Carrier capture and escape processes in (In,Ga)N single-quantum-well diode under forward bias condition by photoluminescence spectroscopy

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Carrier capture and escape processes in the super-bright green (In,Ga)N single-quantum-well (SQW) light-emitting diode (LED) has been studied by photoluminescence (PL) spectroscopy under reverse and forward bias conditions. The PL spectra were measured at 20 K under excitation photon energies above and below the bandgap energy of GaN barrier layers. The PL spectra under both excitation conditions show green emission from the (In,Ga)N SQW layer. The wavelength-integrated PL intensity changes drastically depending on the applied bias voltage. For the excitation below the bandgap energy of GaN (direct excitation), the PL intensity increases with increasing the forward bias voltage up to +2 V and significant reduction of the PL intensity is observed with further increase of the forward bias voltage. On the other hand, for the excitation above the bandgap energy of GaN (indirect excitation), the PL intensity rapidly increases up to +2 V, decreases once, increases again with the maximum value at +3.25 V, and drastically decreases again. These differences of the PL intensity variation reflect carrier escape and capture processes. That is, in the direct excitation condition, the PL intensity variation indicates the effect of the electric field on the radiative recombination and the carrier escape processes. In contrast, in the indirect excitation condition, it is reflected in the carrier transfer and capture processes.

1 Introduction

Recently, (In,Ga)N quantum heterostructure has attracted a great deal of attention because of the development of super-bright blue and green light-emitting diodes (LEDs)[1,2]. Quantum confinement effects on the (In,Ga)N quantum well (QW) 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[3-6]. Furthermore, it has been pointed out that the quantum confined Stark effect caused by an internal piezoelectric field due to lattice mismatch plays an important role in strained (In,Ga)N QWs [7-10]. For optoelectronics devices, because control of the carrier conduction is required, it is important to understand the optical properties and carrier transport in an applied electric field, in particular under forward bias condition, i.e. while a device is operating. In our previous studies [11], we have investigated temperature and injection current dependence of EL spectral intensity of green and blue (In,Ga)N single-quantum-well (SQW) LEDs, fabricated by Nichia Chemical Industry Ltd.[1], and pointed out that the carrier capture processes play an important role for EL efficiency. In this study, we have measured PL spectra of the green (In,Ga)N SQW LED under forward and reverse bias conditions (from –10 to +4.25 V). Comparing PL results taken under direct and indirect excitation, we have investigated carrier capture and escape processes in the (In,Ga)N SQW LED.

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2 Experimental

The super-bright green (In,Ga)N SQW LED on a (0001) sapphire substrate, fabricated by Nichia Chemical Industry Ltd. [2], has been studied in this work. The (In,Ga)N LED sample consists of a 30-nm-thick GaN buffer layer, a 4 μm layer of Si doped n-GaN, a 3 nm (In,Ga)N active layer, a 100 nm layer of Mg doped p-(Al,Ga)N and a 500 nm layer of Mg doped p-GaN. The claimed In concentration in the (In,Ga)N SQW layer is 0.45. The detailed diode heterostructure was described previously [1,2]. The (In,Ga)N 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 closed-cycle He cryostat and PL spectra were measured at 20 K under various applied bias voltages between –10 and +4.25 V. For excitation sources, a second-harmonic light (380 nm) of a pulsed Ti:sapphire laser and a cw He-Cd laser (325 nm) were used to excite below and above the bandgap energy of GaN (direct and indirect excitation of the (In,Ga)N SQW layer), respectively. The average power densities were fixed at 30 W/cm^2. The amplitude modulation of the excitation beam was made by a mechanical chopper. By means of a lock-in detection technique, restricted emission induced by the excitation light was selectively measured in spite of the existence of EL under forward bias voltages.

3 Results and discussion

Figure 1(a) shows PL spectra measured at 20 K under applied bias voltages of –10, –5, –2, 0, +2 and +4 V for the direct excitation conditions. The PL spectrum at +4 V shows almost the same lineshape as the EL spectrum. Two emission bands are clearly observed under the applied bias voltages below +2 V. The higher energy band under the applied voltage of 0 V is located around 525 nm, and the lower one is around 540 nm. The higher energy emission shows a blueshift with increasing the applied reverse bias voltage, and it is located around 505 nm at –10 V, while the lower energy one does not show any significant shifts. The blueshift is related with the compensation of the piezoelectric field by the applied reverse bias voltage [7]. Although it has been reported that the two-components emission from (In,Ga)N LED is observed on the conditions of reverse bias [12], the origin of the emission has not been clear yet.

It is important to note that the PL intensity varies dramatically with changes of the applied bias voltage. The spectrally integrated PL intensity at various applied bias voltages for the direct excitation is shown by solid circles in Fig. 2. It is found that the PL intensity gradually decreases with increasing the applied reverse bias voltage. In this case, since the internal piezoelectric field is cancelled by the applied reverse bias, the transition probability should increase because of increases of the overlap integral between the wave functions of the electrons and holes in the SQW layer. However, the PL intensity is ob-

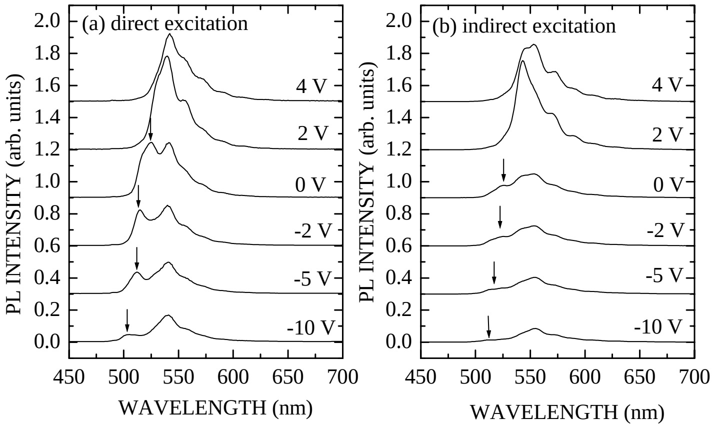

Fig. 1 PL spectra of the (In,Ga)N SQW LED measured at 20 K for the applied voltages of –10, –5, –2, 0, +2, and +4 V. The excitation conditions are (a) direct (λ_{ex}=380 nm) and (b) indirect (λ_{ex}=325 nm) excitation, respectively. The downward arrows show the shift of the higher emission peak.

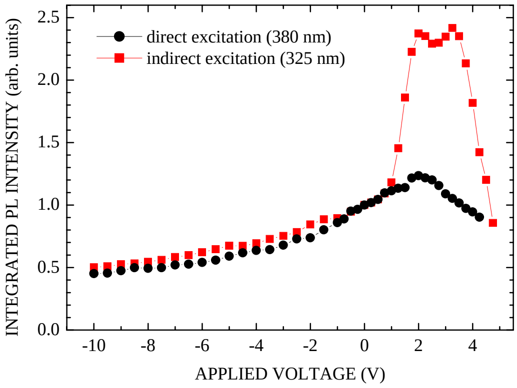

Fig. 2 Spectrally integrated PL intensity between 450 and 700 nm as a function of applied voltage for direct and indirect excitation. The intensity is normalized by the intensity at 0 V for each excitation condition.

served to decrease with increasing the applied reverse bias voltage. This result indicates that the PL quenching under the reverse bias voltages should be due to tunnelling escape of the carriers out of the well induced by the external electric field [13]. The escape processes are schematically shown in Fig. 3(b). Our observation of the photocurrent intensity increases from the SQW layer with the reverse bias (not shown) supports our hypothesis for the PL quenching. On the other hand, the PL intensity increases with increasing the applied forward bias voltage up to +2 V. Significant reduction of the PL intensity is observed with further increase of the forward bias up to +4.25 V. This PL quenching should be also attributed to the carrier escape from the quantum well (shown in Fig. 3(c)), although absorption is expected to decrease by the increase of the electric field in the well due to the spatial separation of the electrons and holes.

In order to investigate the carrier capture processes, we have measured PL spectra under indirect excitation condition. The typical spectra for applied bias voltages of –10, –5, –2, 0, +2 and +4 V are shown Fig. 1(b). Two emission bands are observed as well as the direct condition. The higher energy band under the applied voltage of 0 V is located around 525 nm, and the lower one is around 550 nm. The main emission (the lower energy emission) show no effective shift for the applied bias voltages, while the higher energy emission shows a blueshift with increasing the applied reverse bias voltage (shown by downward arrows to guide the blueshift). By comparison between the direct and indirect excitation, one of the most different feature is the PL intensity variation under the forward bias voltages. The spectrally integrated PL intensity at various applied bias voltages for the indirect excitations is shown by solid squares in Fig. 2. Increasing the reverse bias voltage, the PL intensity gradually decreases just like under the direct excitation condition. Increasing the forward bias voltage, however, the PL intensity rapidly increases up to +2 V, decreases once, increases again with the maximum value at +3.25 V and drastically decreases.

The PL intensity variation for the direct excitation indicates the electric field dependence on the radiative recombination and the carrier escape processes, because the photoexcited carriers are only generated in the (In,Ga)N SQW layer. In contrast, the PL intensity variation for the indirect excitation is reflected in the vertical carrier transfer and capture processes, because the carriers are injected into the well from the p-side, where almost all the carriers are photogenerated due to the expected large absorption coefficient of ~10^5 cm^{-1} for GaN. The observed PL intensity variation for the direct excitation indicates that the internal quantum efficiency is the maximum at +2 V where the junction field is compensated and the flat band condition is obtained. When the device is operating, the internal quantum efficiency decreases because of the carrier escape from the well. For the indirect excitation, it indicates that the carrier capture processes is sensitive to the electric fields. That is, the carriers are easier to capture in the well under the flat band than the reverse bias. Especially, the probability of carrier capture is most efficient at the applied voltage of +3.25 V. On the other side, the observed peak at +2 V indicates the maximum point of the internal quantum efficiency. We find that the luminous efficiency is not good under the large forward bias voltages from the points of the internal quantum efficiency and also the carrier capture. Further

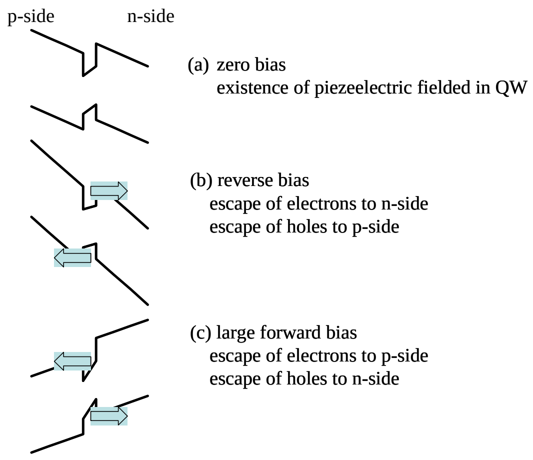

Fig. 3 Schematic diagram of the potential of the (In,Ga)N well with internal piezoelectric fields for (a) zero, (b) reverse, and (c) forward biases.

improvement of luminous efficiency can be expected by controlling the carrier conduction by optimizing the quantum structure, etc.

4 Conclusion

We have investigated carrier capture and escape processes in the super-bright green (In,Ga)N single-quantum-well (SQW) light-emitting diode (LED) by photoluminescence (PL) spectroscopy under reversed and forward bias conditions. The PL spectra were measured at 20 K under the direct and indirect excitation. For the direct excitation, the PL intensity increases with increasing the forward bias voltage up to +2 V and significant reduction of the PL intensity is observed with further increase of the forward bias voltage up to +4.25 V. On the other hand, for the indirect excitation, the PL intensity rapidly increases up to +2 V, decreases once, increases again with the maximum value at +3.25 V, and drastically decreases again. These differences of the PL intensity variation reflect carrier escape and capture processes. These results indicate that the carrier escape processes dominate for the PL quenching not only in reversed bias but also in the large forward bias and that the carrier capture processes is sensitive to the electric fields.

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