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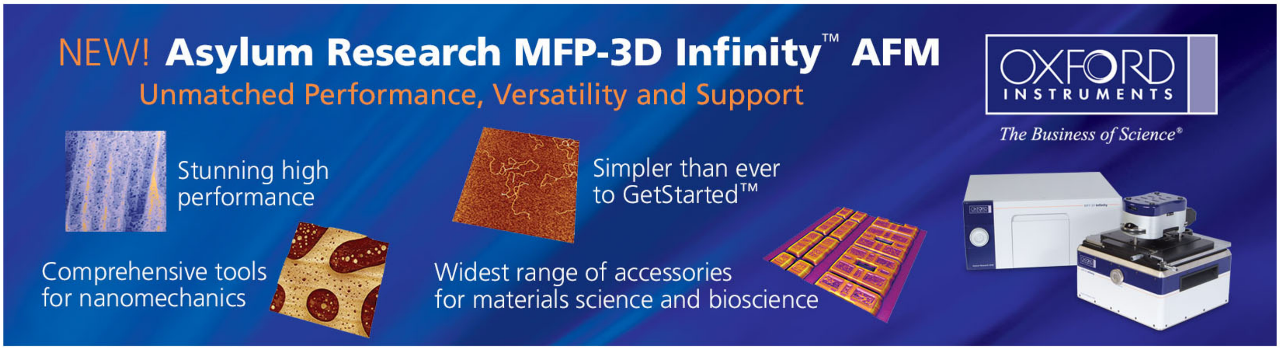

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Efficiency droop alleviation in InGaN/GaN light-emitting diodes by graded-thickness multiple quantum wells

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InGaN/GaN light-emitting diodes (LEDs) with graded-thickness multiple quantum wells (GQW) was designed and grown by metal-organic chemical vapor deposition. The GQW structure, in which the well-thickness increases along [0001] direction, was found to have superior hole distribution as well as radiative recombination distribution by performing simulation modeling. Accordingly, the experimental investigation of electroluminescence spectrum reveals additional emission from the narrower wells within GQWs. Consequently, the efficiency droop can be alleviated to be about 16% from maximum at current density of 30 to 200 $\mathrm{A/cm^2}$, which is much smaller than that for conventional LED (32%). Moreover, the light output power was enhanced from 18.0 to 24.3 mW at 20 $\mathrm{A/cm^2}$. © *2010 American Institute of Physics*. [doi:10.1063/1.3507891]

Solid-state lightings, especially InGaN/GaN light-emitting diodes (LEDs), have been vigorously developed to take the place of traditional lighting source, due to its potentially higher efficiency. However, as the efficiency of LEDs increasing, the upcoming challenge is the efficiency "droop" for high-power applications.[1] It means that the efficiency reduces rapidly when LED operating under high carrier density. The major cause of efficiency droop is still a huge controversy. Various possible mechanisms of droop including carrier overflow,[2] nonuniform distribution of holes,[3,4] Auger scattering,[5] carrier delocalization[6] have been proposed. In recent years, great efforts have been made to reduce the efficiency droop. Most of them are focus on minimizing the carrier overflow by reducing or eliminating the polarization field in the active region, such as using polarization-matched multiple quantum wells (MQWs),[7,8] staggered InGaN quantum wells,[9] and nonpolar or semipolar GaN substrate.[10] But for improving hole distribution, only several approaches, such as *p*-type MQWs[11] or coupled quantum wells,[12] are explored. However, in the *p*-type MQWs, the Mg-dopant is very likely to diffuse into wells, while in the coupled quantum wells, electrons are tend to overflow by using thin barriers. These will result in reduction of radiative efficiency. In this research, we designed and grew a LED structure with graded-thickness multiple quantum wells (GQWs) by using metal-organic chemical vapor deposition (MOCVD). Better hole distribution in such graded-thickness designed MQWs were demonstrated by APSYS simulation as well as the electroluminescence (EL) measurements. As a result, the efficiency droop behavior was alleviated while the radiative recombination was improved.

The LED structures were grown on c-plane sapphire substrates by MOCVD. A 20-nm-thick low temperature GaN nucleation layer followed by a 4 μm *n*-type GaN buffer layer, ten-pair InGaN/GaN superlattice were grown on the top of sapphire. After that, six-pair MQWs were grown with 10-nm-thick GaN barriers. For our designed experiment, the thicknesses of $\mathrm{In_{0.15}Ga_{0.85}N}$ quantum wells for GQW LED structure, controlled by growth time, are 1.5, 1.8, 2.1, 2.4, 2.7, and 3 nm along [0001] direction. While the reference LED structure has a unique well-thickness of 2.25 nm. It's worth noting here that the total volumes of active region for the two samples are the same. Finally, a 20-nm-thick electron blocking layer with $\mathrm{Al_{0.15}Ga_{0.85}N}$ and a 200-nm-thick *p*-GaN layer were grown to complete the epi-structure. For EL measurements, the LED chips were fabricated by regular chip process with ITO current spreading layer and Ni/Au contact metal, and the size of mesa is $300 \times 300\ \mu\mathrm{m}^2$.

It has been reported that, with the same indium content, wider well has longer radiative recombination lifetime.[13,14] In our designed GQWs, the well-thickness gradually increases along [0001] direction. Therefore, one can expect that the holes in wider well tend to escape to the next narrower well before they radiatively recombine with electrons, leading to the hole concentrations decrease in the wider well, but increase in the narrower wells. In other words, the hole distribution will be improved. To prove the above hypothesis, we investigate the carrier distribution of both GQW and reference LED structures mentioned above by APSYS simulation.

Based on our experimental structures, we built up the model of the reference and GQW LED structures. The typical LED structure was composed of 4-μm-thick *n*-type GaN layer ($n\text{-doping}=2\times10^{18}\ \mathrm{cm^{-3}}$), six pairs of $\mathrm{In_{0.15}Ga_{0.85}N/GaN}$ MQWs with 10-nm-thick GaN barriers, 20-nm-thick $p\text{-}\mathrm{Al_{0.15}Ga_{0.85}N}$ electron blocking layer ($\text{p-doping}=5\times10^{17}\ \mathrm{cm^{-3}}$), and 200-nm-thick *p*-type GaN layer ($\text{p-doping}=1\times10^{18}\ \mathrm{cm^{-3}}$). Other material parameters of the semiconductors used in the simulation can be found in Ref. 15. Commonly accepted Shockley-Read-Hall recombination lifetime (several nanoseconds) and Auger recombination coefficient ($2\times10^{-30}\ \mathrm{cm^6/s}$) are used in the simula-

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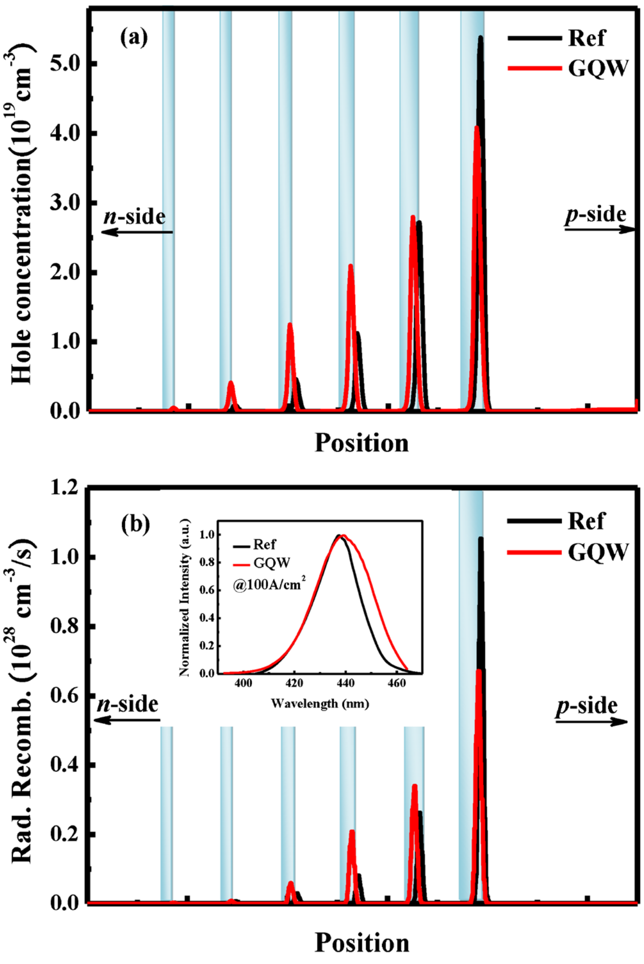

FIG. 1. (Color online) Simulated (a) hole distribution and (b) radiative recombination distribution in reference and GQW LEDs.

tions. Figure 1 shows the simulated hole distribution and radiative recombination distribution along MQWs at 100 A/cm^2. For reference LED structure, it can clearly be seen that holes mostly concentrate in the QW nearest *p*-side (denoted as the first QW), so does the radiative recombination. This phenomenon coincides with the optical measurement result in Ref. 16, which is mainly due to poor transportation of holes. While in the case of GQW LED structure, the hole concentration decreases in the first QW by about 16%, but increases in the second, third, and fourth QWs by 7%, 94%, and 175%, respectively, as compared with reference LED. It indicates that the holes are more capable of transporting across the first QW, consisted with our hypothesis. On the other hand, electrons are relatively not being affected due to their high mobility. Therefore, more wells will participate in the recombination process, as illustrated by the radiative recombination distribution in Fig. 1(b). Accordingly, the simulated EL spectrum of GQW LED at current density of 100 A/cm^2 exhibits lager full width at half maximum (FWHM) than that of reference LED, as shown in the inset of Fig. 1(b). Moreover, due to the relative low carrier densities in the first QW and more uniform of carrier distribution, the possibility of Auger scattering and carrier overflow can be lower. And the alleviation of efficiency droop can be expected.

Figure 2 shows the power-dependent EL average wavelength and FWHM of reference and GQW LED at room temperature. The EL measurement was performed by on-wafer probing with a spectrometer. The emission wavelength (457.7 nm at 1 A/cm^2) and FWHM (21.9 nm at 1 A/cm^2) for GQW LED are larger than those for reference LED (448.5 nm and 17.9 nm), respectively. It could be due to the graded-thickness and wider wells near to *p*-side in GQW. Besides, as increasing the injection current from 1 to 100 A/cm^2, EL spectrum for GQW LED exhibits significant blueshift of 21.8 nm and broadening of about 11.6 nm, compared with 12.6 nm and 8.2 nm, respectively, for reference LED. Generally, the blueshift of the GaN-based LED can be attributed to the band filling effect in localized states and the charge screening effect of quantum confined Stark effect (QCSE).[17] And the broadening of FWHM is mainly due to the band filling effect and self-heating effect. In GQW and reference LEDs, the band filling effect and self-heating effect can be considered to be equivalent because they have the same indium content and total volumes of active region. Thus, there must be other reasons for such significant blue shift and broadening of EL spectra in GQW LED.

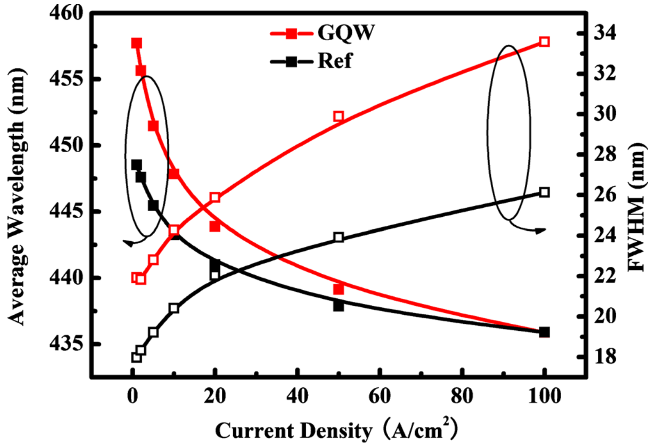

FIG. 2. (Color online) Average wavelength and FWHM as a function of current density for reference and GQW LEDs.

According to the simulated results mentioned above, more holes distribute in the narrower wells in GQW LED structure. Once more carriers radiatively recombine in narrower wells, the intensity of shorter-wavelength part in emission spectrum will rise. Thus, changes in symmetry of spectrum could be expected. To investigate the symmetry of EL spectrum in detail, the asymmetry factor (AsF) was calculated. As illustrated the inset of Fig. 3, it can be defined as the distance from the center line of the peak to the back slope (AB) divided by twice the distance from the center line of the peak to the front slope (2AC), with all measurements made at 50% of the maximum peak height. The calculated AsF under every injection level for both samples are summarized in Fig. 3. It can clearly be seen that, AsF of reference LED decreases slightly from 1.04 to be about 0.98 when injection current increases from 1 to 100 A/cm^2. While GQW LED shows larger variation, the AsF starts at 1.05 (0.1 A/cm^2) and saturates at about 0.89 (after 20 A/cm^2). According to the definition of AsF, if the bluer light emits from narrower wells, the symmetry of spectrum would be interrupted and smaller than 1. Therefore, we can conclude that GQW does have superior radiative recombination distribution, which leads to the EL spectrum blueshifts and broadens significantly with increasing the injection cur-

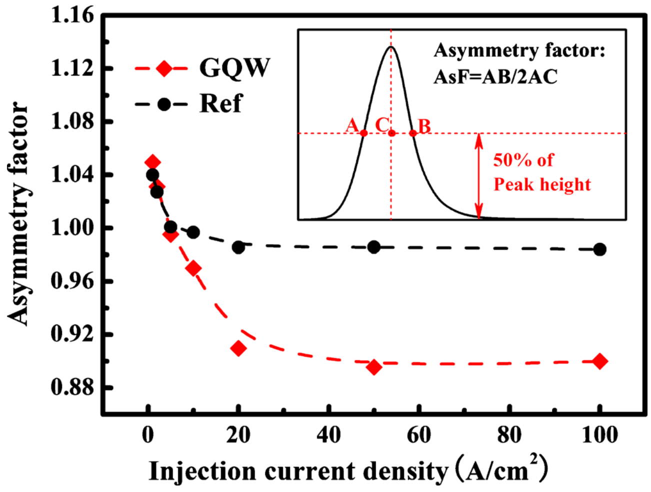

FIG. 3. (Color online) Current-dependent asymmetry factor of EL spectra of reference and GQW LEDs.

rent. These enormous changes in wavelength and linewidth might make the design of the GQW concept impractical for lighting applications. In the future, we will optimize the GQW structure, such as appropriately reducing the indium content of the wider wells, to alleviate these effects.

Finally, we investigated the efficiency droop behaviors in both LEDs. The output powers measured with a calibrated integrating sphere and the normalized efficiency (η) of reference and GQW LED are plotted in Fig. 4 as a function of injection current density. The light output power of GQW LED is found to be enhanced by 35% at 20 A/cm^2, as compared with the reference LED (24.3 mW versus 18.0 mW). This indicates that even with wider wells (worse wave function overlap for electrons and holes) near p-side, the overall efficiency for GQW LED is still higher than reference, and the utilization rate of MQWs is improved. More importantly, the maximum efficiency (η_{peak}) of GQW LED appears at injection current density of 30 A/cm^2, which is much higher than that for reference LED (at 2 A/cm^2). And the efficiency droop, defined as $(\eta_{\text{peak}}-\eta_{200\ \text{A cm}^2})/\eta_{\text{peak}}$, is alleviated from 32% in reference LED to 16% in GQW LED. This improvement could be mainly attributed to the superior hole distribution and radiative recombination distribution, and also the reduction of Auger scattering resulting from the lower carrier concentration in QW nearest p-side.

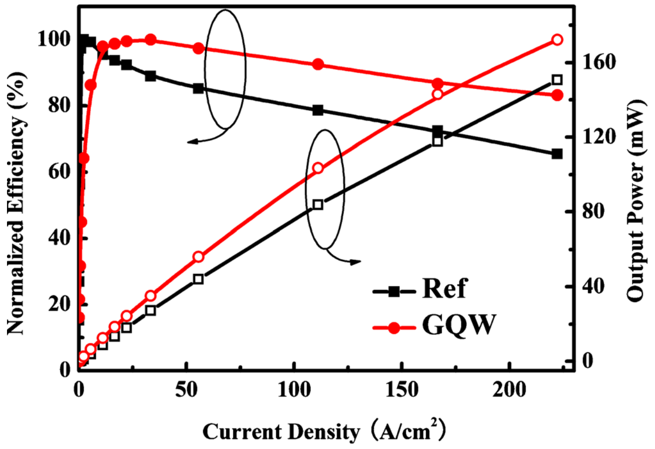

FIG. 4. (Color online) Comparison of normalized EL efficiency and L-I curves.

In conclusion, InGaN/GaN LEDs with graded-thickness multiple quantum wells were investigated both experimentally and numerically. The APSYS simulations indicate that superior hole distribution can be achieved in the GQW designed MQWs, in which the well-thickness increases along [0001] direction. It might be attributed to the longer radiative recombination lifetime in the wider well nearest to *p*-type layer. Moreover, by analyzing the EL spectra in detail, the additional emission from the narrower wells were demonstrated. This indicates that more carriers distribute in the previous wells, which agrees well with the simulated results. As a result, the efficiency droop behavior was alleviated from 32% in reference LED to 16% in GQW LED. In addition, the light output power was enhanced from 18.0 to 24.3 mW at 20 A/cm^2 compared to reference LED with the same active volume. This work implies that with suitable active region design, carrier transportation behavior could be modified, which is very useful for alleviating efficiency droop.

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