Metal Organic Chemical Vapor Deposition Growth of GaN-Based Light Emitting Diodes With Naturally Formed Nano Pyramids

2008 Jpn. J. Appl. Phys. 47 2954

(http://iopscience.iop.org/1347-4065/47/4S/2954)

Japanese Journal of Applied Physics
Vol. 47, No. 4, 2008, pp. 2954–2956

Metal Organic Chemical Vapor Deposition Growth of GaN-Based Light Emitting Diodes With Naturally Formed Nano Pyramids

Ching-Hua CHIU, Chia-En LEE, Ming-Hua LO, Hung-Wen HUANG,
Tien-Chang LU, Hao-Chung KUO, and Shing Chung WANG

Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, R.O.C.

(Received October 2, 2007; revised December 25, 2007; accepted December 25, 2007; published online April 25, 2008)

GaN-based light-emitting diodes (LEDs) with naturally formed nano pyramids roughened surfaces grown by metal organic chemical vapor deposition (MOCVD) were demonstrated. In this study, Mg-treatment, a growth-interruption step and a surface treatment using biscyclopentadienyl magnesium (CP_2Mg), was performed to form the nano pyramids on the surface of a p-type cladding layer, and then a p-type contact layer was grown on the p-type cladding layer, so as to create a p-type contact layer with a rough surface. Assisted by the nano pyramids surface roughening process, the light output power of the LEDs reached 11.3 and 9.7 mW with 10 and 5 min Mg-treatment at a driving current of 20 mA. The light outputs were increased by 48 and 27%, respectively, compared with the results from the LED without Mg-treatment. [DOI: 10.1143/JJAP.47.2954]

KEYWORDS: GaN, Mg-treatment, nano pyramids

1. Introduction

Wide bandgap light-emitting diodes (LEDs), which are III–nitride, ranging from ultraviolet to the short-wavelength part of the visible spectrum have attracted much attention for potential applications such as outdoor displays, exterior automotive lightings, backlight for various handheld devices, printers, liquid crystal display televisions (TV) and rear projection TVs.[1,2] Recently, as the brightness of GaN-based LEDs has increased, applications such as traffic signals backlight for cell phone and short-haul communications have become possible.[3] However, as for the replacement of conventional fluorescent lighting source with solid-state lighting, it still needs a great effort for improving the light extraction efficiency as well as internal quantum efficiency of LEDs. Research into improving the light extraction efficiency (external quantum efficiency) and brightness in the LEDs has been intense. Several methods such as surface roughening,[4,5] inclined side wall,[6] and diffused mirror techniques[7] gradually have been investigated to improve their light extraction efficiency. Among these methods, surface roughening seems to have high probability to provide large enhancement due to random scattering from the roughened surface.

In this research, we fabricated the GaN-based LEDs with nano-roughened surface by naturally formed nano pyramids on the top surface. The nano pyramids formed by the Mg-treatment, a growth-interruption step and a surface treatment using Biscyclopentadienyl magnesium (CP_2Mg), on the surface could enhance the light extraction efficiency effectively. The LEDs with different Mg-treatment time were fabricated and the related electrical and optical properties and comparison of these fabricated LEDs will be discussed in this letter.

2. Experiment

The GaN-based LED samples were grown by metal–organic chemical vapor deposition (MOCVD) with a rotating-disc reactor (Emcore D75TM) on a *c*-axis sapphire (0001) substrate. CP_2Mg and disilane (Si_2H_6) were used as the p- and n-type doping sources, respectively. The LED structure consists of a 30-nm-thick GaN nucleation layer grown at 520 °C on sapphire, a 4-μm-thick Si-doped n-GaN layer grown at 1040 °C, a five pairs of InGaN/GaN multiple quantum well (MQW) structure grown at 760 °C, a 50-nm-thick Mg-doped p-AlGaN electron blocking layer grown at 1040 °C, and a 0.15-μm-thick Mg-doped p-GaN cladding layer also grown at 1050 °C. After the growth of these layers, a growth-interruption step, stopping the Trimethyl-gallium (TMGa) flow while maintaining CP_2Mg flow, the process was called "Mg treatment". The details of the Mg-treatment process could be described elsewhere[8] Two different Mg treatment time were performed in this study. Samples A and B were treated 5 and 10 min, respectively. A second p-GaN contact layer was then grown again after this Mg-treatment process. Finally, a heavily Si-doped short-period superlattice (SPS) was grown on the p-GaN contact layer to improve the Ohmic contact of the p-electrode. Afterwards, the conventional LED, sample A and B with a nano pyramids surface, was fabricated using the standard process (four mask steps) with a mesa area of $300 \times 300\,\mu m^2$.

3. Results and Discussion

Figure 1 shows the scanning electron microscope (SEM) and atomic force microscope (AFM) images of the LED surfaces. Figures 1(a) and 1(b) shows the surface of the conventional LED, without Mg treatment, and there were no pyramid structure observed. The root mean square (RMS) surface roughness of the conventional LED was about 0.3 nm. Figures 1(c) and 1(d) shows the SEM and AFM images of sample A and Figures 1(e) and 1(f) shows that of sample B. One can see as the Mg-treatment time increased, the RMS decreased, from 187.5 to 41.9 nm, which means the base line was gradually filled up. However, the density of the nano-pyramids was increased obviously since the nuclei sites will be increased as the Mg-treatment time increased.[9]

The current–voltage (I–V) characteristics of the conventional, samples A and B LEDs were measured in Fig. 2. The forward voltages of the conventional, samples A and B LEDs were 3.3, 3.34, and 3.52 V at a driving current of 20 mA, respectively. The slightly higher forward voltage of LEDs with nano pyramids was probably due to the nano-roughened process.

Figure 3 shows the electroluminescence (EL) light output power versus driving current (L–I curve) of sample A,

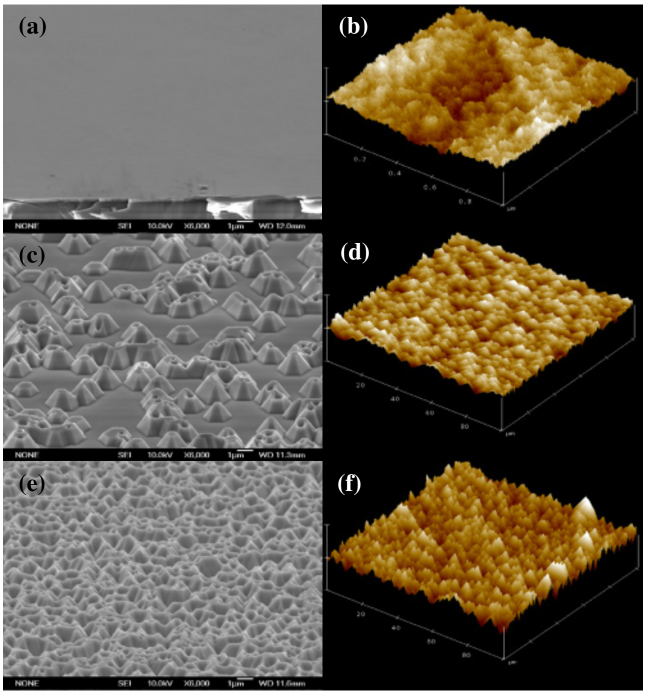

Fig. 1. (Color online) The SEM and AFM pictures of conventional, samples A and B surfaces.

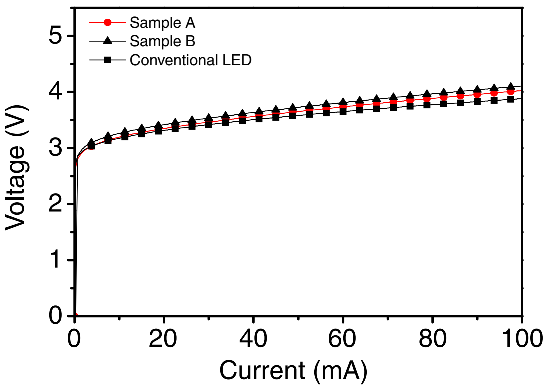

Fig. 2. (Color online) The *I*–*V* forward curve of sample A, sample B and conventional LEDs fabricated in this investigation.

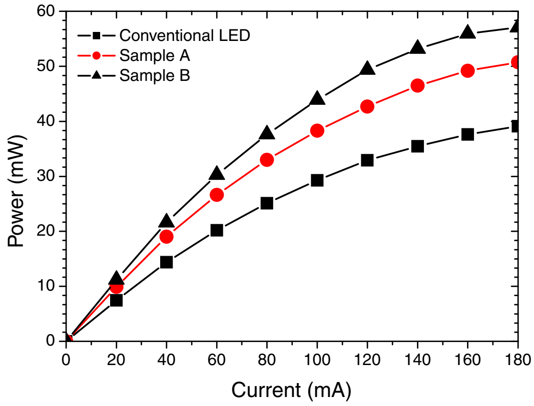

Fig. 3. (Color online) Output power of sample A, sample B, and conventional LEDs measured by an integral-sphere as a function of a forward dc current.

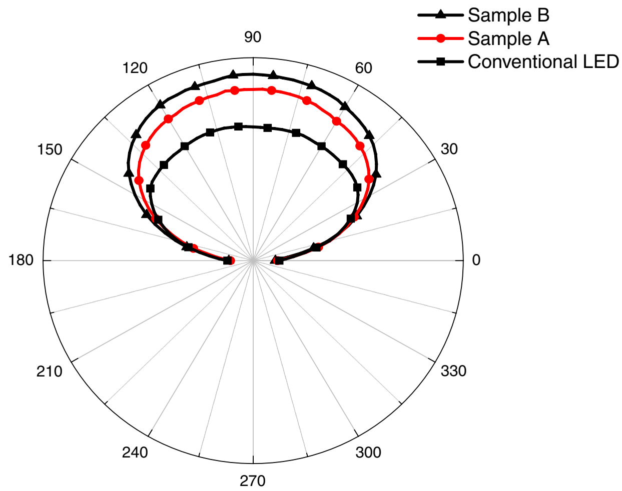

Fig. 4. (Color online) Light output patterns of sample A, sample B, and conventional LEDs.

sample B, and conventional LEDs. Sample B, the LED with 10 min Mg-treatment, and sample A, the LED with 5 min Mg-treatment, produced much higher light output as compared with that of conventional LEDs under all our measurement condition. For instance, the light output powers at 20 mA of sample A, sample B, and conventional LEDs are 9.7, 11.3, and 7.6 mW, respectively. Each measurement result was the average of 20 devices. The measured peak wavelengths of three LEDs were all at 465 nm. Therefore, the light output power at 20 mA of sample A shows 27% enhanced when compared to conventional LED. Sample B increases by 48% as compared with that of conventional LED and increases by 16% as compared with that of sample A in light output power.

Figure 4 shows light output patterns of sample A, sample B, and conventional LED at 20 mA. It is clear from the results that the EL intensities of sample B were larger than those of sample A and conventional LEDs. According to this figure, view angles (half-center brightness or 50% of the full luminosity) of samples A and B are almost the same, i.e., 140°, which a little bit smaller than that of the conventional LED, 150°. However, the overall integrated area of EL intensities of sample B is still larger than that of sample A and conventional LED. Besides, although the view angles of conventional LEDs were larger than that of samples A and B, the enhancement of EL intensity by naturally formed nano pyramids surfaces scheme is obvious.

To understand the light-output enhancement of the LEDs surface nano-roughening process, the propagation of light emitted is schematically shown in Fig. 5. Figure 5(a) shows a simple optical ray trace diagram of a conventional LED. In this case, the guided light emitting with an incident angle larger than the critical angle (~23°, between the interface of GaN material with refractive index of 2.5 and air with refractive index of 1) would be trapped between sapphire substrate and the surrounding air, and finally be vanished through absorption of active layers or electrodes. Figure 5(b) shows the case of sample A with 5 min Mg-treatment. According to this figure, guided light could be extracted outside LED chips by scatterings at nano-roughened surfaces; therefore in this case, the escaping probability of

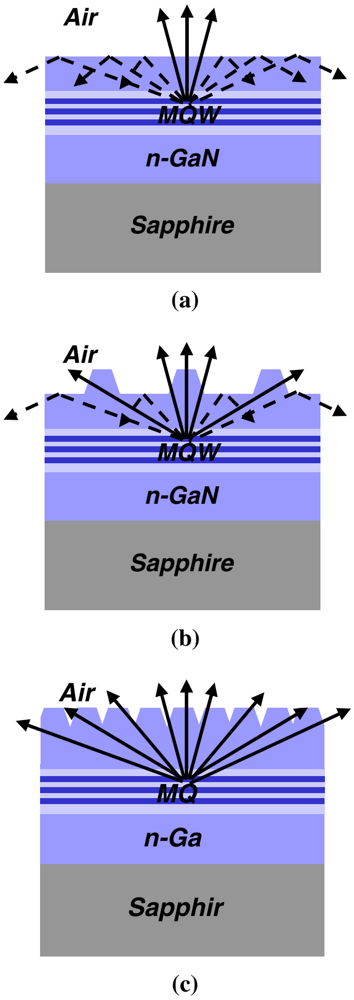

Fig. 5. (Color online) Simple optical ray diagrams of (a) conventional LEDs, (b) sample A with 5 min Mg-treatment, and (c) sample B with 10 min Mg-treatment.

photons is larger as compared with that of conventional LEDs. However, the emitted light strike the flat surface will still be reflected back. In Fig. 5(c), the emitted light will be scattered at nearly all direction because the density of the nano-pyramids was high enough. In addition, according to ref. 10, the large emission enhancement was also due to the greatly increased surface area by Mg-treatment. The nano-roughened surface area of 10 min was larger than 5 min Mg-treatment. Therefore, higher light scattering efficiency could be achieved by longer Mg-treatment time.

4. Conclusions

We have successfully fabricated the GaN-based LEDs with naturally nano-pyramids on p-GaN surface to enhance the light extraction by MOVCD. The LEDs with naturally formed nano pyramids surface by 5 and 10 min Mg-treatment, improved the escape probability of light output inside the LED structures, increasing by 27 and 48% the light output of the GaN-based LED at 20 mA, respectively.

Acknowledgements

We would like to thank Forepi Corporation for the sample supporting. This paper was supported by the National Science Council of the Republic of China (R.O.C.) in Taiwan under Contract Nos. NSC 95-2120-M-009-008, NSC 95-2752-E-009-007-PAE, and NSC 95-2221-E-009-282.

1) S. Nakamura, T. Mukai, and M. Senoh: Appl. Phys. Lett. **64** (1994) 1687.
2) G. B. Stringfellow and G. M. Craford: *High Brightness Light Emitting Diodes: Semiconductors and Semimetals* (Academic, New York, 1997).
3) M. Koike, N. Shibata, H. Kato, and Y. Takahashi: IEEE J. Sel. Top. Quantum Electron. **8** (2002) 271.
4) H. W. Huang, H. C. Kuo, C. F. Lai, C. E. Lee, C. W. Chiu, T. C. Lu, S. C. Wang, C. H. Lin, and K. M. Leung: IEEE Photonics Technol. Lett. **19** (2007) 565.
5) Y. J. Lee, H. C. Kuo, T. C. Lu, and S. C. Wang: IEEE J. Quantum Electron. **42** (2006) 1196.
6) D. Eisert and V. Harle: present at Int. Conf. Numerical Simulation of Semiconductor Optoelectronic Devices, 2002, Session 3.
7) J. K. Kim, H. Luo, Y. Xi, J. M. Shah, T. Gessmann, and E. F. Schubert: J. Electrochem. Soc. **153** (2006) G105.
8) C. S. Chang, S. J. Chang, Y. K. Su, C. H. Kuo, W. C. Lai, Y. C. Lin, Y. P. Hsu, S. C. Shei, J. M. Tsai, H. M. Lo, J. C. Ke, and J. K. Sheu: IEEE Trans. Electron Devices **50** (2003) 2208.
9) C. M. Tsai, J. K. Sheu, W. C. Lai, Y. P. Hsu, P. T. Wang, C. T. Kuo, C. W. Kuo, S. J. Chang, and Y. K. Su: IEEE Electron Device Lett. **26** (2005) 464.
10) I. Schnitzer, E. Yablonovitch, C. Caneau, T. J. Gmitter, and A. Schere: Appl. Phys. Lett. **63** (1993) 2174.