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Characterization of Anomalous Excitation-dependence Luminescence Phenomena in InGaN/GaN Light-emitting Diodes with Electron Blocking Layer

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1. Introduction

In recent years, the III-V group nitride-based low dimensional multiple quantum well (MQW) heterostructures have been investigated extensively. In spite of this striking advanced technology, the emission process and carrier transport mechanism are affected by several peculiarities of this material system and are still under debate. However, carriers overflow from the active region to the cladding layer could critically affect the performance of the device. Low-temperature quenching of the electroluminescence intensity based on InGaN/GaN multiple quantum well light-emitting diode (LED) was observed by several research groups [1]-[3]. However, there are so many quite different explanations that have been proposed to modify the behavior. Lee *et al.* [3] supposed that excitons recombination region shifted from the quantum wells into the p-type cladding layer. The quenching of electroluminescence intensity in nitride-based LED at low temperature is still a subject of controversy and deserves in-depth investigation. In this article, we used a thin layer of material with wider band gap (50 nm AlGaN) as the electron blocking layer (EBL). It was inserted between the active layer and n-type layer for the device, with the purpose of preventing excess electrons injected into the active region, leading the carrier overflow to p-type cladding layer. We investigated the anomalous quenching of the electroluminescence intensity characteristics of InGaN/GaN MQW blue LEDs under varied injection current levels.

2. Experiments

The sample investigated in this study was grown on c-plane sapphire substrate by metal organic vapor phase epitaxy (MOVPE). The conventional structure of the sample was consisted of 2 μm Si-doped n-type GaN layer, followed by a 30 nm $Al_{0.1}Ga_{0.9}N$:Si layer, i.e. electron blocking layer (EBL), an undoped GaN layer with eight periods of $In_{0.15}Ga_{0.85}N$/GaN MQWs and was capped by a 120 nm Mg-doped p-type GaN. The doping level of n- and p-type of GaN were nominally about 5×10^{18} and 1×10^{19} cm^{-3}, respectively. Standard Ni/Au and Ti/Au metallization were used as contacts to n-type and p-type layer, respectively. For temperature-dependent electroluminescence spectra measurements, the device was mounted on a Cu cold stage of a closed-cycle He cryostat, and the luminescence signals were detected by a Si photodiode, employing conventional lock-in detection techniques at temperatures between 20 and 300 K as a function of the injected current between 0.2 and 20 mA.

3. Results and discussion

To determine the EBL characteristics, we measured EL spectra over a broad temperature range with 0.2, 2 and 20 mA. Figs. 1-3 describe the EL spectra as functions of temperature at three different injection current levels. Fig. 1 is from 0.2 mA, Fig. 2 is from 2 mA, and Fig. 3 is from 20 mA, respectively. The EL spectra exhibit intense emission around 450 nm. The intense blue peak in luminescence response is the most remarkable feature of the device at temperature compared with the conventional device. Contrary to the behaviors of blue emission, the device exhibits a pronounced Mg-related emission at 20 K, which is attributed to a shift of the radiative recombination zone due to excess carriers overflowing the barriers [3, 4]. The observation of the abnormal reduction in EL intensity at low temperature, Mg-related peaks are noticed when the temperature is lowered to below about 100 K. In Fig. 1, the EL intensity increases with temperature between 20 K to 160 K, but decreases dramatically above 160 K. This decrease of EL intensity with increasing temperature was ascribed to an enhancement of non-radiative recombination processes. In Fig. 2, a reduction of the EL intensity is clearly seen with decreasing temperature below 170 K. As shown in Fig. 3, the EL intensity increases significantly above 20 K, and the maximum height becomes larger than the others. The EL intensity appeared to be saturated above 150 K.

Fig. 4 shows the evolution of EL emission peak energy over a temperature range from 20 K to 300 K under injection current of 0.2 mA, 2 mA, and 20 mA, respectively. The temperature-induced S-shaped EL shift is strongly affected by the competition of carrier recombination mechanisms with increasing temperature. In the low-temperature region, the red-shift of the peak energy is attributed to carriers having more opportunity to relax into the lower-energy tail states caused by the inhomogeneous potential fluctuations. The reason is that the carrier lifetime tends to increase as the temperature rises [5]. The temperature-induced blue-shift of the emission peak can be demonstrated by the band-tail model with a Gaussian-like distribution of the density of states and the screening effect of the piezoelectric field [6, 7]. With increasing temperature up to 300 K, the red-shift temperature evolutions of the emission peak energy values for different injections are notable and are consistent with temperature-induced band-gap shrinkage of the InGaN MQW structure configurations. As the injection current was increased, we observed the emission peak blue-shift behavior and band filling effect would become conspicuous, and therefore reduced the carrier localization effect.

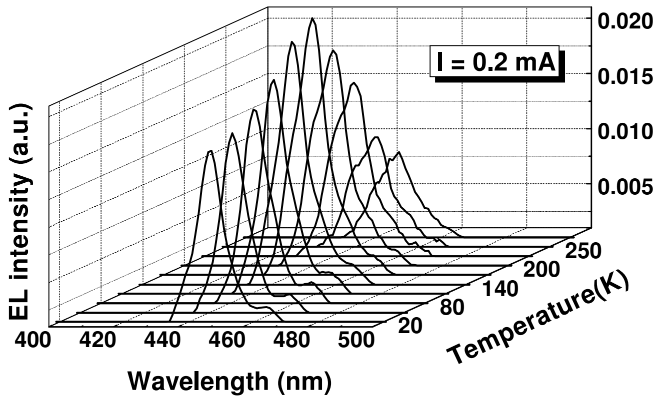

Fig. 1. Temperature-dependent EL spectra of InGaN MQW LED, at injection current of I_f = 0.2 mA.

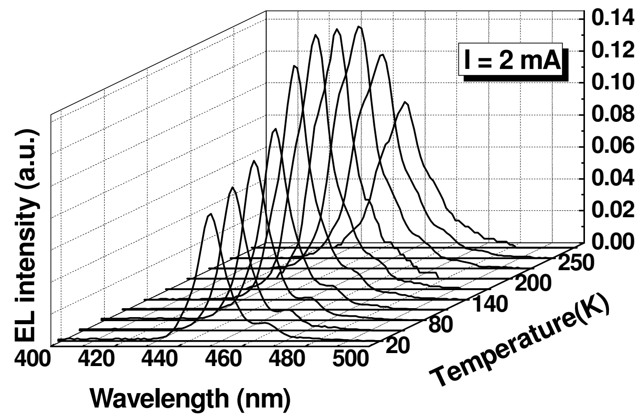

Fig. 2. Temperature-dependent EL spectra of InGaN MQW LED, at injection current of I_f = 2 mA.

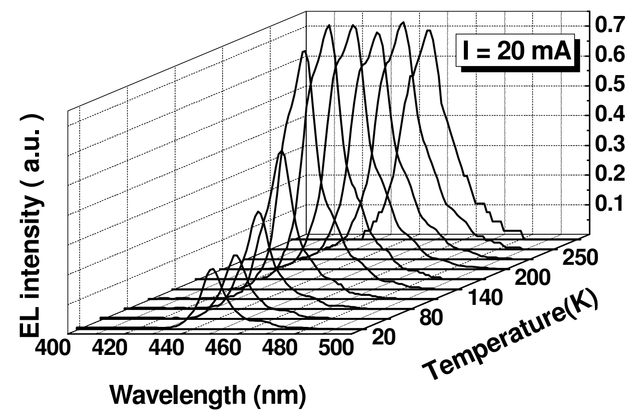

Fig. 3. Temperature-dependent EL spectra of InGaN MQW LED, at injection current of I_f = 20 mA.

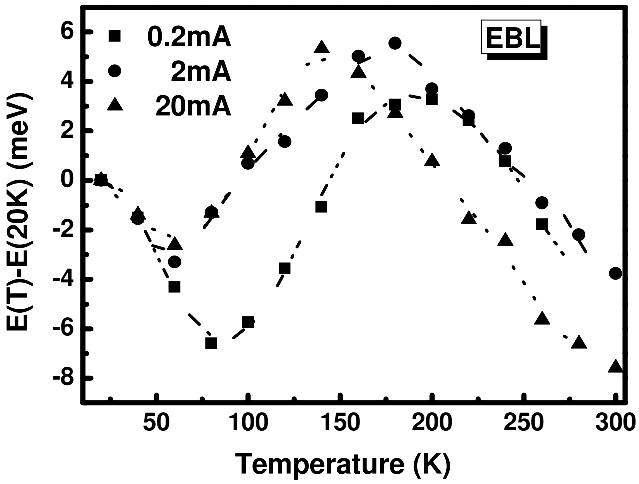

Fig. 4. Temperature dependence in normalized peak energy with injection currents of 0.2 mA, 2 mA, and 20 mA, respectively.

4. Conclusions

Anomalous excitation dependence of electroluminescence phenomena in InGaN/GaN light-emitting diodes with electron blocking layer have been investigates as functions of temperature and injection current levels. As the temperature further decreased to 20 K, the radiative recombination zone gradually shifted 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. It was also accompanied with dramatically reduced EL intensity of the active region. As far as the evolution of the spectral power was concerned, however, there was an initial increase in radiation upon decreasing the temperature until a maximum. This situation arose because non-radiative mechanisms, such as electron-phonon scattering processes, essentially abated as the temperature decreased. As the injection current was increased, we observed the emission peak with blue-shift and band filling effect would become conspicuous, and therefore reduced the carrier localization effect.

Acknowledgements

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