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Temperature Dependent Electroluminescence Anomalies Influenced by Injection Current Level in InGaN Single-Quantum-Well Diodes

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Abstract

Temperature dependence of the electroluminescence (EL) spectral intensity is investigated in the super-bright green InGaN single-quantum-well diode under low injection currents down to 0.01 mA. It is found that a temperature dependent variation pattern of the EL efficiency under very low and high injection currents shows a drastic difference. That is, when the current is low and thus the forward driving voltage is small, the EL intensity persists to increase with decreasing temperature due to the reduced nonradiative recombinations and the efficient carrier capture by the active region. On the other hand, when the injection current is high and the forward voltage is large, the EL intensity is significantly reduced at temperatures below 100 K. This unique EL efficiency variation pattern with temperature and current is explained by external field effects due to the driving forward bias in the presence of internal (piezo and spontaneous polarization) fields.

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1. Introduction

Blue and green light emitting diodes (LED's) using group III-nitride semiconductor quantum structures have been manufactured successfully [1-4]. Such quantum well LED 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 [5-7]. Recently we have investigated temperature dependence of the electroluminescence (EL) spectral intensity, which reveals anomalous EL quenching at lower temperatures below 100 K [6,7]. 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 super-bright green InGaN single-quantum-well (SQW) LED's [2] over a wide temperature range and as a function of wide injection current level to exploit what causes variations of the carrier capture efficiency. Under very low current injection conditions the EL intensity variation pattern with temperature drastically changes. That is, it is found that, when the current is low and thus the forward driving voltage is small, the EL quenching is absent, previously observed below 100 K under high injection currents. This unique pattern of the EL intensity variations with temperature at different injection levels is explained by interplay of external and internal field effects in the presence of strong piezo and spontaneous polarization fields [8].

2. Experiment

Detailed EL spectral characteristics of the super-bright green InGaN SQW-LED sample with ~10^{10} cm^{-2} misfit dislocations, fabricated by Nichia Chemical Industry Ltd. [2], have been studied as a function of lattice temperature with varying the injection current from 2 mA down to 0.01 mA. The nominal InGaN well width is 3 nm and the claimed In concentration in the SQW layer is 0.45 for the green diode [2]. The InGaN SQW layer is confined by p-$Al_{0.2}Ga_{0.8}N$ and n-GaN barrier layers. The detailed diode heterostructure was described previously [1,2]. The SQW-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. Current-voltage characteristics of the diode were measured and found to be similar to the ones reported previously [1,3]. The typical forward voltage at a forward current of 0.1 mA was 2.6 V at 300 K and 3.6 V at 20 K, as shown in Fig. 1 for the green 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 in the diode by decreasing the temperature.

3. Results and discussion

Temperature dependence of the EL spectra at various injection current levels has been measured between 15 and 300 K. Three-dimensional (3D) plots of the EL results at three injection currents of 2.00, 0.05, and 0.01 mA are shown in Figs. 2(a), 2(b), and 2(c), respectively. In the EL spectra of Fig. 2(a) a leading green SQW peak is observed around 540 nm (2.3 eV) with multiple fine structures due to Fabry-Perot fringes. When temperature is slightly decreased to 140 K from 300 K, the EL spectral intensity efficiently increases and reaches the maximum around 140 K. This enhancement of the radiative recombination efficiency observed at 140-260 K is due to the reduced nonradiative recombination at lower temperatures. However, with further decrease of temperature down to 15 K, significant reduction of the EL intensity is observed in agreement with our previous results [6], indicating the reduced carrier capture by the radiative recombination centers in the InGaN well. When the injection current is decreased to 0.2 mA, the EL reduction is similarly observed. However, when the current level is decreased to 0.05 mA as shown in Fig. 2(b), the temperature dependent pattern of the EL efficiency completely changes into the different one, where the EL intensity increases with decreasing the temperature with a local minimum around 60 K. At the lowest current of 0.01 mA in Fig. 2(c), the EL variation pattern is totally different from the one in Fig. 2(a). That is, with the lowest injection current the EL intensity shows the highest value at the lowest temperature of 15 K. This result of Fig. 2(c) is interpreted as showing the EL efficiency basically determined by the radiative recombination efficiency. According to our preliminary photoluminescence (PL) experiments under the direct excitation (where only the InGaN well is photoexcited) and open circuit conditions, the PL intensity proportional to the internal quantum efficiency increases with decreasing the temperature. Thus, the EL intensity increases with decreasing temperature observed at the injection current of 0.01 mA can be understood in terms of the reduced nonradiative recombinations, while the low temperature EL reduction under high injection currents is ascribed to the reduced carrier capture under the higher forward voltage applied to get the same current level.

In order to check the EL efficiency per the number of injected carriers the integrated EL intensity is plotted as a function of temperature in Fig. 3 at fixed injection currents of 2.00 mA, 0.20 mA, 0.05 mA, and 0.01 mA. In this plot the EL intensity is multiplied by 10, 40, and 200 for the injection current of 0.20, 0.05, and 0.01 mA, respectively, to normalize the EL intensity per injected carrier. In general it is seen that the EL efficiency at 200-300 K is higher under the high injection currents. On the other hand, the EL efficiency at 20 K shows the lowest value when the injection current is 2.00 mA. Specifically at 300 K the EL efficiency increases with increasing the current. This behavior is easily explained by the saturation of the nonradiative recombination centers as the number of injected carrier increases. However, this trend is completely changed as the temperature decreases. At 15 K the EL efficiency is the worst at the highest injection level in Fig. 3 and increases with decreasing the current. At intermediate temperatures the EL efficiency shows complicated behaviors, indicating the multiple causes, the quantum efficiency and the carrier capture efficiency, for the determination of the EL efficiency. Here we note that, when the current is low at 0.05 mA and thus the forward driving voltage is small (3.3 V at 15 K), the EL quenching below 100 K is absent due to the efficient carrier capture. On the other hand, when the injection current is high at 2.00 mA and the forward voltage is large (4.4 V at 15 K), the EL quenching below 100 K persists. This temperature dependent pattern of the EL intensity variation at different injection levels must originate from the difference in the driving voltage (external field). When the carrier acceleration voltage (external field) is high at lower temperatures to keep the fixed current, we expect the decreased EL intensity due to the existence of internal fields [8]. That is, under the high applied field condition the carriers can escape out of the well region due to the internal field effects, as schematically illustrated in Fig. 4. This observation is consistent with our recent PL results where the PL intensity at 15 K decreases when the applied forward voltage exceeds +2 V [9] after reaching the maximum intensity at +2 V. We note at 15 K that the PL maximum observed at +2 V is not directly compared with the high EL intensity at +3.3 V, since the direction of carriers (electrons and holes) flow is different between PL and EL. It is also found that the temperature dependent EL variation pattern shows a striking difference between the green and blue SQW diodes due to the different potential depth as well as spatially distributed polarizations owing to the different In content and compositional inhomogeneity in the InGaN well [6]. These results mean that the unusual evolution pattern of the EL intensity with temperature and current can be caused by variations of the actual field distribution (both internal and external fields), which significantly influences the carrier capture efficiency due to the tunneling escape within the SQW layer. It is also noted 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. Therefore, our results suggest importance of the internal (piezo and spontaneous) field effects on the efficient carrier capture processes for explaining the observed enhancement of radiative recombination in the presence of high-density misfit dislocations.

4. Conclusion

Temperature and low injection current dependence of the electroluminescence (EL) spectral intensity has been studied in the super-bright green InGaN single-quantum-well light-emitting diode. It is found that the temperature dependent variation pattern of the EL efficiency is very different under very low and high injection current conditions. This unique variation pattern of the EL efficiency with temperature and current is thus explained by external field effects due to the different forward bias conditions employed in the presence of strong internal fields.

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References

[1] S. Nakamura and G. Fasol, *The Blue Laser Diode* (Springer-Verlag, Berlin, 1997).

[2] S. Nakamura, M. Senoh, N. Iwasa, S. Nagahama, T. Yamada, and T. Mukai, Jpn. J. Appl. Phys., Part 2 34 (1995) L1332.

[3] T. Mukai, K. Takekawa, and S. Nakamura, Jpn. J. Appl. Phys., Part 2 37 (1998) L839.

[4] T. Mukai, M. Yamada, and S. Nakamura, Jpn. J. Appl. Phys. 38 (1999) 3976.

[5] K.P. O'Donnel, R.W. Martin, and P.G. Middleton, Phys. Rev. Lett. 82 (1999) 237.

[6] A. Hori, D. Yasunaga, A. Satake, and K. Fujiwara, Appl. Phys. Lett. 79 (2001) 3723; J. Appl. Phys. 93 (2003) 3152.

[7] A. Hori, D. Yasunaga, A. Satake, and K. Fujiwara, Phys. Status Solidi A 192 (2002) 44.

[8] J. S. Im, H. Kollmer, J. Off, A. Sohmer, F. Scholz, and A. Hangleiter, Phys. Rev. B57 (1998) R9435.

[9] A Satake, A Hori, Y Takahashi, D Yasunaga, and K Fujiwara, Proc. of 26th Intl. conf. on the physics of semiconductors (Edinburg, Scotland, 2002) D110.

Figure captions

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

Fig. 2 Temperature dependence of the EL spectra for the green SQW diode at injection currents of (a) 2.00 mA, (b) 0.05 mA, and (c) 0.01 mA.

Fig. 3 Temperature dependence of the integrated EL intensity for the green SQW diode at four injection currents of 2.00 mA, 0.20 mA, 0.05 mA, and 0.01 mA.

Fig. 4 Schematic model potential structure for carrier capturing influenced by internal and external fields under the forward bias condition.

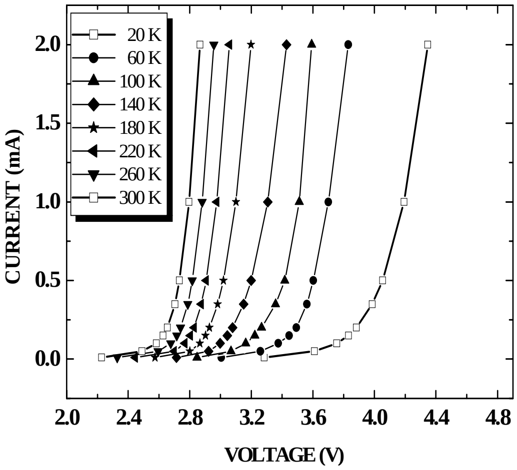

Fig. 1

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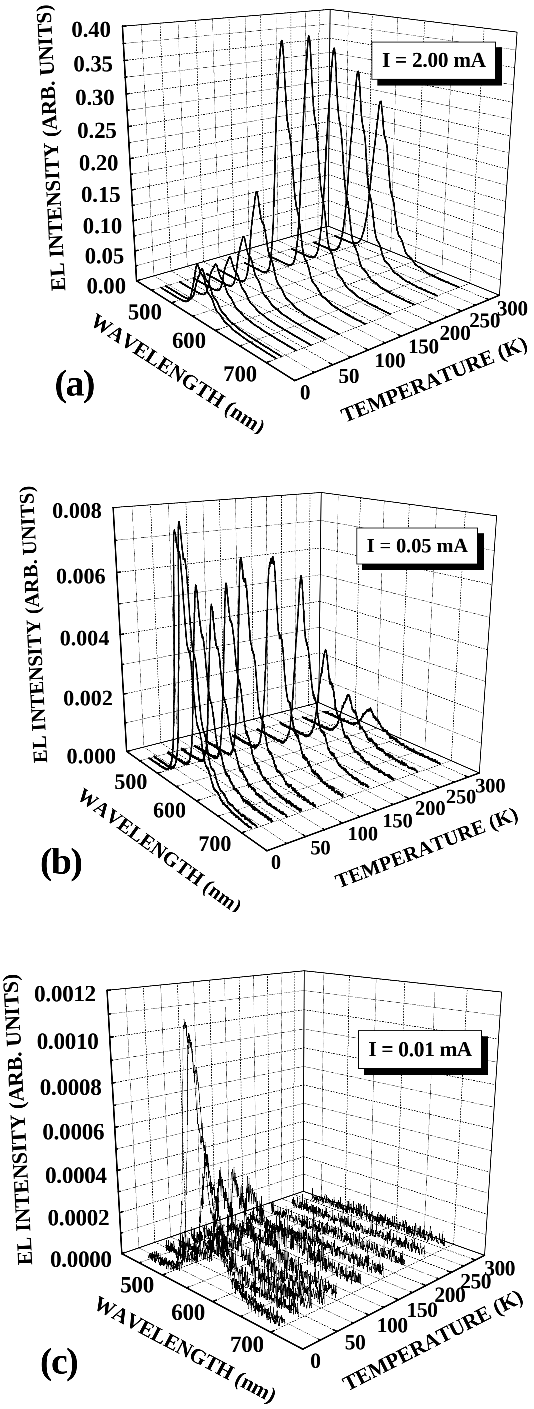

Fig. 2

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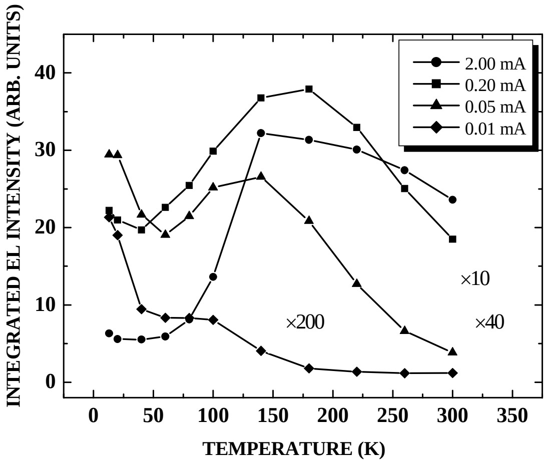

Fig. 3

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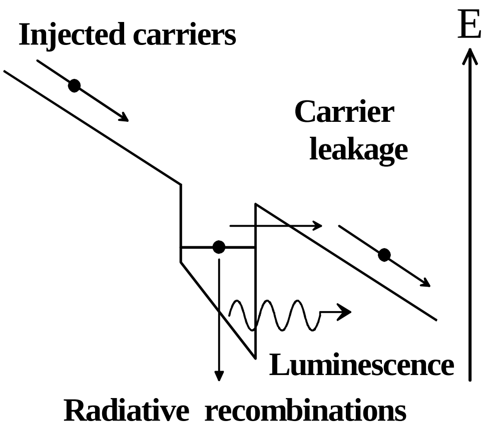

Fig. 4

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