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Optical Properties of InGaN/GaN Light Emitting Diodes Grown by Pulsed-Trimethylindium-Flow Process

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1. Introduction

InGaN/GaN multiple quantum-well (MQW) is widely used as the active layers in light-emitting diodes (LEDs) and laser diodes in the ultraviolet-blue-green range [1,2]. In general, the trimethylindium (TMIn)-flow rate is almost kept constant to grow InGaN layers during. The spatial In concentration fluctuation or the exciton localization effect tend to control the luminescence properties of InGaN/GaN MQW with higher In concentrations in thin wells, while quantum confined Stark effects (QCSE) dominate the recombination emission in the wide wells [3]. Several methods have been reported to improve the emission efficiency of InGaN/GaN MQW, such as addition of InN interfacial layers between wells and barriers, trapezoid/triangular QWs, and growth interruption between wells and barriers [4-6]. Such methods result in interface improvement and formation of QDs-like clusters for strongly localizing carriers to improve emission efficiency of MQW.

2. Experiments

All LED samples used in this work were grown on c-plane (0001) sapphire (Al_2O_3) substrates by metalorganic vapor phase epitaxy (MOVPE) with two TMIn sources. The precursors of Ga, In, N, Mg and Si were TMGa, TMIn, NH_3, Cp_2Mg and SiH_4, respectively. Prior to deposition of the GaN nucleation layer, the sapphire substrates were pre-baked at 1100°C with H_2 ambient for 10 min. The LED structure consists of a 30-nm-thick GaN nucleation layer grown at 550°C, a 4-μm-thick Si-doped GaN layer grown at 1060°C, a 8-pair $In_xGa_{1-x}N$/GaN MQW active layers grown at 770°C, a 50-nm-thick Mg-doped AlGaN electron blocking layer grown at 1050°C, and a 0.15-μm-thick Mg-doped GaN cladding layer grown at 1050°C. For the 8-pair $In_xGa_{1-x}N$/GaN MQW active region, each pair consists of a 2.5-nm-thick $In_xGa_{1-x}N$ well layer and a 13-nm-thick GaN barrier layer. For comparison, two LED samples were grown with different initial TMIn-flow rates (f_{TMIn}) in the well layers. For sample A, the f_{TMIn} was fixed at 230 sccm for overall growth of an InGaN layer. For sample B, a pulse -TMIn-flow process was used. In this process, the initial f_{TMIn} in each InGaN layer was 400 sccm persisting for a 10% growth time of an InGaN layer, and was then switched to 230 sccm with well shutter control. The variation of f_{TMIn} during growth for samples A and B is shown in Fig.1. The fabrication of the LED chips was described in detail elsewhere [7].

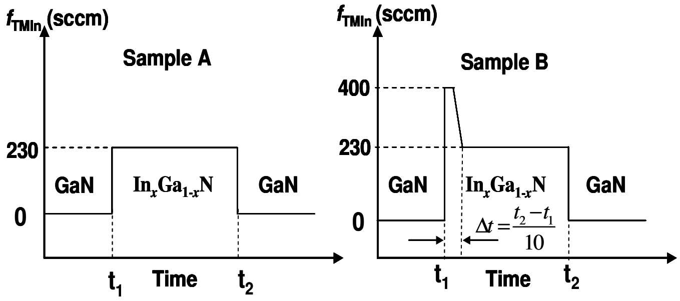

Fig. 1 Schematic diagrams of f_{TMIn} variation over time in InGaN QWs for samples A and B.

3. Results and Discussion

Figure 2 shows the 10K photoluminescence (PL) spectrum of sample A and sample B, which has the typical InGaN-related emission band with peak emission around 2.79 and 2.81 eV for samples A and B with a full linewidth at half-maximum (FWHM) of about 80 and 53 meV, respectively. It can be seen that the PL peak position of sample B blue shifts toward higher photon energy side while its FWHM of PL peak is smaller than that of sample A.

The PL emission energy of samples A and B as a function of temperature are plotted in Fig. 3. It can be seen that both curves do not follow the Varshni law and shows an "S" shape (redshift-blueshift-redshift) over a temperature range from 10 to 300K, indicating clearly the existence of localized states in both samples. In each case, the temperature-dependent emission energy could be fitted based on the band tail model suggested by Eliseev *et al.* as follow [8]

$$E(T) = E(0) - \frac{\alpha T^2}{T+\beta} - \frac{\sigma^2}{k_B T} \qquad (2)$$

The first term describes the energy gap at zero temperature; α and β are known as Varshni's fitting parameters. The third term comes from the localization effect, in which σ indicates the degree of localization effect. K_B is Bolzmann's constant. The value of σ was estimated to be 14.7 and 17.9 meV for samples A and B, respectively; indicating the localization effect of sample B is stronger than that of sample A.

The insets in Fig. 3 show an Arrhenius plot of the normalized integrated PL intensity for the InGaN-related PL emission over the temperature range under investigation. For T > 80K, the thermal quenching can be fitted with activation energies E_A of 35.3 meV and 42.8 meV, respectively, to samples A and B. It has been suggested that the measured activation energy E_A in InGaN samples represents the localization energies of excitons, resulting from band edge fluctuations.[19] It was inferred from the results mentioned above that the In fluctuations or the QD-like regions might be more abundant in sample B than in usual QWs (sample A). These results suggest that the composition fluctuations or QDs-like regions formed by using pulse-TMIn-flow process can provide the necessary confinement for an improved recombination rate.

The fabricated LED samples were tested for their light outputs as a function of injection current (L-I) as shown in Fig. 4. As can see the emission power intensity of sample B is higher than that of sample A for overall driving-current range. At lower driving current of 20 mA, the sample B have a light output power of ~ 3.6 mW 16% greater than ~ 3.1 mW for the sample A. The enhancement of light output increases with the driving current up to ~24% at 60 mA.

3. Conclusions

In conclusion, the optical properties of pulse-TMIn -flow process with an initial f_{TMIn} of 400 sccm during the well layer growth on structural and optical properties of InGaN/GaN MQWs were investigated. The results show that the pulsed-TMIn-flow process can improve the localization effects and the activation energy of InGaN/GaN MQWs. The light output of the GaN LEDs with the pulse-TMIn-flow process is increased up to 24% without any deterioration of interfacial abruptness. We attribute the increase of light output to the improvement of the localization effects and activation energies.

Acknowledgements

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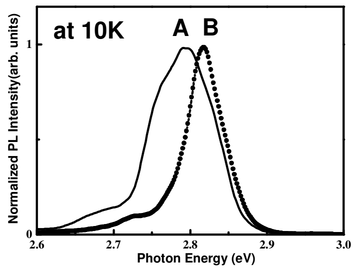

Fig. 2 Normalized PL emission spectra of samples A (solid line) and B (solid circle) at 10K.

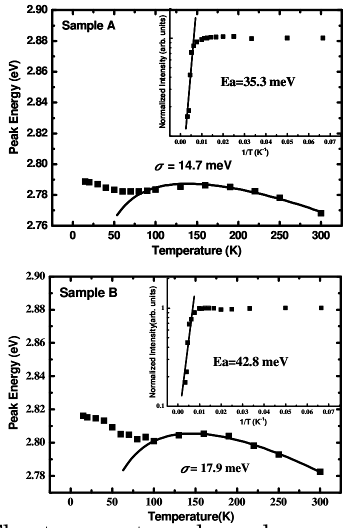

Fig. 3 The temperature-dependence of PL peaks energies and normalized PL intensity (inserts) for samples A and B.

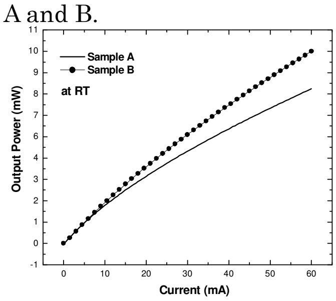

Fig. 4 *L-I* characteristics for the samples A and B.