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

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The phenomena of electroluminescence in InGaN/GaN multiple quantum well (MQW) light-emitting diodes (LEDs) with an n-AlGaN layer and a superlattice of 10 periods of InGaN (10 Å)/GaN (15 Å) serving as the electron tunneling layer (ETL) have been investigated in detail over a broad temperature range from 20 to 300 K at various injection currents. Compared with conventional LEDs with a well-designed ETL, quantum efficiency and temperature insensitivity are found to be improved when an n-AlGaN layer is inserted. This is attributed to the localization effect of the n-AlGaN layer being stronger than that of the ETL layer, as analyzed using the Varshini formula and band-tail model. Nevertheless, the inserted ETL layer with the purpose of improving the carrier injection into the active layer not only increases the carrier recombination quantity, which leads to a marked increase in output light emission intensity, but also reduces the light emission intensity compared with sample with the n-AlGaN layer. Consequently, inserting a blocking layer between an active layer and a p-GaN layer may increase the output light emission intensity of the sample with an ETL. [DOI: 10.1143/JJAP.47.7148]

KEYWORDS: gallium nitride (GaN), multiple quantum well (MQW), light-emitting diode (LED), electron tunneling layer (ETL)

1. Introduction

Recently, GaN-based semiconductors have opened the way to the realization of highly efficient blue/green light-emitting diodes (LEDs), which have already been extensively used in full-color displays and highly efficient light sources for traffic light lamps.[1–3] Despite these strikingly advanced technologies, the emission process and carrier transport mechanism are affected by several peculiarities of these material systems and are still under debate. In further improving the light emission efficiency of these blue/green LEDs, improving the carrier injection into the active region to increase the number of excitons can increase the output light intensity.[4–6] Recently, it has been reported theoretically that a charge asymmetric resonance tunneling (CART) structure can significantly increase the electron capture rate of a multiple quantum well (MQW) active region through electron tunneling. In this study, we used a superlattice of ten periods of InGaN (10 Å)/GaN (15 Å) as the electron tunneling layer (ETL) and then inserted it between the active and n-type layers for the device, with the purposes of improving the carrier injection into the active zone and increasing the carrier recombination quantity to markedly increase the output light emission intensity. We investigated in-depth the phenomena of the electroluminescence characteristics of InGaN/GaN MQW blue LEDs at various injection currents over a wide temperature range from 20 to 300 K. As far as the ability to catch carriers at an injection current is concerned, it is interesting to estimate both the trapping and detrapping cross sections that determine the electron and photon relaxation processes in the MQW heterostructures. However, the high trapping fraction of the total cross section leads to the energetic carriers being circumscribed in the transition zone by the ETL heterostructure. Both the carrier transport mechanism and the abnormal quantum efficiency evolution as a function of temperature were found to be in good agreement with the rate equation model.

2. Experimental Methods

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 samples consisted of a 2 μm Si-doped n-type GaN layer, followed by n-$Al_{0.1}Ga_{0.9}N$ barriers (50 Å) and an eight $In_{0.15}Ga_{0.85}N/GaN$ MQW periods, and was capped by a 120 nm Mg-doped p-type GaN layer. Silane (SiH_4) and bis(cyclopentadienyl) magnesium (Cp_2Mg) were used as either the n- and p-type precursors or dopants, respectively. The doping levels of the n- and p-type GaN layers were nominally about 5×10^{18} and 1×10^{19} cm^{-3}, respectively. The structure of the apropos sample was similar to a structure with different types of barrier in $In_{0.05}Ga_{0.095}N$ (10 Å)/GaN (15 Å), compared with a structure showing only conventional barriers under the active regions, the so-called ETL structure. Photoluminescence (PL) and X-ray diffraction (XRD) measurements were then used to determine the indium and aluminum compositions of the MQW, ETL, and AlGaN layer. Ni/Au and Ti/Au metallization layers were used for the electrodes of n- and p-type layers, respectively, which produced by the standard photolithography processes. 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 temperature range 20 to 300 K, as a function of the injected current between 0.2 and 20 mA.

3. Results and Discussion

Figures 1 and 2 show the EL intensity as a function of temperature for the devices with an n-AlGaN layer and an

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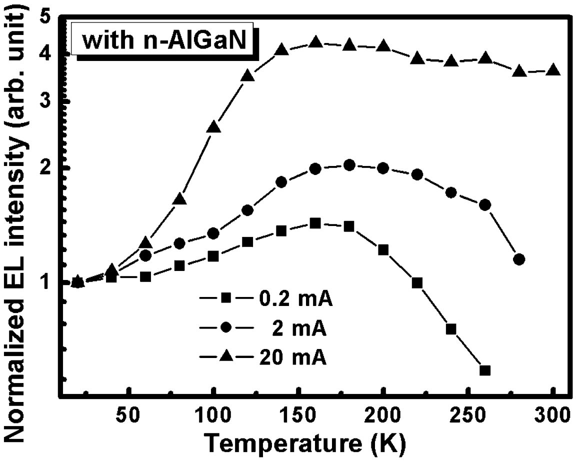

Fig. 1. EL intensity as a function of temperature for InGaN/GaN MQW LEDs with n-AlGaN layer, operated at injection currents of 0.2, 2, and 20 mA.

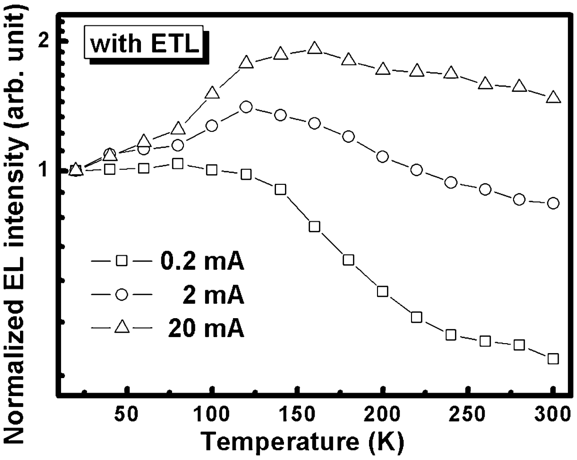

Fig. 2. EL intensity as a function of temperature for InGaN/GaN MQW LEDs with ETL layer, operated at an injection currents of 0.2, 2, and 20 mA.

ETL, for injection currents of 0.2, 2, and 20 mA. The output powers of the LEDs with the ETL and AlGaN layer are 10 and 3.6 mW at 300 K, respectively. Compared with the value of 3.6 mW achieved for the AlGaN layer, the higher optical intensity of 10 mW for the ETL implies a well-designed charge asymmetric resonance tunneling layer for the injection of charge carriers. The intense blue peak in the luminescence response is the most remarkable feature of the device with the ETL at both temperatures compared with the conventional device, indicating that the LED performance is improved by adopting an appropriate heterolayer. Contrary to the behaviors of blue emission, the device with the n-AlGaN layer exhibits a more 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.[7,8]

In Fig. 1, for the injection current of 0.2 mA, the EL intensity increases to 170 K and then significantly decreases. An increase in EL intensity with increasing temperature results from the high band gap energy of n-AlGaN materials that block the flow of injection carriers into the active layer. For this reason, the increasing temperature increases the EL intensity. When the temperature increases to 170 K, the saturation of carriers reduces the EL intensity. The injection currents of 2 and 20 mA show a similar behavior to that of 0.2 mA. After further increases in current and temperature, the light output shows a trend of saturation possibly caused by the heating effect due to a higher injection current level. However, it is important to note that the EL intensity slowly and gradually decreases with increasing temperature at the highest current of 20 mA. This phenomenon is caused by the ratio at which the carriers recombine at different current levels of 0.2, 2, and 20 mA. At 20 mA, the ratio slightly alters the EL intensity at a certain temperature compared with those observed at 0.2 and 2 mA. In Fig. 2, an ETL sample at 0.2 mA shows that the EL intensity decreases with an increase in temperature, similarly to that observed in the conventional sample. For the injection current levels of 2 and 20 mA, the trend of the EL intensity shows a similar phenomenon to that in the case of the n-AlGaN layer. Nevertheless, the inserted ETL layer with the purpose of improving the carrier injection into the active layer not only increases the carrier recombination quantity, which leads to a marked increase in output light emission intensity, but also reduces the light emission intensity compared with sample with the n-AlGaN layer. Consequently, inserting a blocking layer between an active layer and a p-GaN layer may enhance the output light emission intensity of the sample with ETL layer.

Both device intensities at the injection current of 20 mA remained roughly constant between 200 and 300 K, and then, owing to the carrier overflow mechanism, decreased monotonically with temperature, as observed in Figs. 1 and 2. All the efficiencies were normalized to the values observed at 20 K. Both device efficiencies remained roughly constant between 20 and 60 K, and then, owing to the carrier overflow mechanism, decreased monotonically with temperature. The improvement in quantum efficiency in the n-AlGaN sample was found to be significant, up to 1.2 to 3 times more, compared with that in the conventional sample, within the temperature range from 300 to 20 K. As can be seen in Figs. 1 and 2, the introduction of an InGaN (10 Å)/GaN (15 Å) ETL structure into an LED also induces thermal-insensitivity characteristics.

Figures 3 and 4 show the emission peak energies at different current levels with increasing temperature, indicating the localization effect in the n-AlGaN layer and ETL. It can also be observed that the emission peak of the PL spectra exhibited an obvious abnormal red–blue–red shift, i.e., the first red shift is attributed to the carriers captured by deep traps in the MQW, and the subsequent inverse V-shaped shift, the existence of localized states. Compared with the ETL, all the emission peak energies of the n-AlGaN layer shift to the upper-left side, implying that the localization effect of the n-AlGaN layer gradually become stronger. Using the Varshini formula and band-tail model, the temperature-dependent emission energy can be fitted by[8]

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

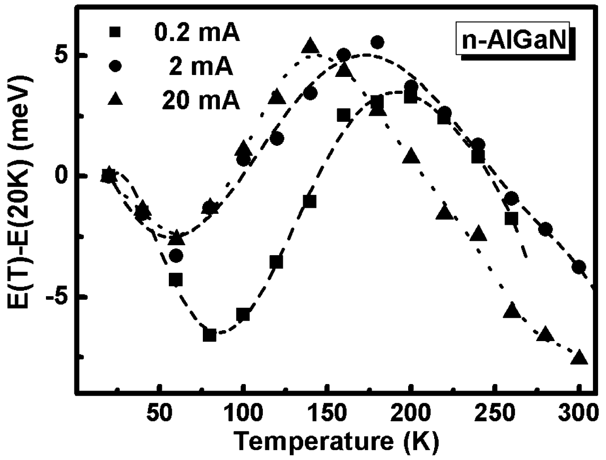

Fig. 3. Temperature-dependent emission peak energy shift of InGaN/GaN MQW LEDs with n-AlGaN layer for injection currents of 0.2, 2, and 20 mA.

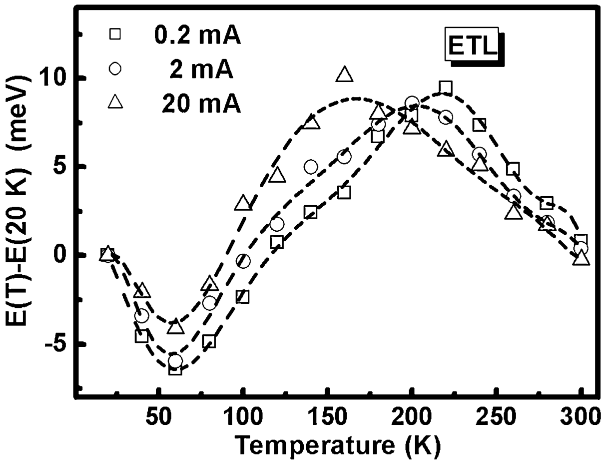

Fig. 4. Temperature-dependent emission peak energy shift of InGaN/GaN MQW LEDs with ETL layer for injection currents of 0.2, 2, and 20 mA.

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 term on the right-hand side of the equation originates from the localization effect, where σ indicates the degree of the localization effect, and k_B is Boltzmann's constant. Using the n-AlGaN layer in the heterostructures, as indicated in Fig. 3, would enhance the value of σ. In Figs. 3 and 4, in comparison with the localization effect, the n-AlGaN layer is stronger than the ETL. We attributed this phenomenon to indium spinodal decomposition and indium clusters leading to the localized states in the quantum wells. After a further increase in the current, the value of σ shows a decreasing trend possibly caused by the band-filling and screening effects produced by a higher injection current level. Simultaneously, the EL intensity markedly rises in the sample with the n-AlGaN layer compared with the sample with the ETL layer, as in Figs. 1 and 2. As shown in Figs. 1–4, it is noted that the blue shift behavior (Figs. 3 and 4) is consonant with the decrease of peak EL intensity (Figs. 1 and 2). The reason for this could be the efficiency of the carrier injection improved by a shift of the zone of radiative recombination which carriers flow into the MQW and the reduction in the degree of the screening effect.

The optical recombination mechanisms can be examined using the rate of carrier density change, as well as the rates of photon production and annihilation, in radiative and nonradiative transition processes. As far as the carrier capture ability of the QWs is concerned, the capture fraction of the excitation cross section suitable for describing the radiative recombination processes in the LED structure. Taking into account the scattering processes, a rate equation model was confirmed to corroborate these unique thermal behaviors and described the carrier trapping and detrapping processes in the MQW heterostructure.[9] As a result, the thermally related abatement of the cross section is sufficiently damaging to augment the radiative recombination in the AlGaN sample over a broad temperature range. However, as far as the quantum efficiency at a constant temperature is concerned, the ETL LED essentially exhibits better device characteristics than the AlGaN-layer LED, as expected. Notwithstanding this, a well-designed InGaN/GaN heterobarrier structure, with a high fraction of captured cross sections can ameliorate the performance of blue MQW LEDs. The exciton wavefunction can be successfully tailored by the nanostructure, which facilitates the localization of the injected carriers and promotes radiative recombination in the active region of the ETL device. Inferentially, the higher the confinement ability for energetic excitons, the larger the cross sections for impinging carriers, inhibiting the radiative recombination in the Mg-doped cladding region and increasing effectively the recombination intensity in the active region.

4. Conclusions

Electroluminescence phenomena in InGaN/GaN multiple quantum well light-emitting diodes with an ETL and an n-AlGaN layer were investigated. It was found that a device with an n-AlGaN structure exhibits a higher quantum efficiency, as well as a higher temperature insensitivity, than conventional MQW LEDs with an ETL. A sample with an ETL enhances the carrier injection and reduces the quantum efficiency that affects the EL intensity of LEDs. The insertion of a blocking layer between MQWs and a p-GaN layer will be the next step to improve the results in this paper. 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. As far as the ability to catch carriers at an injection current is concerned, it is interesting to estimate both the trapping and detrapping cross sections that determine the electron and photon relaxation processes in the MQW heterostructures. The high trapping fraction of the total cross section leads to the energetic carriers being circumscribed in the transition zone by the ETL heterostructure. Both the carrier transport mechanism and the abnormal quantum efficiency evolution as a function of temperature were found to be in good agreement with the rate equation model. These results should greatly aid in the better design and optimization of heterobarriers in optoelectronic heterostructures.

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1) H. Amino, N. Sawaki, I. Akasaki, and Y. Toyota: Appl. Phys. Lett. **48** (1986) 353.
2) H. Amano, M. Kito, K. Hiramatsu, and I. Akasaki: Jpn. J. Appl. Phys. **28** (1989) L2112.
3) S. Chichibu, T. Azuhata, T. Sota, and S. Nakamura: Appl. Phys. Lett. **69** (1996) 4188.
4) Y. Narukawa, Y. Kawakami, M. Funato, Sz. Fujita, Sg. Fujita, and S. Nakamura: Phys. Rev. B **55** (1997) 1938.
5) Y. Narukawa, Y. Kawakami, M. Funato, Sz. Fujita, Sg. Fujita, and S. Nakamura: Appl. Phys. Lett. **70** (1997) 981.
6) P. Riblet, H. Hirayama, A. Kinoshita, A. Hirata, T. Sugang, and Y. Aoyagi: Appl. Phys. Lett. **75** (1999) 2241.
7) T. Wang, H. Saeki, J. Bai, T. Shirahama, M. Lachab, and S. Sakai: Appl. Phys. Lett. **76** (2000) 1737.
8) K. Uchida, T. Tang, S. Goto, T. Mishima, A. Niwa, and J. Gotoh: Appl. Phys. Lett. **74** (1999) 1153.
9) T. E. Nee, J. C. Wang, H. T. Shen, and Y. F. Wu: J. Cryst. Growth **298** (2007) 714.