Significance of vertical carrier capture for electroluminescence efficiency in InGaN multiple-quantum well diodes

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The electroluminescence (EL) spectral intensity has been investigated in the high-brightness green InGaN multiple-quantum-well light emitting diode (LED) in comparison with the single-quantum-well LED over a wide temperature range and as a function of injection current. It is found that the EL variation pattern with temperature and current is dramatically improved when the number of active wells increases as a result of enhanced carrier capture. The importance of vertical carrier capture processes is pointed out to explain the anomalous EL intensity variations at low temperatures.

1 Introduction Blue and green light emitting diodes (LEDs) using group III-nitride semiconductor quantum structures have been manufactured successfully [1-4]. Such quantum well LEDs with a ternary alloy active layer shows very bright emission characteristics in spite of the existence of high-density misfit dislocations. Thus, origins of the high quantum efficiency have been receiving much attention [5-10]. Recently we have investigated temperature dependence of the electroluminescence (EL) spectral intensity in the super-bright green and blue InGaN single-quantum-well (SQW) LEDs, which reveals anomalous EL quenching at lower temperatures below 100 K [6-8]. It is found that the anomalous temperature dependence of the EL efficiency is caused by interplay of the carrier capture and the internal quantum efficiency. In this paper, the EL spectral intensity is investigated in the high-brightness green InGaN multiple-quantum-well (MQW) LED over a wide temperature range and as a function of injection current level in comparison with the green single-quantum-well (SQW) LED. It is found that the variation pattern of the temperature-dependent EL efficiency dramatically changes when the number of wells increases to four from one, suggesting that the carrier capture plays a very important role for the determination of EL efficiency.

2 Experiment EL spectral characteristics of the green InGaN MQW and SQW LED samples, fabricated by Nichia Chemical Industry Ltd., have been studied as a function of lattice temperature with varying the injection current from 1 mA to 10 mA. In the 4-periods green MQW diode the nominal InGaN well width is 2.4 nm and the claimed In concentration in the MQW layer is 0.45. The InGaN QW layer is confined by p-$Al_{0.2}Ga_{0.8}N$ and n-GaN barrier layers. The LED sample was mounted on a Cu cold stage of a temperature-variable closed-cycle He cryostat to vary the sample temperature over a wide range (T = 15-300 K). EL spectra were measured by a conventional lock-in technique, employing a GaAs photomultiplier or a CCD detector. Current-voltage (I-V) characteristics of the green MQW diode at various temperatures were measured, as shown in Fig. 1. They are similar to those for the green SQW diode, as reported previously [1, 3]. It is interesting to note, however, that there exist distinct differences between

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green and blue diodes. That is, the *I-V* characteristics strongly depend on the In content in the active layer, irrespective of the number of well layers. Details of the *I-V* results will be reported elsewhere. The typical forward voltage at a forward current of 10 mA was 3.3 V at 300 K and 4.6 V at 20 K, as shown in Fig. 1 for the green MQW diode. In all the cases the forward voltage to get a certain current level is increased by about 1-1.5 V when the temperature is decreased from 300 K to 20 K. In addition, a discernible change of the *I-V* curvature is seen in Fig. 1 due to modification of the current transport mechanism in the diode by decreasing the temperature.

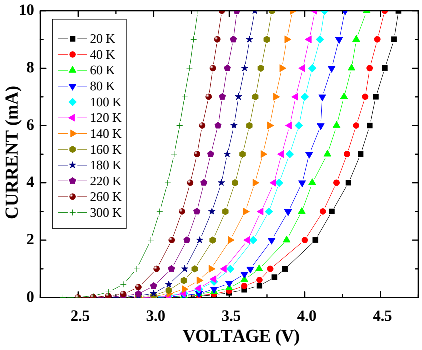

Fig. 1 Current-voltage characteristics of the green InGaN MQW diode as a function of temperature between 20 and 300 K.

3 Results and Discussion Temperature dependence of the EL spectra for the green MQW-LED at a fixed injection current of 10 mA has been measured between 15 and 300 K. Three-dimensional (3D) plots of the EL results for the green MQW-LED are shown in Fig. 2(a) in comparison with those for the green SQW-LED in Fig. 2(b). In the EL spectra of Fig. 2(a) a leading green MQW peak is observed around 540 nm (2.3 eV) with multiple fine structures due to Fabry-Perot fringes. When the temperature is increased from 15 K to 300 K, the EL intensity of the green MQW-LED monotonously decreases primarily due to the decrease of the internal quantum efficiency. This result is very different from the temperature dependence of the EL intensity observed for the green SQW-LED, as shown in Fig. 2(b). That is, the EL efficiency of the green SQW-LED at 10 mA is drastically decreased below 100 K, while that of the green MQW-LED does not show any decreases of the EL efficiency at low temperatures. Previously, we have shown that the EL efficiency of the green SQW-LED also depends on the injection

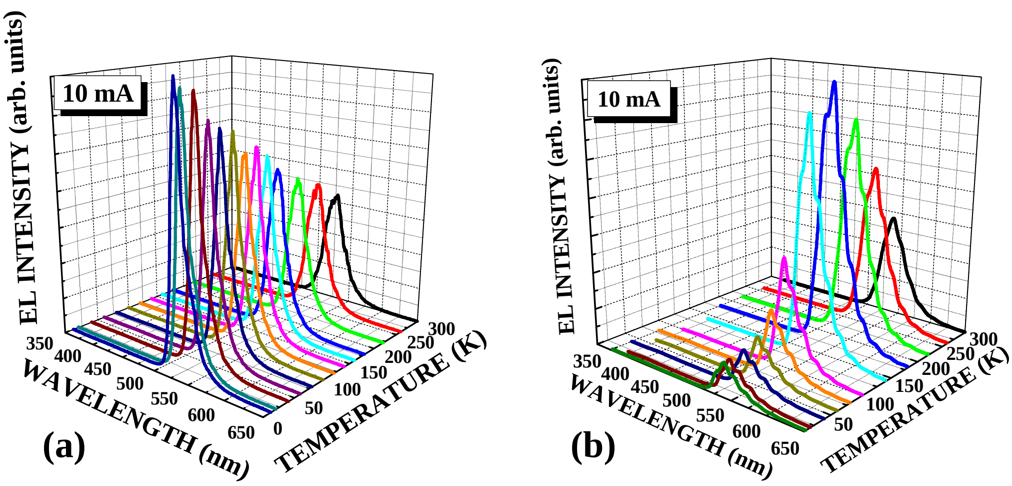

Fig. 2 Temperature dependence of EL spectra for (a) green InGaN MQW-LED in comparison with (b) green SQW diode at a fixed injection current of 10 mA.

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current, and under the very low injection level of 0.01 mA the EL efficiency does not show any decreases with decreasing temperature [8]. We attribute this difference in the temperature-dependent EL variation pattern between high and low injection current levels for the green SQW-LED to the carrier capture efficiency, since the applied forward bias condition is very different. That is, under the high injection current with the higher forward bias the external forward field effects result in the enhancement of the carrier escape, being consistent with the PL results under the forward bias condition [11, 12]. On the other hand, the carrier escape is significantly reduced under the decreased forward bias voltage for the low injection current even at low temperatures. Therefore, the EL results shown in Fig. 2(a) imply that the improvement of the EL efficiency for the green MQW-LED is due to the improved carrier capture efficiency even under the higher forward bias conditions.

In order to confirm the improved EL efficiency of the green MQW-LED, we have also evaluated the EL efficiency as a function of temperature for a lower current, say 2 mA. It is found that the external quantum efficiency, as defined by the number of emitted photons divided by the number of carriers injected, significantly increases when the injection current is decreased (when the forward bias is decreased). The results of the external quantum efficiency for the green MQW-LED and SQW-LED are plotted as a function of temperature in Fig. 3 for two injection currents of 2 and 10 mA. It is clear from Fig. 3 that the EL efficiency is better for the MQW-LED at all temperature regions than for the SQW-LED irrespective of the current level. Here we note that, even when the current is high at 10 mA and thus the forward driving voltage is high, the EL quenching is completely absent for the MQW-LED. Furthermore, at the low injection current of 2 mA the EL efficiency is always found to be higher than at the high current of 10 mA. Therefore, the low temperature EL reduction observed for the SQW-LED under higher injection currents (under higher forward voltages) is ascribed to the enhanced carrier escape from the active QW layer. The significantly improved EL efficiency for the MQW-LED at all temperatures is due to the efficient vertical carrier capture by increasing the number of active QW layers, as illustrated schematically in Fig. 4.

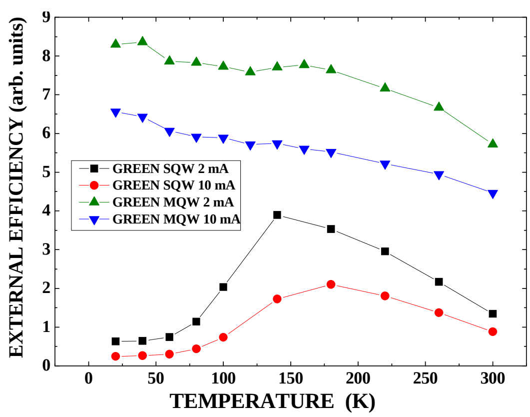

Fig. 3 Temperature dependence of the integrated EL intensity for the green SQW and MQW diodes at two injection currents of 2 and 10 mA

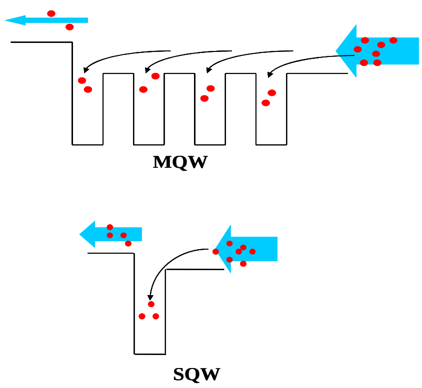

Fig. 4 Schematic conduction band diagrams for carrier capturing by SQW and MQW structures (without including the internal field).

In Figs. 2 and 3 we have shown that the temperature-dependent variation patterns of the EL efficiency are very different for the green InGaN MQW-LED and SQW-LED. That is, for the green MQW-LED the electrically injected carriers are more efficiently captured by active regions even at low temperatures and higher forward driving voltage (external field), confirming the importance of carrier overflow for the anomalous EL quenching for the green SQW-LED. On the other hand, the temperature-dependent EL variation pattern shows a striking difference between green and blue MQW diodes owing to the different In content in the InGaN well (EL results for blue LEDs are not shown here). That is, for blue MQW-LED the anomalous EL quenching persists at lower temperatures, especially when the injection current is high at 10 mA and the forward voltage is high. This EL quenching observed for the blue LEDs below 100 K indicates that the unusual evolution of the EL intensity pattern with temperature and current can be caused by variations of the actual potential field distribution (due to both internal and external field), which significantly influences the carrier capture efficiency within the MQW and SQW layers. It is important to note that the higher field existing in the well decreases the radiative recombination rate due to the quantum confined Stark effect, which also causes the reduced EL intensity [13, 14]. This observation is consistent with our recent PL results where the PL intensity decreases when the applied forward voltage exceeds +2 V [11, 12] after reaching the maximum intensity around +2 V. Therefore, our results suggest importance of the efficient carrier capture processes for explaining the observed enhancement of radiative recombination in the presence of high-density misfit dislocations.

4 Conclusion Temperature dependence of the electroluminescence (EL) spectral intensity has been studied in the super-bright green InGaN multiple-quantum-well (MQW) light-emitting diode in comparison with the single-quantum-well (SQW) LED. The EL efficiency is significantly improved for the MQW-LED in comparison with the SQW-LED irrespective of the temperature range measured under low and high injection current conditions. This unique variation pattern of the EL efficiency with temperature and current strongly suggests that the vertical carrier capture play a critical role for the determination of EL efficiency in the InGaN quantum well diodes.

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