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Impact of forward bias on electroluminescence efficiency in blue and green InGaN quantum well diodes: a comparative study

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Abstract

Electroluminescence (EL) spectral intensity in the high-brightness blue and green InGaN single-quantum-well (SQW) diodes has been comparatively studied over a wide temperature range and as a function of injection current. When the necessary forward bias conditions to get a certain current level are different, it is found that the anomalous EL quenching previously observed below 100 K for the SQW diodes strongly changes and shows a striking difference between the blue and green SQW diodes. This unusual EL evolution pattern is attributed to both internal and external fields, suggesting importance of the internal piezoelectric field effects on the efficient carrier capture processes by localized tail states within SQW under the presence of high-density misfit dislocations.

Keywords: Electroluminescence; III-V semiconductor; Quantum well; Gallium nitrides

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1. Introduction

Blue-green light-emitting diodes (LED's) using group III-nitride semiconductor quantum structures show very bright emission characteristics in spite of the existence of high-density (~10^{10} /cm^2) misfit dislocations [1,2]. Thus, origins of the high quantum efficiency have been receiving much attention [3-9]. 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 [3-6] have been claimed to be important for origins of the high emission efficiency. However, physical mechanisms responsible for such very efficient carrier capture instead of defect trapping still remain to be controversial. To elucidate the problem quantitative evaluation of the electroluminescence (EL) intensity as a function of lattice temperature and current is very important. In this paper, the temperature and injection current dependence of EL spectral intensity of the InGaN blue and green single-quantum-well (SQW) LED's has been carefully studied over a wide temperature range and as a function of wide injection current level. In strong contrast to a commonly expected trend of uniformly reduced non-radiative recombination with decreasing the lattice temperature, anomalous low-temperature EL quenching is observed with its variation pattern changing with the forward bias conditions. Thus, differential quantum efficiencies anomalously decrease at lower temperatures below 100 K for both of the diodes. Dramatic differences in the EL efficiency are observed between the blue and green SQW diodes and discussed in terms of different carrier escape rates under the presence of internal piezoelectric polarization fields [10].

2. Experimental

EL spectral intensity of the super-bright blue and green InGaN SQW-LED's [2] has been measured in details as a function of temperature and current. The nominal InGaN well width is 3 nm and the claimed In concentration in the SQW layer is 0.20 and 0.45 for blue and green diodes, respectively.

The InGaN SQW layer is confined by p-$Al_{0.2}Ga_{0.8}N$ and n-GaN barrier layers in the diodes. The SQW-LED chip was mounted on a Cu cold stage of a temperature-variable closed-cycle He cryostat to vary the sample temperature over a wide range (15-300 K). A typical forward voltage to get a forward current of 2 mA was 2.85 V (4.35 V) at 300 K (15 K) for the green diode. For decreasing the forward current to 0.1 mA this value was decreased to be 2.6 V (3.6 V) at 300 K (15 K). In all 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 15 K [8]. EL spectra were measured by a conventional lock-in technique, using a GaAs photo-multiplier, as a function of current injection level from 0.01 mA to 10 mA. Further details of the experimental method were described elsewhere [8].

3. Results and discussion

Temperature dependence of the EL spectra of the blue and green SQW-LED's at various injection current levels (0.01-10 mA) has been measured between 15 and 300 K. Three-dimensional (3D) plots of the EL results at a fixed current of 0.05 mA are shown in Figs. 1(a) and 1(b) for the blue and green SQW diodes, respectively. In the EL spectra of Fig. 1 leading blue and green EL emission peaks are observed around 468 nm (2.65 eV) and 540 nm (2.3 eV), respectively, with multiple fine structures due to Fabry-Perot intereference fringes. When temperature is slightly decreased to 180 K from 300 K, the EL spectral intensity efficiently increases and reaches the maximum around 140-180 K. This enhancement of the radiative recombination efficiency at 140-260 K is commonly observed for the two diodes, similar to those usually seen due to the reduced non-radiative recombination at lower temperatures. However, with further decrease of temperature down to 15 K, a significant difference is observed in Fig. 1 between the blue and green SQW diodes. That is, the EL efficiency of the blue diode is significantly decreased at lower temperatures (15-80 K) from the maximum value around 140-180 K, while that of the green diode increases with decreasing the temperature furthermore with a local minimum around 60 K. In addition, a short-wavelength peak appears for the blue SQW diode around 400 nm (3.1 eV) at temperatures below 80 K at the expense of the leading SQW peak. This is because of the carrier escape from the SQW layer and the recombination in the GaN barrier regions [8]. It is very important to note that the temperature dependent variation pattern of the EL efficiency completely changes when the injection current is increased to say, 10 mA [8]. At high injection currents under the higher forward bias voltages the EL efficiency always decreases at lower temperatures below 100 K in both cases, although quantitative differences exist in the EL efficiencies. On the other hand, with the lowest injection current of 0.01 mA the EL intensity of the green diode shows the highest value at 15 K and even the blue diode shows at 15 K more than 50 % of the maximum intensity at 180 K. These results mean that the increased EL intensity with decreasing temperature observed at very low injection currents can be understood in terms of the reduced non-radiative recombination, while the low temperature EL reduction under high injection currents is ascribed to the reduced carrier capture under the higher forward voltage applied to obtain the certain current level.

The spectrally integrated EL intensity of the blue and green SQW diodes is shown and compared in Figs. 2(a) and 2(b), respectively, as a function of current at three representative temperatures (20, 180 and 260 or 300 K). Compared with the results at 180 K, the EL intensity versus injection current characteristics at 20 K are quite astonishing, since the EL intensity is very low and shows saturation phenomena at lower output levels. We note that this trend of saturation is even stronger for the blue diode than for the green one. We also note that the initial rate of EL increases with current increments (indicated by dotted lines in Fig. 2), which is proportional to the differential quantum efficiency, is highest at 180 K. At higher injection currents, say 10 mA, the EL intensity of the blue diode is very low at 20 K. The anomalous EL quenching observed below 100 K for the blue SQW diode should be correlated with the electrical injection, since no luminescence quenching was observed for the blue SQW diode at lower temperatures by optical excitation, according to photoluminescence (PL) experiments. If we compare with the blue (a) and green (b) diodes in Fig. 2, it is clear that the saturation level of the EL intensity is much lower in (a) than in (b) at 20 K as well as the slope of the EL intensity versus injection current (I_{EL}–I_e) characteristics (as indicated by dotted lines). In Figs. 3(a) and 3(b) is plotted the slope of I_{EL}–I_e curves as a function of temperature for the blue and green SQW diodes, respectively. Obviously, the slope of the blue diode is much slighter, especially at temperatures below 80 K. These quantitative results of the EL efficiency also indicate that the carrier escape from the localized recombination centers is crucial for the anomalously reduced EL efficiency of the InGaN SQW-LED's at lower temperatures under the higher forward bias conditions.

The observed differences in Figs. 1-3 between the two diodes should be attributed to the different In content in the SQW layer, since all other parameters are the same. The significantly reduced EL intensity of the blue SQW-LED below 80 K is easily explained by considering the shallower SQW potential depth because of the weaker carrier capture (stronger carrier escape) and quantum confinement effects. The observation of the strong 3.1 eV emission band at 15-60 K for the blue SQW diode supports this argument, since those carriers that are not captured by SQW can overflow to the barrier layers where they are either radiatively recombined or nonradiatively extinguished after trapped by defects. Thus, different radiative recombination processes between the blue and green SQW diodes are attributed to the difference in the carrier capture, or escape efficiency.

Above tendency of the EL intensity variations may be analyzed by a rate equation analysis assuming a finite number of carrier (electrons and holes) capture centers N_0 for the number N of centers occupied by carriers [8]. Defining the injection current density as J_c and the carrier trapping (detrapping) cross section by σ_{trap} (σ_{detrap}), the EL intensity is proportional to the product $N_0\ \eta_i\ \sigma_{trap}\ J_c$ in the limit of J_c

$\rightarrow 0$ where η_i is the internal quantum efficiency. In the other limit of $J_c \rightarrow \infty$ (infinite), the EL intensity saturates to the value of $N_0\ R_r\ \sigma_{trap}/(\sigma_{trap}+\sigma_{detrap})$ where R_r is the radiative recombination rate [8]. The former asymptotic formula means that the slope of the (I_{EL}–I_e) characteristics, i.e., the differential quantum efficiency can be varied by η_i and σ_{trap} which are temperature dependent for a given constant value of N_0. At 20 K where the EL intensity saturates to the lowest level (which means the smallest value of $\sigma_{trap}/(\sigma_{trap}+\sigma_{detrap})$), the slope is slightest due to the decreased σ_{trap}, as confirmed in Fig. 3. We note that the increased η_i (which may be checked by PL measurements) at lower temperatures is cancelled by much stronger reduction of the trapping efficiency (increase of the carrier escape rate). We further note that the forward bias voltage to obtain the necessary current level at 20 K is higher than at 300 K, thus causing the higher driving field and the enhancement of the carrier escape. In fact, the external field effects on the photoluminescence efficiency show significant decreases of η_i above +2 V [11]. 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. Therefore, our results suggest importance of the internal piezoelectric 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

Electroluminescence (EL) spectral intensity of the high-brightness blue and green InGaN single-quantum-well light-emitting diodes has been studied as a function of temperature and current. It is found that the EL efficiency shows dramatic variations with temperature and current due to the different bias conditions for the current injection. The anomalously reduced EL efficiency at temperatures below

100 K is enhanced in the blue SQW diode due to the shallow potential depth for tunneling escape. These results are rigorously explained by external field effects, i.e., in terms of changes of the carrier capture cross section by radiative recombination centers under the different forward bias conditions employed in the presence of strong internal fields.

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Figure captions

Fig. 1 Temperature dependence of electroluminescence spectra for (a) blue and (b) green SQW diodes at a weak injection current of 0.05 mA.

Fig. 2 Injection current dependence of the integrated EL intensity of (a) blue and (b) green SQW diodes at three representative temperatures (20, 180, and 260 or 300 K).

Fig. 3 Temperature dependence of the slope of the EL intensity versus injection current (I_{EL}-Ie) characteristics that is proportional to the differential quantum efficiency for (a) blue and (b) green SQW diodes.

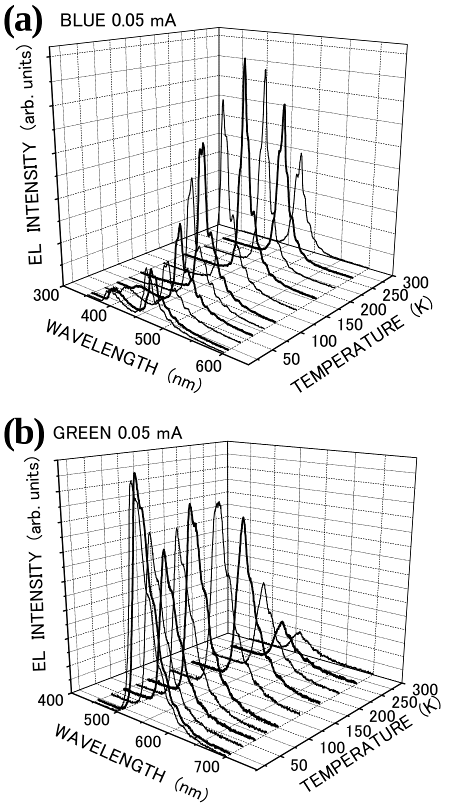

Fig. 1

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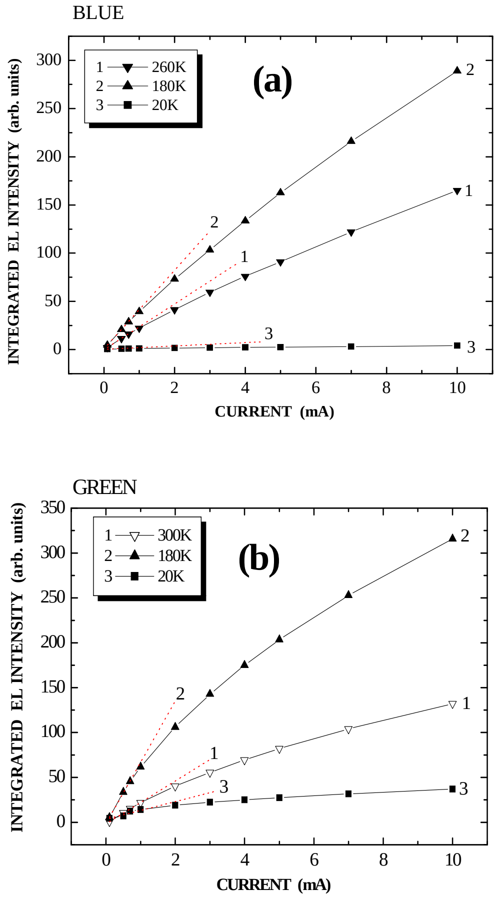

Fig. 2

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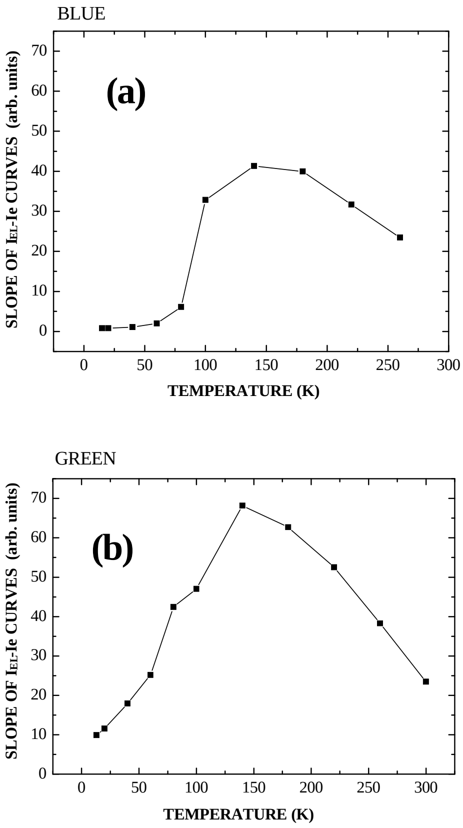

Fig. 3

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