

## Emission dynamics of red emitting InGaN/GaN single quantum wells

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Emission dynamics of two InGaN/GaN single quantum well red emitters were investigated through time-resolved photoluminescence (PL) spectroscopy. A clear phase separation, where a higher energy (blue) emission and a lower energy (red) emission appear simultaneously, was observed. The maximum position of blue emission is consistent with the bandgap value of the InGaN quantum well. As the time after pulsed excitation increases, the higher energy emission decreased more rapidly than that of the lower energy emission. In addition, the temperature dependence of the peak position of lower energy emission showed an initial redshift followed by a blueshift, reflecting the thermal distribution and transfer of localized carriers within different potential minima.

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### 1 Introduction

In spite of the spectacular success of InGaN based blue and green light emitting diodes (LEDs), there are few reports describing longer wavelength emission from InGaN materials. The extension of nitride technology to longer wavelengths, particularly to red emitters, is of significant importance for the application of nitride-based material on full color display and white light emitting devices. Nichia has reported amber and red LEDs through the use of InGaN active layers [1]. The emission efficiency of these LEDs is significantly lower than the efficiency of blue and green LEDs. Thus, it is important to understand the emission mechanism in such long wavelength InGaN emitters in order to find a way to obtain higher efficiencies.

There has been extensive research to explain the anomalous optical properties of InGaN based blue and green emitters (large Stokes shift, broad emission bandwidth, carrier density dependent emission energy, etc) that have focused on the relative importance of the quantum-confined Stark effect (QCSE) due to spontaneous and piezoelectric polarization, or bandgap inhomogeneity due to indium fluctuation/segregation. It is becoming clear that localized emission within the indium-rich potential minima or quantum dot/disk regions contributes to the high emission efficiency in such devices in spite of the poor crystalline quality. In addition, strain-induced piezoelectric polarization can dominate the carrier recombination and optical properties in certain samples. As the emission spectra of InGaN materials extend to longer wavelengths, an increasing Stokes shift between the emission and the absorption edge has been observed [2, 3]. Hence, many authors have incorporated both QCSE and localization effects to account for this large Stokes shift [1–4].

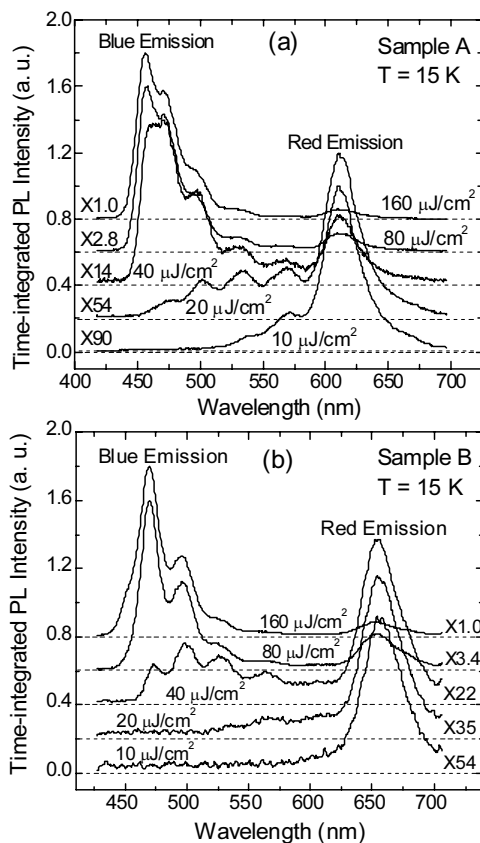
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In this article, time-resolved photoluminescence (PL) spectroscopy of two red InGaN/GaN single quantum well (SQW) structures is presented to explore the emission dynamics and to clarify the contribution of QCSE and localization effects. We observed clear evidence of phase separation where a higher energy (blue) emission and a lower energy (red or near infrared) emission appear simultaneously under high excitation density pulsed excitation. The peak energy of the blue emission is consistent with the average indium concentration characterized by high resolution X-ray diffraction (HR-XRD) and x-ray reflectivity (XRR) measurements. Moreover, the higher energy emission decreases rapidly and shows a dramatic shift to the lower energy emission with increasing time after pulsed excitation, which suggests relaxation of carriers to high indium concentration localized states.

## 2 Experiments and results

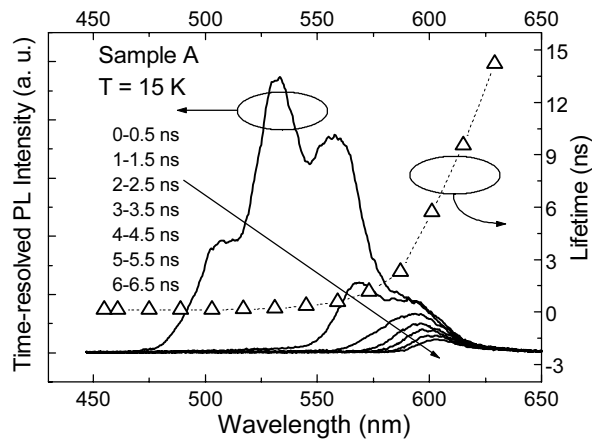
The two InGaN SQW samples studied here were grown by metal-organic vapour phase epitaxy under different growth conditions. These samples are representative of a number of samples studied and elucidate the important carrier dynamics observed in these samples. The sample structures consist of a 17 nm GaN cap layer, ~ 4 nm InGaN quantum well layer, and a 1.5  $\mu\text{m}$  GaN buffer layer which were deposited on (0001) oriented sapphire substrates. The growth details of both samples have been reported earlier [4]. Continuous wave PL spectra of sample A and sample B at low temperature showed a single peak emission with peak energy of 610 nm and 670 nm respectively [4]. Combined HR-XRD and XRR on sample B has revealed a well thickness of ~ 4.2 nm and an average indium concentration of 20%.



**Fig. 1** Time integrated PL spectra of (a) sample A and (b) sample B at 15 K as a function of pump fluence. The scaling of PL emission intensity under each pump fluence is also indicated.

Time-resolved PL measurements were performed with a fast scan streak camera in conjunction with a 25 cm monochromator. A frequency-doubled amplified mode-locked Ti:Sapphire laser was used as the primary excitation source (250 KHz, ~200 fs). The excitation wavelength was chosen at 385 nm in order to selectively excite the InGaN quantum well only. The samples were cooled to approximately 15 K using a closed cycle helium refrigerator.

In comparison with continuous wave PL measurement, pulsed excitation is able to provide significant photogenerated carrier density immediately after pulse excitation. For example, a pump fluence of 100  $\mu\text{J}/\text{cm}^2$  at the wavelength of 385 nm corresponds to a sheet charge density of  $\sim 2.5 \times 10^{13} \text{ cm}^{-2}$  for a 4 nm InGaN thin layer. Under such high photoinjected carrier density, it is possible to completely fill the localized tail states and completely screen the strained induced piezoelectric field (~MV/cm) in the InGaN well. Hence, time-resolved measurements not only can provide valuable information on the carrier recombination dynamics and the related carrier lifetime, but also can identify whether localized emission due to indium fluctuation/segregation or strain induced QCSE dominates the emission mechanism of such InGaN SQW structures.



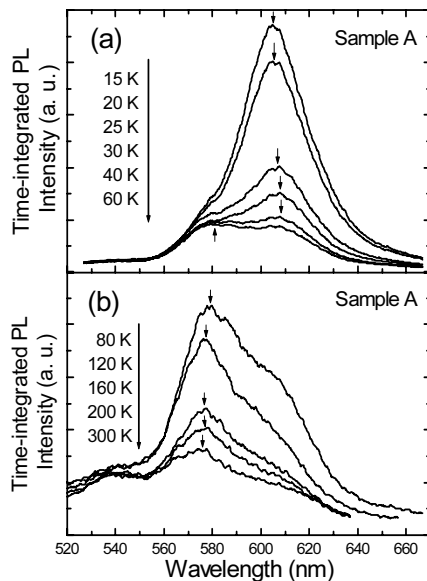
**Fig. 2.** Time-resolved PL spectra of sample A as a function of time delay after pulse excitation and the emission decay time as a function of detection wavelength at 15 K under a pump fluence of  $20 \mu\text{J}/\text{cm}^2$ .

tion channels accounting for the near band edge transition are band-to-band, free exciton, bound exciton, shallow impurity-to-band, or their coupled system. Note that the additional peaks between the blue emission and the red emission are the results of Fabry-Perot interference fringes.

To further verify the origin of the blue emission, the bandgap of InGaN well in sample B is calculated based on the equation provide by Wu et al. [5]:  $E_g(\text{In}_x\text{Ga}_{1-x}\text{N}) = E_g(\text{InN})x + E_g(\text{GaN})(1-x) - 1.42x(1-x)$ , where  $x$  is the average indium concentration (0.20 for sample B, characterized by HR-XRD and XRR),  $E_g(\text{InN})$  and  $E_g(\text{GaN})$  represent the bandgap energies of InN (0.77 eV) and GaN (3.42 eV) respectively. Not surprisingly, the calculated value (466 nm) is remarkably consistent with the peak energy of blue emission without the consideration of QCSE.

Figure 2 shows the time-resolved PL spectra of sample A under a pump fluence of  $20 \mu\text{J}/\text{cm}^2$  at 15 K as a function of time delay. The signal was integrated within a time window of 0.5 ns. At short times

after pulsed excitation, the spectra are significantly broad and extend from 460 nm to 650 nm. The multiple peaks shown in the spectra are caused by the interference fringe, and the origin of the higher energy emission is due to the bandfilling of indium rich localized states. With increasing time delay, the spectra become narrow and dramatically shift to lower energies. This red shift demonstrates a reduction of a strong bandfilling of localized states in the InGaN well as photoinjected carriers recombine. In addition, the emission decay time is plotted as a function of wavelength in Fig. 2. The emission decay time increases from  $\sim 100$  ps to 15 ns with increasing detection wavelength from 460 nm to 660 nm. Specifically, the decay time of blue emission is



**Fig. 3** Time-integrated PL spectra of sample A under a pump fluence of  $5 \mu\text{J}/\text{cm}^2$  as a function of temperature: (a) 15 K to 60 K (b) 80 K to 300 K.

around 120 ps. Such short carrier lifetimes rules out the possibility of deep level blue emission generally observed in GaN, which has a much longer carrier lifetime at low temperature due to the nature of shallow donor to deep acceptor transition [6].

Time-integrated PL spectra as a function of temperature under low injection density were also performed to clarify the recombination nature of the red emission, as shown in Fig. 3. It is noted that the emission peak of sample A exhibits an initial redshift as the temperature is increased 15 K to 60 K. Conversely, as the temperature is increased above 60 K, the emission shifts to a higher energy (580 nm) and the peak energy shows a slight increase with temperature. Similar abnormal temperature dependence of PL line shape of InGaN has been reported in the literature and this abnormal behaviour is assigned to potential fluctuations caused by inhomogeneous indium fluctuations [7,8,9]. The initial redshift results because the carriers which are randomly distributed in the potential minima at low temperature are thermally activated so that they can relax to lower energy level states. As temperature further increases, the emission peak shows a blueshift, indicating the carriers do have sufficient thermal energy to occupy higher energy level states. This effect reflects the thermal distribution and transfer of localized carriers within different potential minima and supports the hypothesis that the observed red emission is due to inhomogeneous indium fluctuation/segregation in these samples.

### 3 Conclusions

In summary, time-resolved PL spectroscopy was used to study the emission dynamics of two InGaN/GaN SQW red emitters. A higher energy (blue) emission and a lower energy (red) emission have been observed simultaneously in these samples under high excitation density. It was observed that the emission lifetime increased as the detected emission photon energy decreased. These results suggest that the blue emission is due to a near band edge transition while the red emission is from localized emission within indium rich potential minima.

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