Enhanced capture of photogenerated carriers by optimum forward bias condition in blue and green (In,Ga)N single-quantum-well diodes

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Vertical capture processes of photogenerated carriers in the *c*-plane blue and green (In,Ga)N single-quantum-well light-emitting-diodes have been investigated by comparing variations in photoluminescence (PL) intensity as a function of applied voltage (−10~+4.5 V) at low temperature (20 K) under direct (λ_{ex}=380 nm) and indirect (λ_{ex}=325 nm) excitation. One striking result of the bias dependent PL intensity is that the photogenerated carriers are efficiently captured into the active layer by optimum forward bias condition. That is, with increasing forward bias, the PL intensity by the indirect excitation is strongly enhanced within a certain specific forward voltage range, while the PL intensity by the direct excitation is moderately varied. The optimum bias condition is caused by interplay of carrier capture and internal quantum efficiency.

1 Introduction The development of III-V nitride semiconductors have been remarkable since the success of blue and green light-emitting-diodes (LEDs) based on (In,Ga)N quantum-well (QW) heterostructures [1,2]. However, the origin of a super-bright emission is still controversially discussed. Especially, a phenomenon that external quantum efficiency droops remarkably at high injection current is an essential issue for achieving high output power LEDs. According to previous reports [3-7], quantum confinement effects on (In,Ga)N QWs and efficient carrier localization at radiative recombination centers such as certain potential minima in inhomogeneous (In,Ga)N QWs are important for the origin of the high emission efficiency by means of spectroscopic studies by electroluminescence (EL), photoluminescence (PL), reflectance and absorption spectral measurements. The internal electric field due to piezoelectric and spontaneous polarization fields play an important role in carrier recombination in strain (In,Ga)N/GaN QWs [8-11]. Recently, we have investigated bias dependence of PL intensity in the green (In,Ga)N single-quantum-well (SQW) LED, fabricated by Nichia, at 20 K under direct excitation by selecting an excitation photon energy [12]. It is found that the internal quantum efficiency decreases due to vertical escape of carriers from the well under excess forward bias. In this paper, we have measured PL spectra at 20 K as a function of applied bias between −10 and +4.5 V under direct (indirect) excitation using excitation photon energy below (above) the bandgap of GaN barrier layers. By comparing PL results taken under the two excitation conditions, vertical capture and escape processes of photogenerared carriers have been investigated in the *c*-plain blue and green (In,Ga)N SQW LEDs. It is found that photogenerated carriers are efficiently captured into an active layer by optimum forward bias condition.

2 Experimental The blue and green (In,Ga)N SQW LED samples, fabricated by Nichia [2], were grown on *c*-plane sapphire substrates by metalorganic chemical vapor deposition. The nominal (In,Ga)N well width is 3 nm and the claimed In concentration in the SQW layer is 0.2 and 0.45 for the blue and green diodes, respectively. The SQW layer is confined by *p*-$Al_{0.2}Ga_{0.8}N$ and *n*-GaN barriers. The detailed diode heterostructure was described previously [2]. The SQW LED chip was mounted on a semi-insulating GaAs wafer piece for wiring. Then, it was fixed on a Cu cold stage of a temperature-controlled closed-cycle He cryostat to cool at 20 K. PL spectra were measured by a conventional lock-in technique, employing a 32-cm monochromator and a GaAs photomultiplier, as a function of applied bias voltage from −10 to +4.5 V (forward currents limited up to 3 mA). A second-harmonic light (λ_{ex}=380 nm) of a pulsed Ti:sapphire laser and a cw He-Cd laser (λ_{ex}=325 nm) were used for direct and indirect excitation, respectively. The average power densities were fixed at 30 W/cm^2. By means of lock-in detection using excitation beam whose amplitude is modulated by a mechanical chopper, restricted emissions induced by the excitation light were selectively measured in spite of the existence of EL under forward bias voltages.

3 Results and discussion Figures 1(a) and 1(b) show PL spectra of the green and blue (In,Ga)N SQW LEDs, respectively, measured at 20 K for the applied voltages of −5, 0 and +3 V under the direct and indirect excitation conditions. The PL intensity is normalized by the spectrally integrated value of a leading emission at 0 V for each excitation condition. In the PL spectra for the green (In,Ga)N LED shown in Fig. 1(a), a leading green emission is observed around 550 nm with multiple fine structures due to Fabry-Pérot fringes. For the indirect excitation, PL peaks are additionally observed around 360 and 380 nm, attributed to GaN layers. The leading green emission by the direct excitation is clearly consisting of two peaks, which are located at 512 and 540 nm under the applied voltage of −5 V. The higher energy peak shows a blueshift with increasing the applied reverse bias (from 525 nm at 0 V to 512 nm at −5 V), while the lower energy peak located at 540 nm does not show any significant shifts. The blueshift may be related with the compensation of the polarization-induced electric field by the applied reverse bias [8]. On the other hand, for the blue (In,Ga)N LED shown in Fig.1(b), a leading blue emission is observed around 470 nm with additional peaks attributed to GaN layers around 360, 380 and 405 nm under the indirect excitation. The blueshift is also observed for the blue emission band though it is small, indicating the existence of polarization-induced electric fields. One remarkable difference between the direct and indirect excitation conditions is that the PL intensity of the leading emission significantly and sensitively varies under the indirect excitation with applied bias, especially, within a specific forward voltage range. It is important to note that the PL intensity by the indirect excitation is strongly enhanced around the forward voltage of +3 V compared to the case of 0 V. That is, the PL intensity is drastically increased by more than two times when the forward bias is optimized, while the PL intensity variation is moderate under the direct excitation.

The variations of integrated PL intensity of the leading emission as a function of applied bias voltage are plotted in Figs. 2(a) and 2(b) for the green and blue (In,Ga)N SQW LEDs, respectively. Circles and squares correspond to the

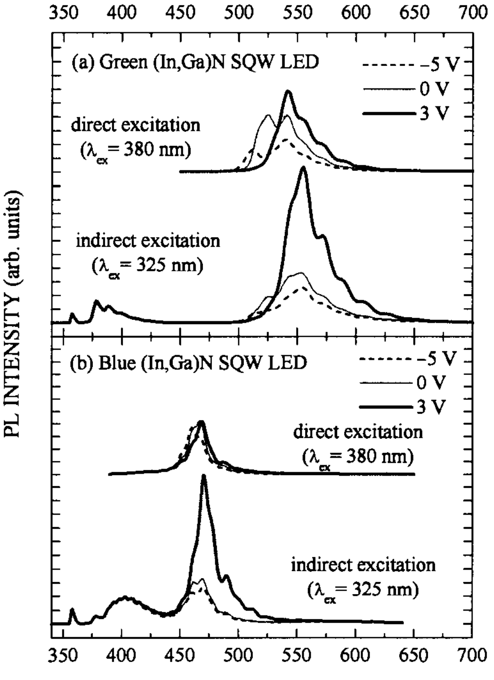

Figure 1 PL spectra of (a) green and (b) blue (In,Ga)N SQW LEDs measured at 20 K for the applied voltages of −5, 0, and +3 V. The excitation wavelength is 380 (325) nm for direct (indirect) excitation.

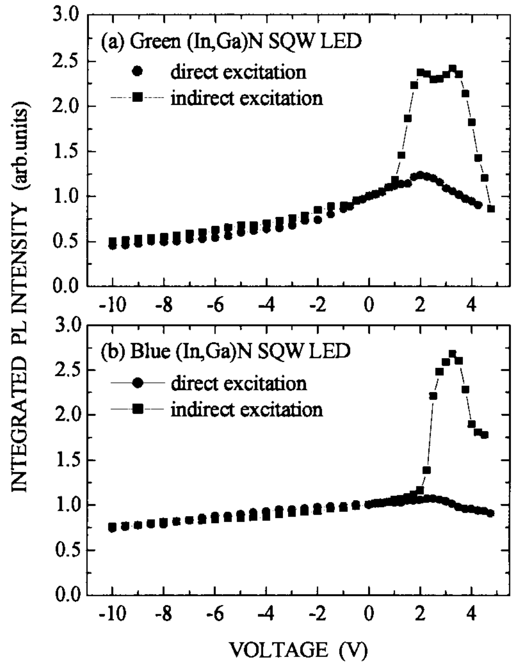

Figure 2 Integrated PL intensity for (a) green and (b) blue (In,Ga)N SQW LEDs as a function of applied voltage under direct (circles) and indirect (squares) excitation conditions. The PL intensity is normalized by the value at 0 V for each case.

PL intensities by the direct and indirect excitation, respectively. The PL intensity is normalized by the value at 0 V for each case. When the reverse bias is increased, the PL intensity gradually decreases for both LEDs and under the two excitation conditions. In this reverse bias case, the radiatve recombination probability should be increased due to the increases of the overlap integral of the electron and hole wave function in the SQW layer, since the internal field is compensated by the applied reverse bias. However, the continuous reduction of the PL intensity is observed with increasing the reverse bias. This result indicates that the PL quenching under the reverse bias should be due to carrier escape out of the well induced by the external electric field [11-13]. According to our preliminary experiments, the photocurrent intensity increases with increasing the reverse bias, which supports our hypothesis of carrier escape for the PL quenching. When the forward bias is increased, we note a striking difference in the PL intensity between the two excitation conditions. For example, in the blue (In,Ga)N LED shown in Fig 2(b), the PL intensity by the indirect excitation drastically enhanced between +2 and +3.25 V, and significantly decreases when the forward voltage exceeds over +3.5 V, while the PL intensity by the direct excitation is moderately varied. The PL decrease is not due to self-heating of the chip because the injection current is less than 0.05 mA at this voltage. The drastic increase of the PL intensity within a specific voltage range is observed in both LEDs. The voltage range for the green LED is wider than that for the blue one.

The PL intensity variation for the case of direct excitation indicates electric field dependent changes of the internal quantum efficiency, because photoexcited carriers are only generated in the (In,Ga)N SQW layer. The internal quantum efficiency is generally determined by radiative and nonradiative recombination rates as well as carrier escape processes. When the bias voltage is applied, the radiative recombination rate may vary by the overlap integral variations of the electron-hole wave function in the QW, and the nonradiative rate may increase if carriers vertically escape from the well. The PL quenching under the reverse bias voltage indicates that the vertical carrier escape is predominant. On the other hand, the PL intensity variation for the case of indirect excitation is influenced not only by the internal quantum efficiency but also by the vertical carrier capture processes, because most of carriers are photogenerated in barrier layers and transferred into the active region. Therefore, the differences of the PL intensity variation between the direct and indirect excitation conditions result from the carrier capture processes. That is, the observed differences between the two excitation conditions indicate that the photogenerated carriers are efficiently captured into the active layer by optimum forward bias. The reduction of the PL efficiency at high forward biases is due to the reduction of the photogenerated carrier capture. The optimum bias condition is caused by interplay of the carrier capture and the internal quantum efficiency due to the presence of polarization-induced electric fields and carrier localization within the radiative recombination region. The observed differencies of the optimum range between the blue and green LEDs is attributed to different carrier capture efficiencies by the well due to the different indium concentrations, being consistent with our previous results that the EL efficiency for the green SQW LED is better than that for the blue one at low temperatures [15].

4 Conclusion We have investigated vertical capture and escape processes of photogenerated carriers in the *c*-plane blue and green (In,Ga)N single-quantum-well light-emitting diodes by comparing variations in photoluminescence (PL) intensity as a function of applied voltage (−10~+4.5 V) at 20 K under direct (λ_{ex}=380 nm) and indirect (λ_{ex}=325 nm) excitation. For the direct excitation, the PL intensity increases with increasing the forward bias voltage up to about +2 V and distinct reduction of the PL intensity is observed with further increase of the forward bias voltage. These results indicate that the carrier escape processes are predominant for the PL quenching. On the other hand, for the indirect excitation, the PL intensity is significantly enhanced within a certain specific voltage range, and drastically decreases by increasing the excess forward voltage. These results indicate that the photogenerated carriers are efficiently captured into the active layer by optimum forward bias. The optimum bias condition is caused by interplay of carrier capture and internal quantum efficiency.

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