

Unusual temperature dependence of electroluminescence intensity in blue InGaN single quantum well diodes

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Abstract

Temperature dependence of electroluminescence (EL) spectral intensity of the super-bright blue InGaN single quantum well (SQW) light emitting diodes (LED's) has been carefully investigated over a wide temperature range ($T = 15\text{-}300$ K) and as a function of injection current level (0.1-10 mA) in comparison with high quality GaAs SQW-LED's. When T is slightly decreased to 180 K, the EL intensity efficiently increases in both cases due to the reduced non-radiative recombination processes. However, further decreasing T below 100 K, striking differences exist in EL intensity as well as injection current dependences between the two types of diodes. That is, the EL efficiency at lower T is found to be quite low for the blue diode in strong contrast to that of red GaAs SQW-LED where significant enhancement of the EL efficiency persists down to 15 K. These results indicate that the carrier capture efficiency of the blue SQW diode is unusually worse at lower T than at $T = 180\text{-}300$ K, reflecting the unique radiative recombination processes under the presence of high-density dislocation ($10^{10}/\text{cm}^2$).

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1. Introduction

Green and blue light emitting diodes (LED's) using group III-nitride semiconductor quantum structures have been manufactured successfully [1, 2]. Such quantum well LED shows very bright emission characteristics in spite of existence of high-density (10^{10} /cm²) misfit dislocations at room temperature [3-5], and thus origins of the high quantum efficiency have been receiving much attention [6-10]. In this paper, temperature and injection current dependences of electroluminescence (EL) spectral intensity of the blue InGaN single quantum well (SQW) LED's with high recombination efficiency, fabricated by Nichia Chemical Ltd. have been carefully studied over a wide temperature range ($T = 15$ -300 K) and as a function of injection current. For comparison, the results are compared with those of high quality GaAs SQW-LED's.

Previous spectroscopic studies by photoluminescence (PL), electroluminescence (EL), reflectance, and photoabsorption spectral measurements suggest that quantum confinement effects on the InGaN alloy well with spatially inhomogeneous In distributions play an important role for the superior luminous efficiency. Especially, it is believed that efficient carrier capturing processes by the localized radiative recombination centers within quantum-dot-like regions are crucial for the origins of the high emission efficiency [6, 8, 9]. However, anomalous temperature dependence of the EL intensity has been observed for the blue SQW LED at lower temperatures below 100 K, especially under high injection current level. This is in strong contrast to the observed trend of reduced non-radiative recombination for the GaAs SQW LED with decreasing lattice temperature. Possible causes for the anomalous EL behaviors of the blue diode are discussed by comparing the EL results of the GaAs SQW-LED's.

2. Experimental

Detailed EL spectral characteristics of the super-bright blue InGaN SQW-LED sample, fabricated

by Nichia Chemical Industry Ltd. [3], have been studied as a function of lattice temperature and injection current. The nominal InGaN well width is 3 nm and the claimed In concentration in the SQW layer is 0.20 for blue diodes [3]. 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, 3]. The red diode grown by molecular beam epitaxy is composed of a 6.4 nm GaAs SQW layer confined by GaAs/AlAs short-period superlattice barriers, embedded in n- and p-AlGaAs clad layers [11]. The SQW-LED samples were mounted on a Cu cold stage of a temperature-variable closed-cycle He cryostat to vary the sample temperature over a wide range ($T = 15\text{-}300$ K). EL spectra were measured by a conventional lock-in technique, employing a GaAs photomultiplier, as a function of current.

3. Results and Discussion

EL spectra of the blue and red SQW-LED's have been measured as a function of temperature between 15 and 300 K and current between 0.1 and 10 mA (or 20 mA). The temperature dependence (between 15 and 260 K) of the EL spectra for the blue SQW diode is plotted in Fig. 1 (a) at a fixed value of 10 mA, together with that of the red SQW diode in (b). In Fig. 1 (a), the blue SQW-LED shows an emission band centered around 2.65 eV at 260 K with multiple fine structures due to Fabry-Perot fringes. When T is decreased slightly to 180 K, the EL intensity of both diodes efficiently increases. However, further decreasing T below 100 K, we find a striking difference in EL intensity between the two cases. That is, the EL efficiency at lower T is quite low for the blue diode. This is in strong contrast to the cases of GaAs SQW-LED where significant enhancement of the EL efficiency is observed due to the reduced non-radiative recombination processes and the enhanced radiative recombination rates.

The EL spectral intensity from the blue SQW layer in fact varies significantly with changing the sample temperature. When T is decreased to 180 K from 300 K, the EL spectral intensity efficiently

increases. This enhancement of the radiative recombination efficiency at 180-300 K is similar to that usually expected for the reduced non-radiative recombinations at lower T . However, important changes appear when T is further decreased down to 100 K. That is, the EL intensity from the blue SQW layer, as shown in Fig. 1(a), is decreased significantly. As T is decreased below 40 K, the reduction of the EL intensity is much more enhanced and a new EL peak appears additionally at 3.1 eV due to the GaN clad layer at the expense of the leading SQW peak [9]. This means that electrically injected carriers are not efficiently captured into the SQW layer and recombined in the blue diode below 100 K.

On the other hand, the EL characteristics observed in Fig. 1(b) for the red diode are totally different from those of the blue diode. That is, the red SQW emission appearing around 1.6 eV shows a monotonous increase in intensity as T is decreased down to 15 K, apart from a minor T -dependent peak energy shift due to the GaAs energy gap changes. At 15-30 K an additional EL peak is observed around 1.68 eV in (b), which is attributed to the GaAs/AlAs short-period superlattice barriers. This is because of the reduced vertical transport of carriers within the superlattice barriers due to the carrier localization within the confinement potential fluctuations [12]. This enhances the radiative recombination efficiency in the barrier layers, as observed in Fig. 1 (b).

In Figs. 2 and 3, the wavelength-integrated EL intensity from the SQW layer is plotted and compared for both diodes as a function of current at various temperatures. We note that the EL intensity versus current curves in Fig. 2 for the blue diode are also astonishing, since the EL reduction at lower T is remarkable at higher injection current. These behaviors of the EL intensity are obviously not because of the heating effects. They reflect the particular recombination processes of the InGaN SQW heterostructures by current injection, since any decreases of the PL intensity are absent at lower T , according to our preliminary PL experiments. In contrast, the EL intensity versus current curves in Fig. 3 for the red diode is reasonable, since the slope of the EL intensity versus current curves that is

proportional to the differential quantum efficiency monotonously increases as T is decreased. This tendency observed for the red diode is consistent with the T -dependent EL spectral characteristics in Fig. 1(b), reflecting the improved internal quantum efficiency with decreasing T .

In order to examine causes of the reduced EL efficiency below 100 K for the blue diode we have also investigated the detailed EL spectral lineshape as a function of injection current. At 160-300 K where the EL efficiency is high, the EL intensity at higher energy sides increases with current due to the band-filling of the localized recombination centers. Similar results are also observed for the green InGaN SQW diodes [10]. This means efficient capturing by the radiative recombination centers at higher T . That is, the injected carriers (electrons and holes) are efficiently captured into the InGaN SQW layer. However, it is found that the band-filling effect is absent at lower T for the blue diode, while it persists for the red diode. This suggests that injected carriers are not effectively captured and populated in the blue SQW layer at temperatures below 100 K, but transferred to non-radiative centers within GaN clad layers, as schematically illustrated in Fig. 4. The carrier transfer to the clad layers is consistent with the appearance of the GaN emission at 3.1eV observed below 100 K. These results indicate that the more efficient carrier capture by SQW rather than by the non-radiative recombination centers in the clad layers is crucial to enhance the radiative recombination at room temperature in the blue diode when the dislocation density is very high ($10^{10}/\text{cm}^2$).

4. Conclusion

Temperature and current dependences of electroluminescence spectral intensity of the super-bright blue InGaN single quantum well light emitting diodes have been studied in comparison with the GaAs single quantum well diodes. We find that, when the temperature is decreased down to 15 K, both diodes show completely different emission characteristics as a function of temperature and current.

That is, the EL efficiency is drastically reduced at lower temperatures for the blue diode, which cannot be simply explained by the radiative recombination efficiency like the red diode. We attribute this unique reduction of EL efficiency of the blue diode due to decreased carrier capturing by the localized radiative recombination centers. This result means that the temperature and injection level dependence of the EL efficiency is caused by interplay of the carrier capture and the internal quantum efficiency.

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Figure captions

Fig. 1. Temperature dependence of electroluminescence spectral intensity at an injection current of 10 mA: (a) the blue SQW diode (upper) between 15 and 260 K and (b) the red SQW diode (lower) between 15 and 300 K.

Fig. 2. Injection current dependence of integrated EL intensity at various temperatures between 20 and 260 K: the blue SQW diode.

Fig. 3. Injection current dependence of integrated EL intensity at various temperatures between 60 and 300 K: the red SQW diode. Irregularity observed at 60 K might be related with the changes of the vertical carrier transport efficiency in the superlattice barriers.

Fig. 4. Carrier-flow model at low temperatures (below 100 K) for the blue SQW diode. Electrically injected electrons are partly captured by the SQW layer to cause the blue EL, while most of electrons are transferred to the p-clad region passing through the p-AlGa_N layer to provide the GaN emission or to be killed by non-radiative recombination processes.