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Enhancement of Carrier Confinement by the Multiquantum Barriers in Blue InGaN/GaN Multiple Quantum Well Light-emitting Diodes

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1. Introduction

Major developments in III-nitride semiconductors have led to the commercial production of InGaN-based blue multiple quantum well (MQW) light-emitting diodes (LEDs) and laser diodes (LDs) [1, 2]. In contrast to striking technological advances, the radiative processes in InGaN structures were not yet well understood. However, carriers overflow from the active layer to the cladding layer could critically affect the performance of these devices. In order to overcome the carrier leakage problem and improve the external quantum efficiency and carrier confinement, it is very effective to increase the effective heterobarrier by utilizing the enhanced wave function confinement by novel multiquamtum barriers (MQBs) [3, 4]. For this work, we investigated in depth the abnormal temperature-dependent characteristics of InGaN/GaN MQW blue LEDs, with and without MQBs. The rate equation models are applied to corroborate the abnormal temperature behaviors of the spectra intensity and the radiative recombination zone shifts for the LEDs with and without MQBs. The results indicate that an MQB structure can significantly suppress carrier leakage, which not only increases the carrier confinement, but also improves the quantum efficiency.

2. Experiments

The samples investigated in this study were grown on c-plane sapphire substrates by metal organic vapor phase epitaxy (MOVPE). The conventional structure of the sample was consisting of 20-nm-thick low temperature GaN nucleation layer, a 3 µm Si-doped n-type GaN layer, followed by an undoped GaN layer with five periods of $In_xGa_{1-x}N$/GaN ($0.15 < x < 0.18$) MQWs and a 100 nm Mg-doped p-type GaN. The doping level of n- and p- type of GaN are nominally about 5×10^{18} and 1×10^{19} cm^{-3}, respectively. For comparison, we also prepared two different types of barriers, that is 5-period $In_{0.005}Ga_{0.995}N$/GaN and bulk GaN barriers, in the active regions of these two devices. The former and latter are the so-called multiquantum barrier (MQB) structures. The x values are evaluated nominally 0.18 by using X-ray diffraction. For temperature-dependent electroluminescence (EL) measurements, the samples were mounted in a closed cycle He cryostat, over a wide temperature range (20 K to 300 K), operated with a current of 20 mA. The EL spectra dispersed by a 0.5-meter monochromater were detected by a Si photodiode employing a conventional lock-in technique.

3. Results and Discussion

To determine the MQB characteristics, we measured EL spectra over a broad temperature range. The inset of Fig. 1 shows the EL spectra of both samples studied at 300 K with current operated at 20 mA. The output powers of the LEDs with MQB and GaN barrier structures are 2.53 and 1.76 mW at room temperature, respectively. Emission peaks can be seen at 433 and 449 nm, with full width at half maximum (FWHM) for 18.11 and 16.47 nm, for samples with MQBs and GaN barriers, at room temperature. Both the higher photon energy and the higher intensity that were observed in the MQB device could be attributed to the quantum-confinement effect, while the broader FWHM is caused mainly by the In-rich InGaN crystallinity. The intense blue peak in the luminescence response is the most remarkable feature of the device with MQB structure at both temperatures compared with the conventional device, indicating an improved LED performance by adopting an appropriate heterobarrier. Contrary to the behaviors of blue emission, the device with GaN barrier exhibits a more pronounced Mg-related emission at 20 K, which was attributed to a shift of the radiative recombination zone due to excess carriers overflowing the barriers [4]-[6].

The temperature-dependences of the QW luminescence and the Mg-related luminescence have been investigated for the both LEDs with MQBs and GaN barriers, with driving current of 20 mA. Both device optical outputs remain roughly constant between 200 and 300 K, and beyond that, due to the carrier overflow mechanism, decrease monotonically with the temperature. When the cryostat temperature is reduced from 200 to 20 K, the MQB sample luminescence decreases by a factor of less than 20, while the emission of the conventional sample shows an up to 236-fold fall in luminescence, implying that the introduction of a well-designed MQB structure into an LED also leads it to have thermal-insensitivity characteristics. There was a slow intensity-collapse rate, resulting from the suppression of the leakage carriers in the MQB structure, leading to the exhibition of a high blue spectral efficiency. The observation of the abnormal reduction of the EL intensity at a low temperature is similar to experimental reports on nitride-based heterostructures by electrical excitation [4]-[6]. Interestingly, according to decreases in blue spectral power, Mg-related peaks are noticed in both devices when the temperature is lowered to below about 120 K. As the temperature was decreased to 20 K, the Mg-related emission of the device with GaN barriers

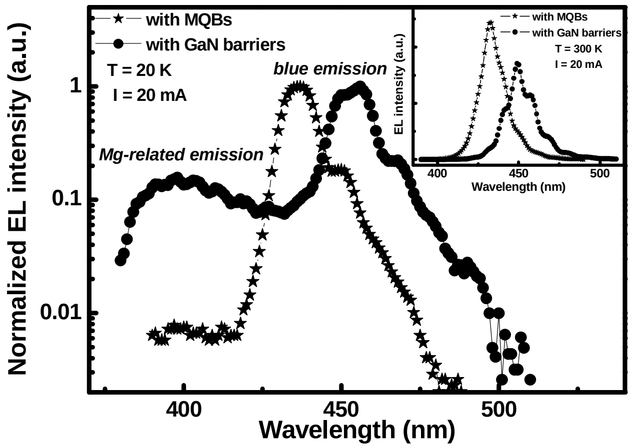

Fig. 1 Normalized electroluminescence (EL) spectra of InGaN/GaN MQW LEDs with multiquantum and GaN barrier structures, measured at 20 K and operated at an injection current of 20 mA. The inset shows the EL spectra for the both samples, measured at 300 K, operated at an injection current of 20 mA.

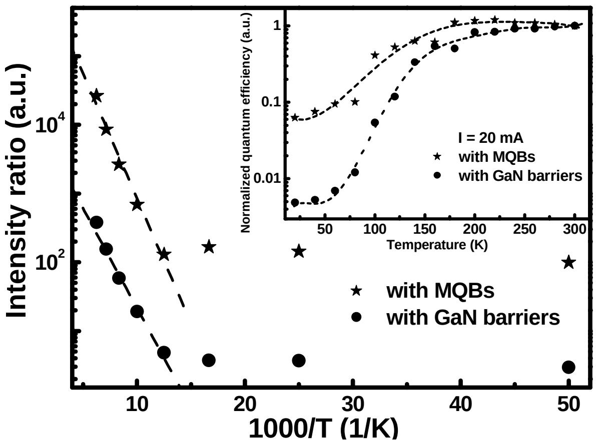

Fig. 2 Arrhenius plot of the intensity ratio of Mg-related emission to blue emission. The inst shows the termperature-dependent quantum efficiency as a function of temperature for devices with multiquantum and GaN barriers.

rose more than ten times larger than that of the devices with MQBs. The results indicate that an MQB structure can significantly suppress carrier leakage, which not only increases the carrier confinement, but also improves the quantum efficiency.

Figure 2 is an Arrhenius plot of the integrated intensity ratio of Mg-related emission to blue emission. Since the availability of holes is the dominant factor for radiative recombination, we expect that the intensity ratio of Mg-related emission to blue emission is a directly proportional to $P_{\mathrm{blue}}/P_{\mathrm{Mg}}$ and therefore exp($-Ea/2kT$), where P_{blue}, P_{Mg} are the hole concentrations in the quantum well and *p*-type GaN, respectively, *Ea* is the activation energy of Mg in GaN. From the Arrhenius plot shown in Fig. 2, the activation energy of Mg in GaN is thus determined to be 120 and 145 meV, for the devices with MQBs and GaN barriers, respectively. This value is in good agreement with the results obtained by Hall measurement [7], and temperature-dependent PL measurements [8]. We observed that the activation energy increased artificially by 1.21 times relative to the conventional GaN barrier as a result of the MQB effect, leading not only to enhanced carrier confinement in the active regions but also to inhibited carrier leakage over the barrier to the p-GaN regions.

The inset of Fig. 2 shows a comparison of the normalized quantum efficiency as a function of the temperature, for the two devices. All the efficiencies were normalized to the values observed at 300 K. Both device efficiencies remained roughly constant, between 200 and 300 K, and then, due to the carrier overflow mechanism, decreased monotonically with the temperature. The improvement of the quantum efficiency of the MQB sample was found to be significant, up to the 1.2 to 10 times, compared with the conventional sample, in the temperature range between 300 and 20 K. As can be seen in Fig. 2, the introduction of a well-designed MQB structure into an LED also leads it to have thermal-insensitivity characteristics.

4. Conclusion

The temperature-dependent electroluminescence (EL) excitation of InGaN/GaN multiple quantum wells (MQW) in blue light-emitting diodes (LEDs) with multiquantum barriers (MQB) and GaN barriers have been investigated. It was found that a device with an MQB structure exhibited higher quantum efficiency, as well as a higher temperature insensitivity, than did the conventional MQW LEDs. As the temperature further decreased to 20K, the radiative recombination zone gradually shifts to p-type GaN region due to the high activation energy of Mg in GaN which resulted in the Mg-related transition emission in the LED, accompanied with dramatically reduced the EL intensity of active region. The improvements of the EL intensity and quantum efficiency for the device with MQBs structure were attributed to that enhanced carrier confinement in the MQW region and inhibited the carriers overflow into the GaN region.

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