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Temperature and injection current dependence of electroluminescence intensity in green and blue InGaN single-quantum-well light-emitting diodes

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Temperature and injection current dependence of electroluminescence (EL) spectral intensity of the superbright green and blue InGaN single-quantum-well (SQW) light-emitting diodes has been studied over a wide temperature range ($T=15-300$ K) and as a function of injection current level (0.1–10 mA). It is found that, when temperature is slightly decreased to 140 K, the EL intensity efficiently increases in both cases, as usually seen due to the improved quantum efficiency. However, with further decrease of temperature down to 15 K, unusual reduction of the EL intensity is commonly observed for both of the two diodes. At low temperatures the integrated EL intensity shows a clear trend of saturation with current, accompanying decreases of the EL differential quantum efficiency. We attribute the EL reduction due to trapping of injected carriers by nonradiative recombination centers. Its dependence on temperature and current shows a striking difference between the green and blue SQW diodes. That is, we find that the blue InGaN SQW diode with a smaller In concentration shows more drastic reduction of the EL intensity at lower temperatures and at higher currents than the green one. This unusual evolution of the EL intensity with temperature and current is due to less efficient carrier capturing by SQW. The carrier capture in the green and blue diodes also shows a keen difference owing to the different In content in the InGaN well. These results are analyzed within a context of rate equation model, assuming a finite number of radiative recombination centers. Importance of the efficient carrier capture processes by localized tail states within SQW at 180–300 K is thus pointed out for explaining the observed enhancement of radiative recombination of injected carriers in the presence of high-density misfit dislocations. [DOI: 10.1063/1.1554475]

I. INTRODUCTION

Superbright green and blue light-emitting diodes (LEDs) using group III-nitride semiconductor quantum structures have been manufactured successfully.[1–3] The InGaN quantum well LEDs show very bright emission characteristics in spite of the existence of high-density ($\sim 10^{10}/\mathrm{cm}^2$) misfit dislocations. Thus, 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 emission efficiency. Although temperature dependencies of the emission energies and their dynamics[5,9,10] have been investigated previously to exploit the origins, quantitative evaluation of the electroluminescence (EL) intensity as a function of lattice temperature and current has not been reported so far. In this article, temperature and injection current dependence of EL spectral intensity of the InGaN single-quantum-well (SQW) LEDs 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 a commonly expected trend of reduced nonradiative recombination with decreasing the lattice temperature, anomalously decreased EL intensity has been observed for both diodes at lower temperatures below 100 K. Dramatic differences are observed in the decreased EL intensity between the green and blue diodes. Under high injection current it is found that the EL intensity at low temperatures is drastically decreased. It shows a clear trend of saturation as a function of current. These behaviors of the EL intensity are discussed within a rate equation model analysis, assuming a finite number of radiative recombination centers in the InGaN well. These results are explained in terms of changes of the carrier capture efficiency due to the different potential depth of the InGaN well.

II. EXPERIMENT

Detailed EL spectral characteristics of the superbright green and blue InGaN SQW–LEDs, 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 $p-\mathrm{Al}_{0.2}\mathrm{Ga}_{0.8}\mathrm{N}$ and n-GaN barrier layers in the diodes. The detailed diode heterostructure was described previously.[1,2] The SQW–LED chip was mounted on a semi-insulating GaAs wafer piece for wiring. Then, we fixed it with metal tape on a Cu cold stage of a temperature-variable closed-cycle He cryostat to vary the sample temperature over a wide

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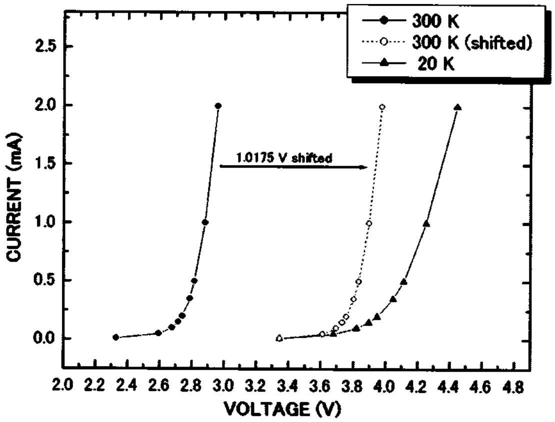

FIG. 1. ($I-V$) curves at 20 and 300 K of green InGaN SQW–LED.

range ($T=15-300$ K). Current–voltage characteristics of the diodes were measured and found to be similar to the ones reported previously.[1,6] The typical forward voltage at a forward current of 0.1 mA was 2.6 V at 300 K and 3.6 V at 15 K, as shown in Fig. 1 for the green diode. In all the cases the forward voltage to get the enough current is increased by about 1 V when the temperature is decreased from 300 to 15 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. EL spectra were measured by a conventional lock-in technique, using a GaAs photomultiplier, as a function of current injection level from 0.1 to 10 mA. For supplementary information about the photoabsorption 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.

III. RESULTS AND DISCUSSION

A. Temperature dependence of EL spectra

EL spectra of the green and blue SQW–LEDs have been measured as a function of current between 15 and 300 K. Three-dimensional (3D) plots of EL spectra for the green and blue SQW diodes are shown in Figs. 2(a) and 2(b), respectively, as a function of temperature at a fixed value of the injection current level of, say 0.1 mA. In the EL spectra of Fig. 2(a) a leading green SQW peak is observed around 2.3 eV with multiple fine structures due to Fabry–Pérot fringes. When temperature is slightly decreased to 140 from 300 K, the EL spectral intensity efficiently increases and reaches the maximum around 140 K. This enhancement of the radiative recombination efficiency at 140–260 K is similar to those usually seen 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.[11,12] That is, it is found that the EL efficiency at lower temperatures (15–80 K) is unexpectedly decreased from the maximum value around 140 K. In Fig. 2(b), a similar plot of EL spectra for the blue SQW diode is shown. It is noted that, with decreasing temperature, the same trend of increases and then decreases of the EL intensity with decrease of temperature is also seen as the green diode for the main blue SQW peak located around 2.65 eV.[11] However, three important differences are pointed out. The first one is that, when temperature is decreased to 140 K, the enhancement of the EL intensity in Fig. 2(b) is moderate in comparison with that of the green diode [shown in Fig. 2(a)]. Second, when temperature is further decreased from 140 to 60 K, the reduction of the EL intensity is much faster and steeper for the blue diode. That is, electrically injected carriers are not efficiently captured and recombined in the blue diode below 80 K. Third, an EL peak appears additionally at 3.1 eV, as seen in Fig. 2(b), below 80 K at the expense of the leading SQW peak.

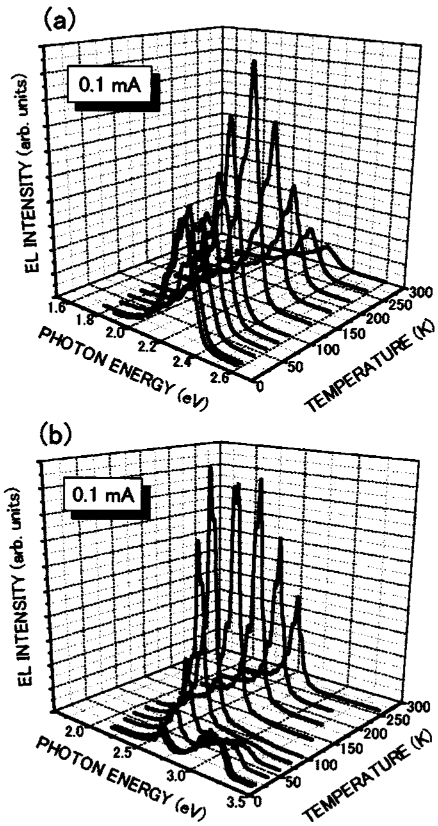

FIG. 2. Three-dimensional plots of EL spectra of (a) green and (b) blue InGaN SQW–LEDs as a function of photon energy and temperature at injection current of 0.1 mA.

In Figs. 3(a) and 3(b), similar 3D plots of EL spectra for the green and blue diodes are also shown as a function of temperature at the highest injection current of 10 mA. Basically the same trend of increases and decreases of the EL intensity with decrease of temperature is also seen in both cases, though quantitative differences in EL intensity exist, if compared with Fig. 2. However, it is now clearer that much more enhanced reduction of the EL intensity is observed below 100 K. That is, under the high injection currents the EL intensity of the green and blue SQW diodes is quite low at lower temperatures. This enhancement of the EL intensity reduction at higher injection currents is even stronger in the case of the blue SQW diode than the green diode, as also seen in Fig. 3(b). We stress that the EL reduction at lower temperatures is remarkable for the blue diode. These behav-

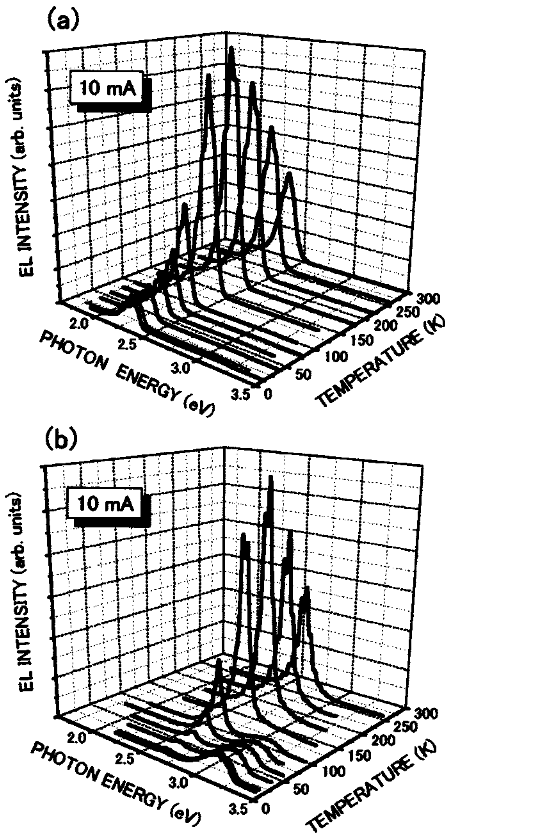

FIG. 3. Three-dimensional plots of EL spectra of (a) green and (b) blue InGaN SQW–LEDs as a function of photon energy and temperature at injection current of 10 mA.

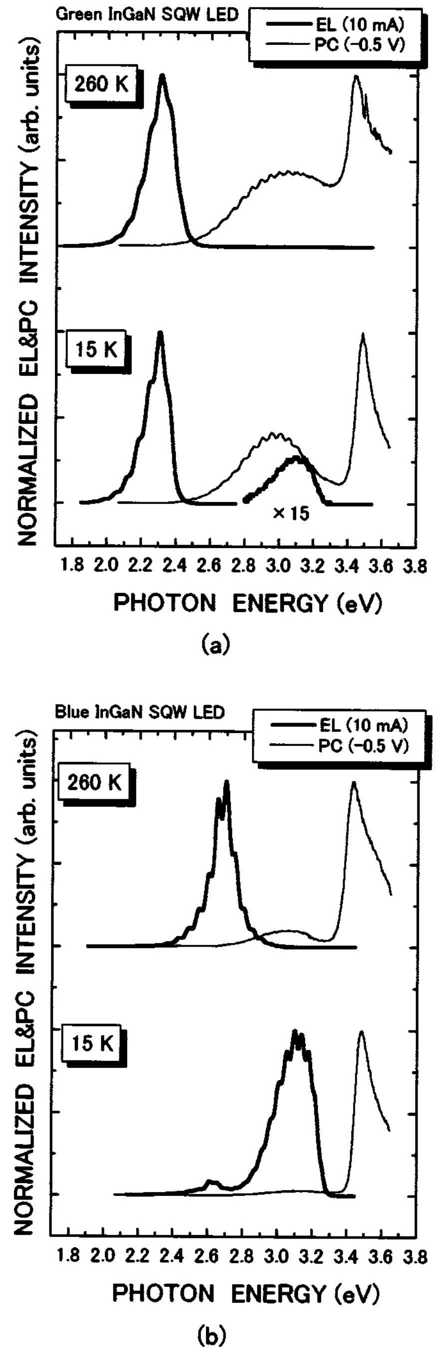

FIG. 4. Normalized EL (thick solid curves) and PC (thin solid curves) spectra of green and blue InGaN SQW–LEDs at 15 and 260 K. For EL spectra the injection current level is fixed at 10 mA, while for PC the bias voltage is -0.5 V (reverse bias).

iors of the EL intensity and spectral characteristics observed at lower temperatures are quite astonishing and they are obviously not because of the heating effects. They reflect the particular recombination processes of the InGaN SQW heterostructures by current injection. This is because, according to our preliminary photoluminescence (PL) experiments, any decreases of the PL intensity are not present at lower temperatures.

In order to further investigate the unique EL spectral properties, PC spectra of the two diodes were measured at 15 and 260 K. The results are shown in Fig. 4, together with the EL spectra. The injection current level for EL is 10 mA and the reverse bias voltage for PC is 0.5 V. The PC and EL spectra are normalized to the respective peak intensity. In the EL spectra at 15 K the green and blue SQW–LEDs show a leading emission band centered around 2.3 eV (540 nm) and 2.65 eV (468 nm), respectively. The emission peak at 2.3 eV (2.65 eV) of the green (blue) SQW–LED is redshifted from the broad absorption peak located around 3.0 eV (3.05 eV) as confirmed by the PC spectra, indicating strong localization of the injected carriers within the SQW emission bands.[4,7,11] At 15 K the green (blue) emission peak energy observed at 2.3 eV (2.65 eV) in Fig. 4 does not show any significant shifts from the one at 260 K. The peak-like nature of the PC transitions indicates excitonic origins of the absorption features in the SQW layer,[4] although the linewidth is very large (170–350 meV) due to inhomogeneous broadening of the confinement potentials. The weaker PC peak observed for the blue SQW diode is ascribed to the smaller In concentration in the well, which should lead to the weaker quantum confinement due to the shallower potential depth. Compared with the PC spectra at the two temperatures, the relative SQW peak intensity is stronger at 260 K than at 15 K in both Figs. 4(a) and 4(b). This result is easily explained by the fact that the excitons can more easily be dissociated into the free carriers at higher temperatures to contribute to the PC signal. In Fig. 4, a strong absorption peak is also observed at 3.45 eV due to the excitonic transitions of the GaN barrier layer[13,14] for both the diodes. It shows a blueshift with decreasing temperature, following the temperature dependence of the band gap energy. In addition, a strong emission around 3.1 eV is definitely observed at 15 K, especially for the blue SQW–LED. We tentatively attribute the emission band to the GaN layer, although the exact origin of such large Stokes shift is not clear at present.

B. Injection current dependence of EL spectra

For investigating causes of the reduced EL efficiency at lower temperatures, the detailed EL spectral line shape has been studied as a function of injection current.[12] The results at 20, 140, and 260 K are shown in Figs. 5(a) and 5(b) for the green and blue diodes, respectively. 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 (from 0.1 to 10 mA), the SQW emission peak of both diodes shows a blueshift. 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 that carriers captured by the SQW layer are filling the localized states towards the higher energy bands. On the other hand, it is clear in Fig. 5 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 temperatures suggests that carriers are not effectively captured by SQW at lower temperatures. But they are transferred to nonradiative recombination centers within the barrier layers. The carrier transfer to the barrier layers is consistent with appearance of the GaN emission at 3.1 eV, which is observed only at lower temperatures (see also Figs. 2–4). Compared with the SQW emission band, more than 30 times stronger barrier emission is observed for the 3.1 eV band at 20 K in the blue diode [see Fig. 4(b)]. This once again indicates that the carrier capture by SQW is weaker in the blue diode than in the green diode. These results indicate that the efficient carrier capture by SQW is crucial to enhance the radiative recombination when the dislocation density is very high ($\sim 10^{10}/\mathrm{cm}^2$).

The observed differences (in Figs. 2–5) between the two types of 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 in the blue SQW–LED below 80 K is easily explained by considering the shallower SQW potential depth because of the weaker carrier capture and quantum confinement effects. The observation of the second EL emission band at 3.1 eV appeared at 15–60 K 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 extinguished nonradiatively after trapped by defects. We note that the weakened quantum confinement seen in the PC intensity of SQW for the blue diode (Fig. 4) is also consistent with the observed trends of the weaker EL intensity. We further note that the green EL intensity is much stronger than the blue one at 15 K. When the carrier acceleration voltage (external field) is higher at lower temperatures than at 300 K, we expect

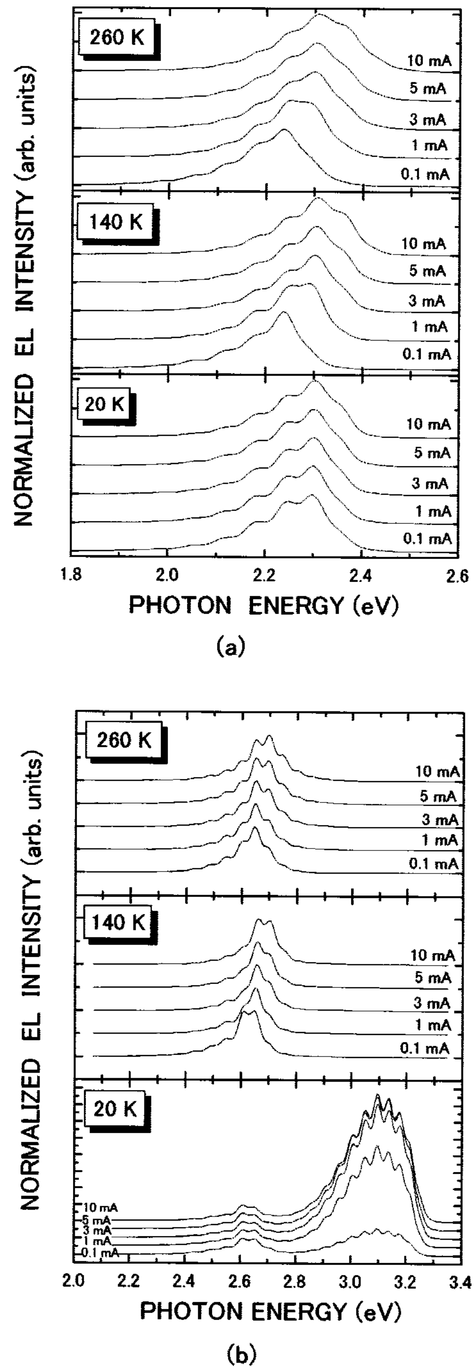

FIG. 5. EL line shape variations of (a) green and (b) blue InGaN SQW–LEDs as a function of injection current at 20, 140, and 260 K. The intensity is normalized to the highest SQW peak in each spectra. The base lines are vertically shifted for clear comparison.

enhanced differences in the decreased EL intensity. The experimental observations (shown in Figs. 2–5) are consistent with this expectation and indicate that the localization and capture of injected electron-hole pairs within the SQW tail states are really stronger in the green SQW–LED. Therefore, these results suggest that the high radiative recombination efficiency in the InGaN SQW–LEDs is originating from the stronger capture rate of injected carriers rather than the intrinsic radiative recombination rates.

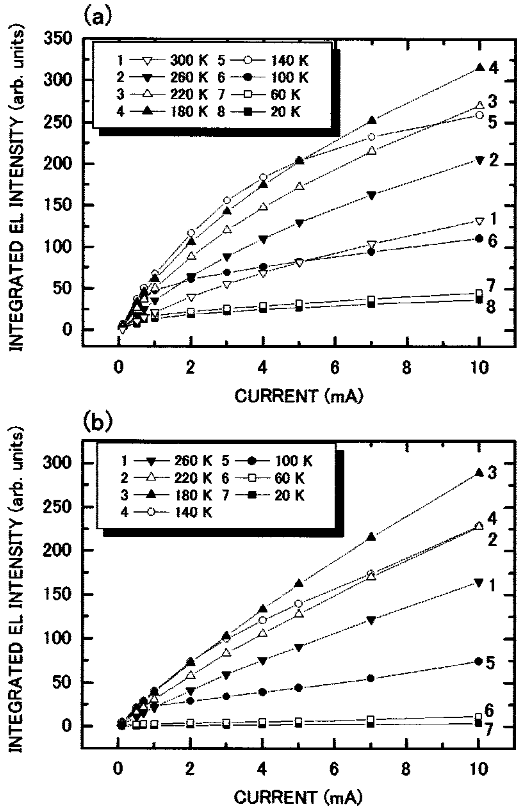

FIG. 6. Integrated EL intensity of (a) green and (b) blue InGaN SQW–LEDs as a function of current at various temperatures. Note that the EL intensity is quite low and flat at 15–80 K, while it shows the highest level around 160–180 K.

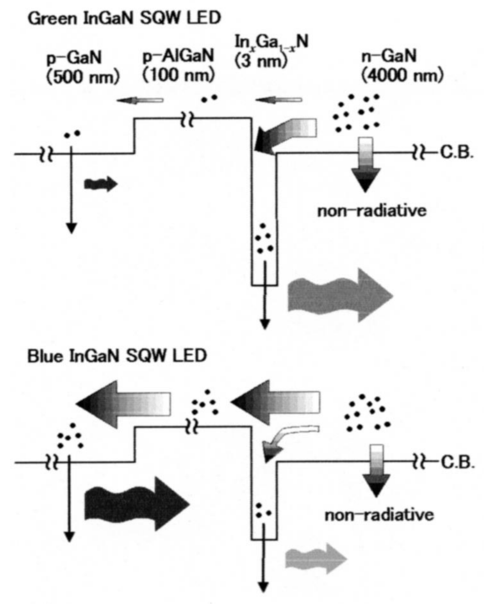

FIG. 7. Model for capture processes in green (upper) and blue (lower) InGaN SQW–LEDs.

C. Temperature and injection current dependence of EL intensity

The spectrally integrated EL intensity of the green and blue SQW diodes is shown and compared in Figs. 6(a) and 6(b), respectively, as a function of current at various temperatures. The EL intensity versus injection current characteristics at intermediate ($\sim$100 K) to low ($\sim$20 K) temperature regimes are quite astonishing, since the EL intensity shows saturation phenomena at lower output levels above 1 mA. We note that this trend of saturation is even stronger at 20 K than at 100 K. We also note that a rate of the EL increases with current increments, which is proportional to the differential quantum efficiency, is highest at the intermediate temperatures (140–180 K). At higher injection currents, say 10 mA, the EL intensity is very low at 20 K. On the other hand, no luminescence quenching was observed for the blue SQW diode at lower temperatures by optical excitation, according to our preliminary PL experiments. Therefore, the anomalous EL quenching observed below 100 K for the blue SQW diode should be correlated with the electrical injection. If we compare with the green (a) and blue (b) diodes in Fig. 6, it is clear that the saturation level of the EL intensity is much lower in (b) than in (a), say at 20 K. These quantitative results of the EL intensity also indicate that the carrier capture by the localized recombination centers is crucial for the enhanced EL performance of the InGaN SQW–LEDs. As schematically illustrated in Fig. 7, different radiative recombination processes between the green and blue SQW diodes are attributed to the difference in the carrier capture efficiency.

The earlier mentioned tendency of the EL intensity can be analyzed by a rate equation analysis similar to the model developed for Er/O doped Si LEDs,[15] assuming a finite number of carrier (electrons and holes) capture centers N_0. If we describe the number of such centers occupied by carriers as N, a rate equation of the change is given by

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

where $R_{\mathrm{trap}}(R_{\mathrm{detrap}})$ are carrier capture, or trapping (escape, or detrapping) rates by the radiative recombination centers. R_r and R_{nr} are radiative and nonradiative 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

$$I_{\mathrm{EL}}=N_0R_rJ_c\,\sigma_{trap}/[J_c(\sigma_{\mathrm{trap}}+\sigma_{\mathrm{detrap}})+R_r+R_{\mathrm{nr}}], \tag{2}$$

where $R_{\mathrm{trap}}=J_c\,\sigma_{\mathrm{trap}}$, $R_{\mathrm{detrap}}=J_c\,\sigma_{\mathrm{detrap}}$ and J_c is the injection current density and $\sigma_{\mathrm{trap}}(\sigma_{\mathrm{detrap}})$ the trapping (detrapping) cross section. In the limit of $J_c\rightarrow\infty$ (infinite), I_{EL} saturates to the value of $N_0\,R_r\,\sigma_{\mathrm{trap}}/(\sigma_{\mathrm{trap}}+\sigma_{\mathrm{detrap}})$. On the other hand, in the other limit of $J_c\rightarrow 0$, one gets $I_{\mathrm{EL}}=N_0\,\eta_i\,\sigma_{\mathrm{trap}}\,J_c$, where η_i is the internal quantum efficiency. The latter equation means that the slope of the EL intensity versus injection current ($I_{\mathrm{EL}}-I_e$) characteristics, i.e., the differential quantum efficiency is determined by both η_i and σ_{trap}. At 20 K where the EL intensity saturates to the lowest level [which means the smallest value of $\sigma_{\mathrm{trap}}/(\sigma_{\mathrm{trap}}+\sigma_{\mathrm{detrap}})$], 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 temperatures 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 enhancement indicates the improved carrier trapping, as shown in Fig. 6 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}. We stress here again at 180 K, for example, that the slope of the EL intensity versus injection current ($I_{\mathrm{EL}} - I_e$) curve (proportional to the product, $N_0\ \eta_i\ \sigma_{\mathrm{trap}}$) is surely steeper for the green SQW diode than the blue one. When the temperature is further increased to 300 K, the slope is decreased again with the EL intensity reduction. This can easily be explained by the reduced internal quantum efficiency (η_i), being consistent with the PL results.

IV. CONCLUSION

Temperature and current dependence of EL spectral intensity has been studied and compared between the superbright green and blue InGaN single-quantum-well light-emitting diodes. It is found that, when the sample temperature is decreased down to 15 K, the EL intensity is drastically reduced. This trend is even enhanced at higher injection currents. This reduction of the EL intensity is much stronger in the blue diode than in the green diode. That is, the blue InGaN SQW diode with a smaller In concentration shows more drastic reduction of the EL intensity at lower temperatures and at higher currents than the green one. This unusual evolution of the EL intensity with temperature and current is due to more efficient carrier capturing by SQW at room temperature than at low temperatures. The carrier capture in the green and blue diodes also shows a keen difference owing to the different In content in the InGaN well. These results are analyzed within a context of rate equation model, assuming a finite number of radiative recombination centers. A clear trend of the EL intensity saturation observed with increasing the current at lower temperatures is rigorously explained by the rate equation analysis. These results mean that the temperature and injection current dependence of the EL efficiency is caused by interplay of the carrier capture and the internal quantum efficiency.

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