RAPID COMMUNICATION

Improvement of green InGaN-based LEDs efficiency using a novel quantum well structure

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The green light emitting diodes (LEDs) have lower quantum efficiency than LEDs with other emission wavelengths in the visible spectrum. In this research, a novel quantum well structure was designed to improve the electroluminescence (EL) of green InGaN-based LEDs. Compared with the conventional quantum well structure, the novel structure LED gained 2.14 times light out power (LOP) at 20-mA current injection, narrower FWHM and lower blue-shift at different current injection conditions.

Keywords: InGaN, novel quantum wells, light-emitting diodes, electroluminescence

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1. Introduction

Light emitting diodes have been playing an important role in solid-state lighting and display applications.[1–3] However, the quantum efficiency of InGaN-based green LEDs is still low due to the deterioration of crystalline quality[4,5] and large quantum confined Stark effect (QCSE)[6–8] caused by the high In concentration. The QCSE leads to the tilt of the energy band in the quantum well under the effect of polarization piezoelectric field, reducing the overlap of electron and hole wavefunctions, resulting in a decrease of the radiative recombination efficiency.[9,10] Researchers are making efforts in overcoming these two challenging problems and various approaches have been attained.[11–18] The InAlGaN/GaN superlattice has been proposed to act as electron blocking layer (EBL) and making a 57% improvement in light output power than conventional EBL structure.[19] The thickness of the EBL also has been optimized to reduce the droop effect.[20] Using growth interruption also has reached higher electroluminescence light output power and lower blue-shift of the peak wavelength.[21–23] The growth pressure,[24] carrier gas type,[25] and the thickness of GaN cap layer[26] have been optimized to improve the crystalline quality. The nanostructure LED[27] and external stress to alleviate the QCSE[28] also gain some excellent results. However, the structure of multi-quantum wells (MQWs) in the active region has not been well studied. In the present report, we demonstrate a novel structure in the active region with superior electroluminescence performance than the conventional structure LED.

2. Sample structures and experimental details

The samples are InGaN-based green LEDs growing on (0001) (*c*-plane) sapphire substrates via metal–organic chemical vapor deposition (MOCVD) technology in AIXTRON 2400G3 system. The precursors are trimethlygallium (TMGa), triethlygallium (TEGa), trimethlyindium (TMIn), and ammonia, while silane (SiH_4) and dicyclopentadienyl magnesium (Cp_2Mg) are used for n-GaN and p-GaN dopants, respectively. Prior to the growth of GaN nucleation layers, the sapphire substrates were exposed in hydrogen (H_2) ambient at 1050 °C to desorb contamination for 8 min. Following the deposition of a 25-nm thick GaN nucleation layer at 530 °C, a 1-μm undoped and 2.5-μm n-doped GaN layer with a doping intensity 5×10^{18} cm^3 was grown at temperature 1050 °C. For sample A (LED A), the active layers consist of 4-periods of GaN(14 nm)/InGaN(2.5 nm) emitting blue light and 1 period of GaN(14 nm)/InGaN(3 nm) emitting green light. While for sample B (LED B), the active layers consist of 4-periods of GaN(18 nm)/InGaN(2.5 nm) emitting green light. Finally, a

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180-nm thick p-GaN layer was deposited. After the growth, all the samples were annealed at 700 °C in N_2 ambient for 20 minutes. All the samples were made to 300 μm × 300 μm area size chips with Ni/Au transparent electrode for p-type and Cr/Ti/Al for p- and n-type electrodes.

Figures 1(a) and 1(b) show the schematic diagrams of sample structure for sample A and sample B, respectively. The structural properties of the two samples were investigated by a high-resolution x-ray diffraction (HRXRD) with a Panalytical system equipped with a four-bounce channel-cut Ge (220) monochromator that delivered a pure CuKα1 line of 1.5406 Å. Electroluminescence (EL) measurements from 5 mA to 150 mA were performed.

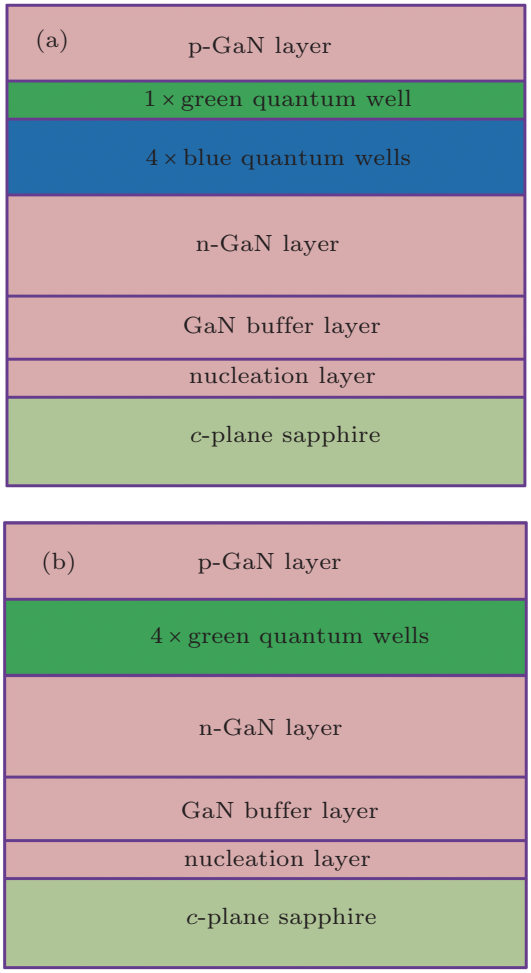


Fig. 1. (color online) Schematic diagram of LED structures for (a) novel quantum well structure LED A and (b) conventional quantum well structure LED B.

3. Results and discussion

The HRXRD ω–2θ curves for the (0002) reflection of the InGaN/GaN MQWs for samples A and B are shown in Fig. 2. The vertical coordinate (intensity) for LED A is transformed in order to separate the two curves in Fig. 2. The main peaks in two spectra originate from the n-GaN layer. The high-order diffraction peaks of the InGaN/GaN structures, where the numbers present different peak orders, can be clearly observed for both samples, indicating that the high-quality periodic MQWs are well formed. The fitting results of the curves indicate that the quantum well parameters coincide well with the structure we proposed as shown in Fig. 1(a). The green quantum well thickness, the barrier thickness, and the indium content are calculated to be 2.8 nm, 13.1 nm, 22% for LED A, and 2.4 nm, 17.3 nm, 26% for LED B.

The EL spectra of LEDs A and B at 20 mA shown in Fig. 3(a) indicate that the two LEDs both emit light at the wavelength of 530 nm. The normalized light out power (LOP) and forward voltage of the two LEDs are shown in Fig. 3(b). At an injection current of 20 mA, the light output power of LED A is 2.14-fold higher than that of LED B, which reveals the novel quantum well structure of LED A is superior to conventional quantum well structure as LED B adopted. The forward voltages of LED A and LED B are 4.24 V and 3.86 V, respectively.

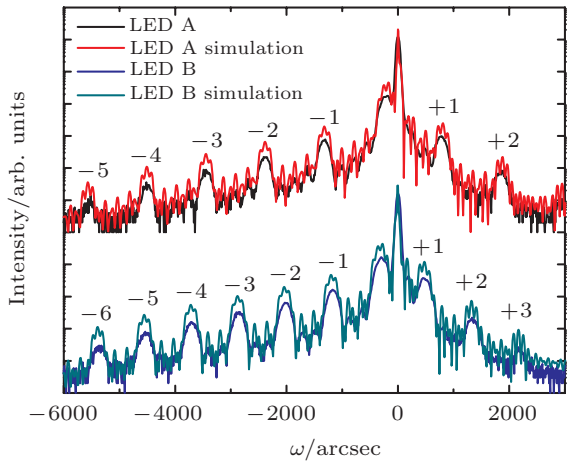


Fig. 2. (color online) HRXRD ω–2θ scan curves and simulation fitting curves of LED A and LED B. The simulation fitting curves coincide well with the experimental data.

For further study, we investigated the peak wavelength and the full width at half maximum (FWHM) of the two samples under different current injections as given in Fig. 3(c). From 5 mA to 150 mA, the LED A shows a 21.3-nm blue-shift while the LED B exhibits 27.1-nm blue-shift. The LED A also has a lower FWHM than that of the LED B under different current injections. At 20-mA current injection condition, the FWHM of the LED A is 41.5 nm less than 43.8 nm of the LED B. The lower blue-shift and FWHM further confirm the superiority of the novel quantum well structure.

In LED A, the new structure has a lower average indium concentration than the conventional quantum wells structure in LED B. The green QW in LED A suffers less strain and has a better crystalline quality and less QCSE than the green QW close to p-GaN in LED B, hence leading a superior EL performance in LED A with 2.14-fold higher LOP, narrower FWHM and lower blue-shift.

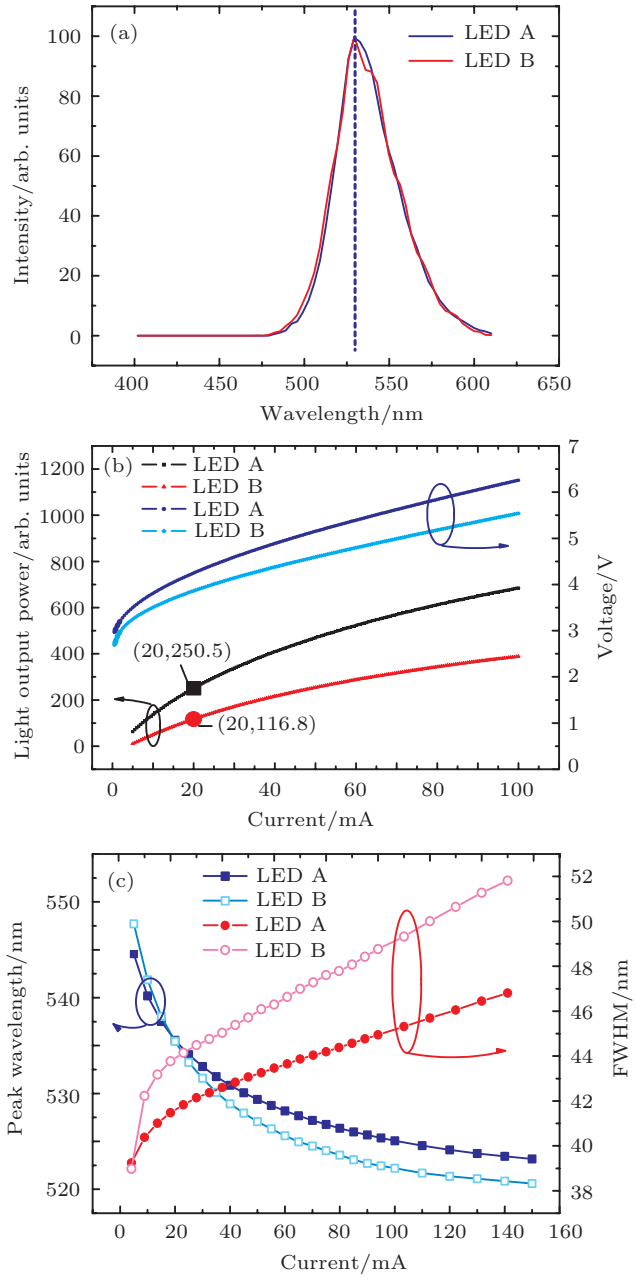


Fig. 3. (color online) The EL performance of LED A and LED B. (a) EL spectra at 20-mA current injection condition for LED A and LED B. Single peaks of green light emission centered at the same peak wavelength of 530 nm are obtained from both samples. (b) The light output power (LOP) and forward voltage of LED A and LED B at different current injections. At 20-mA current injection, the LOP of LED A is 2.14 times higher than LED B, while the forward voltages are 4.24 V and 3.86 V of LED A and LED B, respectively. (c) The peak wavelength and FWHM of LED A and LED B as a function of the injection current. LED A has both lower blue-shift of peak wavelength and narrower FWHM than LED B as the injection current increases.

Since the holes have lower mobility than electrons, they are mainly distributed in the top QW close to the p-GaN layer[29,30] at normal level injection current. One problem of the new structure is that whether the four blue-light-emitting quantum wells will emit light to interfere the purity of the green light under high injection current. We measured the EL spectra with current from 5mA to 150mA for both LED A and LED B in Figs. 4(a) and 4(b), respectively. Figure 4(a) shows that the blue-light-emitting quantum wells start to emit light under 30 mA, and the intensity increases slowly with the increasing of current. But even at the current of 150mA, the blue light integrated intensity is less than 2.5% of the green light integrated intensity. The chromaticity coordinates of LED A under 150mA current injection are $x = 0.1901$, $y = 0.6440$, and $z = 0.1659$, respectively, which is coincident with LED B whose chromaticity coordinates are $x = 0.1825$, $y = 0.6582$, and $z = 0.1593$, respectively, under 150-mA current injection condition.

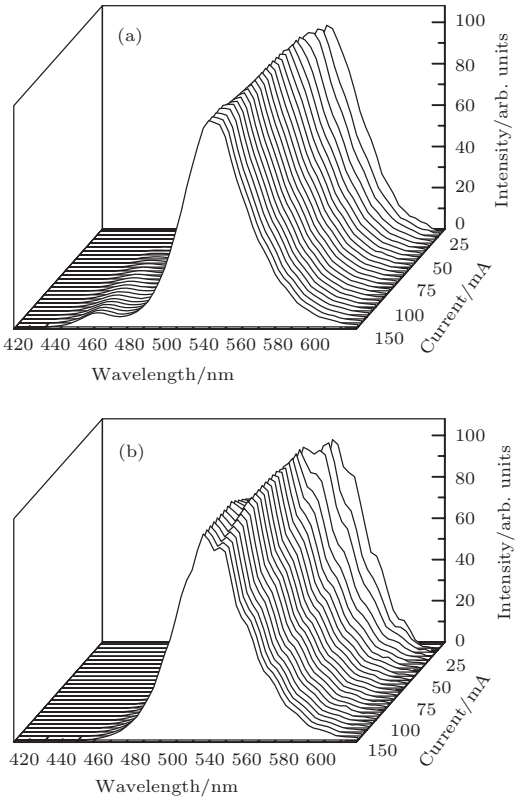


Fig. 4. The EL spectra at different current injections of LED A and LED B. (a) The EL spectra at different current injection of LED A. Even at 150-mA current injection, the blue light integrated intensity is less than 2.5% of the green light integrated intensity, remaining good monochromaticity. (b) The EL spectra at different current injections of LED B. Only one green light emission peak lies in the spectra.

From the above discussions, we conclude that the novel quantum well structure can remarkably improve the EL performance of green LEDs. 2.14 times increase of LOP, lower blue-shift and narrower FWHM indicate the superiority of the novel quantum well structure. The 4 periods blue-light-emitting quantum wells have low photon emissions under different currents so that the new quantum well structure can emit pure green light.

4. Conclusions

In this work, we fabricate a novel quantum well structure with 4 periods of blue-light-emitting quantum wells and 1 period of green-light-emitting quantum well to realize high electroluminescence light output power green LED. Comparing

with the conventional quantum well structure, the novel structure performs 2.14 times higher of LOP and lower blue-shift and narrower FWHM. Also, the novel structure can maintain the purity of the emitting light at different currents, making it a usable design for the LED industry. Our novel quantum well structure gives a new insight of improving the luminescence efficiency of InGaN-based LEDs, which is promising for colorful illumination and high color rendering index white lighting LEDs.

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