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

著者	Hori A, Yasunaga D, Satake A, Fujiwara K
journal or publication title	Applied Physics Letters
volume	79
number	22
page range	3733-3725
year	2001-11-26
URL	http://hdl.handle.net/10228/1611

APPLIED PHYSICS LETTERS VOLUME 79, NUMBER 22 26 NOVEMBER 2001

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

A. Hori, D. Yasunaga, A. Satake, and K. Fujiwara[a]
Kyushu Institute of Technology, Tobata, Kitakyushu 804-8550, Japan

(Received 21 May 2001; accepted for publication 19 September 2001)

Temperature dependence of electroluminescence (EL) spectral intensity of the super-bright green and blue InGaN single-quantum-well (SQW) light-emitting diodes has been studied over a wide temperature range ($T=15-300$ K) under a weak injection current of 0.1 mA. It is found that when T is slightly decreased to 140 K, the EL intensity efficiently increases, as usually seen due to the improved quantum efficiency. However, with further decrease of T down to 15 K, it drastically decreases due to reduced carrier capture by SQW and trapping by nonradiative recombination centers. This unusual temperature-dependent evolution of the EL intensity shows a striking difference between green and blue SQW diodes owing to the different potential depths of the InGaN well. The importance of efficient carrier capture processes by localized tail states within the SQW is thus pointed out for enhancement of radiative recombination of injected carriers in the presence of the high-density dislocations. © *2001 American Institute of Physics.*
[DOI: 10.1063/1.1421416]

Super-bright green and blue light-emitting diodes (LEDs) using group-III nitride semiconductor quantum structures have been manufactured successfully.[1–3] The quantum-well LED shows very bright emission characteristics in spite of the existence of high-density misfit dislocations. Thus, the 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 quantum-dot-like states[4–7] have been claimed to be important for the origins of the high emission efficiency. Although the temperature dependences 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 has not been reported so far. In this letter, the spectral EL intensity of green and blue InGaN single-quantum-well (SQW) LEDs with high recombination quantum efficiency has been studied over a wide temperature range. In 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 two diodes. These results are explained in terms of the carrier capture efficiency due to the different potential depths of the InGaN well.

EL spectral characteristics of super-bright green and blue InGaN SQW-LED chips, fabricated by Nichia Chemical Industry Ltd.[2] have been studied. The nominal InGaN well width is 3 nm and the claimed In mole fraction in the SQW layer is 0.45 and 0.20 for green and blue SQW LEDs, respectively.[2] The InGaN SQW layer is confined by p-$\mathrm{Al_{0.2}Ga_{0.8}N}$ and n-GaN barrier layers. 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 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. EL spectra were measured by a conventional lock-in technique using a GaAs photomultiplier. In order to avoid carrier heating and band-filling effects, the injection current level is kept low at 0.1 mA. For supplementary 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.

EL spectra for the green diode are shown in Fig. 1 as a function of temperature. In the EL spectra, a leading green peak is observed around 2.3 eV with multiple fine structures due to Fabry–Pérot fringes. When T is slightly decreased to 140 K from 300 K, the EL spectral intensity efficiently increases and reaches its maximum around 140 K. This enhancement of the radiative recombination efficiency at 140–260 K is similar to those usually seen for the reduced nonradiative recombination at lower T. However, with further decrease of T down to 20 K, significant reduction of the EL intensity is observed. That is, it is found that the EL efficiency at lower T (80–15 K) is unexpectedly decreased from the maximum value around 140 K. This reduction of the EL efficiency for the green diode is also seen at higher injection currents up to 10 mA, though quantitative differences in intensity exist.

In Fig. 2, a similar plot of EL spectra for the blue diode is shown. It is noted that, with decreasing T, the same trend of increases and then decreases of the EL intensity is also seen as the green diode for the main blue peak located around 2.65 eV. However, three important differences are

---

[a] Author to whom correspondence should be addressed; electronic mail: fujiwara@ele.kyutech.ac.jp

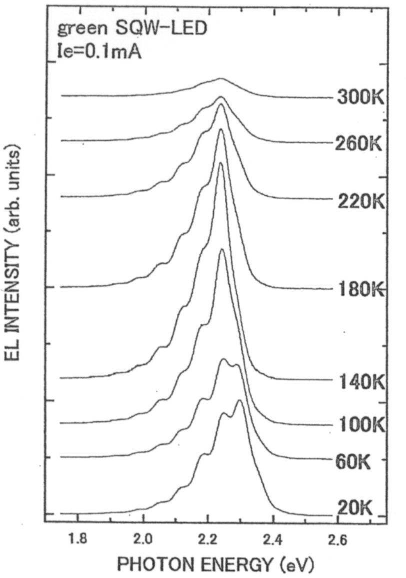

FIG. 1. EL spectra of the green SQW LED as a function of temperature at injection current of 0.1 mA. Spectra are shifted vertically for clarity.

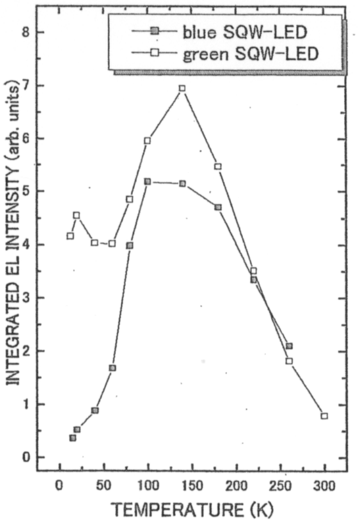

FIG. 3. Wavelength-integrated EL intensity of the green and blue SQW LEDs as a function of temperature. Injection current level used for this plot is 0.1 mA.

pointed out. The first one is that when T is decreased to 140 K, the enhancement of the EL intensity in Fig. 2 is moderate in comparison with that of the green diode (shown in Fig. 1). Second, when T 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, a new EL peak appears additionally at 3.1 eV, as seen in Fig. 2, below 80 K at the expense of the leading SQW peak. In Fig. 3, the wavelength-integrated EL intensity is plotted and compared for both diodes as a function of T. We note that the EL reduction at lower T is remarkable for the blue diode. These behaviors of the EL intensity and spectral characteristics observed at lower T 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, since according to our preliminary photoluminescence (PL) experiments any decreases of the PL intensity are absent at lower T.

In order to investigate the EL spectral properties, PC spectra of the two diodes were measured at 15 K. The results are shown in Fig. 4, together with the EL spectra. The PC and EL spectra are normalized to the respective peak intensity. In the solid EL spectra 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] The peak-like nature of the transitions indicates excitonic origins of the absorption features in the SQW layer,[4] although the linewidth is very large (~350 meV) due to inhomogeneous broadening of the confinement potentials. The weaker PC peak observed for the blue SQW diode is as-

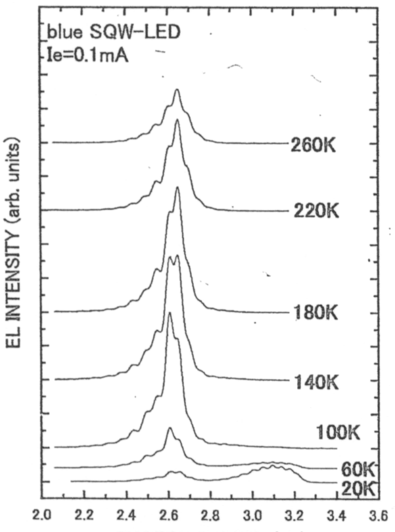

FIG. 2. EL spectra of the blue SQW LED as a function of temperature at injection current of 0.1 mA. Spectra are shifted vertically for clarity.

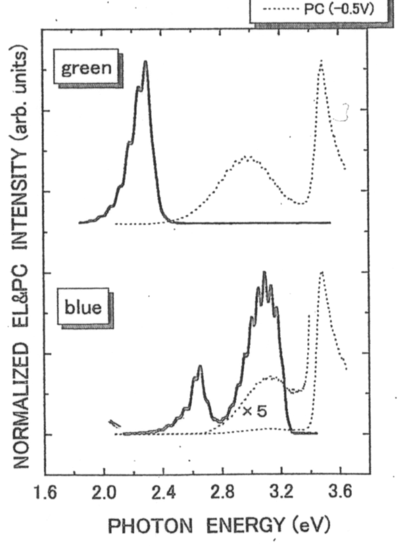

FIG. 4. Normalized EL (solid curves) and PC (dotted curves) spectra of the green and blue SQW LEDs at 15 K. For EL spectra, the injection current level is fixed at 0.1 mA, while for PC the reverse bias voltage is -0.5 V.

cribed to the smaller In concentration in the well, which should lead to the weaker quantum confinement due to the shallower potential depth. In Fig. 4, a strong absorption peak is also observed at 3.45 eV due to the excitonic transitions of the GaN barrier layer[11,12] for the both diodes. In addition, a strong emission around 3.1 eV is definitely observed at 15 K 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.

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 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 appearing at 15–60 K supports this argument, since those carriers that are not captured by SQW can overflow to the clad layers where they are either radiatively recombined or extinguished nonradiatively after being trapped by defects. We note that the weakened quantum confinement seen in the PC intensity of the SQW for the blue diode (Fig. 4) is also consistent with the observed trends of the weaker EL intensity. We 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 T than at 300 K, we expect enhanced differences in the decreased EL intensity. The experimental observations (shown in Figs. 1–3) are consistent with this expectation and indicate that the localization and capture of injected electron–hole pairs or excitons within the SQW tail states is really stronger in the green SQW LED at lower T. 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.

In summary, T dependence of EL intensity of InGaN SQW-LED chips has been studied over a wide T range. It is found that when T is decreased down to 15 K, drastic decrease of the EL intensity is observed due to decreased carrier capture by the localized radiative recombination centers after reaching a maximum at intermediate T ranges. This decrease is more severe for the blue SQW diode. The reduced carrier population in the InGaN well is due to the carrier overflow at lower T. This conversely indicates that efficient carrier capture is crucial to enhance the radiative recombination of injected carriers in the presence of the high-density dislocations.

The authors would like to thank Nichia Chemical Industry Ltd., especially S. Nakamura (presently at the University of California at Santa Barbara) for providing the chip samples used for the present study. The authors also thank K. Satoh and K. Kawashima for their experimental assistance.

[1] S. Nakamura and G. Fasol, *The Blue Laser Diode* (Springer, Berlin, 1997).
[2] S. Nakamura, M. Senoh, N. Iwasa, S. Nagahama, T. Yamada, and T. Mukai, Jpn. J. Appl. Phys., Part 2 **34**, L1332 (1995).
[3] I. Akasaki, Mater. Res. Soc. Symp. Proc. **482**, 3 (1997).
[4] S. Chichibu, T. Azuhata, T. Sota, and S. Nakamura, Appl. Phys. Lett. **69**, 4188 (1996).
[5] Y. Narukawa, Y. Kawakami, S. Fujita, S. Fujita, and S. Nakamura, Phys. Rev. B **55**, R1938 (1997).
[6] T. Mukai, K. Takekawa, and S. Nakamura, Jpn. J. Appl. Phys., Part 2 **37**, L839 (1998).
[7] K. P. O'Donnel, R. W. Martin, and P. G. Middleton, Phys. Rev. Lett. **82**, 237 (1999).
[8] T. Mukai, M. Yamada, and S. Nakamura, Jpn. J. Appl. Phys., Part 1 **38**, 3976 (1999).
[9] C.-K. Sun, S. Keller, G. Wang, M. S. Minsky, J. E. Bowers, and S. P. DenBaars, Appl. Phys. Lett. **69**, 1936 (1996).
[10] P. Perlin, M. Osinski, and P. G. Eliseev, Mater. Res. Soc. Symp. Proc. **449**, 1173 (1996).
[11] J. F. Muth, J. H. Lee, I. K. Shmargin, R. M. Kolbas, H. C. Casey, Jr., B. P. Keller, U. K. Mishra, and S. P. DenBaars, Appl. Phys. Lett. **71**, 2572 (1997).
[12] J. I. Pankove, S. Bloom, and G. Harbeke, RCA Rev. **36**, 163 (1975).