Effects of Temperature on InGaN/GaN LEDs with Different MQW Structures

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The temperature dependence of the emission performance of InGaN/GaN multiple-quantum well (MQW) light-emitting diodes (LEDs) with different configurations adjacent to the MQWs was investigated. For an LED with a p-AlGaN cladding layer above the top GaN barrier of the MQWs, the optical performance was increased and this may be due to a reduction in overflowing of electrons from the quantum wells compared to that of LED without this layer. In addition, as the temperature was increased, the decrease in output power for the LED with a p-AlGaN cladding layer was lower than for the LED without a p-AlGaN layer. As a result, for an LED with a p-AlGaN electron blocking layer, an improved carrier confinement results in less temperature sensitivity to the output power.

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Recently, GaN-based semiconductors have opened the way to the realization of high-efficiency blue light-emitting diodes (LEDs) and thus new application areas, such as solid-state lighting, full color displays, and biochemical sensors, have been developed. When LEDs are operated in these applications, the operating temperature generally fluctuates. The output performance of LEDs could vary as the temperature of the device changes, leading to a change in color due to light intensity fluctuation. Therefore, to make LEDs which can be efficiently used at high temperature, it is important to investigate the effect of temperature on performance of LEDs. In the study, the single-quantum well (SQW) was used as an active layer. When multiple-quantum wells (MQWs) were used for the active layer, the structural and optical qualities of the LEDs could be changed due to an increase in the strain between InGaN well and GaN barrier and, therefore, the performance of LEDs could change.

To investigate the temperature dependence of LEDs, we have studied the effect of temperature on the electrical and optical performance of LEDs with different In compositions in MQWs. We found that, for LEDs with a higher In composition in the MQWs, the output performance of an LED at room temperature increased with increasing In composition while the drop of output performance of LED was higher than that of LED with a lower In composition with increasing temperature. It was concluded that the defect density in the MQWs could influence significantly the output power of LED at higher temperature. It is generally known that the AlGaN cladding layer into the MQWs could be used to enhance the performance of LED. It is, therefore, important to investigate the effect of temperature on the performance of LEDs with an AlGaN cladding layer adjacent to the top GaN barrier of the MQW structure. In this paper, we report on the elevated temperature dependence of performance of InGaAsGaN LEDs with different MQW structures. It was found that the p-AlGaN cladding layer adjacent to the MQWs played an important role in increasing the output efficiency of LEDs at room and high temperatures. For an LED with a p-AlGaN cladding layer, the drop of output power was less than that of LED without this layer as the temperature was increased.

Experimental

All samples reported here were grown on c-plane sapphire substrates with a nominal 30 nm thick GaN buffer layer using low-pressure metalorganic chemical vapor deposition (MOCVD) in a rotating-disc reactor (Emcore D125). An undoped GaN layer was grown on GaN buffer layer, followed by a Si-doped GaN layer. The LED structure was composed of MQWs consisting of five periods of InGaN/GaN and followed by a Mg-doped GaN contact layer. The In composition in the MQWs was around 25%, which was determined by using photoluminescence (PL) and X-ray diffraction measurements. Two samples were prepared and only difference between these two devices was that one sample has a p-AlGaN cladding layer above the top GaN barrier layer of InGaN/GaN MQW structure. The Mg doping concentration in AlGaN layer measured by Hall effect method was around $1 \times 10^{17}$ cm$^{-3}$. Hall effect measurement using InZn alloy dots was carried out with the van der Pauw configuration. For simplicity, these two LEDs noted by LED A and LED B (with p-AlGaN cladding layer), respectively. Two unpackaged LEDs with a device size of 300 × 300 μm were fabricated using standard photolithographic technique, inductively coupled plasma etching, and E-beam evaporation. The detailed procedure for the fabrication process of these LEDs was described in Ref. 4. Current-voltage (I-V) curves were measured using a parameter analyzer (HP 4145A). The relative output power of the LEDs was measured using a photodiode system connected with an optical fiber. The temperature of the LEDs was varied by using a heat controller.

Figure 1. I-V characteristics of the LEDs with and without a p-AlGaN cladding layer above InGaN/GaN MQW structure.
Results and Discussion

Figure 1 shows the I-V curves of LEDs with and without a p-AlGaN cladding layer. For an LED with a p-AlGaN cladding layer, the forward voltage at a current of 20 mA was slightly increased compared to that of an LED without a p-AlGaN cladding layer. This slight increase in the forward voltage could be attributed to a high resistive p-AlGaN cladding layer and also a voltage drop at the heterojunction between GaN and AlGaN interface. In general, it is difficult to grow the p-AlGaN film with high Mg doping density to give a low resistivity p-AlGaN film. If lower resistivity AlGaN film doped with Mg could be grown, the forward voltage should be lowered.

Figure 2 shows the electroluminescence spectra for two LEDs at room temperature. The dominant emission peak wavelength for two LEDs at room temperature is around 480 nm. The peak position for LED B is slightly shorter than that of LED A even though the growth conditions for these two LEDs were same, as shown in Fig. 2a. This could be due to the fluctuation of growth conditions. When we grew several MQW samples under the same growth conditions, the MQW samples had little difference in In composition and/or well and barrier thickness between these samples. So we think that a small difference in EL peak position for these two samples was due to this reason. Figure 2b shows the variation of EL spectra as a function of the temperature. The peak positions for all LEDs shifted slightly toward longer wavelength as the temperature was increased. It is generally known that the bandgap energy of semiconductors should become smaller with increasing temperature. Then, the dominant peak wavelength should become longer with increasing temperature. Here, it can conclude that the small shift of peak wavelength is caused by the bandgap shrinkage effect. But the shift of wavelength of the LEDs was not so much, as shown in Fig. 2b. Hence, because of this, GaN-based semiconductors could be more suitable in high-temperature application than any other conventional III-V compound semiconductors.

Figure 3 shows the output power of the unpackaged two LEDs as a function of injection current at room temperature. The output power of the LEDs increased with increasing injection current. Compared to LED A, the output power of LED B showed a higher value through all injection current ranges. This could be due to the effect of the p-AlGaN cladding layer inserted above the MQWs. In nitride optical devices, such as LEDs and laser diodes (LDs), hole injection into the active layer is important for realization of high efficiency devices, because holes have lower mobility than electrons. In addition, it is difficult to grow good p-GaN and p-AlGaN with high hole density. When the p-AlGaN cladding layer is inserted above MQWs, the electron overflow from the active region could be lowered due to the potential barrier at the interface between GaN barrier and AlGaN layer caused by the difference in the bandgap energy. Based on this assumption, LED B with a p-AlGaN cladding layer showed a higher output power than LED B.

Figure 4 shows the normalized output powers and fitted lines of two LEDs as a function of the temperature at a constant current of 20 mA. The normalization of output powers was conducted by dividing the output power at room temperature. The output power from an LED is expressed by

\[ I_{\text{ph}}(T) = I_{\text{ph}}(0) \exp(-KT) \]  

where \( K \) is a temperature coefficient and \( I_{\text{ph}}(0) \) the optical power at room temperature, respectively. The \( K \) value for LED A is \( 1.6 \times 10^{-2} \text{ K}^{-1} \). Unlike LED A, LED B has two \( K \) values that depend on the temperature range, meaning that the drop of the output power depends largely on the temperature. The \( K \) value is \( 4.5 \times 10^{-4} \text{ K}^{-1} \) for the temperature range below 373 K and \( 6 \times 10^{-3} \text{ K}^{-1} \) for above 373 K, respectively. The output powers of these two LEDs decreased with increasing temperature, as shown in Fig. 4. With in-
creasing temperature, the carriers injected into the MQW active layers were more thermally excited than those at low temperature, resulting in a higher probability escaping the quantum well active region. This leads to a reduced recombination rate of electron-hole pairs in the MQWs. As a result, the output powers of two LEDs decreased with increasing temperature. Compared to LED A, the output power of the LED B decreased more slowly with increasing temperature, as shown in Fig. 4. This means that the output power of LED B with a p-AlGaN cladding layer above MQWs is less sensitive to the temperature than that of LED A without a p-AlGaN cladding layer. As discussed previously, the p-AlGaN cladding layer inserted above the MQWs could prevent electron flow from the MQW active region. When the temperature increased from room temperature, carrier confinement for LED B was better than for LED A due to a p-AlGaN cladding layer so that the probability for radiative recombination was enhanced. This improved confinement resulted in less temperature sensitivity to the output power of LED B. Although the output power of LED B dropped more slowly than that of LED A with increasing temperature, as shown in Fig. 4, the drop rate of output power of LED C at the temperature above 373 K started to increase. This result could be attributed to an increased probability for carriers to escape the quantum-well region because the carriers could have a thermal energy that helps those carriers overcome the potential barrier as the temperature was increased above 373 K. In addition, with increasing temperature, the number of carriers recombining nonradiatively through the defect centers created in the multiple-quantum well during the growth could increase due to an increased defect assisted tunneling, resulting in a decrease in radiative recombination in the quantum well. Based on these facts, optimal electron blocking layer and quantum well designs should be needed to achieve a high LED efficiency when using GaN-based semiconductors.

Conclusions

We have investigated the temperature dependence of the performance of InGaN/GaN LEDs with different MQW configurations. The light output power for an LED with p-AlGaN cladding layer at room temperature was higher than for an LED without this layer. The output power for an LED with a p-AlGaN electron blocking layer above the MQWs dropped more slowly than that of LED without this layer due to a reduction in overflowing electrons from quantum well active region. This result could be attributed to increased radiation recombination in the active region due to better carrier confinement for the p-AlGaN cladding layer.

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References