Yellow-green InGaN-based light emitting diodes with emission peak wavelength red shifts under low injection current

MU-JEN LAI*, LIANN-BE CHANG, RAY-MING LIN, and MING-JER JENG

Department of Electronic Engineering and Green Technology Research Center
Chang Gung University
259 Wen-Hwa 1st Road, Kwei-Shan, Taoyuan, Taiwan
REPUBLIC OF CHINA
D9628201@stmail.cgu.edu.tw

Abstract: We investigate the optical and electrical properties of the yellow-green InGaN-based light-emitting diode (LED) with a InGaN/GaN short-period superlattice and width-modulation quantum wells as the strain-accommodative layer. It is found that the peak wavelength shifts from 568.4 nm at 20 mA to 584.8 nm at 100 mA. The peak intensity of EL spectra doubles when the driving current increases from 20 to 60 mA and decreases to 1.7 times at a driving current of 100 mA. These results are attributed to the state-filling effect and the quantum confined Stark effect (QCSE) of the InGaN/GaN active region are effectively inhibited by inserting the strain-accommodative structure proposed in this work. The bandgap renormalization effect remarkably dominates the EL properties and the heat effect occurs at a driving current over 60 mA.

Key-Words: InGaN, Light-emitting diode, Red-shift, Carrier localization, Bandgap renormalization, Electroluminescence

1 Introduction

Recently, the InGaN-based LEDs have attracted more interest for their extensive optoelectronic applications. High-efficiency LEDs emitting in the region of the yellow-green and green wavelengths have been realized and availably commercialized through the AlInGaP and InGaN material systems. However, it is very difficult to achieve high-efficiency InGaN/GaN quantum well (QW) LEDs near the deep green, orange, and red spectral regions. [1,2] The most difficult point is the large lattice mismatch (11%) between the GaN and InN compound semiconductors. The increase in indium content becomes difficult owing to the miscibility occurs between these two binary compounds. In practice, it can be achieved by reducing the growth temperature to increase the indium composition during the growth of the InGaN well.[3] The other difficult is the piezoelectric fields induced by high strain caused by lattice mismatch. This leads to band bending and the QCSE and results in a reduced overlap between the electron and hole wave functions in QWs. Thus, the internal quantum efficiency is low. [4]

However, there have been several reports about the carrier localization is the critical mechanism to improve the light-emitting efficiency of the InGaN-based QW and the QCSE and state-filling are the reasons for peak wavelength of the EL spectra blue shifts when increasing the driving current. [5-11] The blue-shift phenomenon can be reduced by using an InGaN or an InGaN/GaN superlattice as the strain relief underlayer.[12] In this work, we fabricate the yellow-green InGaN-based LEDs by combinating an InGaN/GaN short-period superlattice and a width-modulation QWs structure as the strain accommodative layer and discuss the optical and electrical properties.

2 Experimental procedures

The LEDs structure used in this experiment was grown by low-pressure metal organic chemical vapor deposition on a C-oriented (0001) 2-in-diameter sapphire substrate. Trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminum (TMAl), and ammonia (NH_3) were used as Ga, In, Al, and N sources, respectively. Silane (SiH_4) and biscyclopentadienyl magnesium (CP_2Mg) were used as the n- and p-dopant sources, respectively. Hydrogen was used as the carrier gas for all layers excluding the InGaN/GaN strain accommodative structure and InGaN/GaN active region. First, the thermal annealing process was carried out at 1080 °C in hydrogen gas. A 25-nm-thick GaN nucleation layer was grown at 530 °C followed by a 1.5-μm-thick undoped GaN layer at 1030 °C, a 1.0-μm-thick grading doped n-GaN layer and a 3-μm-thick heavily doped n-GaN contact layer. The structure of the strain accommodative layers consisted of 10 pairs of $In_xGa_{1-x}N$ (x=0.1) (0.2 nm)

/GaN (1.0 nm) short-period superlattice structures, which were deposited on the top of heavily doped n-GaN contact layer. Then, a width-modulation QWs structure consisting of an $In_xGa_{1-x}N$ (x=0.35) (0.5 nm)/$In_xGa_{1-x}N$ (x=0.35 ramped to 0.25) (0.5 nm)/GaN (14 nm), an $In_xGa_{1-x}N$ (x=0.35) (1 nm)/$In_xGa_{1-x}N$ (x=0.35 ramped to 0.25) (0.5 nm)/GaN (14 nm) and an $In_xGa_{1-x}N$ (x=0.35) (1.5 nm)/$In_xGa_{1-x}N$ (x=0.35 ramped to 0.25) (0.5 nm)/GaN (14 nm) were sequentially deposited on the top of InGaN/GaN short-period superlattice structure. An active region consisting of 4 pairs of $In_xGa_{1-x}N$ (x=0.35) (2 nm)/GaN (14 nm) multiple quantum wells (MQWs) was deposited on the top of width-modulation QWs. Finally, a 30-nm-thick p-$Al_{0.15}Ga_{0.85}N$ layer and a 0.6−1.0-μm-thick p-GaN layer with a textured surface were deposited on the active region. After the growth of LED structure layers, a 30 min thermal activation process was performed at 670 °C and a chip size with dimension 300×250 μm^2 was fabricated by the standard process using lateral eletrodes. A 300-nm-thick indium-tin-oxide (ITO) film was used as the current-spreading layer was deposited by electron-beam evaporation, and Cr/Pt/Au metal films were used as the n- and p-bonding pad contacts.

After finishing the fabrication of the planar LED chip structure, the fabricated chips were bonded on the conventional lead frames of lamp and encapsulated with epoxy resin. All the EL measurements were carried out by the integrating sphere provided by Light Ports Inc. at room temperature (RT) in the dc pulse operation mode (pulse width=20 ms, duty cycle=1%).

3 Results and discussion

Fig. 1 shows the cross-sectional Transmission Electron Microscope (TEM) image of the strain accommodative structure and the MQWs active region included in this experiment. The TEM image distinctly indicates that the the width-modulation QWs structure have obvious thickness difference and indium grading interlayers. Furthermore, the InGaN/GaN MQWs has abrupt interfaces and without any V-pit defects throughout the active region. The image reveals that the crystal quality is sufficiently good. Fig. 2 shows the EL spectra of a yellow-green LED at various forward driving currents ranging from 20 to 100 mA. It is observed that the emission peak wavelengths shifts from 568.4 nm at 20 mA to 584.8 nm at 100 mA. The peak intensity nearly doubles when the driving current increases from 20 to 60 mA, then, decreases to 1.7 times at a driving current of 100 mA.

In order to further explore the mechanism of the red-shift induced by increasing the driving currents, the trend including the red-shift of peak wavelengths and the FWHMs with various forward driving currents are shown in Fig. 3. It is found that the peak wavelength increased and the FWHM broaden as the driving current increases. These trends can not be explained by the the band-filling effect and the QCSE inhibited by the applied bias. It is reasonable to infer that the active region exhibits a weaker QCSE and less localized energy

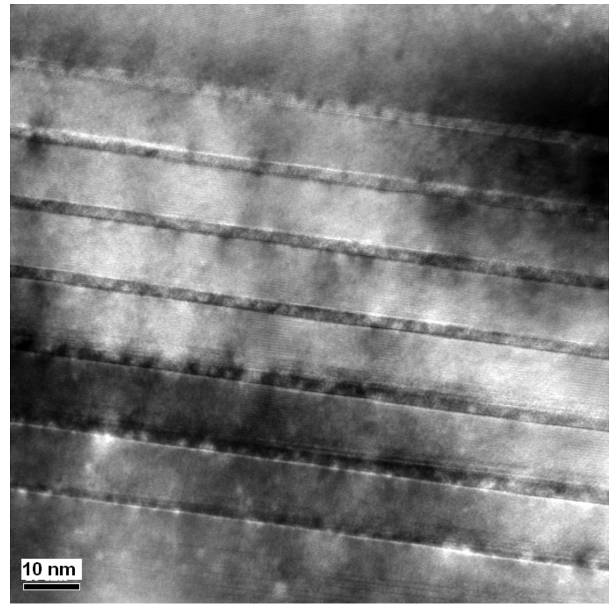

Fig. 1. Cross-sectional TEM image of the strain accommodative structure and MQWs active region consisted of InGaN/GaN.

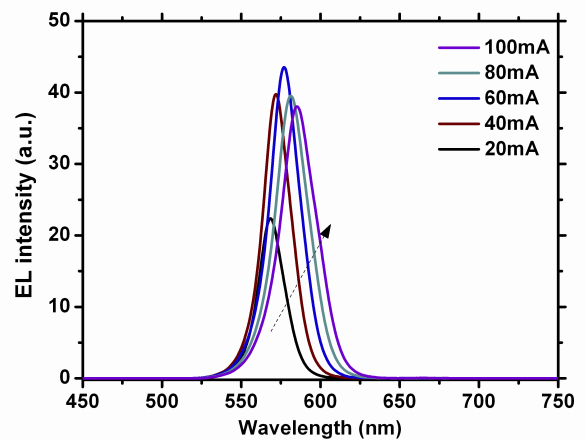

Fig. 2. EL spectra of a yellow-green LED at various forward driving currents.

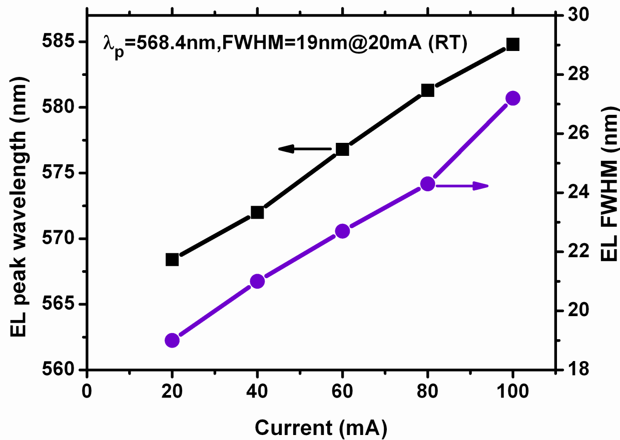

Fig. 3. Variations of the EL peak wavelength and FWHM as a function of driving current.

states. The red-shift at driving current ranging from 20 to 60 mA is due to the effect of bandgap renormalization. The intensity drops at a driving current over 60 mA is owing to the generation of heat. In order to further comfirm the suggestion of less localized energy states, we compare the EL spectrum of another green LED prepared without the strain-accommodative structure to the yellow-green LED at a driving current of 20 mA as shown in Fig. 4. In the case of the yellow-green LED, the emission spectrum shows more symmetric waveform and narrower FWHM. The appearance only can be explained that there exits a weaker potential fluctuation in the yellow-green LED. In other words, the energy states delocalized. Moreover, the EL spectrum as shown in Fig. 2 have the similar properties when increasing the driving current from 20 to 100 mA. Thus, the band gap renormalization effect is the most probable mechanism to dominate the shift of peak wavelength under a driving current below 60 mA.

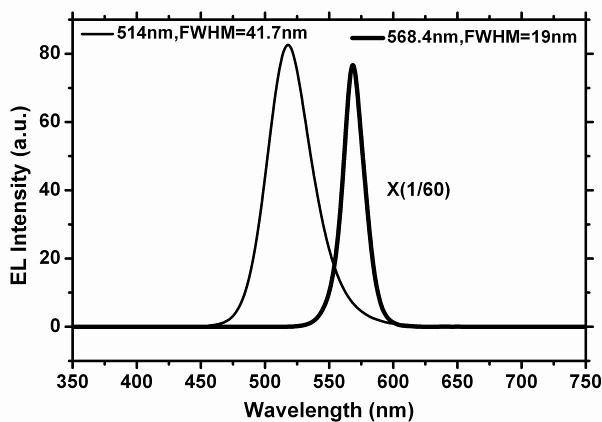

Fig. 4. The EL spectrum of the yellow-green LED in this work compares to another green LED without a strain-accommodative structure at a driving current of 20 mA.

Fig. 5 shows the current-voltage curve of a yellow-green LEDs measured from + 5 volts to -15 volts and has a semi-log scale plots inset. The forward voltage is 3.1 volts at a driving current of 20 mA, and the reverse current is 4.38 pA at –15 volts. It is observed from the inset that the reverse current is not attributed to the mechanism of the defect-assisted tunneling due to the absence of a sudden increase in the slope in the reverse region. The band-to-band tunneling current is inhibited owing to the leakage current is quite low. Therefore, we suggest that the dominance of the current-voltage property is due to the space-charge generation current in the yellow-green LED fabricated in this work.

Moreover, the reliability testing of the yellow-green LED was performed for a period of 168 hrs at RT under applying a driving current at 50 mA. The relative percentage of the EL intensity as a function of time is shown in Fig. 6. The peak intensity was measured at a driving current of 20 mA after a burn-in duty of 24 hrs. It is found that the peak intensity of the yellow-green LED decays only 0.6% after testing period. This result indicates that the characteristic of the yellow-green InGaN-based LED is sufficiently suitable for generenal applications.

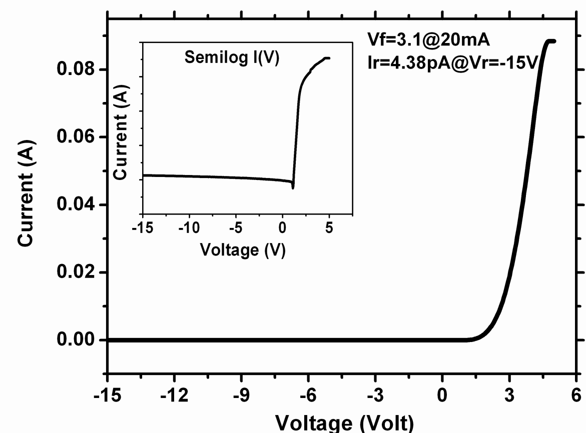

Fig. 5. Current-voltage curve of yellow-green LED with semilog scale inset.

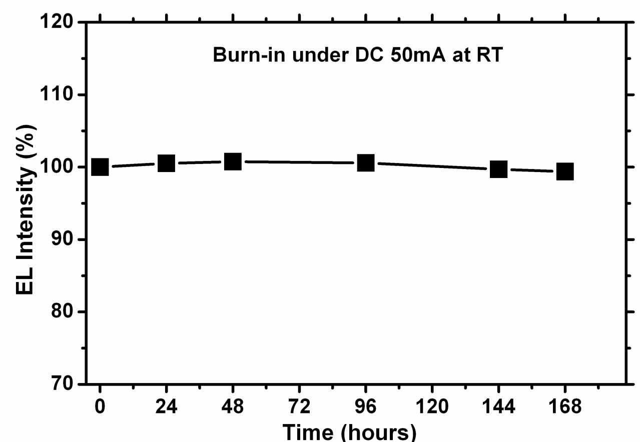

Fig. 6. Relative percentage of the EL intensity as a function of burn-in time.

4 Conclusion

We have demonstrated the red-shift of the EL peak wavelength of a yellow-green InGaN-based LED with a strain-accommodative structure consisting of an InGaN/ GaN short-period superlattice and a width-modulation QWs. It is found that the peak wavelength shifts from 568.4 nm at 20 mA to 584.8 nm at 100 mA. The peak intensity of the EL spectrum doubles when the driving current increases from 20 to 60 mA, and decreases to 1.7 times at a driving current of 100 mA. These results are attributed to the state-filling effect and the QCSE of the InGaN/GaN active region are effectively inhibited by the novel strain-accommodative structure proposed in this work. The bandgap renormalization effect remarkably dominates the EL properties and the heat effect occurs at a driving current over 60 mA. In other observation, the localized energy states caused by a higher indium composition in the InGaN/GaN quantum well does not significantly occur in this work due to the EL spectrum shows symmetric waveform and narrow FWHM.

Nevertheless, the present results of TEM image, the current-voltage curve measurement, and the reliability testing at RT indicate that the fabricated yellow-green LED in this work is sufficiently suitable for genernal applications.

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