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Investigation of Efficiency Droop for UV-LED with N-type AlGaN Layer

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1. Introduction

Recently, the GaN-based ultraviolet light emitting diodes (UV-LEDs) have been focused on as one of the most important targets for the pumping source to develop white-light LEDs. However, as the efficiency of LEDs increasing, the most challenging obstacle is the efficiency “droop” for high-power applications [1-2]. The external quantum efficiency (EQE) reaches its peak at current densities as low as 10 A/cm^2 and monotonically decreases with further increase in current. It means that the efficiency reduces rapidly when the LED driving under high carrier density. Besides, most of the light will be trapped inside the GaN-based LED, resulting in the low light extraction efficiency [3]. Once the light trapped inside, the LED will be reabsorbed eventually. Consequently, self-heating effect will occur and lead to a drop in the quantum efficiency. Naively, one would assume that a semiconductor can absorb light only if the photon energy is larger than the bandgap energy and that the semiconductor is transparent for photon energy below the bandgap. By Urbach tail law, semiconductor indeed absorbs below-bandgap light even though the absorption coefficient is small [4]. From energy point of view, the light is transform to thermal energy, which will influence on the performance of LED device. In this study, we proposed to remove the conventional n-type GaN below InGaN multi-quantum-wells (MQWs) and replaced it with an n-type $Al_{0.03}Ga_{0.97}N$ to improve the optical performance in the UV GaN LEDs.

2. Experiment

The samples in this study were grown on c-plane 2” sapphire substrates by metalorganic chemical vapor deposition (MOCVD) system. The metallorganic compounds of trimethylgallium, trimethylaluminum, trimethylindium and ammonia (NH_3) were employed as the source materials of Ga, Al, In, and N, respectively. Silane and bis-cyclopentadienyl magnesium (Cp_2Mg) were used as the sources for n-type and p-type dopants. Prior to the growth, the sapphire substrates were thermal cleaned in hydrogen ambient at 1100°C. The UV-LED structure with InGaN/AlGaN multi-quantum-well (MQW) is composed of a 30-nm-thick low-temperature (500°C) GaN nucleation layer (GaN NL), a 2-um-thick undoped GaN epilayer (u-GaN), a 2-um-thick Si-doped n-layer, an InGaN/AlGaN multiple quantum wells (MQWs) active layer, a 15-nm-thick Mg-doped AlGaN electron blocking layer (p-AlGaN) and a 0.2-um-thick Mg-doped GaN contact layer (p-GaN). In this study, Si-doped GaN and Si-doped $Al_{0.03}Ga_{0.97}N$ n-type layer were grown and denoted as LED-A and LED-B, respectively. After growth, the LED fabrication processes of UV-LED are the same. Temperature dependent photoluminescence (PL) was used to determine internal quantum efficiency (IQE). Electrical and optical characteristics were measured by electroluminescence (EL).

3. Results and Discussion

Fig. 1 shows the dependence of the IQE of LED-A and LED-B as a function of injected carrier density at 15K and 300K, respectively. As the excitation energy increases, the IQE of LED-A is usually higher than that of LED-B at 300K. The experimental results demonstrated that the IQE are 43% and 39% at a injected carrier density of 8.5×10^{17} #/cm^3, respectively [5], owing to the crystal quality of n-GaN is better than that of n-AlGaN. In addition, the observation of pit density of atomic force microscopy (AFM) morphology (not shown here) is consistent. It is well-known that the pits appearing on the surface in the virtue of the threading dislocations. Thus, it means that defect-induced non-radiative centers deteriorated IQE of LED with n-AlGaN layer.

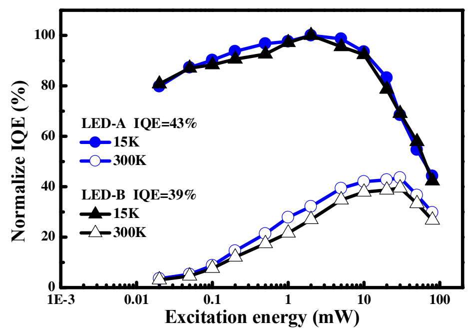

Fig. 1 The IQE of LED-A and LED-B as a function of excitation power at 15K and 300 K

Fig. 2 shows the injection current versus voltage (I-V) characteristics of the both LEDs. At a forward current of 350 mA, the forward voltage is 3.97 and 3.92 V for LED-A and LED-B, respectively. The (I-V) characteristics of both are almost the same. The light output power versus injection current (L–I) characteristics of both UV-LEDs are also shown in Fig 2. The light output powers are 60mW and 63mW with the injection current at 350 mA for LED-A and LED-B, respectively. The light output powers are quite similar for both LEDs at 350 mA. However, when the injection current is increased to 600 mA, the output power of LED-B is much better than LED-A. The light output power for LED-A and LED-B are 70 mW and 86 mW, individually. There is 22% enhancement in LED-B compared to LED-A at 600mA. This indicates that LED-B has higher efficiency at high injection current.

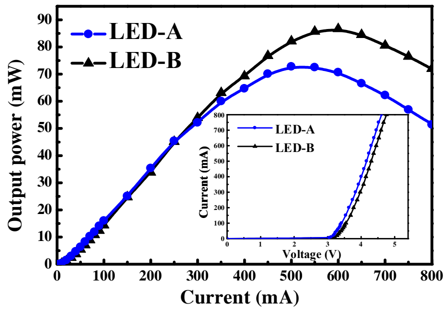

Fig. 2 Injection current versus voltage and the light output power versus injection current characteristics for LED-A and LED-B

As a matter of fact, the self-absorption of emitting light in LEDs will be generated to become heat, which means that the performance of LEDs will deteriorated. Fortunately, the larger band gap of $Al_{0.03}Ga_{0.97}N$ can significantly suppress the self-absorption effect in LEDs. Fig. 3 depicts the variation of the emission peak versus injection current characteristics of these UV-LEDs. It can be seen that the initially peaks of both UV-LEDs are located at about 380 nm, and it shows the red shift with increasing current. However, the red shift magnitude of LED-A (6.6nm) is larger than LED-B (4.3nm). As the injection current increases, the temperature of junction increases. This phenomena is more serious in LED-A than in LED-B. The junction temperature of both two LEDs evaluates that the difference between LED-A and LED-B increases with the increasing current (not shown here). In addition, the full width at half maximum (FWHM) of both UV-LEDs increase with increasing current, and the FWHM variations of LED-A and LED-B are 4.5 nm and 2.6 nm, respectively. In previous studies, it has been reported that self-heating of LED leads to the broadening of FWHM and red shift [6]. Thus, these results indicate that the self-heating phenomenon of LED-A is much serious than LED-B. Furthermore, it was confirmed by using junction temperature analyses (not shown here), which showed that the differentials in temperature between n-type $Al_{0.03}Ga_{0.97}N$ and n-type GaN will increase with the higher operation current. This indicates that the droop effect issue has been improved in ultraviolet LEDs.

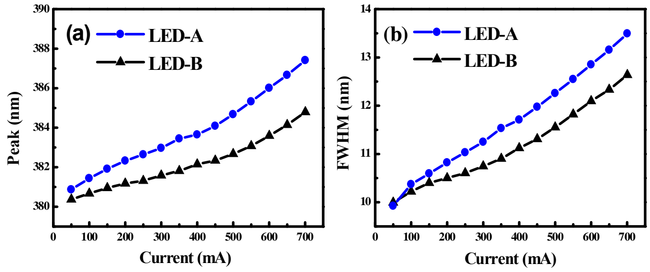

Fig. 3 (a) Peak shift and (b) FWHM versus injection current for LED-A and LED-B

4. Conclusions

In this paper, we used n-type $Al_{0.03}Ga_{0.97}N$ to replace the conventional n-type GaN below MQWs to improve the optical performance in 380nm UV-LEDs. From AFM and IQE measurement, it revealed that the crystal quality of the UV-LED with n-GaN is slightly better than UV-LED with n-AlGaN. Therefore, the light output power of UV-LED with n-GaN was slightly higher below 250 mA. Nevertheless, the output power was enhanced about 22% as the injection current was increased to 600 mA. Furthermore, the EQE was nearly retained in UV-LED with n-AlGaN at the 600 mA (only 20% droop), whereas the UV-LED with n-GaN exhibit as high as 33%. By Urbach tail law, the enhancement may be attributed to the less self-absoption by n-AlGaN. In short, the use of the n- $Al_{0.03}Ga_{0.97}N$ to replace the n-GaN in 380nm UV-LED is suggested to be effective for enhancing the output power at the high injection current.

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