Enhanced Radiative Efficiency in Blue (In,Ga)N Multiple-Quantum-Well Light-Emitting Diodes with an Electron Reservoir Layer

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Abstract: Temperature dependence of the EL spectral intensity is investigated between 20 and 300 K of a particularly designed blue (In,Ga)N/GaN multiple-quantum-well (MQW) light-emitting-diode (LED), which contains an additionally *n*-doped (In,Ga)N electron reservoir layer. The MQW-LED consists of $In_{0.3}Ga_{0.7}N$ MQW layers with a nominal well width of 2.5 nm separated by 6.5 nm GaN barrier layers, prepared by metal-organic vapor-phase epitaxy with and without an *n*-doped $In_{0.18}Ga_{0.82}N$ electron reservoir layer in order to exploit the effects of such additional layer on the carrier capture rates. It is found that by adding the electron reservoir layer, the EL spectral intensity is significantly enhanced over the wide temperature range for a fixed injection current level. These results indicate importance of the electron capture processes by radiative recombination centers in the InGaN MQW.

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1. Introduction

Despite the great successes of blue and green light-emitting diodes (LED's) based on (In,Ga)N quantum-well (QW) heterostructures, the origin of the very bright emission characteristics is still controversially discussed [1-7]. One peculiar fact with this material system is that very efficient luminescence can be observed at room temperature, although the density of misfit dislocations can be as high as 10^{10} cm^{-2} due to the large lattice mismatch between the (In,Ga)N epitaxial layer and the sapphire substrate. Therefore, we expect the existence of a particular physical mechanism, which is responsible for the enhancement of the radiative efficiency in the presence of a high defect density. Previous studies of the temperature-dependent electroluminescence (EL) spectral intensity in single-QW (SQW) diodes [5-7] show that efficient capture processes of injected carriers by localized tail states within the SQW layer play an important role between 180 and 300 K. However, for temperatures below 100 K, an anomalous EL quenching and an EL intensity saturation as a function of current are observed, which we attribute to reduced carrier capture rates. In this paper the temperature dependence of the EL spectral intensity has been investigated between 20 and 300 K of a particularly designed blue (In,Ga)N/GaN multiple-QW (MQW) LED, which contains an additionally *n*-doped (In,Ga)N electron reservoir layer. By comparing the EL spectral charactersitics of the MQW-LED's with and without the electron reservoir layer, enhanced EL efficiency observed in the MQW-LED with the electron reservoir layer is attributed to the improved electron capture by the radiative recombination centers.

2. Experiment

Temperature dependence of the EL spectra has been measured of a particularly designed blue (In,Ga)N/GaN MQW-LED, which contains an additionally *n*-doped (In,Ga)N electron reservoir layer between n-GaN clad and MQW layers. The MQW-LED consists of triple $In_{0.3}Ga_{0.7}N$ layers with a nominal well width of 2.5 nm separated by 6.5 nm GaN barrier layers as schematically shown in Fig. 1. The blue $In_{0.3}Ga_{0.7}N$ MQW LED wafers were prepared by metal-organic vapor-phase epitaxy (MOVPE) without and with an *n*-doped $In_{0.18}Ga_{0.82}N$ electron reservoir layer, named LED I and LED II, respectively [8]. EL spectra of the MQW-LED's, mounted on a Cu cold stage of a closed-cycle He cryostat, were recorded by conventional lock-in techniques at temperatures between 20 and 300 K as a function of current injection level from 1 mA to 10 mA.

3. Results and discussion

Figure 2 shows current-voltage (I-V) curves of the MQW-LED samples at 20 and 300 K. A typical forward voltage for a forward current of 10 mA is 2.9 V at 300 K for the diode with the electron reservoir layer, while the forward voltage is 3.6 V without it. That is, the forward driving voltage necessary to get the same forward current is smaller with the electron reservoir layer than without it. At 20 K this difference between the two diodes becomes even larger than at 300 K. In both cases the forward voltage to get the enough current is increased by about 1 V when the temperature is decreased from 300 K to 20 K. In addition, we find a discernible difference in the exponential slope of logarithmic current (not shown) as a function of voltage between the two samples and also between the room and low temperatures. Further careful examinations and the analysis are necessary to understand such variations of the I-V characteristics, but it is worth noting that the hole quenching at 20 K due to the deep Mg accepter level (~170 meV) in p-GaN cannot explain all the changes, since the p-GaN and p-AlGaN layers are the same between the two samples. Here we emphasize that the addition of the wide n-InGaN layer between the n-GaN barrier and the MQW layer has a significant impact on the I-V curve to reduce the forward voltage.

Figure 3 shows EL spectra of the InGaN MQW-LED samples (a) without (LED I) and (b) with the electron reservoir layer (LED II) for a constant current of 10 mA. EL spectra of the blue MQW LED's show intense emission peaks around 480 nm at 300 K with multiple fine structures due to Fabry-Perot fringes. At 300 K for a fixed injection current of 10 mA, the MQW-LED with the reservoir layer shows a brighter emission characteristic than the diode without the reservoir layer in agreement with the previous result [8]. When temperature is slightly decreased to 140 K, the EL intensity of both diodes efficiently increases due to reduction of non-radiative recombination processes, i. e., an enhancement of radiative recombination rates and the EL spectral peak intensity reaches the maximum around 140 K. This enhancement of the radiative recombination efficiency at 180-300 K commonly observed for the two cases is similar to those usually seen due to the reduced non-radiative recombination at lower temperatures. However, the EL intensity difference persists, that is, the EL emission is always stronger for LED II. With a further decrease of temperature below 100 K, we find an enhanced difference in EL intensity between the two cases. The reduction of the EL efficiency of the LED II without the reservoir layer is significant as shown in Fig. 3, while it drastically improved for the LED II with such layer. This result of the EL improvement is in fact remarkable with the addition of the electron reservoir layer, indicating the importance of the electron capture process by radiative recombination centers in the InGaN MQW layer.

For investigating causes of the reduced EL efficiency at lower temperatures, the EL spectral intensity has also been studied as a function of injection current. When the injection level is increased from 1 to 10 mA, the MQW emission peak of both diodes shows a blue-shift at 20 and 300 K. 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 [3]. This result indicates that the injected carriers (electrons and holes) are efficiently captured by MQW at those temperatures and that carriers captured by the MQW layer are filling the localized states towards the higher energy bands. At the lowest injection current of 1 mA studied here, however, we find that the

EL intensity persists to increase as temperature decreases to 20 K, and that the EL intensity shows the highest intensity at 20 K. This result is very different from the one shown in Fig. 3 for 10 mA. These results mean that the driving forward voltage, which is reduced for LED II plays a role for the enhancement of the EL efficiency at 20 K. The decrease of the EL efficiency at 20 K for the injection current of 10 mA suggests that carriers are not effectively captured by MQW at lower temperatures and at higher forward voltages. But they are transferred to non-radiative recombination centers within the barrier layers. In order to check the carrier transfer to the barrier regions we have measured short wavelength EL spectra covering the spectral regions of the barriers and the reservoir layers, as shown in Fig. 4 for the injection current of 10 mA. The experimental observation for LED II shown in Fig. 4 reveals that the short wavelength emission is in fact increased at lower temperatures (<100 K), indicating the reduced carrier capture rates. On the other hand, the short wavelength emission for LED I at the injection level of 10 mA is much stronger at low temperatures where the MQW EL intensity is reduced. That is, the carrier capture by MQW active layers is weaker in the LED I diode than in the LED II diode. These results mean that the carrier capture by MQW is significantly improveded by the addition of the electron reservoir layer for enhancing the radiative recombination.

4. Conclusion

Temperature dependence of electroluminescence (EL) spectral intensity has been studied and compared between blue $In_{0.3}Ga_{0.7}N$ triple-quantum-well light-emitting diodes with and without an *n*-doped $In_{0.18}Ga_{0.82}N$ electron reservoir layer. It is found that, when temperature is slightly decreased to 140 K, the EL intensity of both diodes significantly increases due to a reduction of non-radiative recombination processes. However, with a further decrease of temperature below 100 K, the EL quenching is observed and we find a striking difference in EL intensity between the two cases. That is, the reduction of the EL efficiency of the LED with the reservoir layer is significantly improved, while it drastically decreases for the LED without such layer. This result indicates the importance of the electron capture process by radiative recombination centers in the InGaN well.

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Figure captions

Fig. 1 Schematic layered heterostructure of the (In,Ga)N/GaN MQW LED with an *n*-type (In,Ga)N electron reservoir layer.

Fig. 2 Current-voltage (I-V) curves at 20 and 300 K of the (In, Ga)N/GaN MQW-LED with and without an n-type (In, Ga)N electron reservoir layer.

Fig. 3 Temperature dependence of the EL spectra of the (In,Ga)N/GaN MQW LED with (lower figure) and without (upper figure) an *n*-type (In,Ga)N electron reservoir layer for a constant injection current of 10 mA.

Fig. 4 Short wavelength EL spectra of the (In,Ga)N/GaN MQW LED with an *n*-type (In,Ga)N electron reservoir layer as a function of temperature for a constant injection current of 10 mA.

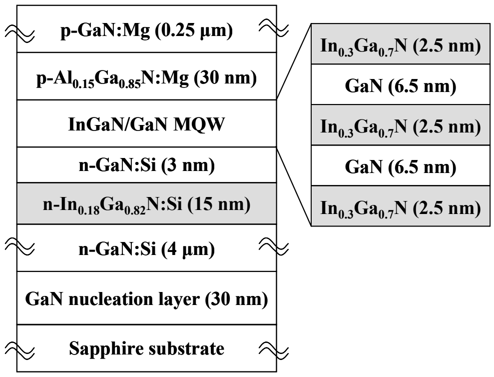

Fig. 1

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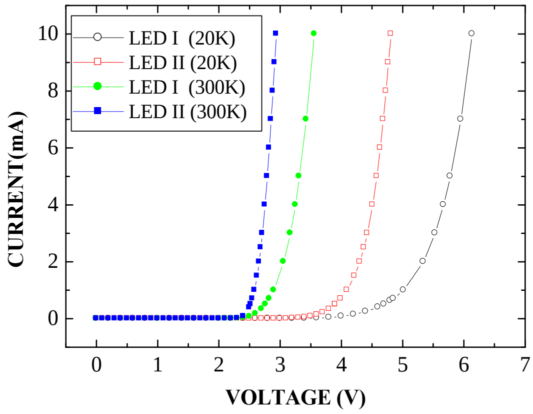

Fig. 2

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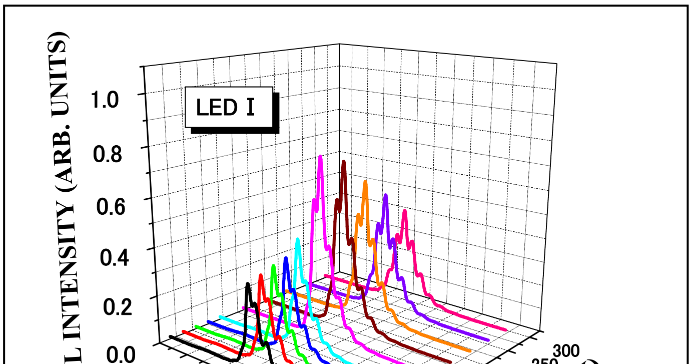

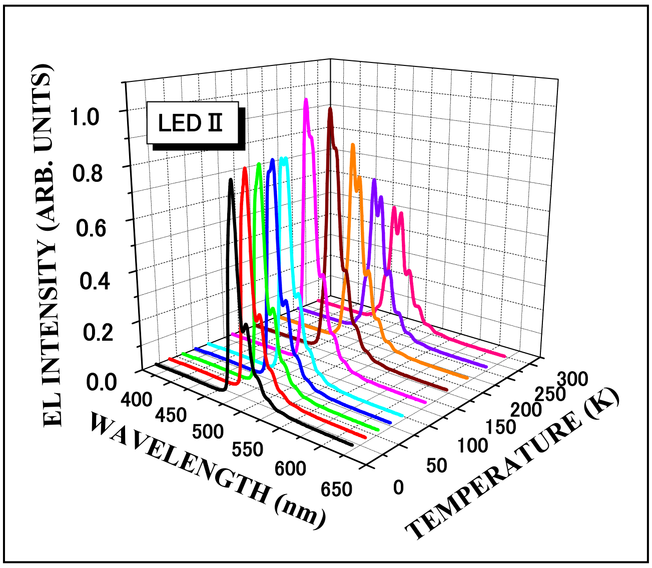

Fig. 3

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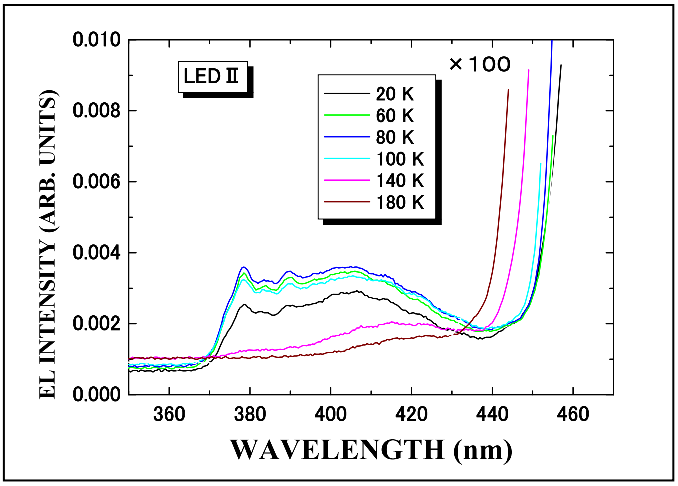

Fig. 4

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