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400-nm InGaN–GaN and InGaN–AlGaN Multiquantum Well Light-Emitting Diodes

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Recenctly, tremendous progress has been achieved in GaN-based blue and green light-emitting diodes (LEDs). These blue/green LEDs have already been extensively used in full-color displays and high-efficient light sources for traffic light lamps. Although these blue/ green LEDs are already commercially available, it is still difficult to achieve LEDs emitting at even shorter wavelength regions, such as ultraviolet (UV) region. Short wavelength emitters are of interest for various fluorescence-based chemical sensing applications, high efficiency lighting, flame detection, and possibly optical storage applications. Conventional nitride-based multiquantum well (MQW) LEDs use InGaN as the material for well layers and GaN as the material for barrier layers. To achieve a short wavelength emitter, one needs to reduce the indium composition in the well layers so as to increase its bandgap energy. However, a reduction in indium composition in the well layers will result in a small bandgap discontinuity at the well/barrier interfaces. Thus, the quantum well depth in the MQW active region will become smaller and the carrier confinement effect will be reduced. As a result, severe carrier leakage problem might occur in the short wavelength InGaN–GaN MQW LEDs. One possible way to solve this problem is to use AlGaN or AlGaInN as the barrier layers instead of GaN. The quaternary AlGaInN permits an extra degree of freedom by allowing independent control of the bandgap and lattice constant. Thus, the use of quaternary AlGaInN for barrier layers could potentially offer better carrier confinement while minimizing lattice mismatch issues. However, it is much more difficult to grow high-quality AlGaInN than AlGaN. Since the bandgap energy of AlGaN is also larger than that of GaN, InGaN–AlGaN MQW should still be able to provide a better carrier confinement, as compared to InGaN–GaN MQW. Also, since the lattice constant of AlGaN is smaller while the lattice constant of InGaN is larger than that of GaN base layer, it is possible to achieve a strain compensated InGaN–AlGaN MQW on GaN with proper composition ratios in InGaN and AlGaN layers. As a result, we could increase the effective MQW critical thickness, and thus reduce the probability of relaxation occurred within the MQW active region. In this study, InGaN–GaN LED and InGaN–AlGaN LED will both be fabricated. The optical and electrical properties of these LEDs will be reported.

The InGaN–GaN MQW LED and InGaN–AlGaN MQW LED structures used in this study were both grown on c–face 2-in sapphire (Al_2O_3) (0001) substrates in a vertical low-pressure organometallic vapor phase epitaxy (OMVPE) reactor with a high-speed rotation disk. Trimethylindium (TMIn), trimethylgallium (TMGa), trimethylaluminum (TMAl), and ammonia (NH_3) were used as the source materials of In, Ga, Al, and N, respectively. Bicyclopentadienyl magnesium (Cp_2Mg) and silane (SiH_4) were used as the p-type and n-type doping sources, respectively. Fig. 1(a) schematically depicts the InGaN–GaN MQW LED structure used in this study. $Al_{0.1}Ga_{0.9}N$ barrier layers, as shown in Fig. 1(b). In order to determine the aluminum composition in the AlGaN layers, we first grew a thick AlGaN layer and then used X-ray diffraction to determine its aluminum composition. Fig. 2 shows the DCXRD spectra of these two LEDs with different barrier layers. Fig. 3 shows RT PL spectra of the MQW LED structures with AlGaN and GaN barrier layers. It was found that PL peak wavelength and PL FWHM of the sample with AlGaN barrier layers were

397 and 14.5 nm, respectively. Fig. 4 shows the forward I–V and dynamic resistance characteristics of the two different types of MQW LEDs. Fig. 5 shows the RT EL spectra of the two different types of MQW LEDs with a 20-mA dc injection current. As shown in Fig. 6, we can thus plot the energy band diagram of $In_{0.05}Ga_{0.95}N$–GaN MQW structure and $In_{0.05}Ga_{0.95}N$–$Al_{0.1}Ga_{0.9}N$ MQW structure. In other words, we could increase the conduction band discontinuity from ΔE_2=84.7 meV in $In_{0.05}Ga_{0.95}N$–GaN MQW structure to ΔE_1=211.4 meV in $In_{0.05}Ga_{0.95}N$–$Al_{0.1}Ga_{0.9}N$ MQW structure. As a result, we could achieve a much larger EL intensity from the InGaN–AlGaN MQW LED, as shown in Fig. 5. The relationship between LED output power and injection current was also measured. Fig. 7 shows the output power as a function of injection current for these two LEDs.

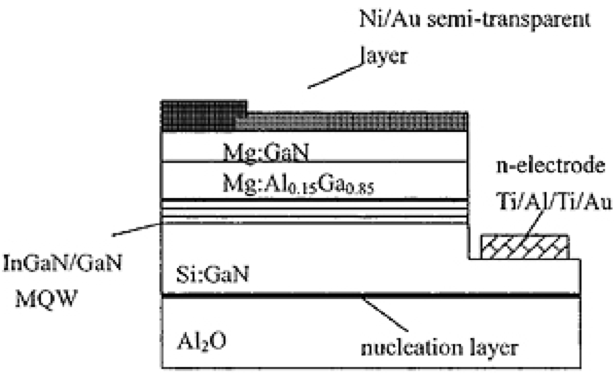

Fig. 1(a). Schematic structure of InGaN–GaN MQW LED.

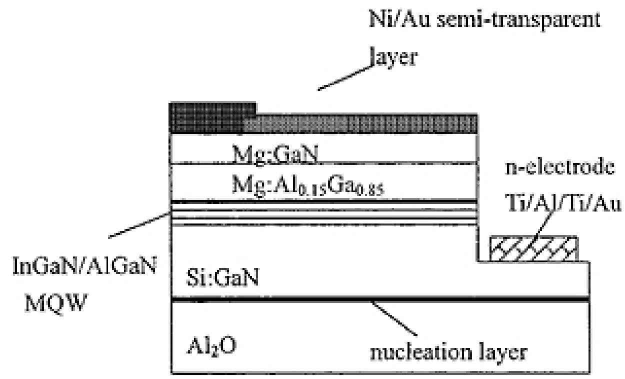

Fig. 1(b). Schematic structure of InGaN– AlGaN MQW LED used in this study.

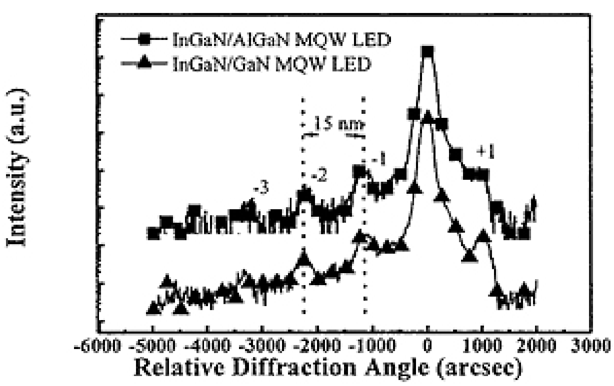

Fig. 2. DCXRD spectra of these two LEDs with different barrier layers.

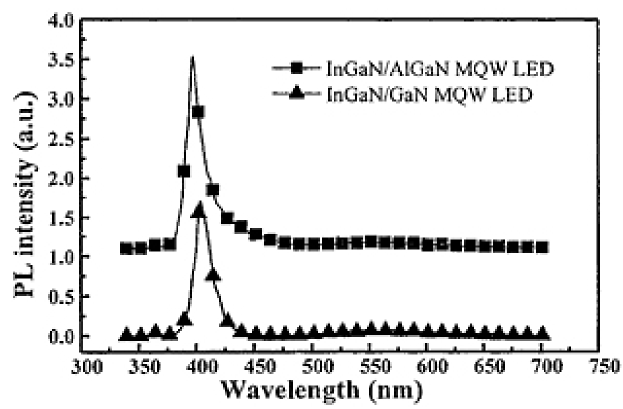

Fig. 3. RT PL spectra of the MQW LED structures with AlGaN and GaN barrier layers.

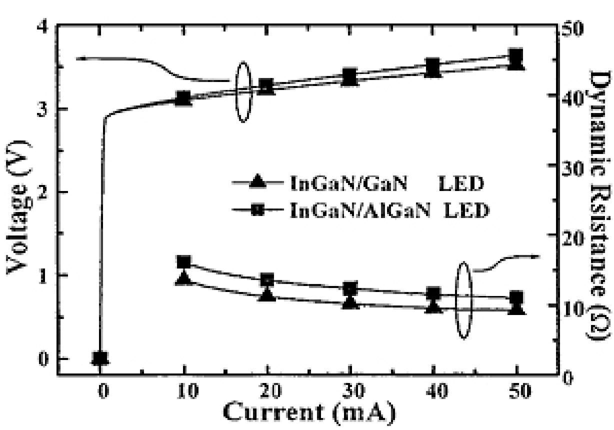

Fig. 4. Forward I–V and dynamic resistance characteristics of the two different types of MQW LEDs.

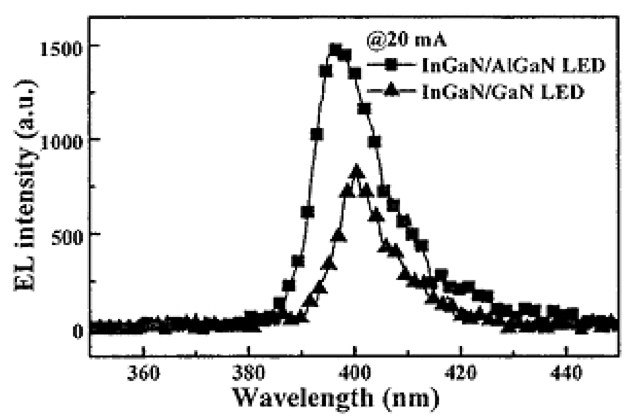

Fig. 5. RT EL spectra of the two different types of MQW LEDs with a 20-mA DC injection current.

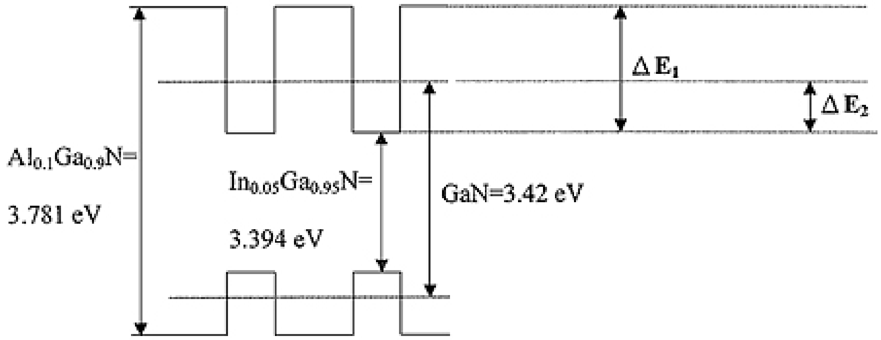

Fig. 6. Energy band diagram of $In_{0.05}Ga_{0.95}N$–GaN MQW structure and $In_{0.05}Ga_{0.95}N$–$Al_{0.1}Ga_{0.9}N$ MQW structure.

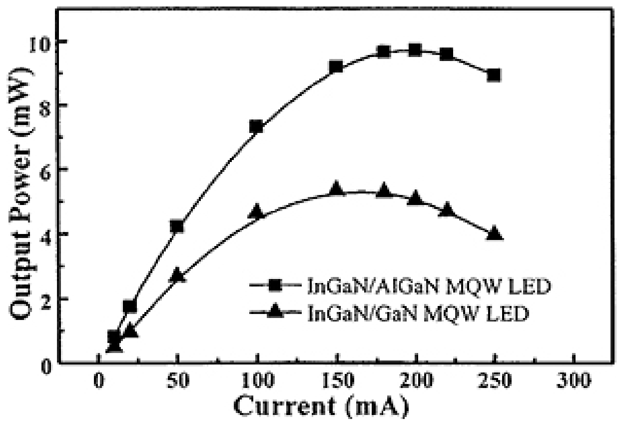

Fig. 7. Output power as a function of injection current for these two LEDs.

In summary, the 400-nm $In_{0.05}Ga_{0.95}N$–GaN MQW LED structure and $In_{0.05}Ga_{0.95}N$–$Al_{0.1}Ga_{0.9}N$ LED structure were both prepared by OMVPE. It was found that the use of Al Ga N as the material for barrier layers would not degrade crystal quality of the epitaxial layers. It was also found that the 20-mA EL intensity of InGaN–AlGaN MQW LED was two times larger than that of the InGaN–GaN MQW LED. The larger maximum output intensity and the fact that maximum output intensity occurred at larger injection current suggest that AlGaN barrier layers can provide a better carrier confinement and effectively reduce leakage current.

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