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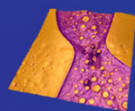
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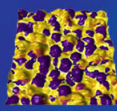
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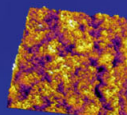


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Improved hole distribution in InGaN/GaN light-emitting diodes with graded thickness quantum barriers

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InGaN/GaN light-emitting diodes (LEDs) with graded-thickness quantum barriers (GTQB) are designed and grown by metal-organic chemical-vapor deposition. The proposed GTQB structure, in which the barrier thickness decreases from the n-GaN to p-GaN side, was found to lead to an improved uniformity in the hole distribution and thus, radiative recombination rates across the active region. Consequently, the efficiency droop was reduced to 28.4% at a current density of 70 A/cm², which is much smaller than that of the conventional equal-thickness quantum barriers (ETQB) LED, which is 48.3%. Moreover, the light output power was enhanced from 770 mW for the ETQB LEDs to 870 mW for the GTQB LEDs at 70 A/cm². © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4811698>]

GaN light-emitting diodes (LEDs) industry has boomed up for many years as it is believed that LEDs will replace the traditional lighting systems as the next generation lighting source. However, there are still some issues to be overcome before the LEDs could penetrate extensively into the lighting market. One of the issues is the efficiency droop,¹ which is a well-known problem that the internal quantum efficiency (IQE) decreases with the increasing injection current. The reasons of the droop, though it still remains debatable, may stem from the electron overflow,² Auger recombination,³ and/or insufficient hole injection.⁴ A lot of experiments and simulations have been carried out to address this problem. For example, hole transport and distribution improvement across the multiple quantum wells (MQWs) have been considered both theoretically and experimentally through the quantum barrier (QB) architecture design, including p-doped QBs,⁵ p-InGaN as last QB,⁶ and a graded indium composition in the QBs.⁴ All these designs on QBs have already shown promising results on the alleviation of efficiency droop problem with the reported experimental support. Unfortunately, the growth windows to realize these QB designs are quite narrow. In the design of the p-doped QBs or the p-InGaN as the last QB, the magnesium dopants could easily diffuse into the QW during the growth of the p-doped QB, which will induce nonradiative recombination centres and, hence, reduce the efficiency.⁷ Meanwhile, the graded indium content in QBs may degrade the crystal quality due to a lower growth temperature of the InGaN layer. Tsai *et al.* have shown numerical results by grading the barriers thickness through theoretical simulation.⁸ However, the corresponding experimental results, along with the experimental

analyses, are still missing and the underlying physics has not yet been investigated or proven. In this work, we present both experimental and theoretical results on the advantage of QBs with a graded thickness in homogenizing the hole distribution and suppressing the efficiency droop. In addition, here, we show that the LED with graded barriers design could outperform the LED with equal barrier thickness design only in the high-current regime, which was not revealed in the previous reports.

InGaN/GaN LEDs studied in this work were grown by an Aixtron metal-organic chemical-vapor deposition (MOCVD) system. Two-inch patterned sapphire substrates with periodic cone patterns (with a diameter of 2.4 μm, a height of 1.5 μm, and a pitch of 3 μm) were used. The growth started with a 30 nm thick low-temperature u-GaN buffer, followed by a u-GaN interlayer (~150 nm thick). Subsequently, a high-temperature u-GaN was grown with a thickness of 5 μm and followed by a 3 μm Si-doped n-GaN layer. Five pairs of MQWs with a quantum well thickness of 3 nm were grown at 750 °C using different designs of quantum barriers. The quantum barriers were grown at 800 °C. Equal-thickness quantum barrier (ETQB) LEDs with the barrier thickness of 12 nm were grown as a reference sample. The graded-thickness quantum barrier (GTQB) LEDs have graded barrier thickness, which changes from 12.0 nm, 7.2 nm, 6.6 nm, and 6.0 nm towards p-GaN (along the growth direction). The structures were finally covered with a 30 nm p-Al_{0.2}Ga_{0.8}N electron blocking layer and a 200 nm thick p-GaN layer. The indium contacts on the epi-wafers were made in a circular area of a 1.5 mm diameter for characterization purposes. Electroluminescence (EL) spectra were tested on the epi-wafers using the LED quick tester (M2442S-9A Quatek Group) and the optical power was measured by the integrating sphere attached to an Ocean

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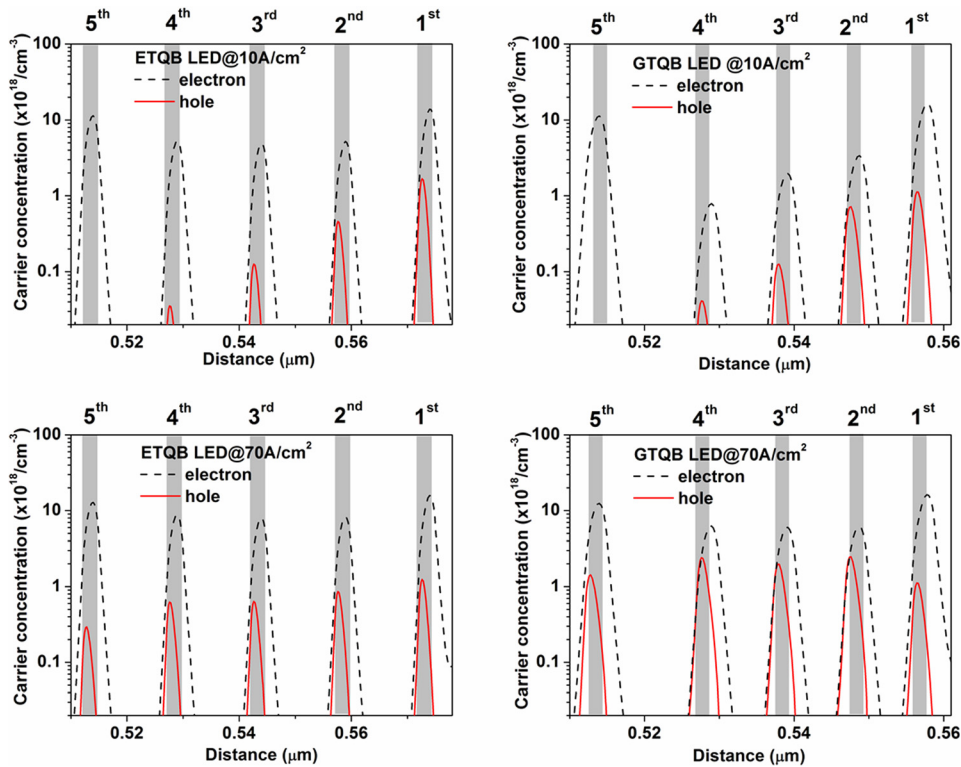


FIG. 1. Simulated electron and hole concentrations under low current (10 A/cm^2) for (a) the ETQB LED and (b) the GTQB LED. Simulated electron and hole concentrations under high current (70 A/cm^2) for (c) the ETQB LED and (d) the GTQB LEDs.

Optics spectrometer (QE65000), which was calibrated with a standard light source.

Based on our grown structures, numerical simulations were performed using APSYS to understand the working mechanisms of the two sets of LEDs. The simulator solves Schrödinger–Poisson equations self-consistently. The simulation has also taken the Coulomb interaction into consideration with the typical dielectric constants of III-nitrides.⁹ The simulation parameters including the Auger recombination coefficients, the Shockley-Read-Hall recombination coefficient, the energy band offset ratio for the MQWs, and the polarization level for devices along the *c*-orientation can be found in our previous publication.¹⁰

Figs. 1(a)–1(d) show the simulation results for the carrier concentration distribution of the ETQB and GTQB LEDs under the low current density (10 A/cm^2) and high current density (70 A/cm^2) regimes, respectively. As depicted in Figs. 1(a) and 1(b), under the low current density regime, a more uniform hole distribution in the MQWs is found in the GTQB LED compared to the ETQB LED. This is because of the thinner quantum barrier thickness in the GTQB LED enhances the tunneling of holes across the quantum barriers. On the other hand, the electron distribution is found to have

a larger penetration into the first quantum well in the GTQB LED as compared to that in the ETQB LED. This is the result of weaker quantum confinement effect of the thinner quantum barriers in the GTQB LED. Under the high current density (70 A/cm^2) regime, as shown in Figs. 1(c) and 1(d), significant hole accumulation is observed in the QWs close to the p-GaN side in the ETQB LED, which is the result of the low tunneling rate of holes caused by the thicker quantum barriers. On the contrary, a significant portion of holes penetrate into the 3rd, 4th, and 5th QWs in the GTQB LED, which makes the hole distribution in the MQWs even more uniform than the case of low current density. This could be due to the further enhancement of hole tunneling rate with a thinner quantum barrier at the high current density.

Figs. 2(a) and 2(b) show the simulated radiative recombination rates for the ETQB and GTQB LEDs, both at the low (10 A/cm^2) and high current injection (70 A/cm^2) levels, respectively. It can be seen that at the low current density of 10 A/cm^2 , the radiative recombination rate is the strongest in the first QW both for the ETQB and GTQB LEDs. The radiative recombination rate in the first QW of the GTQB LED is slightly less than that of the ETQB LED, which is due to the weaker quantum confinement effect of the thinner QB

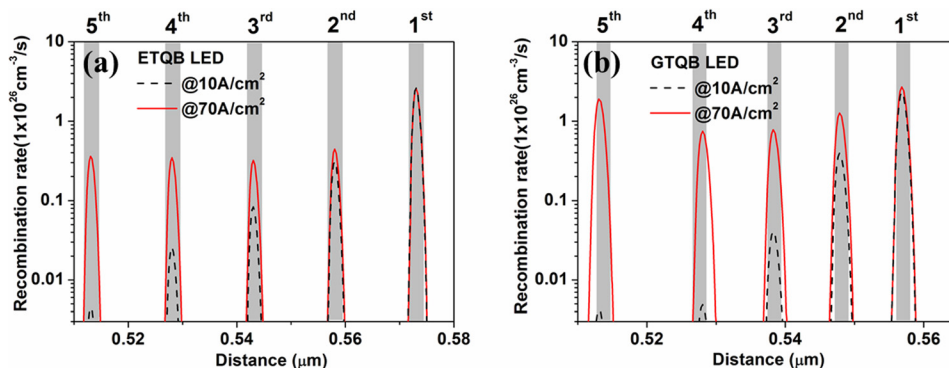


FIG. 2. Simulated recombination rate of (a) the ETQB LED and (b) the GTQB LED at low (10 A/cm^2) and high current (70 A/cm^2) injection.

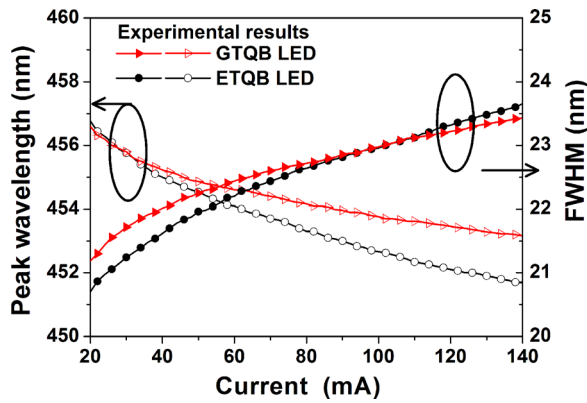


FIG. 3. Experimentally measured peak wavelength and FWHM as a function of the current for the ETQB and GTQB LEDs.

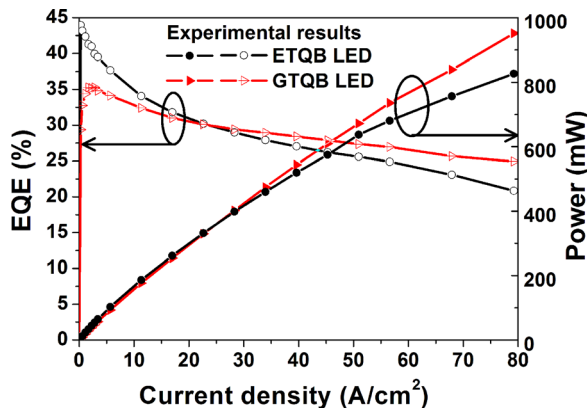


FIG. 4. Experimentally measured EQE and optical output power with increasing the current density for the ETQB and GTQB LEDs.

thickness in GTQB LED. When the current density increases to 70 A/cm^2 , the radiative recombination rates in the 3rd, 4th, and 5th QWs have been enhanced in the GTQB LED more significantly than those in the ETQB LED. The characteristics of the radiative recombination rate distribution in the ETQB LED and the GTQB LED are consistent with those of the carrier distribution (as shown in Fig. 1). This is again due to the enhanced hole transport by reducing the QB thickness in the GTQB LED.

Fig. 3 illustrates the peak wavelength and full-width at half-maximum (FWHM) of the experimentally measured EL spectra as a function of the current density for both devices. It is shown that both the emission peaks exhibit a blue shift and broadened FWHM with the increasing current density. However, the blue shift rate and the magnitude of the broadening of FWHM with the increasing current density of the GTQB LED are much smaller than those of the ETQB LED. Generally, the blue shift of the peak wavelength can be interpreted by the screening of piezoelectric field induced quantum confined Stark effect (QCSE), while the broadened FWHM is commonly known as the band-filling effect by carriers in the QWs.¹¹ With the help of these simulation results shown in Figs. 1 and 2, it can be deduced that the smaller blue shift rate with the increasing current density in the GTQB LED could be resulted from the graded QB thickness. As reported, a thinner QB can reduce the strain to the QW, thus resulting in a smaller QCSE.¹² The smaller broadening magnitude of the

FWHM in the GTQB LED is attributed to the reduced band-filling effect benefiting from the improved carrier distribution in the InGaN/GaN QWs, as shown in Fig. 1.

Finally, the external quantum efficiency (EQE) and optical power as a function of the current density are depicted in Fig. 4 for both devices. Compared with the ETQB LED, the GTQB LED shows lower levels of EQE and optical power at the low current injection regime of $<22 \text{ A/cm}^2$. We attribute this to the weaker quantum confinement of the electrons within the QWs of the GTQB LED due to the thinner QB thickness, as indicated in Figs. 1(a) and 1(b). However, the EQE and optical power of the GTQB LED surpass those of the ETQB LED as the current density increases beyond 22 A/cm^2 . For example, when we evaluate the performance of the GTQB and ETQB LEDs at the current density of 70 A/cm^2 , the optical output power of the GTQB LED is 870 mW, which is about 13% higher than that of the ETQB LED (770 mW). The efficiency droop of the EQE (droop = $\frac{EQE_{\text{max}} - EQE}{EQE_{\text{max}}}$) of the GTQB LED at 70 A/cm^2 is only 28.4%. This is much smaller than that of the ETQB LED, which is 48.3%. The improvement of the optical power and EQE at the high current density is well attributed to the improved hole transport in the GTQB LED, as demonstrated in Figs. 1 and 2.

In summary, based on both the experimental and numerical results, we show that, by grading the quantum barrier thickness along (0001) direction, a much more uniform hole distribution in QWs can be obtained in the GTQB LED. As a result, the radiative recombination and, thus, the optical output power are enhanced in the GTQB LED, accompanied with a reduced efficiency droop.

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