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Temperature and current dependent capture of injected carriers in InGaN single-quantum-well light-emitting diodes

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Abstract

Temperature and injection current dependence of electroluminescence (EL) spectral intensity of the super-bright 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). It is found that, when T is decreased slightly to 140 K, the EL intensity efficiently increases due to reduced non-radiative recombination processes. However, further decrease of T below 100 K, it drastically decreases due to the reduced carrier capturing by the localized recombination centers and shows a clear trend of saturation, accompanying decreases of the EL differential efficiency. These results are analyzed within a context of rate equation model assuming a finite number of radiative recombination centers.

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1. Introduction

In spite of great successes of blue and green light-emitting-diodes (LED's) based on InGaN quantum heterostructures [1-3], origins of the very bright emission characteristics have been still controversial under the influence of high-density (10^{10} /cm²) misfit dislocations [4-8]. 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 [8, 9]. In this paper, temperature and injection current dependence of electroluminescence (EL) spectral intensity of the InGaN single-quantum-well (SQW) LED's with high recombination efficiency, has been carefully studied over a wide temperature range and as a function of injection current level. In strong contrast to the commonly expected trend of reduced non-radiative recombination with decreasing lattice temperature, anomalous temperature dependence of the EL intensity has been observed at lower temperatures below 100 K. Under high injection current it is found that the EL intensity is drastically decreased and shows a clear trend of saturation as a function of current. These behaviors of the EL intensity are analyzed within a rate equation model, assuming a finite number of radiative recombination centers in the InGaN well.

2. Experimental

Detailed EL spectral characteristics of the super-bright green and blue InGaN SQW-LED sample, fabricated by Nichia Chemical Industry Ltd [2], 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 0.45 and 0.20 for green and blue diodes, respectively [2]. The InGaN SQW layer is confined by p-Al_{0.2}Ga_{0.8}N and n-GaN barrier layers in the diodes. 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 ($T = 15\text{-}300\text{ K}$). EL spectra were measured by a conventional lock-in technique, employing a GaAs photomultiplier, as a function of current from 0.1 mA to 10 mA.

3. Results and discussion

EL spectra of the blue and green SQW-LED have been measured as a function of current between 15 and 300 K. The temperature dependence of the EL spectra for the green diode, as an example, is plotted in Fig. 1 at two fixed values of the injection current level (10 mA in (a) and 0.1 mA in (b)). At 300 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) due to the band-filling effect on the excitonic localized recombination centers at 300 K. The EL spectral intensity from the green SQW layer varies significantly with changing the sample temperature. 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 140-300 K is similar to those usually expected for the reduced non-radiative recombinations at lower T in many cases of the GaAs based LED's. However, further decreasing of T down to 15 K, drastic reduction of the EL intensity is observed. That is, it is found that the EL efficiency at lower T is quite low. This reduction of the EL efficiency at lower T is stronger at 10 mA than at 0.1 mA. In Fig. 2, the spectrally integrated EL intensity is plotted as a function of temperature at various current levels. From this plot, it is seen 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. We also note that a rate of the EL increases with the current, which is proportional to the differential efficiency, is highest at the intermediate T . 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 the similar EL quenching is observed also for the blue diode at higher injection current.

The above mentioned tendency of the EL intensity can be analyzed by a rate equation analysis similar to the model described in ref [10], assuming a finite number of carrier (electrons and holes) capture centers N_0 within the quantum-dot-like regions. If we describe the number of such centers occupied by carriers as N , a rate equation of the change is given by,

$$dN/dt = (N_0 - N)R_{\text{trap}} - N(R_{\text{detrap}} + R_r + R_{\text{nr}}), \quad (1)$$

where R_{trap} (R_{detrap}) are carrier capture, or trapping (escape, or detrapping) rates by the radiative recombination centers and R_r and R_{nr} are radiative and non-radiative recombination rates, respectively. At steady state the EL intensity, I_{EL} that is proportional to the product of N and R_r is expressed after simple manipulation by a simple equation,

$$I_{\text{EL}} = N_0 \cdot R_r \cdot Jc \cdot \sigma_{\text{trap}} / [Jc(\sigma_{\text{trap}} + \sigma_{\text{detrap}}) + R_r + R_{\text{nr}}], \quad (2)$$

where $R_{\text{trap}} = Jc \cdot \sigma_{\text{trap}}$, $R_{\text{detrap}} = Jc \cdot \sigma_{\text{detrap}}$, and Jc is the injection current density and σ_{trap} (σ_{detrap}) the trapping (detrapping) cross section. In the limit of $Jc \rightarrow \infty$, I_{EL} saturates to the value of $N_0 \cdot R_r \cdot \sigma_{\text{trap}} / (\sigma_{\text{trap}} + \sigma_{\text{detrap}})$. On the other hand, in the other limit of $Jc \rightarrow 0$, one gets $I_{\text{EL}} = N_0 \cdot \eta_i \cdot \sigma_{\text{trap}} \cdot Jc$, where η_i is the internal quantum efficiency. The latter equation means that the slope of the EL intensity versus injection current ($I_{\text{EL}}-I_e$) characteristics, i.e., the differential quantum efficiency is determined by both η_i and σ_{trap} . To testify the $I_{\text{EL}}-I_e$ curves the integrated EL intensity is plotted in Fig. 3 as a function of

current at three representative temperatures (300, 180, and 20 K). At 20 K when the EL intensity quickly saturates to the lowest level, the slope is slight due to the decreased σ_{trap} . We note that the increased η_i (which may be checked by PL measurements) at lower T is cancelled by much stronger reduction of the trapping efficiency. When the temperature is increased to around 180 K, the observed increase of the slope together with the EL intensity enhancement (see Fig. 3) indicates the improved carrier trapping (slope), as shown in Fig. 4 in detail. This finding is consistent with the model equation in the limit of $J_c \rightarrow \infty$ where the saturation level is enhanced as a result of increased σ_{trap} . When the temperature is further increased to 300 K, the slope is decreased again with the EL intensity reduction, although the carrier capture is still efficient enough. This result can also easily be explained by the reduced internal quantum efficiency (η_i) according to the latter equation, being consistent with our PL results (not shown).

4. Conclusion

Temperature and current dependence of electroluminescence spectral intensity of the super-bright InGaN single quantum well light emitting diodes has been studied. We find that, when the temperature is decreased down to 15 K, the EL intensity is drastically reduced as well as the injection current dependence. We attribute this reduction due to decreased carrier capture by the localized radiative recombination centers. A clear trend of the EL intensity saturation observed with increasing the current at lower temperatures are rigorously explained by a rate equation analysis, assuming a finite number of radiative recombination centers and variations of the carrier capture processes with temperature. These results mean 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 of the green diode at two injection current levels of (a) 10 mA (right) and (b) 0.1 mA (left)

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

Fig. 3. Injection current dependence of integrated electroluminescence intensity at three representative temperatures (20, 180, and 300)

Fig. 4. Temperature dependence of the slope of the EL intensity versus injection current (I_{EL} - I_e) characteristics that is proportional to the differential quantum efficiency for the green diode