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Anomalous Electroluminescence Phenomena in InGaN/GaN Multiple Quantum Well Light-emitting Diodes with Electron Tunneling Layer

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1. Introductions

Recently, GaN-based semiconductors have opened the way to the realization of high-efficiency blue/green light emitting diodes (LEDs) which have already been extensively used in full-color displays and high efficient light source for traffic light lamps. In spite of this striking advanced technology, the emission process and carrier transport mechanism are affected by several peculiarities of this materials system and are still under debate. In order to further improve the light-emitting efficiency of these blue/green LEDs, increasing the carrier injection into the active region to raise the number of excitons can enhance the output light intensity. In this article, we used a thin layer of ten periods InGaN(10Å)/GaN(15Å) superlattice than the material of the active region as electron tunneling layer (ETL), inserted between the active layer and n-type layer for the device, with the purpose of improving the carrier injection into the active zone and increase the carrier recombination quantities to lead the clear enhancement of output light emitting intensity. We in-depth investigated the anomalous phenomena of the electroluminescence characteristics of InGaN/GaN multiple quantum well (MQW) blue LEDs under varies injection current levels over a wide temperature range from 20 K to 300 K.

2. Experiments

The samples investigated in this study were grown on c-plane sapphire substrate by metal organic vapor phase epitaxy (MOVPE). The conventional structure of the sample was consisting of 2 μm Si-doped n-type GaN layer, follow by ten periods of InGaN(10Å)/GaN(15Å) as the electron tunneling layer (ETL), an undoped GaN layer with eight periods of $In_{0.15}Ga_{0.85}N$/GaN multiple quantum well (MQW) and is capped by a 120 nm Mg-doped p-type GaN. The doping levels 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 layer, that is ten periods of InGaN(10Å)/GaN(15Å) and bulk n-AlGaN barriers, in the active regions of these two devices. Standard Ni/Au and Ti/Au metallization were used as contacts to n-type and p-type layer, respectively. For temperature-dependence electroluminescence (EL) spectra measurements, the devices were 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 over a temperatures range form 20 to 300 K, as a function of the injected current between 0.2 to 20 mA.

3. Results and Discussion

Fig. 1 and 2 have shown the EL intensity as a function of temperature for the devices with n-AlGaN layer and ETL, for injection current of 0.2, 2, and 20 mA. The intense blue peak in the luminescence response is the most remarkable feature of the device with ETL structure at both temperatures compared with the conventional device, indicating an improved LED performance by adopting an appropriate heterolayer. Contrary to the behaviors of blue emission, the device with n-AlGaN layer 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. After the current and temperature are increased further, the light output shows a trend of saturation possibly caused by the heating effect formed by a higher injection current level.

It can also be observed that the emission peak of the PL spectra exhibited an obvious blue-red shift, i.e., inverse V-shaped shift, implying the existence of localized states. By using the Varshini formula and band-tail model, the temperature-dependent emission energy can be fitted by

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta} - \frac{\sigma^2}{k_B T}$$

where the first term $E_g(0)$ describes the energy gap at zero temperature; α and β are known as Varshini's fitting parameters. The third item on the right of the equation originates from the localization effect, where σ indicates the degree of localization effect, and k_B is Boltzmann's constant. The value of σ would be enhanced by using n-AlGaN layer in the heterostructures. Compared with the localization effect, an n-AlGaN layer is stronger than a ETL. We attributed this phenomenon to indium spinodal decompositions and indium clusters leading to the localized states in the quantum wells. After the current are increased further, the value of σ shows a trend of decrease possibly caused by the band-filling effect and screening effect formed by a higher injection current level. At the same time, the EL intensity remarkably rises for sample with n-AlGaN than ones with ETL.

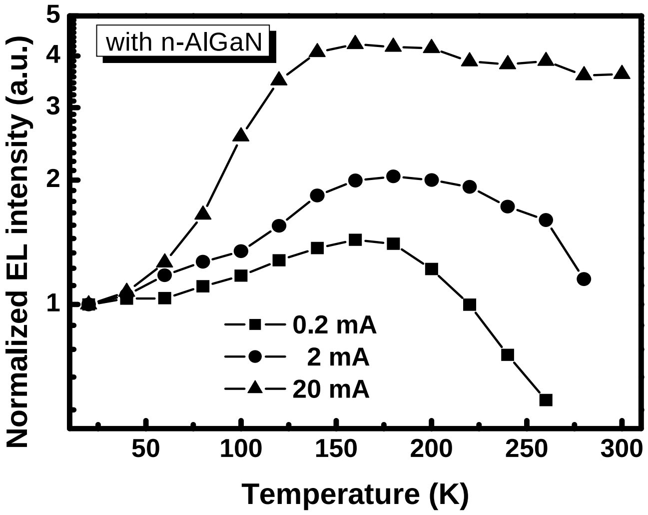

Fig. 1 The EL intensity as a function of temperature for the devices with n-AlGaN layer, for injection current of 0.2, 2, and 20 mA.

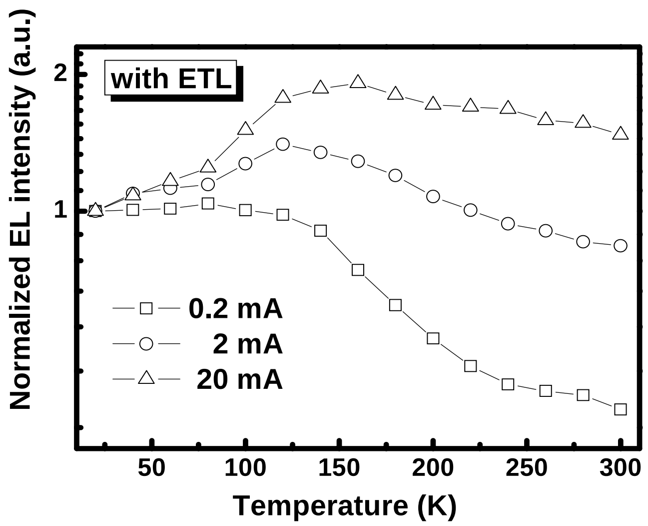

Fig. 2 The EL intensity as a function of temperature for the devices with ETL, for injection current of 0.2, 2, and 20 mA.

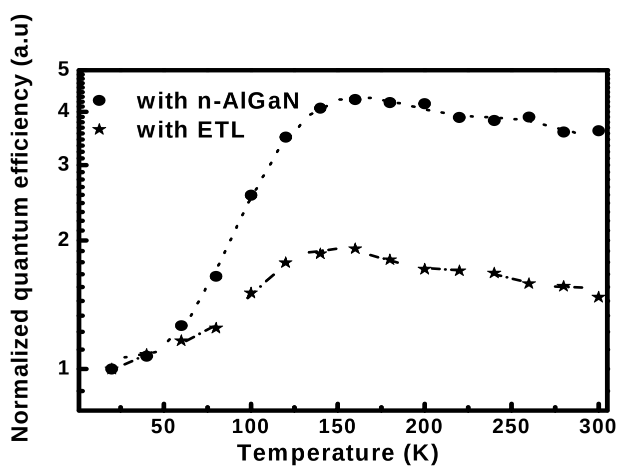

Fig. 3 The sample with ETL and n-AlGaN. Ideality factor and EL intensity with varied temperature for injection current=0.2,2,20 mA.

Both device efficiencies remained roughly constant, between 200-300 K, and then, due to the carrier overflow mechanism, decreased monotonically with the temperature. The improvement of the quantum efficiency of the n-AlGaN sample was found to be significant, up to the 1.2 to 3 times, compared with the conventional sample, in the temperature range between 300 and 20 K. As can be seen in Fig. 3, the introduction of a well-designed ETL structure into an LED also leads it to have thermal-insensitivity characteristics. As far as the ability to catch carriers from an injection current is concerned, it is interesting to estimate both the trapping and detrapping cross sections that determine the electron and the photon relaxation processes in the MQW heterostructures. The high trapping fraction of the total cross sections leads to the energetic carriers being circumscribed in the transition zone by the ETL heterostructure. Because of the abatement of the radiationless process at a low temperature, the luminescence response to the electrical excitation is determined by the quasi-static carrier distribution. The exciton wavefunction can be successfully tailored by the nanostructure, which facilitates the localization of the injected carriers, as well as promoting radiative recombination in the active region of ETL device.

4. Conclusion

Anomalous electroluminescence phenomena in InGaN/GaN multiple quantum well light-emitting diodes with electron tunneling layer and n-AlGaN layer were investigated. It was found that a device with an n-AlGaN structure exhibited a higher quantum efficiency, as well as a higher temperature insensitivity, than did the conventional MQW LEDs with ETL. However, the high trapping fraction of the total cross sections leads to the energetic carriers being circumscribed in the transition zone by the ETL heterostructure. Both the EL excitation cross section and the abnormal quantum efficiency evolution as a function of temperature were found to be in good agreement with the rate equation model.

Acknowledgements

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