Improved performance of 375 nm InGaN/AlGaN light-emitting diodes by incorporating a heavily Si-doped transition layer

Shih-Cheng Huang,[a, e] Kun-Ching Shen,[a] Po-Min Tu,[b] Dong-Sing Wuu,*[a, d]
Hao-Chung Kuo,[b] and Ray-Hua Horng[c]
[a] Department of Materials Science and Engineering, National Chung Hsing University, Taichung 40227, Taiwan, ROC
[b] Department of Photonics and Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu 30010, Taiwan, ROC
[c] Department of Electro-Optical Engineering, National Cheng Kung University, Tainan 70101, Taiwan, ROC
[d] Department of Materials Science and Engineering, Da-Yeh University, Changhua 51591, Taiwan, ROC
[e] Advanced Optoelectronic Technology Inc., Hsinchu 30352, Taiwan, ROC

ABSTRACT

High performance 375-nm ultraviolet (UV) InGaN/AlGaN light-emitting diodes (LEDs) was developed using a heavy Si-doping technique with metalorganic chemical vapor deposition (MOCVD). From the transmission electron microcopy (TEM) image, the dislocation density was reduced after inserting a heavily Si-doping growth mode transition layer (GMTL) between un-doped GaN layer and Si-doped $Al_{0.02}Ga_{0.98}N$ contact layer. The internal quantum efficiency (IQE) of the sample with GMTL measured by power-dependent photoluminescence shows 39.4% improved compared with the sample without GMTL. When the vertical type LED chips (size: 1mm×1mm) driving by a 350-mA current, the output powers of the LEDs with and without GMTL were measured to be 286.7 mW and 204.2 mW, respectively. As much as 40.4% increased light output power was achieved. Therefore, using the GMTL to reduce dislocation defects would be a promising prospective for InGaN/AlGaN UV LEDs to achieve high internal quantum efficiency.

Keywords: Light emitting diodes, Si-doping

*dsw@dragon.nchu.edu.tw; phone: 886-4-22840500 ext. 714; fax: 886-4-22855046

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1. INTRODUCTION

Recently, group III nitride-based ultraviolet (UV) light emitting diodes have attracted great attention because of the promising potential to replace conventional mercury-contained lamps for some applications including UV sensing, curing and photocatalysis. The UV LED can also be used as a pumping source for developing white-light LEDs to solve the low color-rendering-index problem which made by the combination of an yttrium-aluminum-garnet phosphor wavelength converted with a blue InGaN LED chip [1]. All of these applications require high performance UV emitters especially for the light output power. It is well known that high efficiency radiative recombination in blue and green InGaN multiple quantum wells LEDs has been mainly attributed to the localized states due to phase separation or fluctuations in the indium mole fraction in the InGaN/GaN quantum wells. However, the InN mole fraction in active region of InGaN based UV LEDs is much lower than blue or green LEDs, so the radiative efficiency of UV LEDs is more sensitive to the defect density.

Generally, dislocations normally act the non-radiative centers in the light emitting devices. Unfortunately, the dislocation density is as high as the level of 10^9-10^{10} per square centimeter when the nitride materials are grown on lattice mismatched substrates. Therefore, how to further reduce the dislocation density is the most important task to fabricate the high-performance UV LEDs. Several approaches have been implemented to reduce the dislocation density in the GaN LEDs [2-6]. In this study, we report a novel in-situ growth mode transiting technique to improve the internal quantum efficiency (IQE) of UV InGaN/AlGaN LEDs.

2. EXPERIMENTIAL PROCEDURE

All samples used in this study were grown on 2” c-plane sapphire substrates by metalorganic chemical vapor deposition (MOCVD) system. Trimethylgallium, trimethylindium, trimethylaluminum, and ammonia (NH_3) were employed as the reactant source materials for Ga, In, Al, and N, respectively. Bicyclopentadienyl magnesium and silane were used as the p-type and n-type doping sources, respectively. Prior to the growth, the sapphire substrates were thermal cleaned in hydrogen ambient at 1100°C. The InGaN/AlGaN multi-quantum-well (MQW) LED structure consists of a low-temperature (500°C) 30-nm-thick GaN buffer layer, a 2-μm-thick un-doped GaN layer, a 50-nm-thick heavily Si-doped growth mode transition GaN layer (GMTL), a 2.5-μm-thick Si-doped $Al_{0.02}Ga_{0.98}N$ contact layer, an

InGaN/AlGaN MQW active region, a 15-nm-thick Mg-doped AlGaN cladding layer, and a 0.2-μm-thick Mg-doped GaN contact layer. The InGaN/AlGaN MQWs active region consists of ten periods of 3-nm-thick $In_{0.03}Ga_{0.97}N$ well layers and 11-nm-thick $Al_{0.06}Ga_{0.94}N$ barrier layers. The doping concentration of Si-doped $Al_{0.02}Ga_{0.98}N$ contact layer and GMTL is 4.5×10^{18} cm^{-3} and 1.2×10^{20} cm^{-3} which can be controlled by the silane flow rate. In addition, similar UV-LED structure without the GMTL was also grown for comparison.

The distribution and bending behavior of threading dislocations (TDs) were observed by transmission electron microscopy (TEM). The surface morphologies of the as grown GMTL and Si-doped $Al_{0.02}Ga_{0.98}N$ contact layers with different overgrowth times on the GMTL were examined by scanning electron microscopy (SEM). The power and temperature dependent photoluminescence (PL) measurements were carried out using a frequency-tripled Ti:sapphire laser with an emission wavelength of 266-nm. Finally, the LED wafers were processed into vertical type chips (size: 1mm×1mm). The LEDs chips with and without GMTL were marked as G-LEDs and C-LEDs, respectively. The light output-current (L-I) characteristics of the LED devices were measured by integrating sphere detector and Keithley 2400 at room temperature.

3. RESULTS AND DISCUSSION

Fig. 1 shows the power-dependent IQE as a function of injected carrier density at 20 K and room-temperature (RT) for both C-LED and G-LED. The IQE is defined as the collected photon numbers divided by the injected photon numbers and normalized to the maximum efficiency achieved at 20 K. For the two LEDs, the IQE curves are very similar at 20 K. At low excitation carrier density ($< 10^{16}$ cm^{-3}), the IQE increase may be attributed to the saturation of nonradiative recombination centers by photo-generated carriers. It seems that the nonradiative centers still influence the efficiency at low-temperature. Moreover, the IQE decreases with a further increase in the excitation carrier density ($> 10^{16}$ cm^{-3}). This phenomenon is quite similar to “efficiency droop”, the gradual decrease of the power efficiency of LEDs as the injection current increases. Although several mechanisms for explaining the efficiency droop have been reported, including carrier leakage and carrier overflow, direct or indirect Auger recombination, defects (or dislocations) [7] mains unclear. According to our experimental data, we infer that the low-temperature IQE decrease at high excitation carrier density is due to the carrier overflow and dislocation density, which is further discussed in Fig. 2. As the temperature increases to RT, the significant IQE reduction was attributed to nonradiative recombination at defects and dislocations. In addition, the rise rate of the IQE with increasing excitation carrier density in G-LED is faster than in C-LED. This is because the influence of nonradiative recombination was greatly diminished by reducing the TDs using GMTL. The IQE of G-LED was enhanced by 40.6 % compared to that of C-LED. Furthermore, it was observed the IQE droop degree in G-LED at RT is relatively slow in C-LED. It may allow us to attribute the effect of TDs in efficiency droop: at low-temperature, the contribution of dislocations to the IQE droop is weak, and another factor such as carrier overflow is dominant at high excitation carrier density; at room-temperature, the droop efficiency involved with the dislocation contribution leads to a more severe droop trend, which can be suppressed by using low dislocations G-LED.

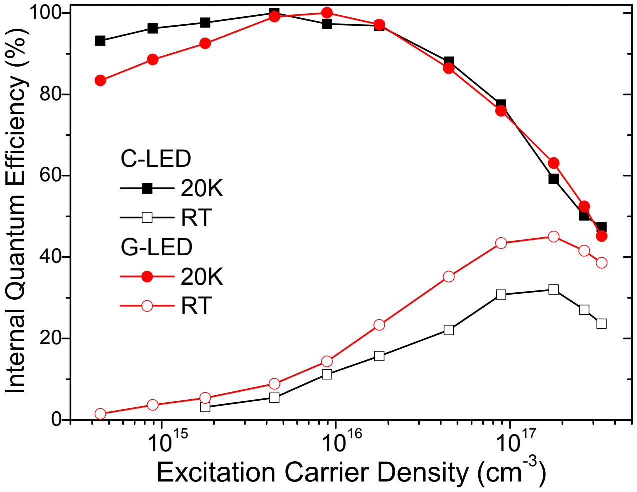

Fig. 1 Internal quantum efficiency of LEDs at 20 K and RT as a function of excitation carrier density.

Fig. 2 shows the PL spectra of G-LED at 20 K under three different excitation carrier densities. At an excitation carrier density over 10^{16} cm^{-3}, a shoulder peak at 380 nm appears in the spectrum and the intensity proportion of the shoulder peak over the main peak gradually increases as excitation carrier increases. The shoulder peak was attributed to the electron overflow into *p*-AlGaN at high carrier density [8]. Likewise, increased carrier density, which reveals the 380 nm peak, corresponds to the onset of efficiency droop (Fig. 1). It indicates that the carriers generated by high excitation exceed the recombination ability in the QW and overflow to *p*-AlGaN layer, emitting 380 nm wavelength photons. Moreover, in contrast with RT, there is no extra peak in PL spectra of G-LED even at high excitation intensity, as shown in the inset of Fig. 2. A similar PL spectrum also occurs in C-LED at 20K and RT. To summarize, the GMTL leads to the superior IQE performance of G-LED not only by decreasing carrier consumption at nonradiative recombination centers but also by partially mitigating the efficiency droop tendency.

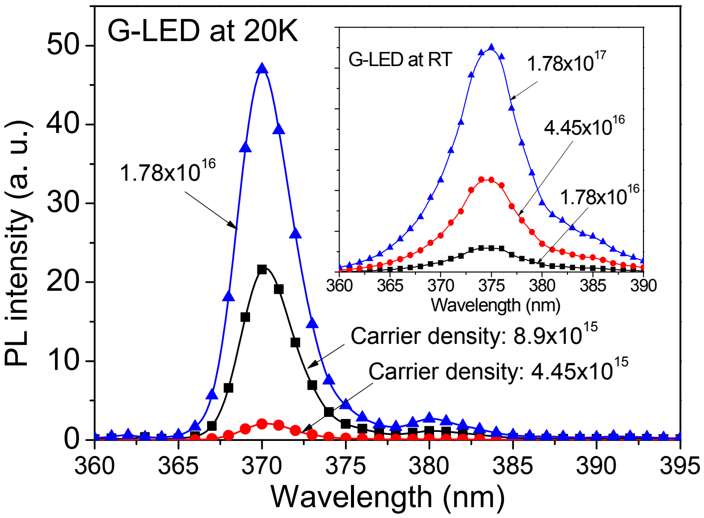

Fig. 2 PL spectra of G-LED with three different excitation carrier densities at 20 K. In the inset, PL spectra of G-LED with three different excitation carrier densities at RT.

Fig. 3 illustrates the I-V characteristics of both UV-LEDs. With an injection current of 350 mA, the forward voltages were almost the same for both UV-LEDs. However, for the reverse-bias case with a reverse voltage of 5.0 V, the reverse currents were 0.005 and 0.048 μA for G-LED and C-LED, respectively. The inset of Fig. 6 shows the reverse-bias I-V characteristics of the C-LED and G-LED. This significant improvement is suggested to be originated from the suppression of leakage current due to the reduction of TDs as discussed above.

Fig. 4 presents the electroluminescence light output power as a function of injection current for both of C-LED and G-LED. Here all chips were Au-wire bonded and packaged using the epoxy-free metal can (TO-66). Clearly, the light output power of the G-LED is much higher than the C-LED over the injection current range of 0 to 1000 mA. When the vertical-type LED chips was driven with a 350 mA injection current, the output power of the LEDs with and without GMTL were measured to be 286.7 and 204.2 mW, respectively. In particular, the light output power of G-LED is enhanced by a factor of approximately 40.4% at an injection current of 350 mA. The inset in Fig. 7 shows the photograph of the vertical-type G-LEDs chip lighting on.

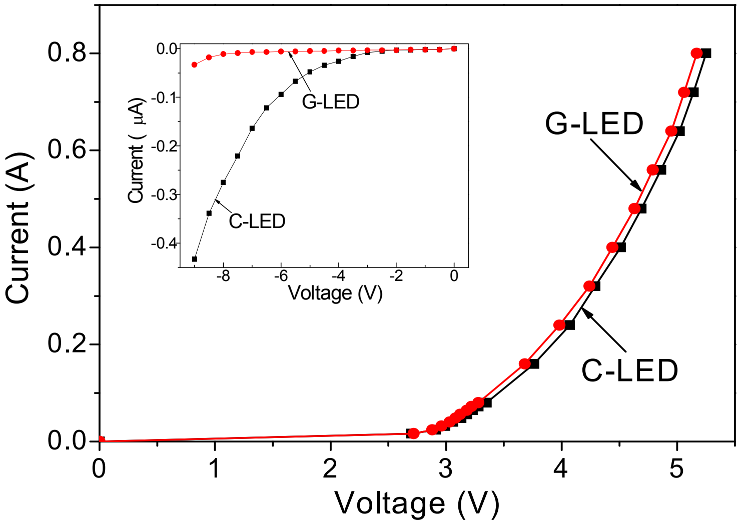

Fig. 3 Forward-bias I-V characteristics of the C-LEDs and G-LEDs. The inset shows the reverse-bias I-V characteristics of the C-LEDs and G-LEDs.

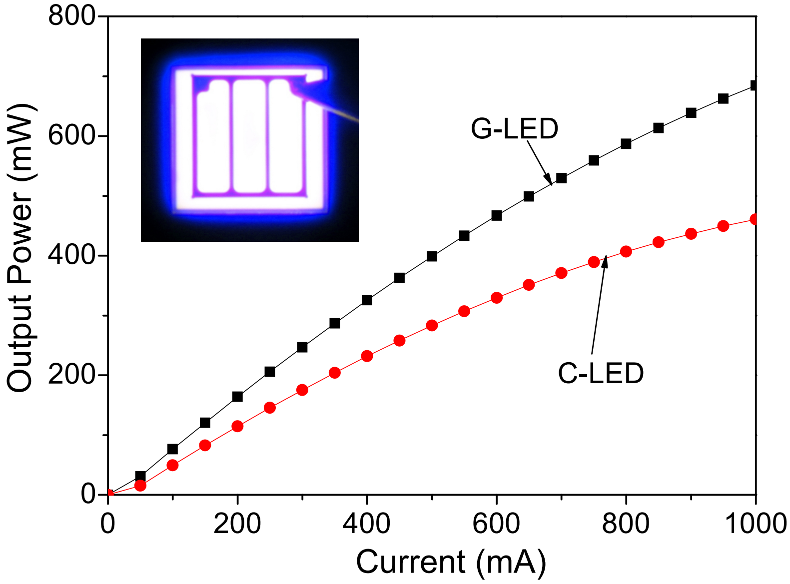

Fig. 4 LED output power as functions of injection current of G-LED and C-LED. In the inset, photograph of the G-LEDs chip lighting on at 350 mA.

4. SUMMARY

High-quality UV-LED was successfully fabricated by MOCVD system by inserting the GMTL between un-doped GaN and Si-doped $Al_{0.02}Ga_{0.98}N$. Cross-sectional TEM observations revealed that the TDD in the Si-doped $Al_{0.02}Ga_{0.98}N$ layer was reduced effectively. As a result, the reverse-bias current of the LED with GMTL was much smaller than that of the LED without GMTL. Meanwhile, the relative light output power was found to be enhanced by a factor of approximately 40.4% at an injection current of 350-mA. Based on the results obtained, the use of the GMTL is suggested to be effective for elevating the quality of GaN-based UV emitters.

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