High-efficiency InGaN based quantum wells (QWs) light emitting diodes (LEDs) play an important role in solid-state lighting.\textsuperscript{1–4} The existence of polarization fields in InGaN QW lead to charge separation in the QW, which significantly reduces the electron-hole wave function overlap ($\Gamma_{e,hb}$) and radiative recombination rate ($\sim |\Gamma_{e,hb}|^2$) of the InGaN QW. The commonly used approaches to extend the green spectral regime (\(\lambda > 525 \text{ nm}\)) are as follows: (1) increase In-content in InGaN QW or (2) increase thickness of the InGaN QW. Both approaches lead to detrimental charge separation effect. Recently, several approaches have been proposed to address the charge separation issues in InGaN QW by employing nonpolar InGaN QW,\textsuperscript{5} InGaN QW with AlGaN \(\delta\)-layer,\textsuperscript{6,7} staggered InGaN QW,\textsuperscript{8,9} type-II InGaN-GaNAs QW,\textsuperscript{10,11} and strain-compensated InGaN-AlGaN QW.\textsuperscript{12,13}

In this work, we present the growths and characteristics of three-layer staggered InGaN QW LEDs emitting in the 520–525 nm spectral regime employing graded growth-temperature profile, with the QW structure designed for improved overlap $\Gamma_{e,hb}$. Previously, the two-layer staggered InGaN QW\textsuperscript{8,9} was employed for 460 nm emitting LEDs, and the In-contents in QWs were engineered by changing the [TMIn]/[TEGa] molar flux ratios during the InGaN QW growth. For low In-content InGaN QWs applicable for blue-emitting LEDs, the In-content can be modified by changing the [TMIn]/[TEGa] molar flux ratio. However, for high In-content InGaN QWs applicable for green-emitting LEDs, the compositional engineering of the In-contents in the QW layers is most efficiently accomplished by grading the growth temperature.

In our current studies, the three-layer staggered InGaN QW LEDs were grown by metal-organic chemical vapor deposition (MOCVD) with graded growth-temperature profile [Fig. 1(a)] while keeping constant [TMIn]/[TEGa] molar ratio. The incorporation of indium into the InGaN layer is very sensitive to the growth temperature. As shown in Fig. 1(a), the three-layer staggered In$_{0.15}$Ga$_{0.85}$N/In$_{0.17}$Ga$_{0.83}$N/In$_{0.19}$Ga$_{0.81}$N QW structure is composed of three layers (layers 1, 2, and 3). The growth condition for the three-layer staggered InGaN QW is designed as follows: layer 1 is grown at $T_1$ (\(\text{°C}\)) for $t_1$ (s), layer 2 is grown at $T_2$ (\(\text{°C}\)) for $t_2$ (s), and layer 3 is grown at $T_3$ (\(\text{°C}\)) for $t_3$ (s). Between the layers 1 and 2, the temperature is ramped up from $T_1$ (\(\text{°C}\)) to $T_2$ (\(\text{°C}\)) by $t_p$ (s). In contrast, between layers 2 and 3, the temperature is ramped up from $T_2$ (\(\text{°C}\)) to $T_3$ (\(\text{°C}\)) by $t_p$ (s).

FIG. 1. (Color online) (a) Schematics of the growth temperature, TMIn-flow rate, and In-content for the growths of three-layer staggered InGaN QW with graded growth-temperature profiles and (b) the In-contents in MOCVD-grown In$_{0.19}$Ga$_{0.81}$N layer as a function of growth temperature.
is ramped down from \( T_2 \) (°C) to \( T_1 \) (°C) by \( t_p \) (s). The real growth temperature profile contains brief overshoot during the ramp-up and ramp-down layer growths. By utilizing the graded growth-temperature profile, the composition of In-content in the InGaN layer can be engineered to form three-layer staggered InGaN QW structure.

Numerical models based on self-consistent six-band \( k \cdot p \) formalism for wurtzite semiconductor\(^{13-17}\) were employed to optimize the spontaneous emission characteristics of staggered InGaN QW. The simulation predicts that the use of three-layer staggered InGaN QW, instead of two-layer staggered InGaN QW, leads to further improvement in its overlap \( \Gamma_{e,\text{hh}} \). For the optimized three-layer staggered InGaN QW (\( \Gamma_{e,\text{hh}}=29.9\% \)) emitting at 525 nm, the overlap \( \Gamma_{e,\text{hh}} \) is improved by 15% in comparison to that of the optimized two-layer staggered InGaN QW (\( \Gamma_{e,\text{hh}}=26.3\% \)). The conventional InGaN QW emitting at 525 nm has relatively low overlap (\( \Gamma_{e,\text{hh}}=14.5\% \)). The radiative recombination rate of optimized three-layer staggered InGaN QW (two-layer staggered InGaN) is calculated as ~3.5 times (or 2.4 times) higher than that of conventional InGaN QW. Thus, the use of three-layer staggered InGaN QW over two-layer staggered InGaN QW is important, in particular for extending the emission wavelength into green spectral regime and beyond. Our growth experiments also indicated that the use of three-layer staggered InGaN QW for achieving peak emission wavelength up to 525–550 nm as more practical.

Figure 1(b) shows the calibration studies of the In-content incorporation in MOCVD-grown \( \text{In}_x \text{Ga}_{1-x} \text{N} \) layer grown on GaN template as a function of growth temperature. The growths of InGaN layers employed TMIn, TEGa, and NH\(_3\) as the precursors, and N\(_2\) gas was employed as carrier gas. The V/III and [TMIn]/[TEGa] molar ratios were kept constant at 10200 and 0.38, respectively. The calibrations of the In-contents in the InGaN alloy grown at various growth temperatures were performed by x-ray diffraction measurements. Our studies indicated that the In-content decreases following a relatively linear relation with increasing growth temperature. The In-content in InGaN layer decreases from 28% to 18% as the growth temperature increases from 720 °C to 780 °C.

The device characteristics of the three-layer staggered InGaN QW LEDs grown by graded growth-temperature profile were compared to those of the conventional InGaN QW (\( \Gamma_{e,\text{hh}}=14.5\% \)). Both conventional and three-layer staggered InGaN QW were grown by MOCVD on 2.5 μm thick \( n \)-doped GaN (\( T_g \approx 1075^\circ \text{C} \)) grown on c-plane double-side polished sapphire substrate, employing a low temperature 30 nm GaN buffer layer (\( T_g \approx 515^\circ \text{C} \)). The conventional QW structure consists of four periods 3.5 nm thick \( \text{In}_{0.24} \text{Ga}_{0.76} \text{N} \) QWs, which was grown at 740 °C with growth time \( t_p=\text{1.09 min} \). The In-content in conventional InGaN QW was calibrated as 24%. The staggered InGaN QW LED consists of four periods of the three-layer staggered InGaN QW. The three-layer staggered InGaN QW consists of three InGaN layers with the higher In-content InGaN layer (layer 2, \( T_g \approx 725^\circ \text{C} \)) in the center sandwiched between two lower In-content InGaN layers (layers 1 and 3, \( T_g \approx 755^\circ \text{C} \)). The growth times for the layers 1, 2, and 3 are \( t_1=0.25 \text{ min}, t_2=0.29 \text{ min}, \) and \( t_3=0.25 \text{ min} \), respectively, with the ramp up and ramp down times of \( t_p=0.15 \text{ min} \). From our calibration studies, we estimated the In-contents in the three-layer staggered InGaN QW as 21%, 28%, and 21%, with thicknesses of 1.05, 1.4, and 1.05 nm, respectively. Both the conventional InGaN QW and three-layer staggered InGaN QW were designed for achieving similar peak emission wavelength in LED operation with nominally similar total QW thickness. All device structures employed 10 nm \( n \)-GaN barrier layer between QW active regions. On top of the upper barrier layer, 200 nm thick \( p \)-type GaN with Mg doping of 3 \( \times 10^{17} \text{ cm}^{-3} \) were grown. The LED devices were fabricated as bottom-emitting square devices, and Ti/Au as \( n \)-contact and Ni/Au as \( p \)-contact were evaporated followed by contact annealing.

The luminescence characteristics of both the conventional and three-layer staggered InGaN QW samples were studied by power-density-dependent cathodoluminescence (CL) measurements at room temperature. The CL measurements employed 10 keV electron beam in spot mode (area \( =1.965 \times 10^{-9} \text{ cm}^2 \)). The high electron beam accelerating energy of 10 keV was utilized to penetrate through the 200 nm thick \( p \)-GaN layer, which was grown on top of the InGaN QW active region. The effect of different excitation pumping power density on the CL intensity was studied for both of the conventional and three-layer staggered InGaN QW LED samples.

Figure 2(a) shows the measured CL spectra plotted against CL pump current (shown for 600, 700, 800, and 900
the three-layer staggered InGaN LED shows enhancement by measured under continuous wave operation. The peak EL for nA).

FIG. 3. (Color online) (a) EL spectra and (b) light output power vs current density for conventional InGaN QW and three-layer staggered InGaN QW LEDs emitting with peak wavelengths at 520–525 nm, with the corresponding band lineups schematic of three-layer staggered InGaN QW.

In summary, the use of three-layer staggered InGaN QWs resulted in improved active region for nitride LEDs emitting at 520–525 nm. The power dependent CL measurement indicated 1.8–2.8 times enhancement for the three-layer staggered InGaN QW. The output power and radiative efficiency of three-layer staggered InGaN QW LED improved by 2.0–3.5 times, in comparison to those of conventional InGaN QW LED. The improvement in radiative efficiency of three-layer staggered InGaN QW LED can be attributed to the increase in radiative recombination rate of the QW, in agreement with theory.

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