

High-Indium-Content InGaN/GaN Multiple-Quantum-Well Light-Emitting Diodes

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High-indium-content InGaN/GaN multi-quantum-well (MQW) light-emitting diode (LED) structures were epitaxially grown by metalorganic vapor phase epitaxy (MOVPE). With 70% indium in the InGaN well layers, it was found that the photoluminescence (PL) full-width at half maximum (FWHM) is stronger than that in the case of low-indium-content InGaN/GaN MQW LED structures. It was also found that the peak position of electroluminescence (EL) fabricated In_{0.7}Ga_{0.3}N/GaN LED depends strongly on injection current. As injection current increased from 1 mA to 150 mA, it was found that the output color of the In_{0.7}Ga_{0.3}N/GaN LED changed from orange to yellow, to yellowish green, and finally to yellowish white. [DOI: 10.1143/JJAP.42.2281]

KEYWORDS: InGaN/GaN, LED, PL, EL, high indium content

1. Introduction

Recently, tremendous progress has been achieved in GaN-based blue- and green-light-emitting diodes (LEDs).^{1,2)} These blue-/green-LEDs have already been extensively used in full-color displays and as highly efficient light sources for traffic light lamps. It has been shown that these nitride-based LEDs are highly efficient, highly reliable and can be operated at high speed. For LEDs operated in long-wavelength regions, such as those of yellowish green and yellow, AlGaInP-based LEDs are already commercially available and are extensively used. However, there are some problems with AlInGaP LEDs. The first one is that AlInGaP LEDs, prepared on GaAs substrates, contain toxic atoms such as As and P in their materials. In this respect, nitride-based LEDs are more environmentally friendly.³⁾ The other problem is that the output power of AlInGaP LEDs decreases rapidly at high temperatures.⁴⁾ It has been shown that the output power of AlInGaP LEDs could be reduced by 50% by increasing temperature from 0 to 40°C.⁵⁾ In contrast, the output power of nitride-based LEDs is almost independent of temperature due to the large conduction band discontinuity between InGaN well layers and (Al)GaN barrier layers. Although it is also possible to fabricate nitride-based LEDs operating in long-wavelength regions by increasing the indium content in the InGaN well layers, only a few reports regarding long-wavelength nitride-based LEDs are available in the literature.^{5,6)} This is due to the fact that a high indium content in InGaN well layers will result in a significant degradation of the crystal quality of epitaxial layers. In this paper, we report the growth of InGaN/GaN multi-quantum-well (MQW) LED structures with a high indium content of 70% in InGaN well layers and the fabrication of In_{0.7}Ga_{0.3}N/GaN LEDs. The photoluminescence (PL) properties of the as-grown epitaxial layers will be reported. The electroluminescence (EL) and Commission International de l'Eclairage (CIE) characteristics of the fabricated high-indium-content InGaN/GaN MQW LEDs will also be reported.

2. Experiments

The samples used in this study were grown on (0001)-oriented sapphire substrates using a low-pressure metalorganic vapor phase epitaxy (LP-MOVPE) system.^{7–13)} The

gallium, indium and nitrogen sources were trimethylgallium (TMGa), trimethylindium (TMI) and ammonia (NH₃), respectively. Bicyclopentadienyl magnesium (Cp₂Mg) and disilane (Si₂H₆) were used as the p-type and n-type doping sources, respectively. Figure 1 shows the top view and the schematic structure of the high-indium-content LEDs used in this study. Prior to the sample growth, the sapphire substrate was heated up to 1200°C in H₂ ambient to remove surface contaminations. A 25-nm-thick GaN nucleation layer was then grown at a low temperature of 560°C, followed by a 2-μm-thick Si-doped GaN grown at 1150°C, a 9-period unintentionally doped InGaN/GaN MQW active region grown at 680°C, and a 0.1-μm-thick Mg-doped Al_{0.2}Ga_{0.8}N cladding layer grown at 1100°C. Finally, a 0.3-μm-thick Mg-doped GaN layer was also grown at 1100°C to serve as the p-contact layer. The growth rate was kept at 2 μm/h throughout the sample growth. Each InGaN/GaN pair consists of a 2.5-nm-thick In_{0.7}Ga_{0.3}N well layer and a 12-nm-thick GaN barrier layer. In order to achieve nitride-based LEDs with a long emission wavelength, we maintained the indium mole fraction of the InGaN active layer at 0.7. A Bio-Rad rpm 2000 room temperature PL system, with a low 7 mW HeCd laser operated at 325 nm, was then used to measure the quality of the as-grown samples. After PL measurements, the surface of the p-type GaN layer was partially etched until the n-type GaN layer was exposed. A Ni/Au transparent contact was subsequently evaporated onto the p-type GaN surface to serve as the p-electrode. On the

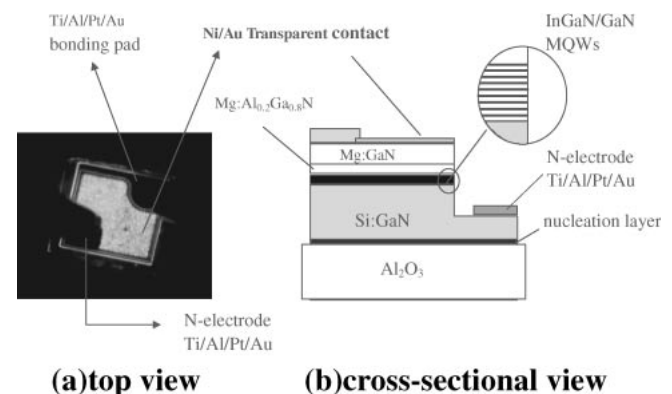


Fig. 1. (a) Top view and (b) cross-sectional view of high-indium-content LEDs used in this study.

other hand, a Ti/AI/Pt/Au contact was deposited onto the exposed n-type GaN layer to serve as the n-type electrode to complete the fabrication of the high-indium-content $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LEDs. The room-temperature EL characteristics of these fabricated LEDs were then evaluated at different amounts of DC injection current into these LEDs. The output power and efficiency of these high-indium-content InGaN/GaN LEDs were then measured using the molded LEDs with the integrated sphere detector from the top of the devices.

3. Results and Discussion

Figure 2 shows the room-temperature PL spectra of the fabricated $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED. It was found that the measured peak wavelength and full-width at half maximum (FWHM) were 578.7 nm and 55.6 nm, respectively. Compared with conventional low-indium-content InGaN/GaN blue-/green-LEDs, it was found that the FWHM of our high-indium-content $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED was larger. Such a large PL FWHM suggests that a high indium mole fraction in the InGaN well layers results in poor crystal quality. The other possible reason for the large PL FWHM is that a much larger lattice mismatch induces strain in the high-indium-content InGaN/GaN LEDs.¹⁴⁾ The room temperature EL of the high-indium-content InGaN/GaN LEDs with different amounts of DC injection current is shown in Fig. 3. At 1 mA

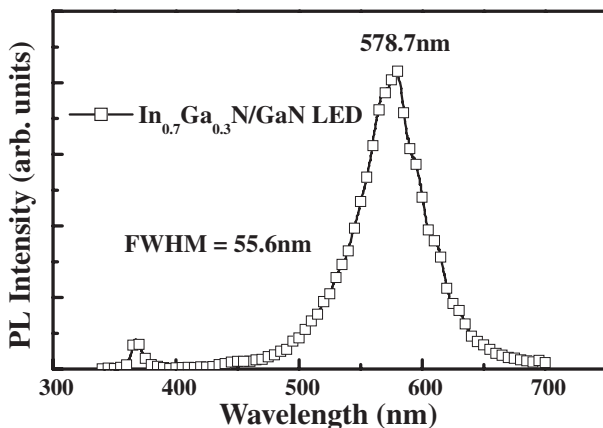


Fig. 2. Room-temperature PL spectra of the fabricated $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED.

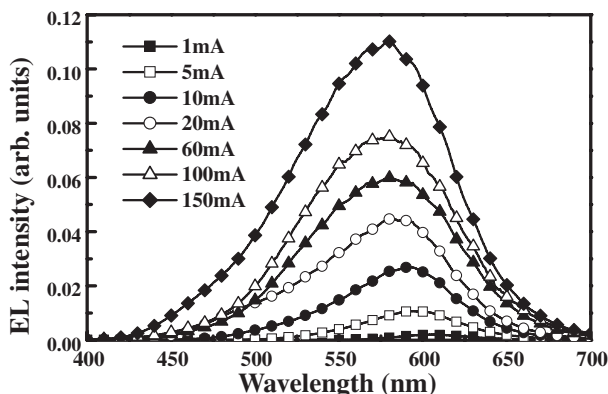


Fig. 3. Room-temperature EL of the high-indium-content InGaN/GaN LEDs with different amounts of DC injection current.

current injection, the EL peak wavelength of the $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED was observed at 597 nm. In other words, the output color of the fabricated $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED was close to orange under small current injection. It was found that the EL intensity increased significantly as the injection current increased. We also observed a large 83 meV EL blue shift from 597 nm to 574 nm as the injection current was increased from 1 mA to 20 mA. Although similar EL blue shifts were also observed in conventional low-indium-content InGaN/GaN blue-/green-LEDs, the EL blue shift was much more significant for the $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED. It is known that a strain induced piezoelectric field induces a large quantum confined Stark effect (QCSE) in nitride-based LEDs. The large EL blue shift observed in our $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED can be attributed to the fact that the injection current weakens the QCSE, thus, the transition energy increases. As a result, a large blue shift in EL spectra is observed from the $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED. On the other hand, the strain effect in the conventional low-indium-content blue/green InGaN/GaN LEDs is smaller due to their relatively small lattice mismatch. Thus, the EL peak position is less sensitive to the amount of injection current. It is also possible that the large EL blue shift is due to the filling of band-tail states (i.e., localized states) in which carriers or excitons recombined for emission as the injection current increases.¹⁵⁻¹⁷⁾ The localized states may be formed with indium compositional fluctuation in the InGaN well layers due to phase separation or indium segregation. Since the indium composition in our $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}$ well layers is high, the compositional fluctuation (i.e., dot formation) should also be larger than that in the case of conventional low-indium-content InGaN/GaN blue-/green-LEDs. As a result, a large blue shift in EL spectra is observed from the $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED.

Figure 4 shows the observed EL peak position as a function of injection current for the high-indium-content $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED. As shown in Fig. 4, the EL peak position blue-shifted rapidly as the injection current was increased from 1 mA to 20 mA. Such an observation indicates that the output color of the high indium content $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED was unstable under low current injection. On the other hand, the EL peak position stayed at around 574 nm when the injection current was larger than 40 mA. Although the peak position remained at approxi-

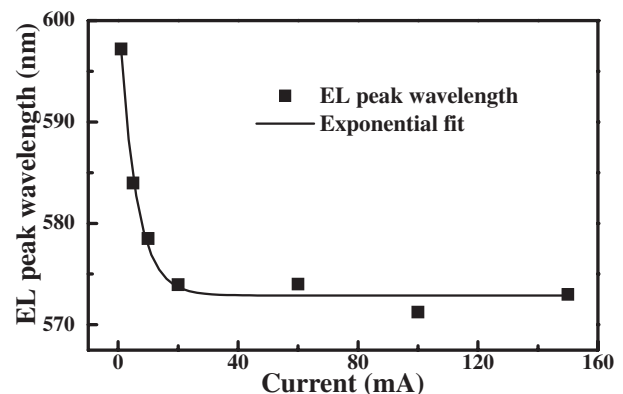


Fig. 4. Observed EL peak position as a function of injection current for the high-indium-content $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED.

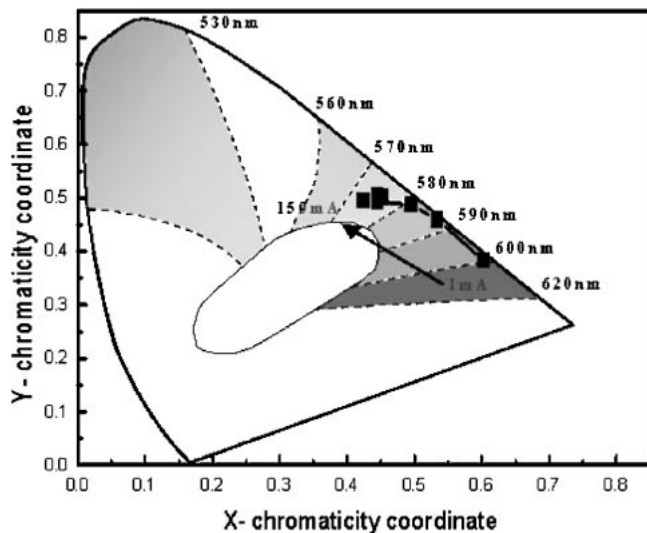


Fig. 5. CIE chromaticity diagram for the high-indium-content $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED at different injection currents.

mately 574 nm at high injection current, it should be noted that the tail on the short-wavelength side of the EL peak seems to increase faster than that on the long-wavelength side as the injection current increases. The CIE characteristics of the fabricated high-indium-content $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED were also evaluated. Figure 5 shows the CIE chromaticity diagram for the high-indium-content $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED at different injection current. It can be seen that the output color of the high-indium-content $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED changed from orange to yellow, to yellowish green, and finally to yellowish white, as the injection current increased. The mechanisms for such changes are still unclear. A detailed study on these issues is currently underway and will be reported elsewhere.

4. Conclusions

In summary, high-indium-content InGaN/GaN MQW LED structures were epitaxially grown by MOVPE. With 70% indium in the InGaN well layers, it was found that the PL FWHM is stronger than that in the case of low-indium-content InGaN/GaN MQW LED structures. It was also

found that the EL peak position of the fabricated $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED depends strongly on injection current. As injection current increased from 1 mA to 150 mA, it was found that the output color of the $\text{In}_{0.7}\text{Ga}_{0.3}\text{N}/\text{GaN}$ LED changed from orange to yellow, yellowish green, and then to yellowish white.

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