Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials, Tokyo, 2010, pp411-412

Reduction in efficiency droop in InGaN/GaN MQWs light-emitting diodes grown on free standing GaN substrate

Ching-Hsueh Chiu[1], C. L. Chao[1,2], Da-Wei Lin[1], Zhen-Yu Li[1], Hao-Chung Kuo[1*], Tien-Chang Lu[1], Shing-Chung Wang[1]

[1]Department of Photonics and Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu 30010, Taiwan

[2]Electronics and Opto-electronics Research Laboratories, Industrial Technology Research Institute, Hsinchu 31040, Taiwan

[*]hckuo@faculty.nctu.edu.tw

1. Introduction

The wide band gap GaN-based semiconductors have attracted much attention for practical application, such as short-haul optical communication, traffic and signal lights, backlights for liquid-crystal displays, and daily lightings. Typically, GaN-based light emitting diodes (LEDs) was grown on sapphire and SiC substrate by heteroepitaxial techniques, such as metal-organic chemical vapor deposition (MOCVD) [1-3]. However, the low thermal conductivity and insulating properties make sapphire less perfect as a substrate for the growth of GaN epilayers. Unfortunately, a major issue in the production of blue-violet optoelectronic devices is the lack of a readily available substrate for the growth of GaN films of high crystallographic quality. Although several attempts have been made to solve this problem, the most promising approach is to seed a free-standing (FS) GaN substrate from a sacrificial substrate. In this paper, we grow GaN-based LED structure on FS GaN substrate successfully. The LEDs fabricated on the FS GaN template exhibited smaller blue shift (1.2 nm) in emission peak wavelength of electroluminescent spectrum, which demonstrated an enhancement in the light output and reduction in efficiency droop at high inject current compared with the conventional LEDs.

2. Experiment and Discussion

Figures 1(a) and 1(b) show the picture of sapphire and free-standing GaN substrate, respectively. In Fig. 1(b), a complete 2 in. self-separated FS GaN substrate was demonstrated. Detailed of the HVPE process was reported elsewhere[?]. Following HVPE growth, we deposited a GaN-based LED structure on the FS GaN template by MOCVD system. In addition, the same GaN-based LED structure was also grown on planar sapphire for comparison (denoted as conventional LEDs).

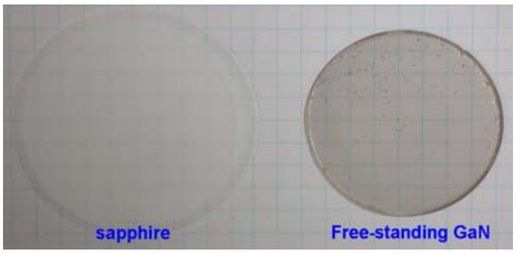

Fig. 1 A pictures of sapphire and free-standing GaN. No cracks in the FS-GaN.

During the growth, trimethylgallium (TMGa), trimethylindium (TMIn) and ammonia (NH_3) were used as gallium, indium, and nitrogen sources, respectively. Silane (SiH_4) and biscyclopentadienyl magnesium (CP_2Mg) were used as the *n*-dopant and *p*-dopant source, respectively. The epitaxial structure of both samples was as follows, consisting of 30-nm GaN nucleation layer (GaN NL), 1-µm *un*-doped GaN (*u*-GaN), 3-µm *n*-doped GaN (*n*-GaN), 8-pairs InGaN/GaN multi-quantum wells (MQWs), and 0.15-µm *p*-doped GaN (*p*-GaN) cap layer.

Figure 2 (a) and (b) shows optical morphology images of GaN-based LED structure grown on sapphire and FS GaN substrate, respectively. The LED on sapphire exhibits a lot of hexagonal hillocks, as shown in Fig. 2 (a). The GaN films grown on sapphire were found that the occurrence of inversion domain leads to the three-dimensional pyramidal growth as result of the polarity dependence of the growth rate. The inversion domain consists of material of Ga-polarity, which grows faster than the surrounding matrix of N-polarity. The inversion domain boundaries can act as the nucleation source for the N-polar material around the inversion domain and the hillock will develop. The dislocation acts as a step source that leads to the formation of a hexagonal hillock on the surface. In contrast, the homeepitaxial LED surface is defect free (Fig. 2b). The smoother surface of the homoepitaxial LED is likely indicative of very abrupt heterostructural interfaces.

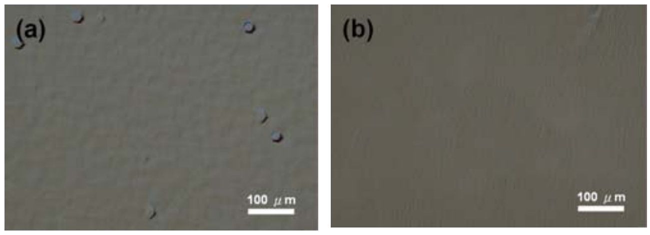

Fig. 2 Optical Normarski micrographs of surface morphology for the LED grown on (a) sapphire and (b) GaN.

Fig. 3 (a) shows the EL spectra of the LED grown on FS GaN substrate at various injection current levels. One can see that the spectral peak blue shifts by about 1.2 nm (from 443 nm at 0.1 mA to 441.8 nm at 120 mA) when the injection current increases from 0.1 to 120 mA. Fig. 3 (b) shows the counterparts of LED grown on sapphire. Here, one can see that the spectral peak blue shifts by 4 nm (from 447 nm at 1 mA to 443 nm at 120 mA). On the other hand, for all samples, the emission peak wavelength exhibited slight red shift as the injection current increases from 0.1 to 1 mA, which is attributed to the increased carrier density in the deeper QWs. Therefore, as the current level increases, the red-shift phenomenon of emission peak wavelength in EL spectrum will reaches a saturated condition until the carrier density fill the deeper QW. In other words, the screening of the quantum-confined stark effect (QCSE) starts to play the major role in spectral shift [5]. Wherever, when the injection current increases from 0.1 to 120 mA, the blue shift of about 1.2 nm for LED grown on FS GaN substrate is still significantly smaller than that of about 4 nm for the LED grown on sapphire in the same current range. The smaller EL blue shift caused by the QCSE screening can be attributed to two possible mechanisms. First, as the injection current increases, the carrier densities in the deeper QWs increase and hence the emission wavelength of LED will be tended to longer wavelength for balancing the blue shift caused by the QCSE screening. Second, the composition clustering in the deeper QWs of higher indium contents is expected to be stronger, the stronger carrier localization guarantees the overlap of electron and hole wave functions and reduces the QCSE and its screening effect. The emission peak wavelength of electroluminescence spectra for the LED on FS GaN substrate are located at 443 nm, which is about 3 nm longer than sapphire substrate specimen. This discrepancy may be attributed to a slightly different growth temperature of the InGaN layers due to the differences in the substrate thermal conductivity and thermal coupling of the substrates to the susceptors.

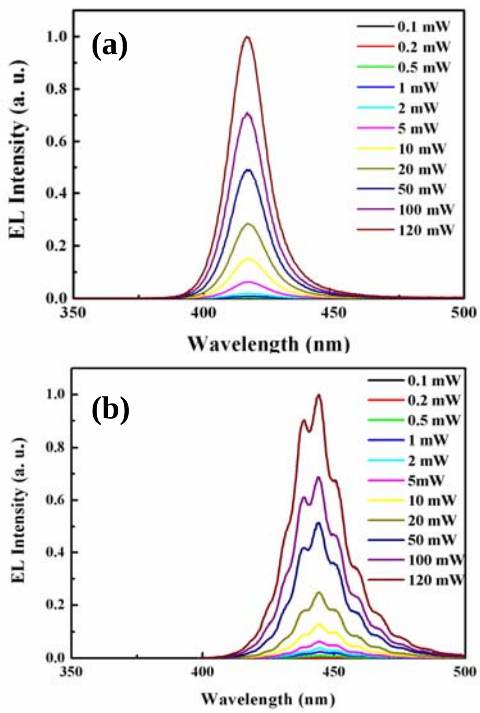

Fig. 3 EL spectra of the LED grown on (a)GaN and (b) sapphire at various injection current levels.

Figure 4(a) shows the light-output power and forward voltage of the two samples as a function of injection current (pulsed mode). The LED on GaN significantly outperforms the LED on sapphire, largely due to better heat dissipation through the GaN substrate. Fig. 4(b) shows the external quantum efficiency. The LED grown on GaN exhibits little change in the efficiency as current increases. In contrast, the LED grown on sapphire has a peak efficiency that is small than that of LED grown on GaN. The efficiency peak for the two samples occurs at approximately 5 mA; however, as the forward current is increased to 300 mA, efficiency of LED grown on GaN and sapphire are reduced by 23% and 39%, respectively. Thus, the LED grown on FS GaN substrate have little efficiency droop. Besides, the remarkable improvement of the optical performance at low injection levels is attributed to better material quality on FS GaNsubstrate. The superior performance at high currents is due to several reasons including improved radiative efficiency, heat dissipation, and current spreading.

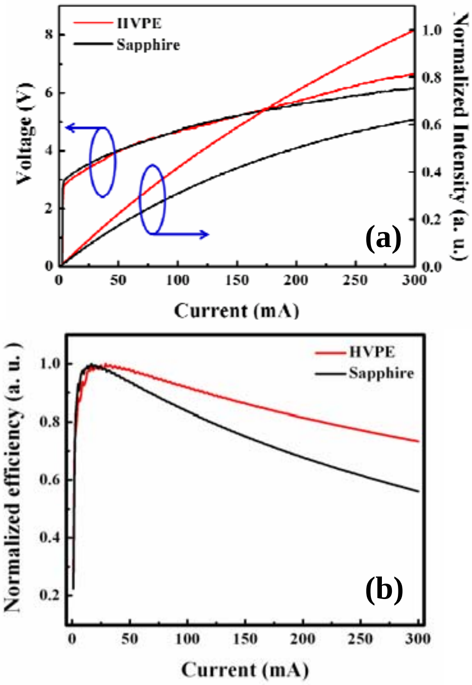

Fig. 4 (a) Light-output power, forward voltage, and (b) efficiency as a function of current for the LED grown on GaN and sapphire.

3. Conclusions

In conclusion, we grow LED structure on the 300 μm-thick GaN substrates successfully. The LEDs fabricated on the FS GaN template exhibit smaller electroluminescent peak wavelength blue shift (1.2 nm), which demonstrated an enhancement in the light output and reduction in efficiency droop at high inject current. Thus, the LED on FS GaN substrate significantly outperforms the LED on sapphire due to better heat dissipation through the GaN substrate.

Acknowledgements

The study was supported by the National Science Council NSC 98-3114-E-009-002-CC2 in Taiwan, R.O.C.

References

[1] 1. E. F. Schubert, *Light Emitting Diodes*, 1st ed. (Cambridge University Press, Cambridge, 2003)

[2] J. Han, M. H. Crawford, R. J. Shul, J. J. Figiel, L. Zhang, Y. K. Song, H. Zhou, and A. V. Nurmikko, *Appl. Phys. Lett.* **73**, 1688 (1998).

[3] S. Nakamura, S. Pearton, and G. Fasol, The Blue Laser Diode: The Complete Story, 2nd ed. Berlin, Germany: Springer, 2000.

[4] C. L. Chao, C. H. Chiu, Y. J. Lee, H. C. Kuo, Po-Chun Liu, Jeng Dar Tsay, and S. J. Cheng, Appl. Phys. Lett., **95**, 051905 (2009).

[5] Jeng-Hung Chen, Zhe-Chuan Feng, and J. Nelson, Thin Solid Films. **498,** 123-127(2006).