Gradient Doping of Mg in p-Type GaN for High Efficiency InGaN–GaN Ultraviolet Light-Emitting Diode

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Abstract—The performance of an InGaN–GaN multiple quantum-well (MQW) ultraviolet (UV) light-emitting diode (LED) with an emission of 385 nm was enhanced by a gradient doping of Mg in the p-GaN layer. The optical output power was enhanced by 21% at an input current of 20 mA compared to that of a UV LED with a uniformly doped p-GaN layer. The improved performance of the UV LED could be attributed to the decrease in diffusion of Mg into MQW and the suppression of electron transport from the conduction band of the MQW to the acceptor level of the deep donor acceptor pair bands in the p-GaN layer by a gradient doping of Mg in p-GaN layer.

Index Terms—Doping, (In)GaN, light-emitting diode (LED), near ultraviolet (UV).

I. INTRODUCTION

Ultraviolet (UV) light-emitting diodes (LEDs) and laser diodes are very important devices in the application of solid-state lighting, biochemical detection, and lithography. To produce a high brightness GaN-based LED, one of the most important issues is an efficient current injection into the LED through the p-GaN layer. Therefore, most studies of the p-GaN layer have been mainly focused on the improvement in conductivity and hole concentration of the p-GaN layer to lower the resistivity of p-type ohmic contact [1]–[8]. However, the effect of distribution of Mg dopant in the p-GaN layer on the internal quantum efficiency of UV LEDs has not been investigated. The Mg diffuses to the QW during the growth of p-GaN layer, resulting in a decrease of the emission efficiency of multiple quantum-well (MQW) because the Mg can act as the nonradiative recombination center [9]. In addition, the nonradiative transition of carriers from the conduction band of MQW to an acceptor level of the deep donor acceptor pair bands in the p-GaN, resulting in a further decrease in the quantum efficiency of the UV LED.

In this study, we report on an investigation of the gradient doping of Mg in p-GaN in a UV LED to suppress the diffusion of Mg into MQW and the nonradiative transition of carriers between the conduction band of the MQW and the acceptor level of the DDAP bands in the p-GaN: Mg layer.

II. EXPERIMENT AND RESULT

The In$_{0.05}$Ga$_{0.95}$N–GaN MQW UV LED samples were grown on a (0001) sapphire substrate by metal–organic chemical vapor deposition. The substrates were initially treated in H$_2$ at 1050 °C, followed by the growth of a 25-nm-thick low-temperature GaN buffer layer at 550 °C. After high-temperature annealing of the buffer layer, a 2-μm-thick undoped GaN layer and a 2-μm-thick n-GaN layer were deposited at a temperature of 1040 °C. The InGaN–GaN MQWs were subsequently grown at a low temperature of 800 °C, consisting of five periods of 8-nm GaN barriers and 2-nm InGaN wells. The last InGaN QW was capped with a 12-nm-thick undoped GaN barrier layer. Finally, a 0.25-μm-thick p-GaN layer with a hole concentration of $3 \times 10^{17}$ cm$^{-3}$ and hole mobility of 5 cm$^2$/V·s was grown on the MQW at the temperature of 980 °C. To confirm the effect of Mg diffusion into MQW, the thickness of p-GaN layer was varied from 0.1 to 0.25 μm. To study the tunneling of electrons from the conduction band of MQW to the acceptor level of the DDAP bands in the p-GaN, the UV LED structures were grown using a p-GaN layer in which the Mg concentration was gradually increased across the p-GaN layer. To measure hole concentration and mobility of p-GaN layer, we prepared 0.1-μm-thick p-GaN: Mg samples which were uniformly doped by Mg dopant on the 2-μm-thick insulating undoped GaN layer. We performed the Hall effect measurement using the van der Pauw method at room temperature to measure the hole concentration in p-GaN: Mg. The detailed procedure for the fabrication of LEDs with a size of $300 \times 300 \mu$m$^2$ has been published elsewhere [11].

Fig. 1 shows the electroluminescence (EL) spectra of the UV LEDs as a function of the thickness of the p-GaN layer with a hole concentration of $3 \times 10^{17}$ cm$^{-3}$ at the input current of 20 mA. The UV light is decreased with increasing the thickness of the p-GaN layer. The decrease in the UV emission can be explained in two ways. First, the Mg can diffuse to the MQW during the growth of p-GaN layer, resulting in a significant decrease of the emission efficiency of MQW because the Mg acts as the nonradiative recombination center [9]. The emission intensity of MQW is further degraded by the diffusion of Mg deep into MQW with increasing the thickness of p-GaN layer.
Second, the UV light emitted from MQW can be absorbed by the DDAP bands of the p-GaN layer. As shown in the inset of Fig. 1, the photoluminescence (PL) spectrum of the p-GaN layer shows that the energy gap of the DDAP band in the p-GaN layer is 413 nm (3.0 eV) indicating that the UV light can be absorbed by the DDAP band of the p-GaN layer. The absorption coefficient of the p-GaN layer at the emission of 3.22 eV is about 600 cm$^{-1}$ and the transmittance of UV emission with p-GaN thickness of 100, 170, and 250 nm is estimated to be 99.4%, 98.9%, and 98.5%, respectively. This result shows that the absorption of UV light in p-GaN is very low and this is not the main reason for the large decrease of EL emission with increasing the thickness of p-GaN, as shown in Fig. 1. Therefore, the decrease of EL emission intensity with increasing the thickness of the p-GaN layer is attributed mostly to the Mg diffusion into MQW.

The Mg concentration in the 0.1-m-thick gradually doped p-GaN:Mg layer (GD p-GaN) and uniformly doped p-GaN:Mg layer (UD p-GaN) were measured by secondary ion mass spectrometry (SIMS). Fig. 2 compares the Mg concentrations in two samples as a function of the film depth of the p-GaN layer. The flow rate of biscyclopentadienyl magnesium (Cp$_2$Mg) was linearly increased for GD p-GaN and the Cp$_2$Mg flow rate was kept constant for UD p-GaN with increasing the thickness of the p-GaN layer. Fig. 2 clearly shows that Mg concentration in the GD p-GaN is gradually increased across the p-GaN layer while that of a UD p-GaN is same across the p-GaN layer. Fig. 2 also shows that Mg atoms in the UD p-GaN diffuse into MQW and the 12-nm-thick GaN barrier layer is slightly p-doped by Mg in the LED with UD p-GaN while the GaN barrier layer is not doped by Mg in the LED with GD p-GaN.

We measured the temperature-dependent PL intensity to determine the carrier loss from the conduction band of the MQW to the acceptor level of the p-GaN layer. Fig. 3(a) shows that the integrated PL intensities of UV LEDs with GD and UD p-GaN are quenched with increasing temperature in the range from 10 K to 140 K. The quenching of PL intensity with increasing the temperature can be attributed to the escape of carriers from the quantum well by thermal energy with increasing temperature. It is noted that as shown in Fig. 3(a), the integrated PL intensity from the LED with GD p-GaN slowly decreases as the temperature is increased from 10 K to 140 K compared to that for the LED with UD p-GaN. This result indicates that another mechanism besides the quenching by thermal energy is responsible for the difference in the reduction of PL intensities since both LEDs have the same MQW structure. The slow decrease of PL intensity of the LED with GD p-GaN can be attributed to the lack of the carrier transition from the conduction band of MQW to the acceptor level in the DDAP bands of the GaN barrier layer and the decrease in the carrier transition from the conduction band of MQW to the acceptor level of the DDAP bands in the p-GaN layer due to the decrease in density of Mg in the p-GaN layer compared to the LED with UD p-GaN, as shown in Fig. 3(b) and (c). It has been reported that the acceptor level of the DDAP bands in the p-GaN layer is in the range of 215–350 meV from the valance band depending on the Mg-doping concentration [13]. In our UV LEDs, the valance band offset between the In$_{0.15}$Ga$_{0.85}$N QW and GaN barrier layer is 34 meV, assuming that offset ratios of conduction bands and valence bands are approximately 80% and 20% [14]. This indicates that the acceptor level of the DDAP bands is higher than the valance band offset in the InGaN QW and that electrons in the conduction band of the MQW can non-radiatively recombine the holes in the acceptor level of DDAP bands in the GaN barrier layer and the p-GaN layer, as shown.
with GD p-GaN was increased by 21% compared to that of a UV LED with UD p-GaN at an input current of 20 mA, as shown in Fig. 4(b). This improvement in the optical output power of UV LED with GD p-GaN is believed to be due to the reduction in carrier transition from the conduction band of the MQW to the lowered acceptor level in the DDAP bands in p-GaN:Mg layer and the decrease in diffusion of Mg into MQW.

III. SUMMARY AND CONCLUSION

The effect of the gradient doping of Mg in the p-GaN layer on the performance of a UV LED with an emission of 385 nm was investigated. The UV LED with GD p-GaN showed that output power were significantly enhanced compared to a UV LED with UD p-GaN. These results were attributed to the reduction of diffusion of Mg into MQW and a decrease in the carrier transition from the conduction band of the MQW to the acceptor level of the DDAP band in the p-GaN:Mg layer.

REFERENCES