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Improvement of Electrical and Optical Properties of InGaN/GaN-Based Light-Emitting Diodes with Triangular Quantum Well Structure

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Abstract−Substantial improvement of electrical and optical properties of InGaN/GaN multiple quantum wells (MQWs) was obtained with a triangular band structure. Transmission electron microscopy (TEM) images from the triangular MQWs showed the formation of uniformly and densely distributed quantum dots having diameters of 20-50 nm. The light-emitting diodes (LEDs) with the triangular QWs showed a lower operation voltage, a higher light output power, and higher intensities and narrower line widths of electroluminescence spectra than those with the rectangular QWs. Very bright and uniform light emission from the triangular MQW LEDs was also observed at a low injection current, but spatially non-uniform emission from the rectangular ones.

Key words: InGaN/GaN, Quantum Well Structures, Light-emitting Diodes

INTRODUCTION

In recent years, wide bandgap semiconductors of group III-nitride have been widely used for the commercial production of optical devices. InGaN alloy is especially very important for applications of the III-nitride materials in blue light-emitting diodes (LEDs) and laser diodes (LDs) [Crowell et al., 1998; Nakamura et al., 1997, 2000; Wang et al., 2001], because the alloy constitutes the active region in the form of quantum well (QW). Also GaN and AlGaN are usually adopted for the barrier of QW in accordance with the emitting spectrum range of interest. The most commonly used QW structure is a rectangular-type band structure with constant In composition in the well layer of InGaN. In this case, the band edges in the well are expected to have oppositely directed triangular-like shape in the conduction and valence band edges. As a result, a spatial direct band gap lower than the indirect gap caused by the internal field would be induced, resulting in poor light emission. To improve the emission efficiency or suppress the piezoelectric field effect, we examined a triangular-shaped band structure of the InGaN QW for the first time [Choi et al., 2003], which is a graded index separate confinement structure.

In this paper, we report the electrical and optical properties of the LEDs fabricated by using multiple InGaN/GaN triangular QWs. The triangular band structure in the QW was obtained by linearly grading the In composition in the InGaN well. Their characteristics were compared with those of the LEDs having a rectangular QW structure in terms of I-V characteristics, output power, and electroluminescence (EL) spectrum. The InGaN/GaN triangular-type MQW LEDs showed much improvement of properties over the conventional rectangular ones.

EXPERIMENTAL

The samples used in this work were grown on c-plane sapphire substrates by low-pressure metal-organic chemical vapor deposition (MOCVD) system. We first grew a 3 μm-thick n-type layer at 1,130 °C on a GaN nucleation layer grown at 560 °C, and then grew a five-periods of $In_xGa_{1-x}N$/GaN MQWs with an x value of maximum 0.25 at 795 °C. The well and barrier width were in a range of 28-32 Å, and 80 Å thick, respectively. The source materials were trimethylgallium (TMGa), trimethylindium (TMIn), and ammonia (NH_3). The triangular-shaped InGaN/GaN QWs were grown by

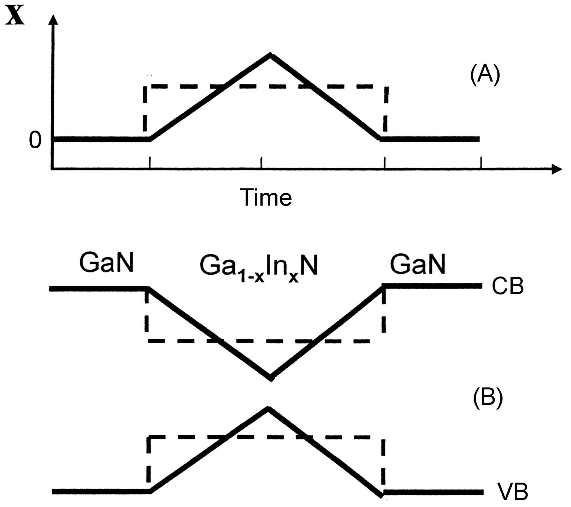

Fig. 1. (A) Variation of In content (x) with time during the growth of InGaN well layer and (B) energy structure of a triangular quantum well (solid line) compared with rectangular one (dotted line).

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linearly changing the In composition (or the flow rate of TMIn) with time during the growth process as shown in Fig. 1(A), in which solid and dotted lines represent triangular and rectangular types, respectively. By contrast, the rectangular-type QWs were grown at a constant flow rate of TMIn. The resulting triangular-shaped band structure is schematically compared with the rectangular one in Fig. 1(B), in which the internal electric field effect is neglected. Transmission electron microscopy (TEM) was carried out by using a JEOL 2010 operated at 200 kV, and photoluminescence (PL) was measured as a function of temperature with an He-Cd laser operating at 325 nm.

For fabrication of the InGaN/GaN MQW LED chips, the processing procedures were summarized as follows: 1) SiO_2 film was deposited by PECVD onto the epiwafer as an etch mask before ICP mesa etching, 2) inductively coupled plasma (ICP) etching with Cl_2/Ar was carried out to form a mesa structure, 3) Au(6 nm)/Ni(6 nm) bi-layer for transparent layer was deposited on the p-GaN by e-beam evaporation and lift-off, 4) Ti(30 nm)/Al(70 nm) bi-layer for n-type contact was deposited and patterned by lift-off, and 5) Ni/Au (30 nm/100 nm) bilayer was deposited as the p-type electrode. These metal contacts were annealed at 500 °C for 20 seconds under ambient air. The LED chip size was $320\times320\ \mu m^2$. Details of the ICP etching for mesa structure are available elsewhere [Hahn et al., 2000, 2002; Im et al., 2001]. The output power and current-voltage (I-V) characteristics were measured at room temperature with an HP 4155A semiconductor parameter analyzer.

RESULTS AND DISCUSSION

The cross-sectional high-resolution TEM images of the triangular (top) and rectangular (bottom) QW structures are shown in Fig. 2. The triangular QWs exhibit good periodicity and abruptness of the interface between well (InGaN, dark area) and barrier (GaN, bright area), unlikely the rectangular QWs. It is also seen that In-rich well layers well defined and narrower in the former than the latter. A plan-view of TEM image of the triangular quantum wells is shown in Fig. 3. The QD sizes are in a range of 20-50 nm, much smaller than those in rectangular QWs (~100 nm) [Jeong et al., 2001]. It is known that QDs in the InGaN/GaN QWs are generally formed at higher In compositions (>15%). As the In content is graded during the growth of the triangular QW structure, QDs in the triangular QW become smaller than those in the rectangular QW. The formed QDs act as radiative recombination centers of localized excitons, resulting in stronger emission with more QDs. It is also interesting to see that the QDs are surrounded by dislocation lines, implicating an interaction between the dislocation and the nucleus of QD formation. This result indicates that we can control the size and the distribution of quantum dots in the InGaN/GaN QW system by grading the In composition.

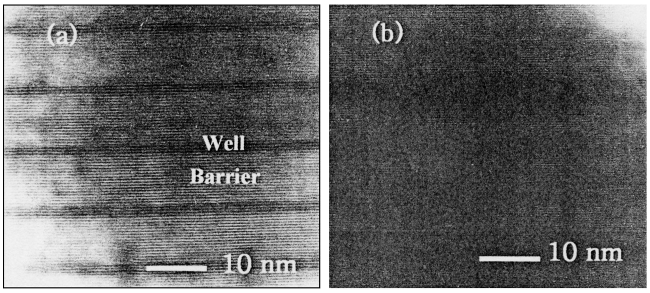

Fig. 2. Cross-sectional high-resolution TEM images of the triangular (top) and rectangular (bottom) QW structures.

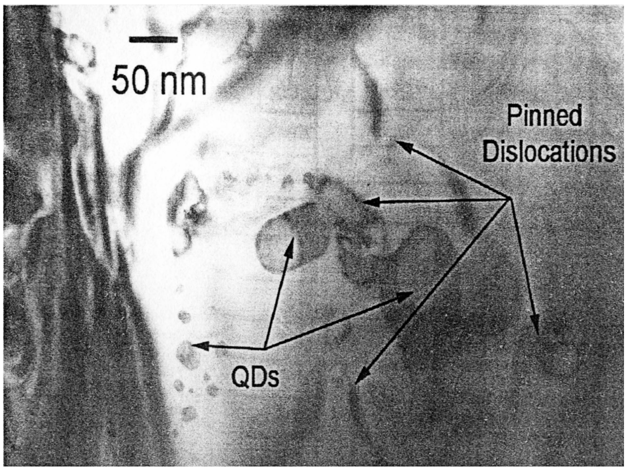

Fig. 3. Plan-view of TEM image of the triangular quantum wells.

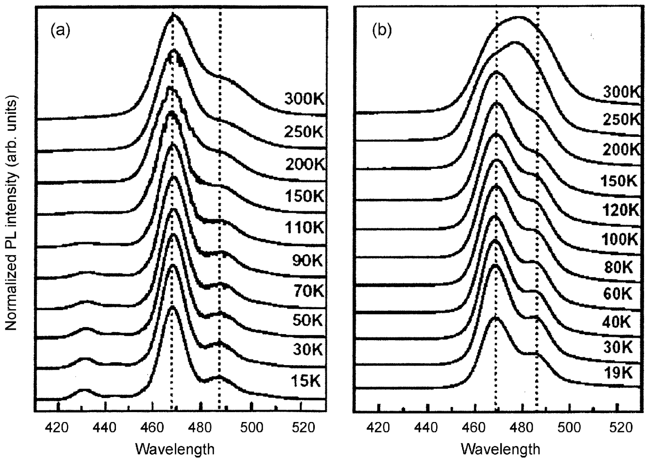

Fig. 4. PL variation as a function of temperature for the triangular (a) and the rectangular (b) QWs, respectively.

Fig. 4 shows the comparison of the temperature-dependent PL spectra of the triangular QWs with those of the rectangular ones. The PL intensity is generally stronger in the triangular QW than that in rectangular one, while the full width at half maximum (FWHM) of PL peak in the former is much smaller than that in the latter. The peak energy of the triangular QW is also almost independent of temperature and the intensity decreases with increasing the temperature. In general, the PL spectrum is composed of multiple peaks. In fact, the PL spectra in Fig. 4(b) cannot be fitted by two Gaussian peaks. It seems that the dominancy of each peak depends upon temperature and consequently determines the apparent behavior of PL. The size and the spatial distribution of QDs might be partially responsible for the multiple peak behavior and thus the phenomena are expected to be more complicated in the rectangular QWs. The PL peak near 430 nm, observed only in the triangular QW, is likely due to the sub-band transition because the lower main peaks are probably attributed to QDs. In the case of the rectangular QW, the

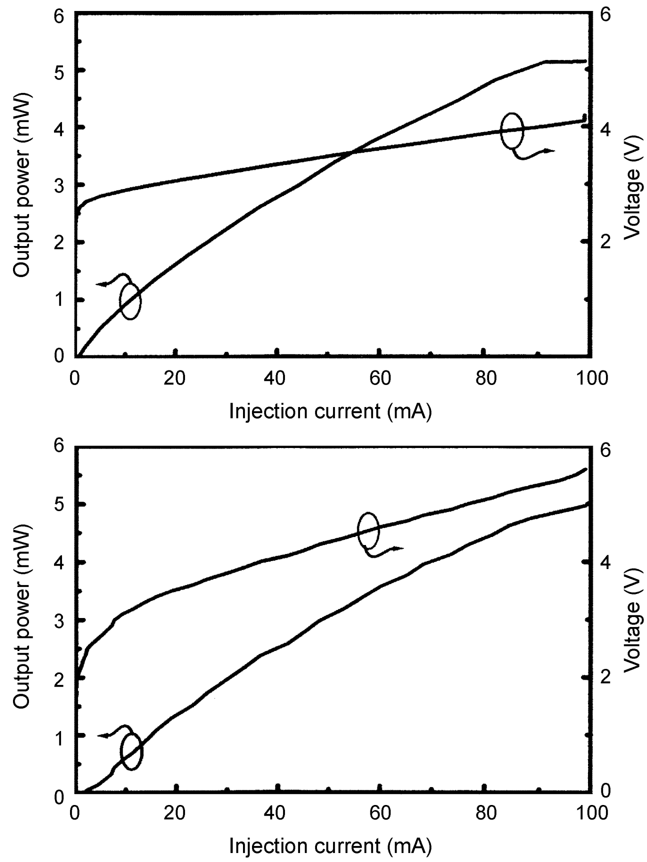

Fig. 5. Effect of quantum structures on voltage and output power of InGaN/GaN multiple quantum well LEDs as a function of injection current: (top) triangular QWs, (bottom) rectangular QWs.

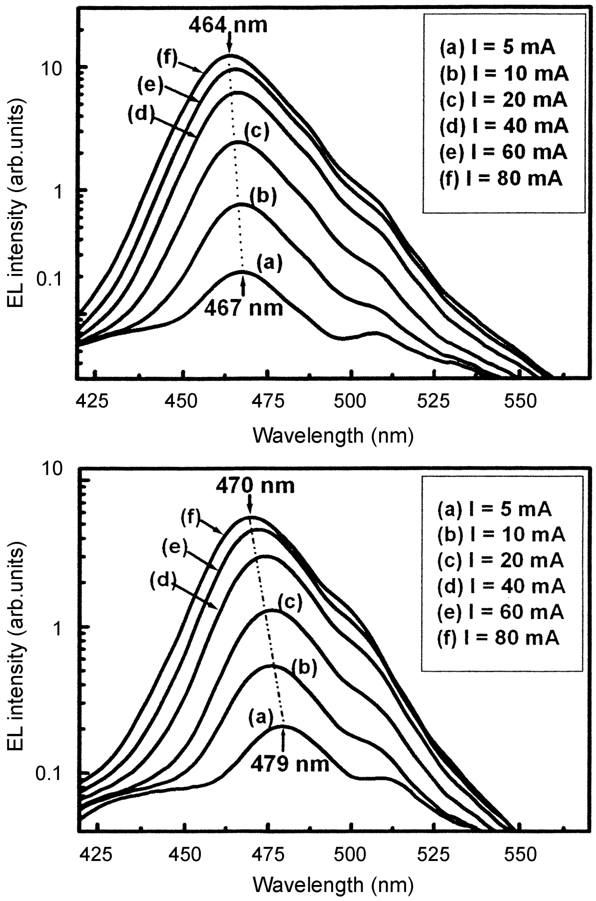

Fig. 6. EL spectrum of the InGaN/GaN MQW LED as a function of injection current at 20 °C: triangular (top) and rectangular (bottom) quantum wells.

QWs are wide and the sub-energy band would be very near the QW band edge. Therefore, the sub-band transition peak will merge into the nearby main PL peak associated with QDs. It is also seen that two PL peaks are distinct near the band edge at lower temperatures for both structures. At a lower temperature, a higher energy peak is dominant, but a peak in-between two peaks becomes dominant at a higher temperature in the rectangular QW.

Fig. 5 shows the I-V characteristics (top) and output power as a function of injection current (bottom) of the InGaN/GaN MQW LEDs, compared with the triangular and the rectangular QW structures, respectively. The LEDs with triangular QWs showed a lower operation voltage of about 3.2 V than that of rectangular QWs (3.7 V) at 20 mA injection current (top). Also, the triangular-type MQW LEDs showed a higher light output power than the rectangular MQW LEDs (bottom). We believe that this is attributed to the formation of densely and uniformly distributed QDs in triangular QW structures.

Fig. 6 shows the EL spectra as a function of injection current of the InGaN/GaN MQW LEDs measured at room temperature. The triangular MQW LEDs (top) showed higher intensities and narrower line widths than those of the rectangular MQW LEDs (bottom). This is presumably due to the size distribution and/or compositional fluctuation of QDs. Above all, the peak energy is almost independent of the injection current in the triangular-QW-based LEDs as shown in Fig. 4(a). By contrast, the energy in the rectangular-QW-based-LED exhibits slight blue shift with increasing the injection current. The blue shift of the EL of the rectangular MQW LEDs with increasing injection current is attributed to the quantum confined stark effect (QCSE), resulting from piezoelectric fields induced by the lattice mismatch [Im, 1998]. Although not illustrated, from PL spectra measured as a function of temperature, we observed that the PL peak energy of MQW with triangular structure was almost independent of temperature. This indicates that we achieved high quality InGaN films having densely and uniformly distributed

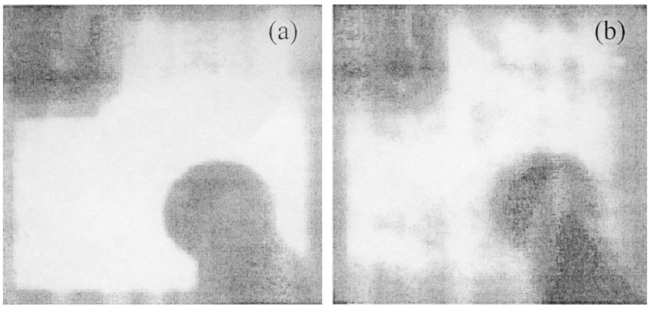

Fig. 7. Light emission images of the InGaN/GaN multiple quantum well LEDs having (left) triangular and (light) rectangular type band structures.

QDs using triangular QW structure for the active layer.

Fig. 7 shows initial light emission images of both kinds of LED. The emission does not exhibit spatially uniform glow with the rectangular QW LED (a), which has been related with the non-uniformly distributed defects in the QWs. [12]By contrast, the triangular QW LED (b) shows a uniform emission glowing from quite uniformly distributed smaller QDs, indicating that rather uniform distribution of QDs is obtained. These results lead to a conclusion that QD engineering by changing the QW structure is a feasible tool to improve the electrical and optical properties of InGaN/GaN MQW LEDs or LDs. However, to further elucidate the properties and emission mechanism of the InGaN/GaN MQW LEDs with the triangular quantum well structure, more detailed study is required.

SUMMARY AND CONCLUSIONS

InGaN/GaN MQW LED structures with triangular quantum wells were fabricated and compared with rectangular ones in terms of structural, electrical and optical properties. The LEDs with triangular QWs showed a lower operation voltage and a higher light output power than those with the rectangular MQW LEDs. This is presumably due to the formation of densely and uniformly distributed QDs in triangular QW structures, which are much smaller than those in rectangular QWs. EL spectra as a function of ambient temperature measured at injection current of 20 mA showed that as temperature is increased the EL intensity in the triangular QW LED is slightly decreased, while the EL intensity in the rectangular QW LED is drastically decreased. We also observed very bright and uniform light emission from the triangular MQW LEDs at a low injection current, but spatially non-uniform emission from the rectangular MQW LEDs, indicating that quality InGaN films having densely and uniformly distributed QDs with the triangular QW structure for the active layer were obtained. The InGaN/GaN triangular MQW LED is more efficient and stable than the conventional rectangular ones.

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