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Effect of Multiquantum Barriers on Carrier Transport Mechanism of InGaN/GaN Multiple Quantum Well Light-emitting Diodes

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1. Introduction

Gallium-nitride-based material semiconductors have been used for a variety of applications high-power and high-temperature devices, due to wide band gap, chemical stability and relative highly saturation drift velocities [1]. The presence of piezoelectric polarizations and spontaneous polarizations, and spinodal decompositions in the wurtzite epitaxial heterolayers grown incoherently on the (0001) orientation sapphire substrates, has inherently led to abnormal electronic and optical properties of nitride materials and devices [2]. To understand substantially the unique spectral response, it is necessary to examine the electronic transport behavior in heterodevices. On the other hand, from a study of the internal quantum efficiency aspects of the carrier action in the recombination zone, a remarkable reduction in the degree of leakage electrons and holes over the light-emitting layer was observed when adopting a multiquantum barrier (MQB) structure [3]. In this work, we present a study of the correlations between electrical and optical characteristics of blue InGaN/GaN multiple quantum well (MQW) light-emitting diodes (LEDs) with MQBs. We conclude that a well-designed MQB structure can indeed improve LED performance significantly.

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 $In_{0.16}Ga_{0.83}N$/GaN 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. We prepared well-designed types of barrier, which is 5-period $In_xGa_{1-x}N$/GaN, in the active regions of these devices. It is the so-called multiquantum barrier (MQB) structures. The values of x for the low-, medium-, and high-indium-content $In_xGa_{1-x}N$/GaN MQB samples were 0.005, 0.01, and 0.02, respectively. For current-voltage measurements, a Keithley 2430 as a current source drove the samples mounted in a closed-cycle helium cryostat. 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 elucidate the unique correlations between the carrier transport and optical characteristics of InGaN/GaN MQW LEDs, it is of interest to examine the radiative recombination of the confined electrons and holes at low temperature. Fig. 1 was shown the normalized EL intensity and ideality factors as a function of temperature for device with MQBs. The composition of In is 0.005, 0.01, and 0.02 respectively. A pronounced increase in the factor n is obtained, corresponding to blue emission decreasing monotonically with the temperature, as indicated in the figure. The observation of the reduction of the EL intensity at a low temperature is similar to experimental reports, where the abnormal behaviors manifested the peculiar radiative mechanisms of the nitride-based QW heterostructures by electrical excitation [3]. As In composition decreased, there was a low 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 dependence of ideality factor on temperature is given by $n=1+T_0/T$, where T is the measurement temperature. The so-called pseudotemperature T_o is a temperature-independent parameter associated with the interface-state distribution at constant current. As shown in Fig. 1, we also could find that the ideality factors are inversely dependent with temperature T. The small T_o associated with a small characteristic energy and charge population of the multilayer interface states is obtained for each sample at the higher temperature regime. Because an effective density of state (DOS) is inversely dependent on the above-mentioned characteristic energy, an electron-hole recombination probability with a large DOS at higher temperature is greater than that with a small DOS at lower temperature. As In composition decreased, there was a high T_o, resulting in the augment the spectral radiations at a temperature above 180 K, due to the decreased interface-state distribution and greater DOS.

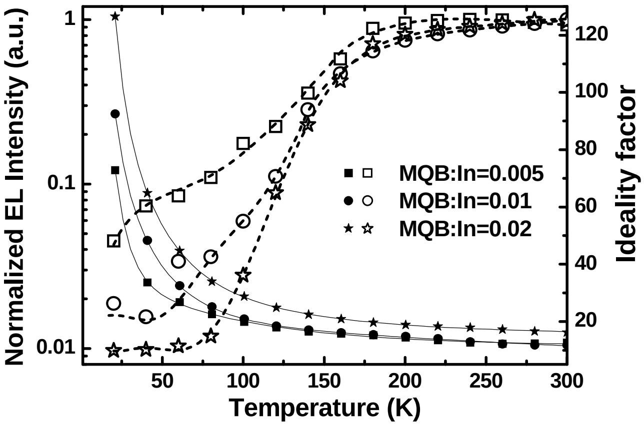

Fig. 1. Normalize EL intensity and ideality factor and as a function of temperature for the LEDs with MQBs. The In compositions of the MQBs for these samples were 0.005, 0.01, and 0.02, respectively.

Consider the tunneling currents in reverse biased junctions was expressed with this formulary,

$$J_r = -V_j C_1 \exp[C_2 /(V_{bi} - V_j)^{1/2}]$$

where C_1, C_2 and V_{bi} are constants. The curves as shown in Fig. 2 does not fit in usual model because the current of this model may be the result of some other mechanism, such as surface leakage or a more complex tunneling mechanism. At more negative reverse voltages (V_j < 3 V), the current is temperature sensitive and is found to obey a power law where $I \propto V^p$. Because of the power-law dependence, this behavior is believed to be the result of space-charge-limited current. Not all of the junctions exhibited the temperature-independent region but were found to have more conventional current–voltage characteristics. As In composition decreased, it was found that the p values increased, indicated space-charge-limited current dominated and influenced the carrier transport mechanism, resulting in the augment of the ideal factor and reduction of the luminescence efficiency of the InGaN/GaN MQW LEDs with MQBs.

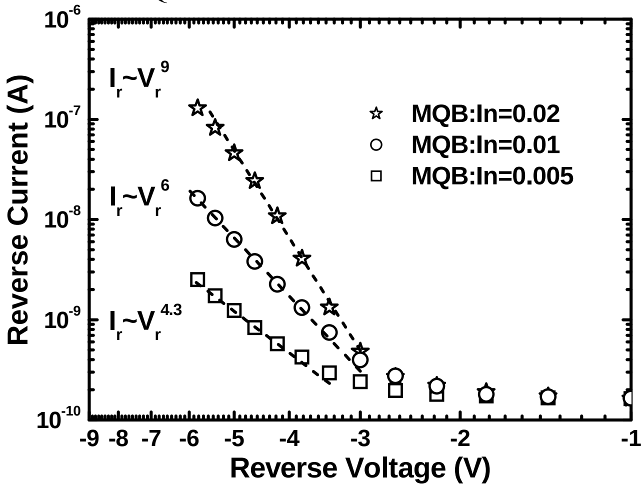

Fig.2. Reverse current vs voltage on a log-log scale for the LEDs with MQBs. The In compositions of the MQBs for these samples were 0.005, 0.01, and 0.02, respectively.

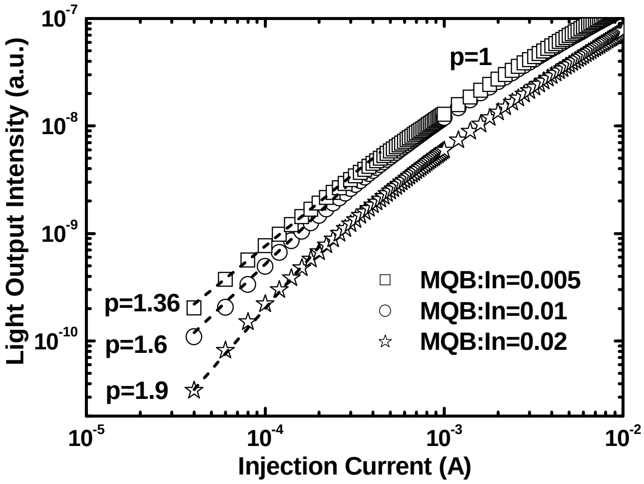

Fig. 3. Dependence of light output on the injection current for the LEDs with MQBs. The In compositions of the MQBs for these samples were 0.005, 0.01, and 0.02, respectively.

Fig. 3 shows the light output intensity-current (L-I) characteristics of the LEDs with MQBs. It is quite clear that the light output L varies as I^p in a specific injection regime according to the L-I characteristics of the samples. At low injection current ranges, the parameter *p* lowered from 1.9 to 1.36 with decreasing In compositions due to the suppression of nonradiative tunneling processes in space charge regions and substantial reduction of threading dislocation density. Under high injection conditions, the diffusion-recombination mechanism dominated, i.e. the parameter *p* approached to one. This results were indicated that not only the inhibitions of nonradiative recombinations, but also the enhancements of localization effects.

4. Conclusion

Unique correlations between the electrical characteristics and optical properties of the InGaN/GaN MQW LED were investigated over a broad range of temperatures. From the EL spectra measured at various temperatures, we found that the T_o effect reduces the spectral intensity. These observed correlations suggest that the carrier-transport process is essentially responsible for the luminescence characteristic improvements. This results were indicated that not only the inhibitions of nonradiative recombinations, but also the enhancements of localization effects.

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