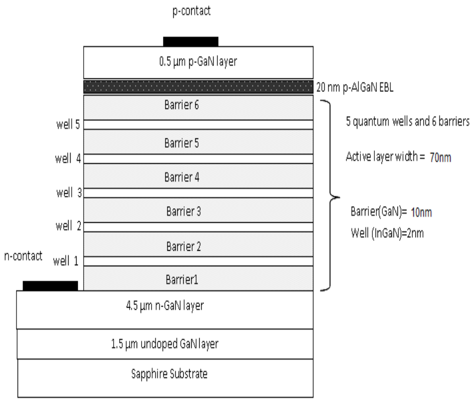
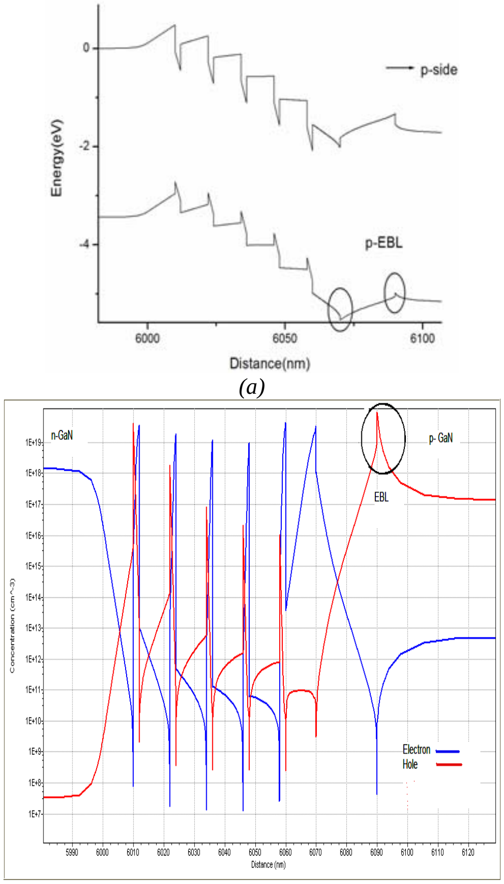


Fig. 1. Basic LED structure.

3. Results and discussion

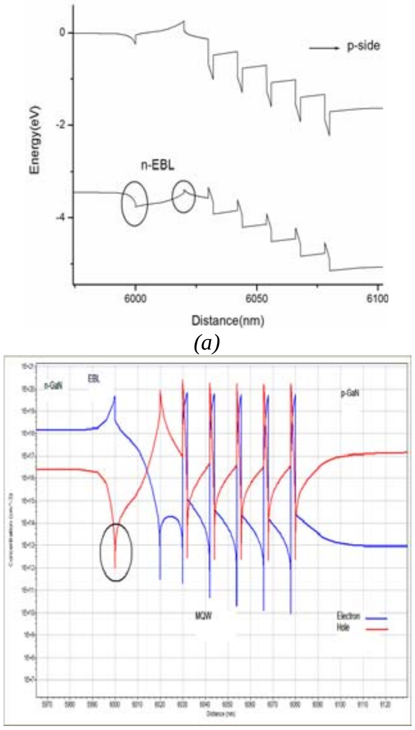
We have investigated the effect of EBL on InGaN/GaN MQW LED and compared the results for the LED structure with p-AlGaN EBL, n-AlGaN EBL and without EBL



(a)

(b)

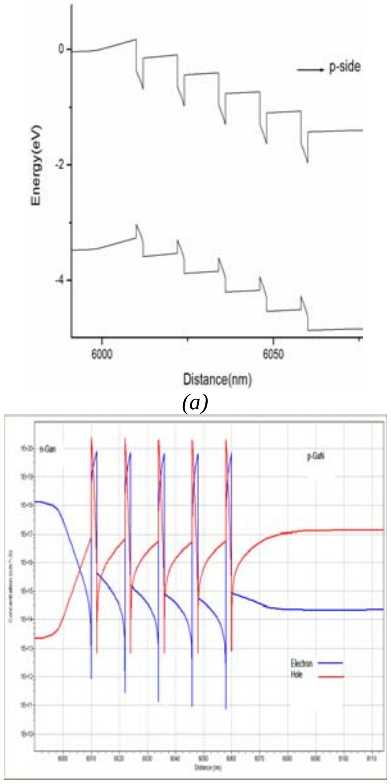
Fig. 2. (a) Band diagram for the structure with p-AlGaN EBL; (b) and corresponding carrier concentration plot with distance.



(a)

(b)

Fig. 3. (a) Band diagram for the structure with n-AlGaN EBL (b) and corresponding carrier concentration plot with distance.



(a)

(b)

Fig. 4. (a)Band diagram for the structure without any EBL (b) and corresponding carrier concentration plot with distance.

Figs. 2, 3 and 4 describe the calculated band diagrams of LEDs at a current density of 140 A/cm^2 to explain the effect of EBL at relatively higher current density in detail. The band diagrams were obtained by using the LED simulator SILENSE. Figs. 2 and 3 show that there are spikes and notches in the valence bands [circles in Figs. 2 and 3] at the interfaces of the GaN barrier/p-AlGaN EBL/p-GaN due to the existence of a polarization field in the three layers. Holes from p-GaN tend to accumulate at the notch and spread laterally (normal in the growth direction), and holes feel a potential barrier at the spike and the hole injection to the MQW is limited by the existence of the EBL. Same spikes and notches are present in the valence band of n-AlGaN case, blocking electron injection from n-GaN side. However, there is no spike or notch in the valence band of structure without EBL, as shown in Fig.4.

Figs. 2(b), 3(b) and 4(b) are the calculated carrier concentrations at 140 A/cm2 for the structures with p-AlGaN EBL, n-AlGaN EBL and without any EBL respectively, using same simulator. Electrons are uniformly distributed throughout the entire MQW region, but hole distribution is quite different in LEDs with and without an EBL. In Fig. 4(b) it can be seen that the carrier concentration is relatively uniform in the MQW. However, in Figs. 2(b) and 3(b), the concentration of the hole shows non uniform distribution and decreases rapidly as the position of the well layer moves farther from p-GaN. Figs. 2(b) and 3(b), also show that the concentration of the hole drastically increases at the interface between the EBL and the p-GaN layer due to a notch in the valence band [as shown in circles in Figs. 2(b) and 3(b)], which forms a two-dimensional hole gas-like layer. However, the hole concentration decreases rapidly across the MQW region due to a potential spike at the interface between the GaN barrier and the EBL in LEDs with EBL structure as shown in Figs. 2(a) and 3(a). Figs. 2(b), 3(b) and 4(b) show that the calculated hole concentrations of the well near p-GaN in LEDs with p-AlGaN EBL, with n-AlGaN EBL, and without EBL are 1e10^{16} /cm^3, 1e10^{20} /cm^3, and 1.5e10^{20} /cm^3, respectively, while electron concentrations of three LEDs are fairly constant and uniformly distributed across the MQW region. These results indicate that hole injection is decreased by EBL.

In the next stage, we explain the difference of IQE behavior of LEDs with and without an EBL at low and high current densities as followings. At low current density, EBL can effectively block the electron flow by a high barrier height between GaN barrier and EBL in conduction band and the confined electrons can participate in radiative recombination. Meanwhile, the accumulated holes at the notch formed between EBL and p-GaN can easily tunnel into MQW region via EBL with the assistance of intermediate states in EBL, even though EBL appears to block holes in the valence band. As a result, LEDs with an EBL show higher IQE at low current density. At high current density, however, EBL cannot effectively block electrons due to the decreased potential barrier height between GaN barrier and EBL in conduction band, as shown in Figs. 2(a) and 3(a), and electrons tend to overflow. This indicates that the electron concentrations in three LEDs at high current density are not significantly different and the hole injection process to the MQW region becomes a limiting factor in determining IQE. Furthermore, the hole transport to the MQW is dominated by a diffusion process since the tunneling process is negligible compared to the diffusion process at high current density [10]. Consequently, the potential barrier due to EBL suppresses the diffusion of holes from the p-GaN layer to the MQW region at high current density, resulting in a lower IQE of LEDs with an EBL compared to LEDs without an EBL.

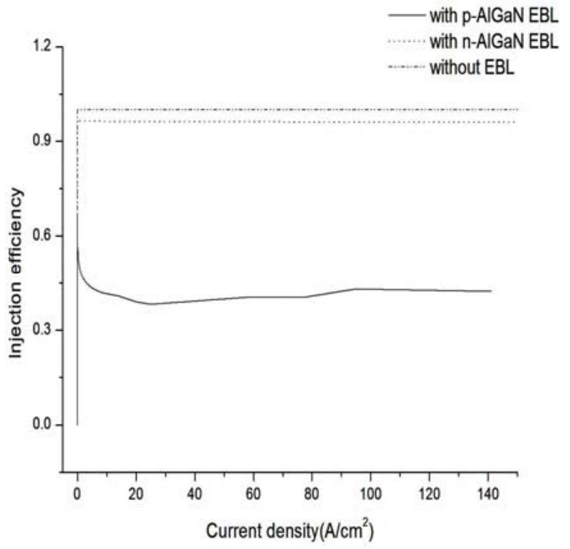


Fig. 5. Injection efficiency verses current density curve for the structure with p-AlGaN EBL, n-AlGaN EBL and without any EBL.

Fig. 5 shows that injection increases for structure without EBL as compared to p-AlGaN EBL and n-AlGaN EBL. The structure having n-AlGaN EBL has higher injection efficiency than p-AlGaN EBL because of less EBL barrier height in n-AlGaN case as shown in Figs. 2 and 3.

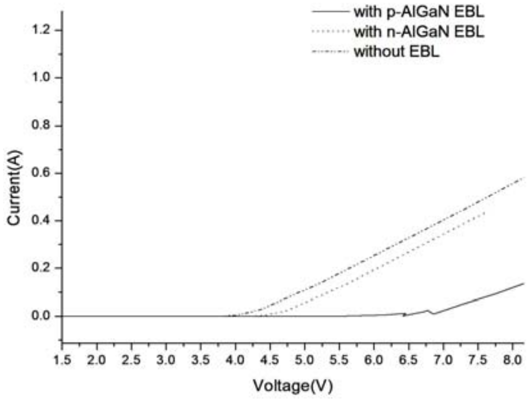


Fig. 6. I-V characteristics for the structure with p-AlGaN EBL, n-AlGaN EBL and without any EBL.

Fig. 6 shows the V-I (voltage-current) characteristics of LEDs. It was observed that for without EBL structure has less turn-on voltage. The increase in forward voltage can be attributed to an increase in the series resistance due to the blocking of the hole flow by an increase of the band offset in the valance band of a MQW.

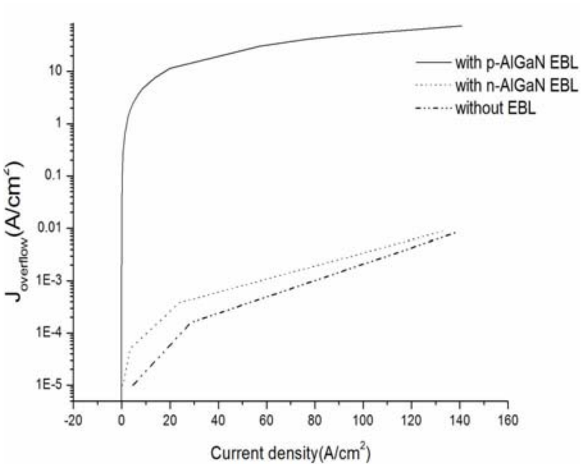


Fig. 7. Variation of overflow density for the structure with p-AlGaN EBL, n-AlGaN EBL and without any EBL.

At high current density EBL cannot effectively block electrons due to the decreased potential barrier height between GaN barrier and EBL in conduction band, as shown in Figs. 2 and 3 therefore electrons tend to overflow. It can be clearly seen from the Fig. 7 that without EBL has less overflow.

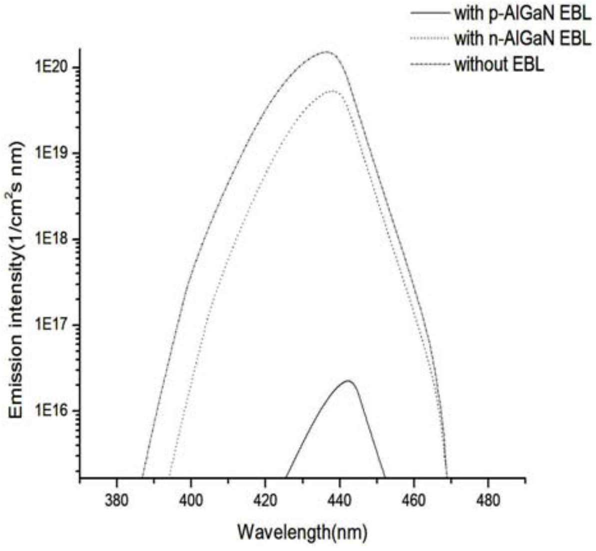


Fig. 8. Emission intensity verses wavelength curve for the structure with p-AlGaN EBL, n-AlGaN EBL and without any EBL.

Emission intensity increases for blue LED without an EBL as compared to p-AlGaN EBL and n-AlGaN EBL because of higher radiative recombination rate, as shown in Fig. 8. Also bandwidth of emission spectra is found to be broader in case of the LED structure without EBL, without changing peak wavelength.

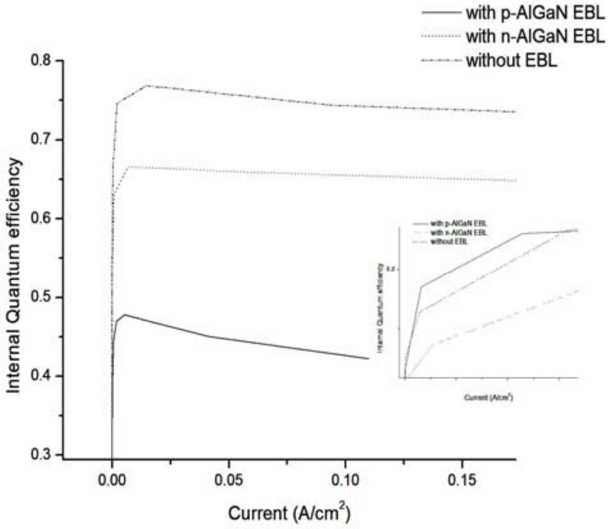


Fig. 9. Variation of IQE for the structure with p-AlGaN EBL, n-AlGaN EBL and without any EBL.

At low current density, IQE for EBL structure is higher. However, IQE for LED without an EBL is higher as compared to p-AlGaN EBL and n-AlGaN EBL at higher current density as displayed in Fig. 9. Increased radiative recombination rate due to an increased hole concentration is the main reason for the higher IQE.

5. Conclusions

We investigated the effect of the AlGaN EBL on efficiency droop in InGaN/GaN MQW LEDs. At low current density, LEDs with p-AlGaN EBL show a higher IQE than LEDs with n-AlGaN and without EBL. However, LEDs without an EBL show a higher IQE at high current density. The suppression of efficiency droop in LEDs without an EBL at high current density is attributed to an increased hole injection efficiency.

Acknowledgments

Authors gratefully acknowledge support by Director, C.E.E.R.I., Pilani.

References

[1] H. Morkoc, Handbook Of Nitride Semiconductors And Devices Wiley-VCH, Berlin (2008)
[2] M. H. Kim, M. F. Schubert, Q. Dai , J. K. Kim, E. F. Schubert , J. Piprek, Y. Park, **91**, 1835071 (2007).
[3] J. S. Cabalu, C. Thomidis, T. D. Moustakas, S. Riyopoulos, L. Zhou, D. J. Smith, J. Appl. Phys. **99**, 064904-1 (2006).

[4] J. Piprek, Semiconductor Optoelectronic Devices Academic Press, San Diego, 2003.
[5] M. Shatalov, A. Chitnis, A. Koudymov, J. Zhang, V. Adivarahan, G. Simin, M. A. Khan, Japanese Journal of Applied Physics. **41**, L1146 (2002).
[6] C. H. Jang, J. K. Sheu, C. M. Tsai, S. C. Shei, W. C. Lai, S. J. Chang, IEEE Photonics Technology Letters. **20**, 1142 (2008).
[7] G. Franssen, P. Perlin, T. Suski, Phys. Rev. B. **69**, 045310 (2004).
[8] E. F. Schubert Light-Emitting Diodes Cambridge University Press, Cambridge 2003.
[9] S. H Yen, M. C. Tsai, M. L. Tsai, Y. J. Shen, T. C. Hsu, Y. K. Kuo, IEEE Photonics Technology Letters. **21**, 975 (2009).
[10] S. H. Han, D. Y. Lee, S. J. Lee, C. Y. Cho, M. K. Kwon, S. P. Lee, D. Y. Noh, D. J. Kim, Y. C. Kim, S. J. Park, Applied Physics Letters **94**, 231123 (2009).

---

[*] Corresponding author: sumitra@ceeri.ernet.in