Asymmetric external electric field effects on luminescence intensity of InGaN single-quantum-well light-emitting diode

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Abstract. Temperature dependence of electroluminescence (EL) spectra of the super-bright green InGaN single-quantum-well (SQW) light-emitting diode (LED) has been studied over a wide temperature range (T=15-300 K) and as a function of injection current level. The EL intensity efficiently increases due to reduced non-radiative recombination processes when temperature is slightly decreased to 140 K from 300 K. However, with further decrease of temperature down to 15 K, it drastically decreases due to the reduced carrier capture. In order to pursue origins of the EL quenching at low temperatures, bilateral electric field dependence of the quantum efficiency have been studied at 15 K by photoluminescence (PL) measurements. It is found that the PL intensity gradually decreases with increasing the reverse bias voltage down to –10 V due to tunneling escape of the carrier out of the well. On the other hand, while the PL intensity increases with increasing the forward bias voltage up to 2 V, however, drastic reduction of the PL intensity is observed with further increase of the forward bias voltage up to 4.25 V. This PL quenching in both field directions means that spatial separation of the electron and holes plays an important role in the EL efficiency because of the existence of large internal piezoelectric and spontaneous field. These results suggest that both internal and external field effects are crucial to the unique temperature dependence of the EL efficiency.

1. Introduction

Recently, group III-nitride semiconductor quantum structures have been successfully applied to super-bright blue and green light-emitting diodes (LEDs) [1,2]. The quantum well (QW) LED shows very bright emission characteristics in spite of the existence of high-density misfit dislocations. Thus, the origins of high quantum efficiency have been receiving much attention [3-16]. However, they have been still controversial. Previous spectroscopic studies by electroluminescence (EL), photoluminescence (PL), reflectance and photoabsorption spectral measurements suggest that quantum confinement effects on the InGaN QW and efficient carrier capturing processes by localized radiative recombination centers such as certain potential minima in inhomogeneous InGaN QWs are important for the origin of the high emission efficiency.

On the other hand, it has been pointed out that the quantum confined Stark effect caused by an internal piezoelectric field due to lattice mismatch plays an important role in strained InGaN QWs [9-12]. In this work, temperature dependence of EL spectral intensity of the green InGaN single-quantum-well (SQW) LED has been studied over a wide temperature range and as a function of injection current. Bilateral electric field dependence of the internal quantum efficiency has also been studied at 15 K by PL measurements under both forward and reverse bias conditions.

2. Experimental

The super-bright green InGaN SQW LED sample, fabricated by Nichia Chemical Industry Ltd. [2], has been studied in this work. The nominal InGaN well width is 3 nm and the claimed In concentration in the InGaN SQW layer is 0.45. The InGaN SQW layer is confined by p-$Al_{0.2}Ga_{0.8}N$ and n-GaN barriers. The detailed diode heterostructure was described previously [1,2]. The InGaN SQW LED chip was mounted on a semi-insulating GaAs wafer piece for wiring. Then, it was fixed 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, as a function of injection current from 0.1 to 10 mA. PL spectra were measured at 15 K under various applied bias voltages between –10 and 4.25 V. For PL excitation, a second-harmonic light (380 nm) of the pulsed Ti:sapphire laser was used to directly excite the InGaN SQW layer. By means of lock-in detection, restricted emission induced by the excitation light was selectively measured in spite of the existence of EL under forward bias voltages.

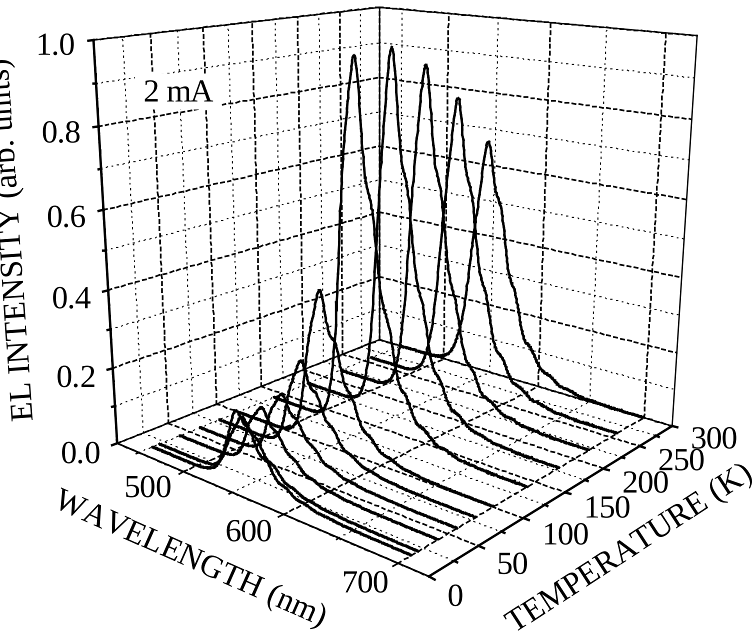

Figure 1. Temperature dependence of EL spectra of the green InGaN SQW LED at an injection current of 2 mA.

3. Results and discussion

EL spectra of the green InGaN SQW LED has been measured as a function of injection current over a wide temperature range between 15 and 300 K. Current-Voltage characteristics of the diode has been also measured and found to be similar to the ones reported previously [1,6]. Typical forward voltage at a forward current of 0.1 mA is 2.6 V at 300 K and 3.6 V at 15 K, respectively. The temperature dependence of the EL spectra for the green InGaN SQW LED, for example, is shown in Fig. 1 at a fixed value of the injection current of 2 mA. At 300 K, the green InGaN SQW LED shows an emission band centered around 540 nm (2.3 eV) at the current level of 2 mA with multiple fine structures due to Fabry-Perot fringes. The emission peak shows a blueshift with increasing the injection current due to the band-filling effect on the localized recombination centers at 300 K. The EL spectral intensity varies significantly with changes of the sample temperature. When temperature is slightly decreased from 300 to 140 K, the EL spectral intensity efficiently increases. This enhancement of the EL efficiency is similar to that usually expected for the reduced non-radiative recombination at lower temperatures. However, with further decrease of temperature down to 15 K, a drastic reduction of the EL intensity is observed. That is, it is found that the EL efficiency at lower temperatures is quite low.

This reduction of the EL efficiency at lower temperatures is also seen at other injection currents. Figure 2 shows the spectrally integrated EL intensity as a function of inverse temperature at various injection current levels between 0.1 and 10 mA. It is seen

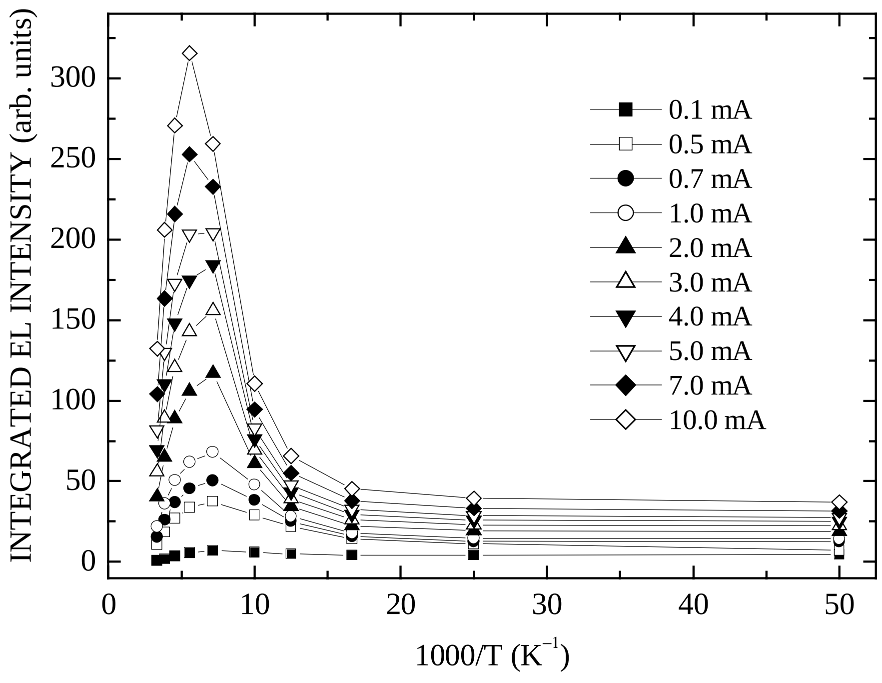

Figure 2. Spectrally integrated EL intensity of the green InGaN SQW LED as a function of inverse temperature at various injection currents from 0.1 to 10 mA.

that the EL intensity versus injection current characteristics at intermediate to low temperature regimes are quite astonishing, since the EL intensity shows saturation phenomena at lower output levels. At higher injection currents, say 10 mA, the EL intensity is very low at 15 K. This phenomenon observed at 15 K is obviously not because of the heating effects and reflects the particular recombination characteristics of the InGaN SQW heterostructures by current injection. The similar low temperature EL quenching is also observed for other InGaN SQW LEDs [13].

In order to investigate causes of the reduced EL efficiency at lower temperatures, we have studied the detailed EL spectral line shape as a function of injection current [14]. At higher temperatures where the EL efficiency is high, the spectral line shape shows a blueshift with increasing the injection current due to the band-filling of the localized recombination centers. On the other hand, the spectral line shape does not change with current at lower temperatures where the EL efficiency is quite low. The saturation of the EL intensity has been clearly observed with increasing the injection current at lower temperatures. This trend of the EL intensity saturation has been rigorously explained by the rate equation analysis, assuming a finite number of radiative recombination centers [15]. These results suggest that the temperature and injection current dependence of the EL efficiency is caused by interplay of the carrier capture processes and the internal quantum efficiency.

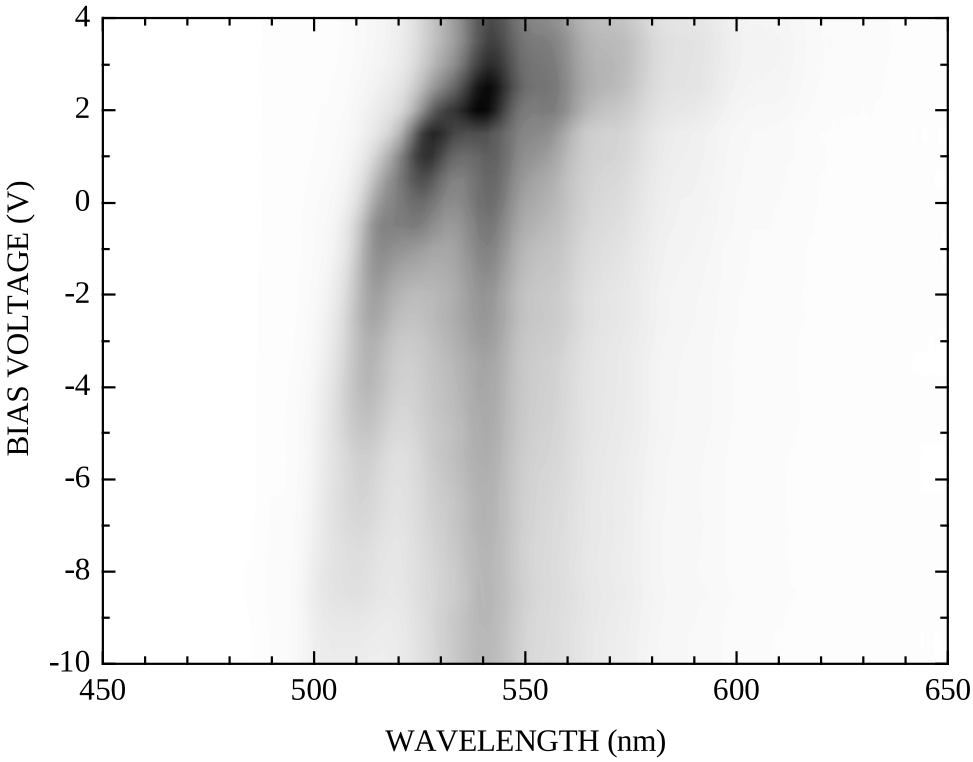

Figure 3. A grey-scale plot of PL spectral intensity of the green InGaN SQW LED as a function of wavelength and applied bias voltage measured at 15 K.

The electric field effects on the internal quantum efficiency are good approaches to clarify the physical mechanism of the reduction of the EL efficiency with decreasing temperature. Therefore, bilateral field dependence of the internal quantum efficiency has been studied by PL measurements under both forward and reverse bias conditions. Figure 3 shows the PL spectral intensity of the green InGaN SQW LED measured at 15 K under various applied voltages between –10 and 4 V using a grey-scale representation. Typical PL spectra under applied bias voltages of –10, –5, –2, 0, 2 and 4 V, are shown in Fig. 4. The PL spectrum at 4 V is almost the same as the EL spectrum. Two emission bands are clearly observed under the applied bias voltages below 2 V. The higher energy band under the applied voltage of 0 V is located around 525 nm, and the lower one is around 540 nm. The higher energy emission shows a blueshift with increasing the applied reverse bias voltage, and it is located around 505 nm at –10 V, while the lower energy one does not show any significant shifts. The blueshift might be related with the compensation of the piezoelectric field by the applied reverse bias voltage [9]. Although it has been reported that the two-components emission from InGaN LED is observed on the conditions of reverse bias [16], the origin of the emission has not been clear yet.

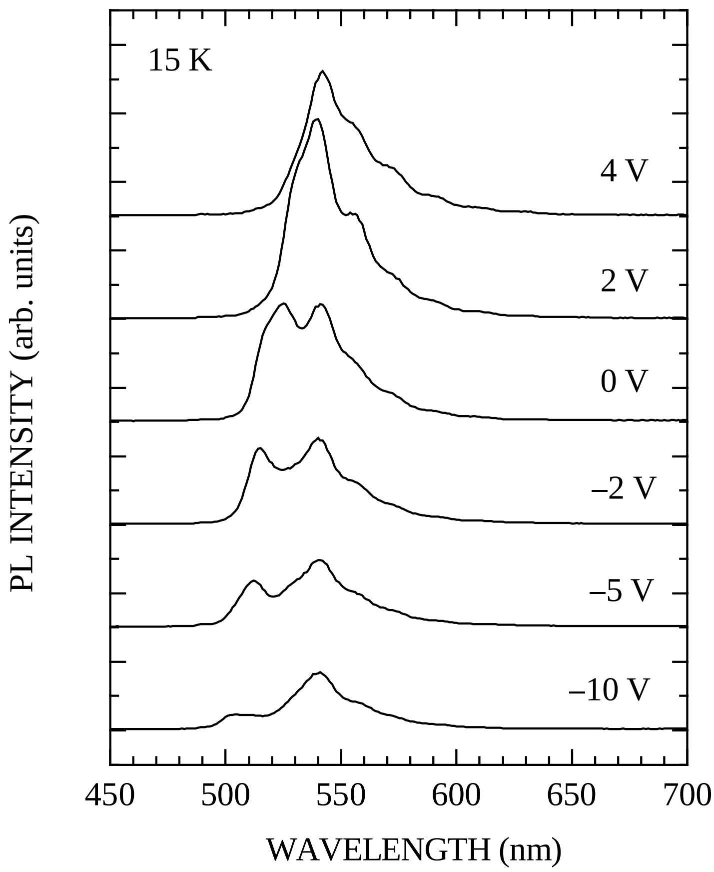

Figure 4. PL spectra of the green InGaN SQW LED measured at 15 K under applied bias voltages of –10, –5, –2, 0, 2 and 4 V. Base lines of the PL spectra are vertically shifted for clarity.

It is important to note that the PL intensity varies dramatically with changes of the applied bias voltage. Figure 5 shows the spectrally integrated PL intensity at various applied bias voltages. It is found that the PL intensity gradually decreases with increasing the applied reverse bias voltage. In this case, since the internal piezoelectric field is cancelled by the applied reverse bias, the transition probability should increase because of increases of the overlap integral between the wave functions of the electrons and holes in the SQW layer. However, the PL intensity is observed to decrease with increasing the applied reverse bias voltage. This result indicates that the PL quenching under the reverse bias voltages should be due to tunneling escape of the carriers out of the well induced by the external electric field [17]. Our observation of the photocurrent intensity increases from the SQW layer with the reverse bias (not shown) supports our hypothesis for the PL quenching. On the other hand, while the PL intensity increases with increasing the applied forward bias voltage up to 2 V, however, significant reduction of the PL intensity is observed with further increase of the forward bias up to 4.25 V. This PL quenching means that the spatial separation of the electrons and holes under the influence of the forward bias [18] plays an important role in the EL efficiency.

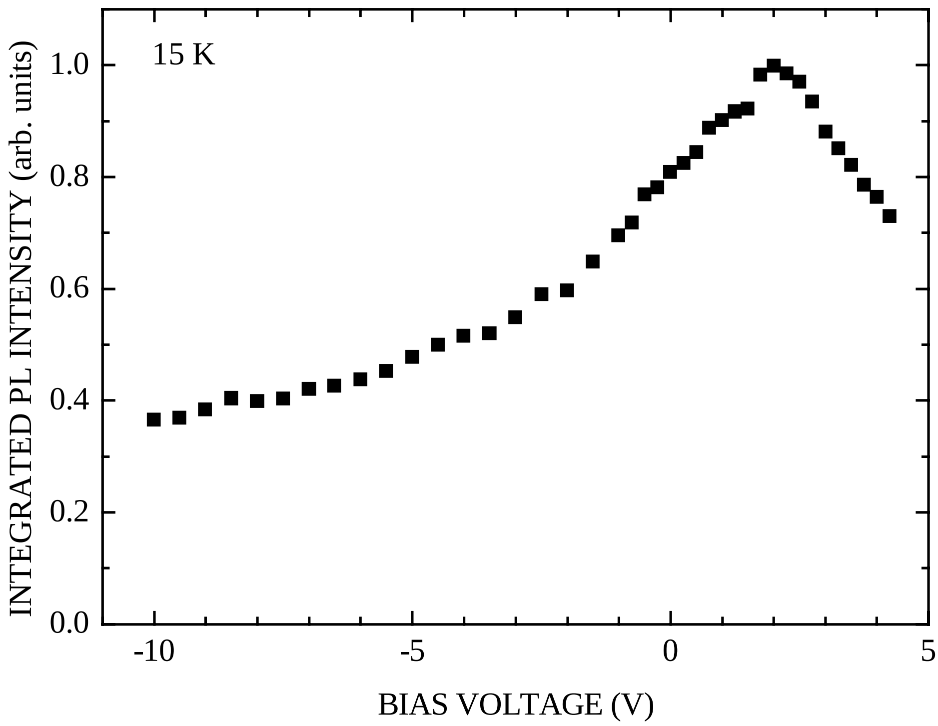

Figure 5. Spectrally integrated PL intensity of the green InGaN SQW LED at various applied bias voltages between –10 and 4.25 V measured at 15 K.

4. Conclusion

Temperature dependence of electroluminescence (EL) spectral intensity of the super-bright green InGaN single-quantum-well light-emitting diode has been studied. We find that, the EL intensity is drastically reduced with decreasing temperature down to 15 K. We attribute the reduction due to decreased carrier capture by the localized radiative recombination centers. At lower temperatures, the saturation of the EL intensity has been clearly observed with increasing the injection current. This trend of the saturation is explained by a rate equation analysis, assuming a finite number of the radiative recombination centers. These results suggest that the temperature and injection current dependence of the EL efficiency is caused by interplay of the carrier capture processes and internal quantum efficiency. We have also studied electric field dependence of the internal quantum efficiency at 15 K by means of photoluminescence (PL) measurements under the applied bias voltages between –10 and 4.25 V. We find that the PL intensity gradually decreases with increasing the reverse bias voltage due to the tunneling escape of the carriers out of the well. On the other hand, while the PL intensity increases with increasing the forward bias voltage up to 2 V, however, drastic reduction of the PL intensity is observed with further increase of the forward bias voltage. This PL quenching under the forward bias condition is attributed to spatial separation of the electrons and holes. These results mean that both internal and external field effects are crucial to determine the temperature dependence of the EL efficiency.

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