AIP Applied Physics Letters

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Citation: Applied Physics Letters **99**, 171106 (2011); doi: 10.1063/1.3655903
View online: http://dx.doi.org/10.1063/1.3655903
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/99/17?ver=pdfcov
Published by the AIP Publishing

Hole transport improvement in InGaN/GaN light-emitting diodes by graded-composition multiple quantum barriers

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(Received 4 July 2011; accepted 30 September 2011; published online 25 October 2011)

Graded-composition multiple quantum barriers (GQB) were designed and incorporated in c-plane InGaN/GaN light-emitting diodes (LEDs) grown on c-plane sapphire substrate to improve hole transport and efficiency droop. The simulation of GQB LED design predicts enhancement of the hole transport in the active region at both low and high current densities. The fabricated LED with GQB structure exhibits lower series resistance and substantially reduced droop behavior of only 6% in comparison with 34% for conventional LED, supporting the improvement of hole transport in our design. © *2011 American Institute of Physics*. [doi:10.1063/1.3655903]

InGaN/GaN light-emitting diodes (LEDs) grown on c-plane sapphire substrate have recently become a favorable choice for applications in energy saving solid-state lighting.[1] One key feature that still needs to be solved is the so-called "efficiency droop." Despite the various arguments have been proposed and discussed, electron overflow out of the active region, Auger recombination, and insufficient transport of holes have been identified as the most possible reasons for droop.[2–4] Among these factors, poor transport of holes might be the most important one. Because it could lead to the accumulation of these carriers at the quantum wells near *p*-GaN, which increase the possibilities for the overflow of electrons and Auger recombination at high carrier concentration. As a result, improving hole transport in the active region has been proposed as a mean to reduce droop behavior. Various designs such as coupled multiple quantum wells (MQWs),[5] non-polarized active region,[6] and graded-well-thickness structure[7] were reported and proved to be effective. In our former research work, we have demonstrated that leveling the triangular barriers at valence band by using a graded-composition electron blocking layer (GEBL) can effectively enhance the transport of holes across the EBL.[8] In this paper, we report a new design of the barrier layers in MQWs by grading the composition of barriers from $In_xGa_{1-x}N$ to GaN along [0001] direction, to form a graded-composition multiple quantum barriers (GQB) and show the improvement in transport of holes in active region and substantial reduction in efficiency droop behavior. The injected holes do not accumulate at the well closest to *p*-GaN, denoted as the last well, and uniformly spread in the active region. The droop behavior predicted by our simulation agrees well with the experiments.

For conventional LEDs operated under forward bias, the band diagram of multiple quantum barriers (MQBs) shows triangular shape due to the internal polarization field and forward bias,[6] as shown in Fig. 1. The valance band of MQBs shows an upward slope from the *n*-GaN side toward *p*-GaN side, which retards the holes to travel across the triangular barrier. But if the composition of indium in barriers decreases from the *n*-GaN side toward *p*-GaN side, the bandgap broadens gradually. As a result, the barrier in valance band could be leveled down and even overturned, while the slope of conduction band could be enhanced. This could enhance the hole transporting across the barriers.

We then simulated the band diagrams and carrier distributions in GQB LED using APSYS simulation software. The simulation LED structures were composed of 4-μm-thick *n*-type GaN layer (*n*-doping $= 2 \times 10^{18}\,cm^{-3}$), six pairs of $In_{0.15}Ga_{0.85}N$/GaN MQWs with 2.5-nm-thick wells and 10-nm-thick barriers, 20-nm-thick *p*-$Al_{0.15}Ga_{0.85}N$ EBL (*p*-doping $= 5 \times 10^{17}\,cm^{-3}$), and 200-nm-thick *p*-type GaN layer (*p*-doping $= 1 \times 10^{18}\,cm^{-3}$). For the GQB LED, the composition of indium was graded from 5% to 0% along [0001] direction and compared with the conventional LED with GaN barriers. Commonly accepted physical parameters were adopted to perform the simulations, the percentage of screening effect of 50%, the Shockley-Read-Hall recombination lifetime of 1 ns, and the Auger recombination coefficient in quantum wells with order of 10^{-31} cm^6/s, respectively.[9] Other material parameters used in the simulation can be referred to Ref. 10. The calculated band diagrams of conventional and GQB LEDs at current density of 100 A/cm^2 are shown in Fig. 1. The triangular barriers in valance band are partially leveled in GQB LED. Unexpectedly, the quasi-Fermi-level for holes in GQB LED is lower than that of conventional LED. This phenomenon could further favor the transport of holes in active region.

Figures 2 and 3 show the calculated carrier concentration in the active region for conventional and GQB LEDs at current density of 20 and 200 A/cm^2, respectively. At low current density of 20 A/cm^2, holes appear to hop out of the

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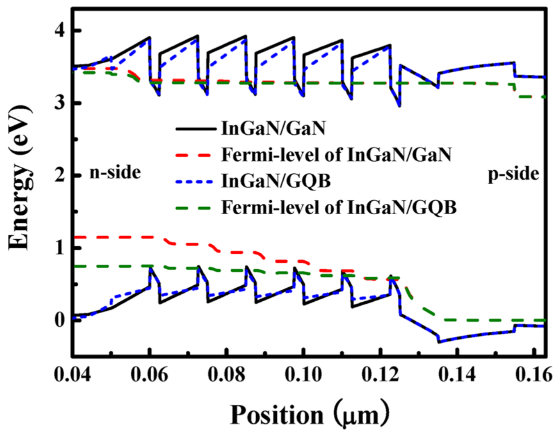

FIG. 1. (Color online) Calculated band diagrams of the conventional and GQB LEDs.

last well and spread to the others for GQB LED, as shown in Fig. 2(b). The hole concentrations in the last well are about 8.5×10^{28} and $3.5 \times 10^{28}\,\text{cm}^{-3}$ for conventional and GQB LEDs, respectively. While they are about 1.3×10^{28} and $5.8 \times 10^{28}\,\text{cm}^{-3}$ in the fifth well for conventional and GQB LEDs, respectively. These results indicate that GQB LED has better hole transport even at low current density, lowering the hole concentration at the last well. At high current density of 200 A/cm^2, hole distribution in GQB LED is more uniform than that at low current density. Such improved hole distribution is useful for droop reduction.[5] Meanwhile, the calculated electron concentration in the active region for conventional and GQB LEDs was shown in Figs. 2 and 3. At either low or high current density, electron concentration in GQB LED is higher than that in conventional LED, which could be attributed to lower electron overflow for GQB LED. The distribution of electrons in GQB LED seems to be more uniform than that in conventional LED, which might corresponds to better transport of holes. From the simulation results, hole and electron distributions in GQB LEDs, either at low or high current density, are favorable for reduction of droop behavior.

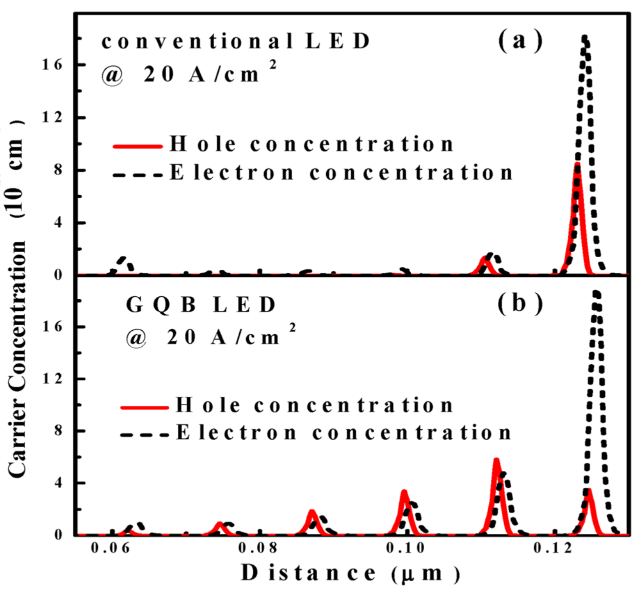

FIG. 2. (Color online) Calculated carrier concentrations at current density of 20 A/cm^2 for (a) conventional and (b) GQB LEDs.

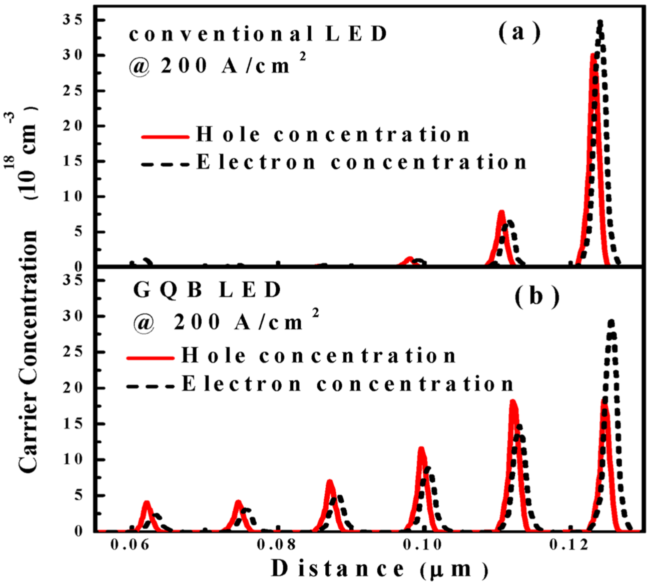

FIG. 3. (Color online) Calculated carrier concentrations at current density of 200 A/cm^2 for (a) conventional and (b) GQB LEDs.

In light of simulation results, we have grown the LED structures with GaN barriers and GQB on c-plane sapphire substrates by metal-organic chemical vapor deposition (MOCVD). After depositing a low temperature GaN nucleation layer, a 4 μm n-type GaN layer, and ten-pair InGaN/GaN superlattice prestrain layer, the rest of the LED structures were grown based on our simulation design. The graded composition barriers were grown using In/Ga ratio ramping to prevent the change in the growth rate. Finally, the LED chips were fabricated by regular chip process with ITO current spreading layer and Ni/Au contact metal. The LED has a typical chip size of $300 \times 300\,\mu\text{m}^2$. The emission wavelengths of both types of LEDs were around 450 nm at 22 A/cm^2.

The *I-V* characteristics of conventional and GQB LEDs are shown in the inset of Fig. 4. The series resistance is

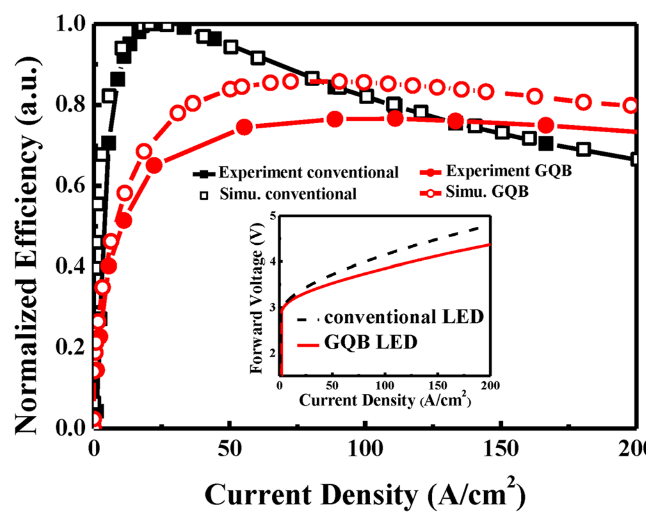

FIG. 4. (Color online) Experiment and simulation normalized efficiency for conventional and GQB LEDs. The inset figure shows *I-V* characteristics of conventional and GQB LEDs.

reduced from 8.2 Ω in conventional LED to 6.5 Ω in GQB LED, which indicates a certain degree of the improvement in hole transport. As a result, the forward voltage at 22 A/cm^2 is reduced from 3.4 V in conventional LED to 3.27 V in GQB LED. The normalized efficiency of conventional and GQB LEDs as a function of current density was investigated by experiment and simulation, as illustrated in Fig. 4. It can be seen that the experimental data have similar droop behavior to simulation results. However, the efficiency of GQB LED shows slightly lower value in experiment. This can be attributed to non-optimized epitaxial parameters for graded-composition barriers. The most important result is the reduction of efficiency droop, defined as $(\eta_{peak} - \eta_{200\,Acm^{-2}})/\eta_{peak}$, which is reduced from 34% for conventional LED to 6% for GQB LED. This result confirms that the graded barrier design did contribute to the reduction of efficiency droop.

Although the efficiency droop has been reduced, the efficiency of GQB LED at 20 A/cm^2, which is the typical operation current density for most LEDs, is only 70% of that of conventional LED. This phenomenon has also been observed in other droop-reduction methods related to the layer design of MQBs (Ref. 5) or low polarization field structures.[6,11] To understand this, the radiative recombination distribution in the active region for both LEDs was calculated and illustrated in Fig. 5. The results show that the radiative recombination distribution in GQB LED is more uniform than that in conventional LED, at current density of 20 A/cm^2; however, the total amount of radiative recombination in GQW LED is only 70% of that in conventional LED. At 200 A/cm^2, the total amount of radiative recombination in GQW LED is 119% of that in conventional LED. The reason could be referred to the poor spatial distribution overlap between holes and electrons. For good hole transport as GQB LED, the spatial distributions of holes and electrons are quite different. As shown in Figs. 2 and 3, at current density of 20 A/cm^2, most of the electrons still concentrate in the last well, while the hole concentration in the last well is less than that in fifth well. That is, the spatial overlap between electrons and holes in GQB LED is not the optimal situation at low current density. While at 200 A/cm^2, such mismatch is alleviated due to much more holes are injected. However, in conventional LED, both holes and electrons concentrate at the wells near *p*-GaN, so the radiative recombination is quite effective at that location. These results indicate that to reduce droop behavior without deteriorating the total recombination, one should pay more attention to the spatial distribution between holes and electrons.

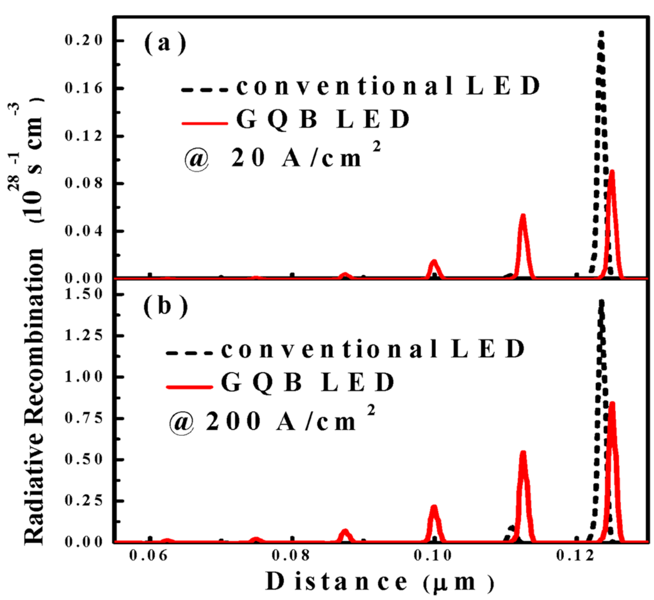

FIG. 5. (Color online) Calculated radiative recombinations of conventional and GQB LEDs at current density of (a) 20 A/cm^2 and (b) 200 A/cm^2.

In summary, we have designed a graded-composition multiple quantum barriers for InGaN/GaN LED to improve the hole transport in active region. The simulation results showed that the triangular barrier of multiple quantum barriers at valance band could be balanced by increasing the band gap of $In_xGa_{1-x}N$ along [0001] direction. As a result, the hole transport in MQWs was significantly enhanced at either low or high current density, which is beneficial for droop reduction. The GQB LED was realized by MOCVD, and the *I-V* curve showed that GQB LED has lower series resistance than the conventional one and the efficiency droop was reduced from 34% in conventional LED to only 6% in GQB LED, which is in agreement with our simulation results. Beyond these, the efficiency of GQB LED at 20 A/cm^2, was found to be only 70% of that in conventional LED. The reason for such low recombination could be attributed to the poor spatial distribution overlap between holes and electrons. These results indicate that although the improvement in hole transport facilitates the reduction of efficiency droop, spatial distribution between electrons and holes should be taken into consideration.

The authors would like to thank Dr. T.C. Hsu, Dr. M. H. Hsieh of Epistar Corporation for their technical support. This work was funded by the National Science Council in Taiwan under Grant No. NSC 100-3113-E-009-001-CC2.

[1]S. Pimputkar, J. S. Speck, S. P. DenBaars, and S. Nakamura, Nat. Photonics **3**, 180 (2009).
[2]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).
[3]A. David, M. J. Grundmann, J. F. Kaeding, N. F. Gardner, T. G. Mihopoulos, and M. R. Krames, Appl. Phys. Lett. **92**, 053502 (2008).
[4]C. H. Wang, J. R. Chen, C. H. Chiu, H. C. Kuo, Y. L. Li, T. C. Lu, and S. C. Wang, IEEE Photon. Technol. Lett. **22**, 236 (2010).
[5]X. Ni, Q. Fan, R. Shimada, Ü. Özgür, and H. Morkoç, Appl. Phys. Lett. **93**, 171113 (2008).
[6]S. C. Ling, T. C. Lu, S. P. Chang, J. R. Chen, H. C. Kuo, and S. C. Wang, Appl. Phys. Lett. **96**, 231101 (2010).
[7]C. H. Wang, S. P. Chang, W. T. Chang, J. C. Li, Y. S. Lu, Z. Y. Li, H. C. Yang, H. C. Kuo, T. C. Lu, and S. C. Wang, Appl. Phys. Lett. **97**, 181101 (2010).
[8]C. H. Wang, C. C. Ke, C. Y. Lee, S. P. Chang, W. T. Chang, J. C. Li, Z. Y. Li, H. C. Yang, H. C. Kuo, T. C. Lu, and S. C. Wang, Appl. Phys. Lett. **97**, 261103 (2010).
[9]J. Piprek, *Nitride Semiconductor Devices: Principles and Simulation* (Wiley, Berlin, 2007), p. 279.
[10]I. Vurgaftman and J. R. Meyer, J. Appl. Phys. **94**, 3675 (2003).
[11]M. F. Schubert, J. Xu, J. K. Kim, E. F. Schubert, M. H. Kim, S. Yoon, S. M. Lee, C. Sone, T. Sakong, and Y. Park, Appl. Phys. Lett. **93**, 041102 (2008).