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Anomalous temperature dependence of electroluminescence intensity in InGaN single quantum well diodes

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Abstract

Temperature dependence of electroluminescence (EL) spectral intensity of the super-bright green InGaN single quantum well (SQW) light emitting diodes (LED’s), fabricated by Nichia Chemical Industry Ltd, has been studied over a wide temperature range (T = 15-300 K) and as a function of injection current level. It is found that, when T is decreased slightly to 140 K, the EL intensity efficiently increases probably due to reduced non-raiative recombination processes and/or increased carrier capture by the localized radiative recombination centers. However, decreasing T, furthermore, down to 15 K, it drastically decreases due to the reduced carrier capture and population, accompanying disappearance of injection current dependent line-shape changes (blue-shift) caused by band-filling of the localized recombination centers. These results indicate that the efficient carrier capture by SQW is crucial to enhance the radiative recombination of injected carriers in the presence of the high dislocation density.

Keywords: Wide band gap semiconductors, Electroluminescence, Recombination

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1. Introduction

Super-bright green and blue light emitting diodes (LED's) using group III-nitride semiconductor quantum structures have been manufactured successfully [1-3]. Such quantum well LED shows very bright emission characteristics in spite of existence of high-density misfit dislocations, and origins of the high quantum efficiency have been receiving much attention [4-8]. Previously quantum confinement effects on the InGaN alloy well and efficient carrier capturing by the localized radiative recombination centers in the quantum-dot-like states [4-7] have been claimed to be important for origins of the high recombination efficiency. In this paper, temperature dependence of electroluminescence (EL) spectral intensity of the green InGaN single quantum well (SQW) LED's with a high recombination quantum efficiency, fabricated by Nichia Chemical Industry Limited [2], has been studied over a wide temperature range and as a function of injection current level. In contrast to a commonly expected trend of reduced non-radiative recombination with decreasing the lattice temperature, anomalous temperature dependence of the EL intensity has been observed at lower temperatures below 100 K. Careful analysis of the detailed EL spectral line-shape as a function of injection current reveals that the efficient carrier capture by SQW is crucial to enhance the radiative recombination when the dislocation density is very high (10^{10} /cm^3).

2. Experimental

EL spectral characteristics of the super-bright green InGaN SQW-LED sample, fabricated by Nichia Chemical Industry Ltd [2], have been studied as a function of lattice temperature. The nominal InGaN well width is 3 nm and the claimed In concentration in the SQW layer is 0.45 [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, as a function of current injection level up to 10 mA. In order to get information about the absorption spectra, photocurrent (PC) spectra were also measured using a combination of a halogen lamp and a monochromator for illumination and a dc electrometer for current detection.

3. Results and discussion

EL and PC spectra of the green SQW-LED have been measured between 15 and 300 K. Fig. 1 shows the typical EL (solid curves) and PC (dotted curves) spectra normalized by the respective peaks at 260 K and 15 K. The injection current level for EL is 10 mA and the reverse bias voltage for PC is -0.5 V. At 260 K the green SQW-LED shows an emission band centered around 2.3 eV (540 nm) at the current level of 10 mA with multiple fine structures due to Fabry-Perot fringes. The emission peak shows a blue-shift with increasing the injection current (from 0.1 to 10 mA) and is red-shifted from the broad absorption peak located around 3.0 eV (410 nm) as confirmed by the PC spectrum, indicating strong localization of the injected carriers within the SQW region [4,7]. The peaked nature of the transition that is rather enhanced at 15 K directly indicates the excitonic origin of the absorption transition in the SQW layer, although the linewidth is very large (170-300 meV) due to inhomogeneous broadening of the confinement potentials. At 15 K the emission peak energy is observed also at 2.3 eV in Fig. 1 which does not show any significant shifts from the one at 260 K. In Fig. 1 (at 15 K), an absorption peak is observed at 3.45 eV due to the A and B excitonic transitions of the GaN barrier layer [9]. It shows a blue-shift with decreasing the temperature, following the temperature dependence of the band gap energy [10,11]. In addition, a weak emission around 3.1 eV is observed at 15 K in Fig. 1. We attribute the emission band to the GaN layer, although the exact origin of the Stokes-shift is not clear at present.

The EL spectral intensity from the green SQW layer varies significantly with changing the sample temperature. The temperature dependence of the EL spectra is plotted in Fig. 2 at a fixed value of the injection current (10 mA). When *T* is slightly decreased to 140 K from 300 K, the EL spectral intensity efficiently increases. This enhancement of the radiative recombination efficiency at 140-220 K is similar to those usually expected for the reduced non-radiative recombination at lower *T* in many cases of the GaAs based LED's. However, decreasing *T* down to 15 K, furthermore, drastic reduction of the EL intensity is observed. That is, it is found that the EL efficiency at lower *T* is quite low. This is in strong contrast to the usual cases of GaAs based LED where significantly reduced non-radiative recombination processes are expected at lower *T*. This reduction of the EL efficiency at lower *T* is also seen at other injection currents between 0.5 and 10 mA. In Fig. 3, the spectrally integrated EL intensity is shown as a function of current and temperature to illustrate three-dimensional light-output versus current and temperature characteristics. 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 above 1 mA. 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. We note that this trend is even stronger at 15 K than at 120 K.

In order to investigate causes of the reduced EL efficiency at lower *T*, the detailed EL spectral line-shape has been studied as a function of injection current. The results at 260, 140 and 20 K are shown in Fig. 4. At 140-300 K where the EL efficiency is very high, the spectral line-shape changes drastically with increasing the current, when the injection level is increased by two orders of the magnitude. That is, the EL intensity significantly increases at higher energy sides with the current level due to the band-filling of the localized recombination centers [6]. This result indicates that the injected carriers (electrons and holes) are efficiently captured by SQW at those temperatures and more carriers captured by the SQW layer are filling the localized states at higher energies when the current is increased. On the other hand, it is clear in Fig. 4 that the line-shape does not change with the current at 20 K where the EL efficiency is quite low. Absence of the band-filling effects at lower *T* suggests that carriers are not effectively captured by SQW at lower *T*, but are transferred to non-radiative recombination centers within the barrier layers. The carrier overflow to the barrier layers is consistent with appearance of the GaN emission at 3.1 eV, which is observed only at lower *T* (see Fig. 1). These results indicate that the efficient carrier capture by SQW is crucial to enhance the radiative recombination when the dislocation density is very high (10^{10} /cm^3).

4. Conclusion

Temperature dependence of electroluminescence spectral intensity of the super-bright green InGaN single quantum well light emitting diode has been studied. We find that, when the temperature is decreased down to 15 K, the EL intensity drastically changes due to decreased carrier capture by the localized radiative recombination centers. The injection current dependent line-shape changes (blue-shift) caused by band-filling effects of the localized recombination centers allows us to evaluate the population at the localized states at various temperatures. The reduced carrier population due to the carrier overflow to the barriers at lower temperatures conversely indicates that the efficient carrier capture is crucial to enhance the radiative recombination of injected carriers in the presence of the high dislocation density.

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References

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

[2] S. Nakamura et al., Jpn. J. Appl. Phys. **34** (1995) L1332.

[3] I. Akasaki, Ret. Soc. Symp. Proc. **482** (1997) 3.

[4] S. Chichibu, T. Azuhata, T. Sota and S. Nakamura, Appl. Phys. Lett. **69** (1996) 4188.

[5] Y. Narukawa et al., Phys. Rev. B**55** (1997) R1938.

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

[7] K.P. O’Donnel et al., Phys. Rev. Lett. **82** (1999) 237.

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

[9] J.F. Muth et al., Appl. Phys. Lett. **71** (1997) 2572.

[10] J.I. Pankove, S. Bloom and G. Harbeke, RCA Review **36** (1975) 163.

[11] J-L. Reverchen et al., J. Appl. Phys. **88** (2000) 5138.

Figure captions

Fig. 1

EL (solid curves) and PC (dotted curves) spectra of the green SQW-LED at 260 K and 15 K. For EL spectra the injection current level is fixed at 10 mA, while for PC the reverse bias voltage is -0.5 V.

Fig. 2

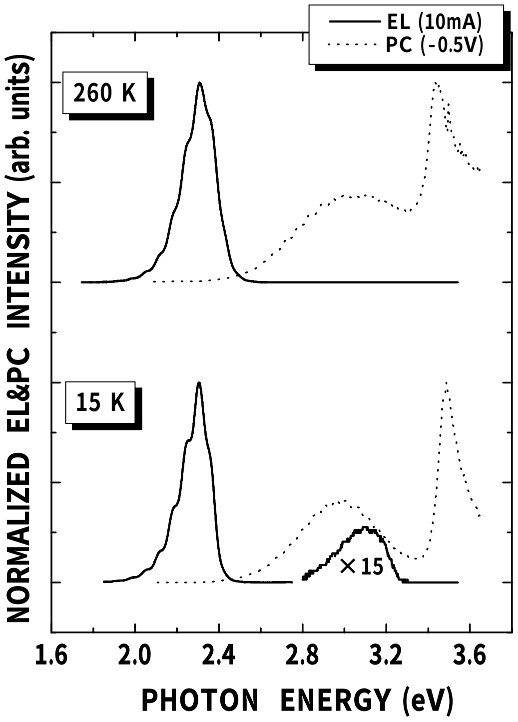
Three-dimensional plot of EL spectra of the green SQW-LED as a function of lattice temperature at a fixed value of injection level of 10 mA.

Fig. 3

Three-dimensional plot of integrated EL intensity of the green SQW-LED as a function of injection current and lattice temperature.

Fig. 4

EL line-shape variations of the green SQW-LED as a function of injection current at 260, 140 and 20 K.



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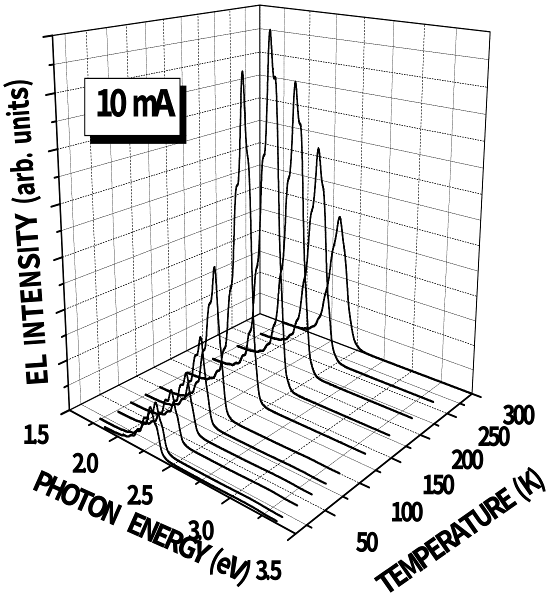

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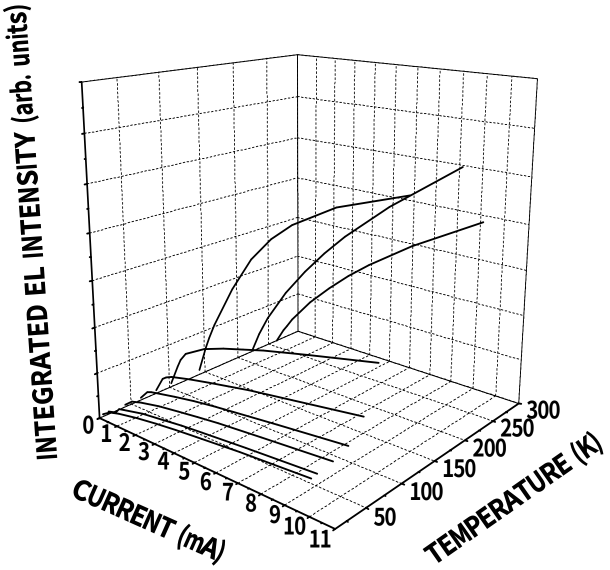

Fig. 3 Hori, Yasunaga, Satake, Fujiwara

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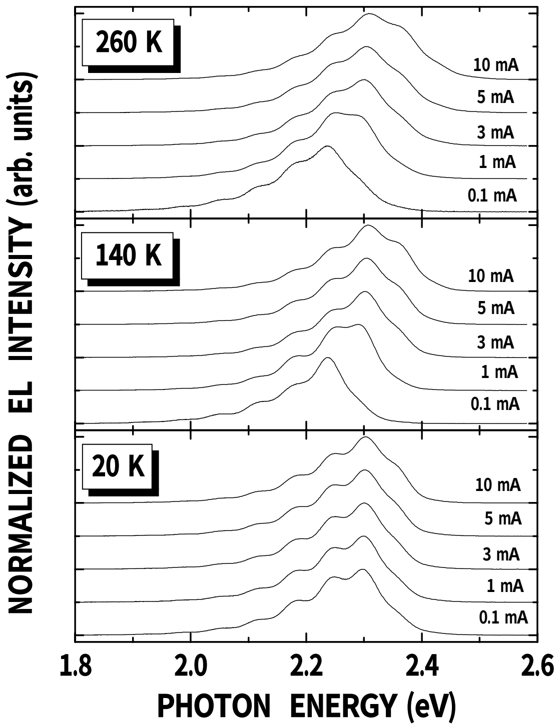

Fig. 4 Hori, Yasunaga, Satake, Fujiwara

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