Effect of electron blocking layer on efficiency droop in InGaN/GaN multiple quantum well light-emitting diodes

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The effect of an electron blocking layer (EBL) on the efficiency droop in InGaN/GaN multiple quantum well light-emitting diodes (LEDs) is investigated. At low current density, the LEDs with a *p*-AlGaN EBL show a higher external quantum efficiency (EQE) than LEDs without an EBL. However, the EQE of LEDs without an EBL is higher than LEDs with an EBL as injection current density is increased. The improved EQE of LEDs without an EBL at high current density is attributed to the increased hole injection efficiency. © *2009 American Institute of Physics*.
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Recently, there has been much progress in the performance of InGaN/GaN light-emitting diodes (LEDs). As the efficiency of LEDs improves, LEDs find more applications such as back light unit, automotive headlights, and general illumination.[1] However, as injection current increases in InGaN/GaN multiple quantum well (MQW) LEDs, we observe a unique phenomenon called "efficiency droop" that is the reduction in LED efficiency at high injection current density.[2] It was reported that Auger nonradiative recombination plays a major role in the efficiency droop of MQW LEDs at high current density and a double-heterostructure is proposed as an active layer to solve the problem.[3,4] Kim *et al.*[5] reported that a polarization field in the active region, due to a lattice mismatch between the InGaN well layer and the GaN barrier layer of MQWs, causes inadequate confinement of electrons in the active region, which then causes electron overflow to the *p*-type region and results in an efficiency droop. In addition, it has been reported that at high current density, the carriers escape from In localized states and recombine nonradiatively in high-density defect sites.[2,6] The dependence of dislocation density and well thickness on efficiency droop has also been reported as an explanation for electron overflow as a major cause of efficiency droop.[7,8] However, the origin of efficiency droop is still under debate. To improve the efficiency of MQW LEDs, the electron blocking layer (EBL) has played an important role in effectively confining electrons in the MQW region of most MQW LEDs.[9] In this study, we investigated the effect of EBL on efficiency droop in InGaN/GaN MQW LEDs.

InGaN/GaN MQW LEDs were grown on a (0001) sapphire substrate using metal organic chemical vapor deposition. At first, a sapphire substrate was cleaned in H_2 at 1020 °C, followed by the growth of a 25 nm thick low temperature GaN buffer layer at 550 °C. After high temperature annealing of the buffer layer, 5 μm thick undoped GaN and Si doped *n*-GaN layers were grown at a temperature of 1100 °C. Then, an InGaN/GaN MQW consisting of five pairs of 3 nm undoped InGaN wells and 12 nm Si doped GaN barriers was grown on an *n*-GaN layer. For a comparative study, three LED samples were prepared. For LED A, Mg doped *p*-GaN contact layer was grown directly on the MQW without a *p*-AlGaN EBL with a thickness of 150 nm. In LEDs B and C, Mg doped *p*-AlGaN EBLs with Al compositions of 22% and 32% were grown on the MQWs, respectively, followed by the *p*-GaN contact layer. The Al composition of the *p*-AlGaN EBLs was measured using high resolution x-ray diffraction ω-2θ scans for the GaN (0004) reflection (data not shown). The thickness of the *p*-AlGaN EBL was 40 nm. LEDs with a size of 550×550 μm^2 were fabricated using a conventional mesa structure method. Indium tin oxide was used as a transparent conducting layer and Cr/Au was deposited as *n*-type and *p*-type electrodes. The measured peak wavelength of electroluminescence was 450 nm at 20 mA. The light output power of packaged LEDs was measured in an integrating sphere at room temperature in an ac current mode with a pulse duration of 1 ms to eliminate the heating effect.

Figure 1 shows the measured voltage-current (*V-I*) curve of the LEDs. In LEDs A, B, and C, the forward voltages at 20 mA are 3.03, 3.12, and 3.20 V, respectively. The increment in forward voltage in LEDs with an EBL is attributed to low hole concentration in *p*-AlGaN due to a high Mg activation energy for the *p*-AlGaN layer ($\geq$200 meV), as compared to *p*-GaN.[10] Figures 2(a) and 2(b) show the light output power of LEDs A, B, and C as a function of current

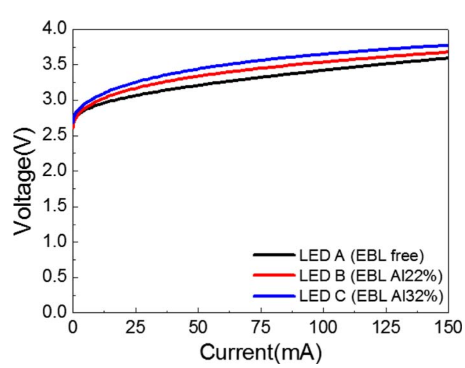

FIG. 1. (Color online) *V-I* curves of the LEDs A, B, and C.

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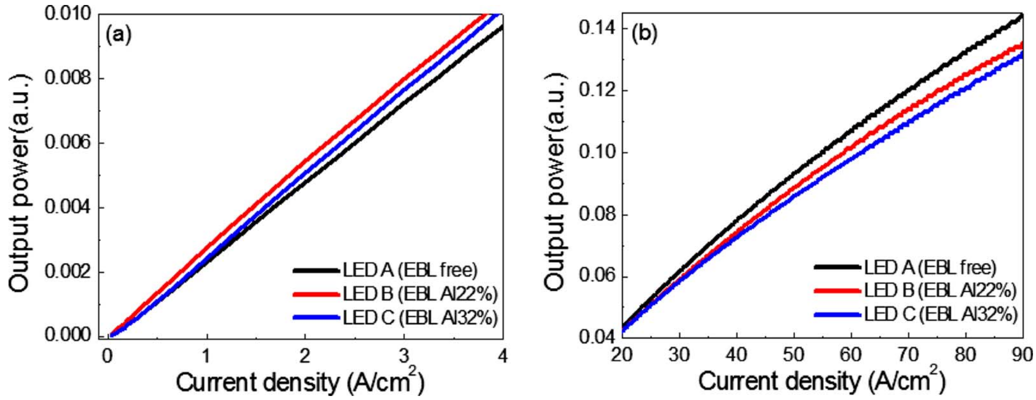

FIG. 2. (Color online) Light output power vs current density of LEDs A, B, and C, (a) at low current density and (b) at high current density.

density. Figures 2(a) and 2(b) show that the output power of the three LEDs increases sublinearly as the current density increases. At low current density [Fig. 2(a)], the output power of LEDs B and C is higher than LED A. However, as current density further increases [Fig. 2(b)], the output power of LED A surpasses other LEDs, and the difference of output power becomes larger as the current density increases. Figure 3 is the measured external quantum efficiency (EQE) for all three LEDs. All the LEDs show a maximum EQE at very low current density (below 5 A/cm^2), then the EQE drops rapidly with current density. At low current density (below 15 A/cm^2), the EQE of LEDs B and C is higher than LED A. However, at a current density of about 15 A/cm^2, the EQE of LED A surpasses the EQE of LEDs B and C, and the EQE of LED A is higher by 5.6% and 8.6% than those of LEDs B and C, respectively, at 90 A/cm^2. This result is very interesting because most LEDs use an EBL to improve efficiency by confining electrons in the MQW, but this study shows that the EQE of LEDs without an EBL is higher than that of LEDs with an EBL at high current density. Therefore, efficiency droop is improved in LEDs without an EBL.

Figures 4(a)–4(c) are the calculated band diagrams of LEDs A, B, and C at 90 A/cm^2 to explain the effect of EBL at high current density in detail. The band diagrams were obtained by using the LED simulator SILENSE. Figures 4(b) and 4(c) show that there are spikes and notches in the valence bands [circles in Figs. 4(b) and 4(c)] at the interfaces of the GaN barrier/*p*-AlGaN EBL/*p*-GaN due to the existence of a polarization field in the three layers.[11] 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. However, there is no spike or notch in the valence band of LED A, as shown in Fig. 4(a). Figures 4(d)–4(f) are the calculated carrier concentrations at 90 A/cm^2 for LEDs A, B, and C, 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(d), it can be seen that even though the concentration of the hole decreases in the well near *n*-GaN, it is relatively uniform in the MQW. However, in Figs. 4(e) and 4(f), the concentration of the hole shows nonuniform distribution and decreases rapidly as the position of the well layer moves farther from *p*-GaN. Figures 4(e) and 4(f) 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. 4(e) and 4(f)], 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 B and C, as

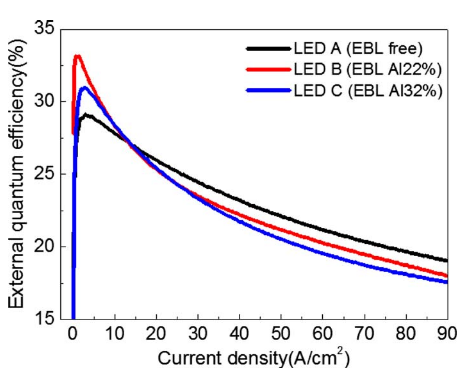

FIG. 3. (Color online) EQE vs current density of LEDs A, B, and C.

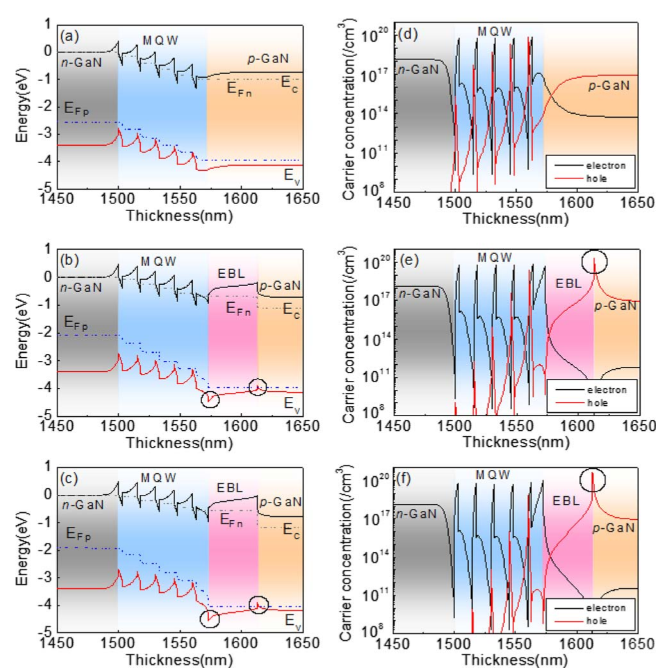

FIG. 4. (Color online) Calculated band diagrams of LEDs at 90 A/cm^2, (a) LED A, (b) LED B, and (c) LED C. Calculated carrier concentrations of LEDs at 90 A/cm^2, (d) LED A, (e) LED B, and (f) LED C.

TABLE I. Estimated efficiencies of the well near p-GaN in LEDs A, B, and C at 90 A/cm^2. A is the Shockley–Read–Hall recombination coefficient (5.4×10^7/s), B is the bimolecular recombination coefficient (2.0×10^{-11} cm^3/s), C is the Auger recombination coefficient (2.0×10^{-30} cm^6/s) (Ref. 3), n is the electron concentration, and p is the hole concentration.

	n (/cm^3)	p (/cm^3)	An (/cm^3 s)	Bnp (/cm^3 s)	Cn^2p (/cm^3 s)	Efficiency (%)
LED A	6.69×10^{19}	6.67×10^{19}	3.61×10^{27}	8.92×10^{28}	5.97×10^{29}	12.9
LED B	6.73×10^{19}	2.27×10^{19}	3.63×10^{27}	3.06×10^{28}	2.06×10^{29}	12.7
LED C	6.71×10^{19}	6.61×10^{18}	3.62×10^{27}	8.87×10^{27}	5.95×10^{28}	12.3

shown in Figs. 4(b) and 4(c). Figures 4(d)–4(f) show that the calculated hole concentrations of the well near p-GaN in LEDs A, B, and C are 6.67×10^{19}/cm^3, 2.27×10^{19}/cm^3, and 6.61×10^{18}/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 and deteriorated with increasing Al composition of the EBL.

We explain the difference of EQE 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.[12,13] As a result, LEDs with an EBL show higher EQE 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. 4(b) and 4(c), and electrons tend to overflow.[5] 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 EQE. 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. 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 EQE of LEDs with an EBL compared to LEDs without an EBL.

We estimated the efficiencies of the well near p-GaN in three LEDs at 90 A/cm^2 and the results are summarized in Table I. The efficiency was calculated by using the following equation:

$$\text{Efficiency} = \frac{Bnp}{An + Bnp + Cn^2p}, \tag{1}$$

where n and p are electron and hole concentration, respectively. A, B, and C are coefficients of Shockley–Read–Hall nonradiative recombination, bimolecular radiative recombination, and Auger nonradiative recombination, respectively, and the values of these coefficients are shown in Ref. 3. As shown in Table I, the calculated efficiencies of three LEDs show the same trend as compared to that of Fig. 3 obtained at 90 A/cm^2. Equation (1) can be rewritten to show an important factor, which dominates the efficiency in three LEDs, as follows:

$$\text{Efficiency} = \frac{1}{\dfrac{An}{Bnp} + 1 + \dfrac{Cn}{B}}. \tag{2}$$

Cn/B is a constant value since the electron concentrations are almost same in three LEDs. Equation (2) shows that the efficiency is increased with increasing the hole concentration (p) and bimolecular radiative recombination rate (Bnp). This indicates that the increased bimolecular radiative recombination rate due to an increased hole concentration is the main reason for the higher EQE and the suppression of efficiency droop of LEDs without an EBL at high current density.

In conclusion, we investigated the effect of the p-AlGaN EBL on efficiency droop in InGaN/GaN MQW LEDs. At low current density, LEDs with an EBL show a higher EQE than LEDs without an EBL. However, LEDs without an EBL show a higher EQE at high current density. The increment in EQE for LEDs without an EBL is 5.6% and 8.6% at 90 A/cm^2, compared to LEDs with a p-$Al_{0.22}GaN$ and a p-$Al_{0.32}GaN$ EBL, respectively. The suppression of efficiency droop in LEDs without an EBL at high current density is attributed to an increased hole injection efficiency.

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[1]E. F. Schubert and J. K. Kim, Science **308**, 1274 (2005).
[2]T. Mukai, M. Yamada, and S. Nakamura, Jpn. J. Appl. Phys., Part 1 **38**, 3976 (1999).
[3]Y. C. Shen, G. O. Mueller, S. Watanabe, N. F. Gardner, A. Munkholm, and M. R. Krames, Appl. Phys. Lett. **91**, 141101 (2007).
[4]N. F. Gardner, G. O. Mueller, Y. C. Shen, G. Chen, S. Watanabe, W. Goetz, and M. R. Krames, Appl. Phys. Lett. **91**, 243506 (2007).
[5]M. H. Kim, M. F. Schubert, Q. Dai, J. K. Kim, E. F. Schubert, J. Piprek, and Y. Park, Appl. Phys. Lett. **91**, 183507 (2007).
[6]Y. Yang, X. A. Cao, and C. Yan, IEEE Trans. Electron Devices **55**, 1771 (2008).
[7]M. F. Schubert, S. Chhajed, J. K. Kim, E. F. Schubert, D. D. Koleske, M. H. Crawford, S. R. Lee, A. J. Fischer, G. Thaler, and M. A. Banas, Appl. Phys. Lett. **91**, 231114 (2007).
[8]Y.-L. Li, Y.-R. Huang, and Y.-H. Lai, Appl. Phys. Lett. **91**, 181113 (2007).
[9]E. F. Schubert, *Light-Emitting Diodes* (Cambridge University Press, Cambridge, 2003).
[10]M. Suzuki, J. Nishio, M. Onomura, and C. Hongo, J. Cryst. Growth **189**, 511 (1998).
[11]S. Heikman, S. Keller, Y. Wu, J. S. Speck, S. P. DenBaars, and U. K. Mishra, J. Appl. Phys. **93**, 10114 (2003).
[12]X. A. Cao, E. B. Stokes, P. M. Sandvik, S. F. LeBoeuf, J. Kretchmer, and D. Walker, IEEE Electron Device Lett. **23**, 535 (2002).
[13]C. L. Reynolds, Jr., and A. Patel, J. Appl. Phys. **103**, 086102 (2008).