P-side up AlGaInP-based light emitting diodes with dot-patterned GaAs contact layers

Ray-Hua Horng,[1,*] Bing-Rui Wu,[1,2] Chi-Feng Weng,[1] Parvaneh Ravadgar,[3] Tzong-Ming Wu,[2] Sing-Ping Wang,[4] Jr-Hau He,[4] Tsung-Hsien Yang,[5] Yi-Ming Chen,[5] Tzu-Chieh Hsu,[5] Ai-Sen Liu,[5] and Dong-Sing Wuu[2,6]

[1]*Institute of Precision Engineering, National Chung Hsing University, 250 Kuo Kuang Road, Taichung 40227, Taiwan*
[2]*Department of Materials Science and Engineering, National Chung Hsing University, No. 250, Kuo Kuang Road, Taichung 40227, Taiwan*
[3]*Department of Photonics and Advanced Optoelectronic Technology Center, National Cheng Kung University, No. 1, University Road, Tainan 70101, Taiwan*
[4]*Department of Electrical Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan*
[5]*Epistar Corporation, No. 5, Li-hsin 5th Road, Hsinchu Science Park, Hsinchu 30075, Taiwan*
[6]*Department of Electrical Engineering, Da-Yeh University, No. 168, University Road, Dacun, Changhua 51591, Taiwan*
**huahorng@nchu.edu.tw*

Abstract: High-brightness p-side up AlGaInP-based red light emitting diodes (LEDs) with dot-patterned GaAs contact layer and surface rough structure are presented in this article. Initial LED structure of p-GaP/AlGaInP/GaAs is epitaxially grown using metal organic chemical vapor deposition technique. Using novel twice transferring process, the p-GaP layer is remained at the top side as both the current spreading and-window layer. Dot patterned GaAs contact dots are formed between main structure and rear mirror to improve light reflection and current spreading. Moreover, the surface of p-GaP window is further textured by nano-sphere lithography technique for improving the light extraction. Significant improvement in output power is found for AlGaInP LEDs with GaAs contact dots and roughened p-GaP window as compared with those of LEDs with traditional n-side up and p-side up structures without roughened surfaces.

OCIS codes: (230.0230) Optical devices; (230.3670) Light-emitting diodes.

References and links

1. R. Windisch, B. Dutta, M. Kuijk, A. Knobloch, S. Meinlschmidt, S. Schoberth, P. Kiesel, G. Borghs, G. H. Dohler, and P. Heremans, "40% efficient thin-film surface-textured light-emitting diodes by optimization of natural lithography," IEEE Trans. Electron. Dev. **47**(7), 1492–1498 (2000).
2. E. Jang, S. Jun, H. Jang, J. Lim, B. Kim, and Y. Kim, "White-light-emitting diodes with quantum dot color converters for display backlights," Adv. Mater. **22**(28), 3076–3080 (2010).
3. J. T. Wessels, U. Pliquett, and F. S. Wouters, "Light-emitting diodes in modern microscopy: from David to Goliath?" Cytometry A **81A**(3), 188–197 (2012).
4. M. R. Krames, O. B. Shchekin, R. Mueller-Mach, G. O. Mueller, L. Zhou, G. Harbers, and M. G. Craford, "Status and future of high-power light-emitting diodes for solid-state lighting," J. Disp. Technol. **3**(2), 160–175 (2007).
5. C. T. Lee, U. Z. Yang, C. S. Lee, and P. S. Chen, "White light emission of monolithic carbon-implanted InGaN-GaN light-emitting diodes," IEEE Photon. Technol. Lett. **18**(19), 2029–2031 (2006).
6. I. H. Tan, D. A. Vanderwater, J. W. Huang, G. E. Hofler, F. A. Kish, E. I. Chen, and T. D. Ostentowski, "Wafer bonding of 75 mm diameter GaP to AlGaInP-GaP light-emitting diode wafers," J. Electron. Mater. **29**(2), 188–194 (2000).
7. R. H. Horng, D. S. Wuu, S. C. Wei, C. Y. Tseng, M. F. Huang, K. H. Chang, P. H. Liu, and K. C. Lin, "Wafer-bonded AlGaInP/Au/AuBe/SiO2/Si light-emitting diodes," Jpn. J. Appl. Phys. **39**(Part 1, No. 4B), 2357–2359 (2000).
8. R. H. Horng, Y. C. Lien, W. C. Peng, D. S. Wuu, C. Y. Tseng, C. H. Seieh, M. F. Huang, S. J. Tsai, and J. S. Liu, "High-brightness wafer-bonded indium-tin oxide/light-emitting diode/mirror/Si," Jpn. J. Appl. Phys. **40**(Part 1, No. 4B), 2747–2751 (2001).

9. R. H. Horng, S. H. Huang, D. S. Wuu, and C. Y. Chiu, “AlGaInP/mirror/Si light-emitting diodes with vertical electrodes by wafer bonding,” Appl. Phys. Lett. **82**(23), 4011–4013 (2003).
10. S. W. Chiou, C. P. Lee, C. K. Huang, and C. W. Chen, “Wide angle distributed Bragg reflectors for 590 nm amber AlGaInP light-emitting diodes,” J. Appl. Phys. **87**(4), 2052–2054 (2000).
11. R. H. Horng, C. E. Lee, C. Y. Kung, S. H. Huang, and D. S. Wuu, “High-power AlGaInP light-emitting diodes with patterned copper substrates by electroplating,” Jpn. J. Appl. Phys. **43**(No. 4B), L576–L578 (2004).
12. R. H. Horng, D. S. Wuu, C. H. Seieh, W. C. Peng, M. F. Huang, S. J. Tsal, and J. S. Liu, “Water bonding of 50-mm-diameter mirror substrates to AlGaInP light-emitting diode wafers,” J. Electron. Mater. **30**(8), 907–910 (2001).
13. R. H. Horng, S. H. Huang, D. S. Wuu, and Y. Z. Jiang, “Characterization of large-area AlGaInP/mirror/Si light-emitting diodes fabricated by wafer bonding,” Jpn. J. Appl. Phys. **43**(5A), 2510–2514 (2004).
14. R. H. Horng, D. S. Wuu, S. C. Wei, C. Y. Tseng, M. F. Huang, K. H. Chang, P. H. Liu, and K. C. Lin, “AlGaInP light-emitting diodes with mirror substrates fabricated by wafer bonding,” Appl. Phys. Lett. **75**(20), 3054–3056 (1999).
15. R. H. Horng, T. M. Wu, and D. S. Wuu, “Improved light extraction in AlGaInP-based LEDs using a roughened window layer,” J. Electrochem. Soc. **155**(10), H710–H715 (2008).
16. S. C. Hsu, D. S. Wuu, C. Y. Lee, J. Y. Su, and R. H. Horng, “High efficiency 1-mm2 AlGaInP LEDs sandwiched by ITO omni-directional reflector and current-spreading layer,” IEEE Photon. Technol. Lett. **19**(7), 492–494 (2007).

1. Introduction

Light-emitting diodes (LEDs) are a popular solid-state lighting technique using in our daily life all around us. In the past few decades, LEDs have experienced many evolutions both in terms of performance and market volume because of their low power consumption and environmentally friendly characteristics. Today, they have been popularly applied in various fields such as traffic signals, automotive lighting, indoor/outdoor illuminations and displays [1–3]. Nevertheless, there are still many groups trying to improve efficiency, brightness, reliability, and lifetime of LEDs [4, 5].

It is well known that AlGaInP quaternary material systems can be precisely lattice matched to GaAs substrates without generating much misfit dislocations during metal organic chemical vapor deposition (MOCVD) growth. Therefore, AlGaInP-based LEDs present superior internal quantum efficiency. Moreover, the advantage of AlGaInP-based LEDs is their direct band-gap which could be tuned from red to yellow regions by controlling the composition of elements.

Nevertheless, the GaAs substrate possesses poor thermal conductivity and transparency for the visible light application, which significantly limit the heat dissipation and light extraction of large-area AlGaInP-based LEDs. Therefore, AlGaInP LED epitaxial layers must be transferred to other substrates such as mirror/Si or mirror/Cu which have higher thermal conductivities [6–9]. To improve the AlGaInP device performance, different techniques are reported, such as optimum design of device structure, bonding to a transparent substrate or substrate with reflector structure [10], surface texturing by natural lithography [11], and inserting a mirror layer [12,13].

Thin film n-side up AlGaInP LEDs wafer bonding to the Si substrate with mirror structure by one-time bonding technique have has been developed for a long time [9,14]. It indeed solves the absorption light and thermal dissipation problems of GaAs substrate. However, the p-GaP window layer is embedded between p-AlGaInP cladding layer and mirror structure for this kind of n-side up AlGaInP LEDs. Here, the p-GaP window layer cannot fully play the function of window layer. Even though, we had fabricated thin film p-side up AlGaInP LEDs using the patterned Cu substrate by electroplating [11]. At that time, AlGaInP LED is fabricated into the lateral contact pad structures to overcome the n-AlGaInP ohmic contact problem. Nevertheless, the lateral metal contact structures have to face the current crowding problems under high current injection.

In this work, a twice transferring technique to fabricate p-side up AlGaInP LEDs with vertical metal contacts has been developed, which can emit light from p-GaP window layers. The n-type GaAs contact layer with and without dot-patterned structure are used to provide Ohmic contact layer. The p-GaP window layer with and without surface texturing are also compared to study their light extractions.

#190249 - $15.00 USD Received 8 May 2013; revised 14 Jul 2013; accepted 30 Jul 2013; published 14 Aug 2013

2. Experimental detail

The schematic diagram of a p-side up AlGaInP-based red LED (emitting wavelength: 626 nm) with structure of surface roughened p-GaP window/p-cladding AlGaInP/ MQWs/n-cladding AlGaInP/GaAs contact layer/Ohmic contact metals/mirror/Cu substrate is displayed in Fig. 1. The thin GaAs contact layer plays an important role to form an Ohmic contact with rear electrode (AuGeNi) and copper layer (Cu). Since the thin GaAs contact is an absorbing layer, the dot-patterned GaAs contact layer is also prepared to evaluate the effects of light reflection from the bottom mirror (Ag) and Ohmic contact metal (AuGaNi). To further improving the output light, the surface of p-GaP window is also textured using nano-sphere lithography technique which has been described elsewhere [15].

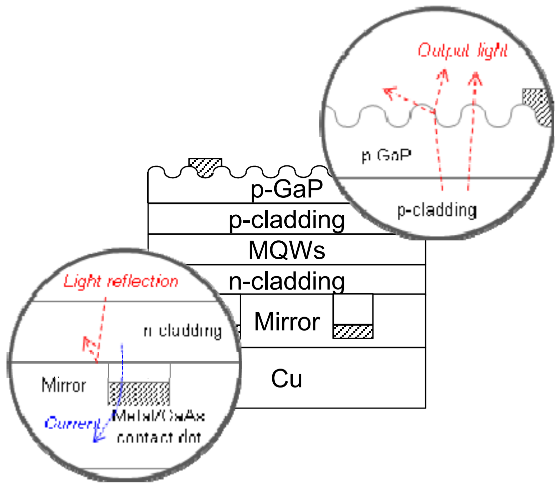

Fig. 1. Schematic diagram of a p-side up AlGaInP-based LED with dot-patterned GaAs Ohmic contact and surface texturing structure.

Figures 2(a)-2(e) illustrate the process flow chart of twice transferring of a thin film p-side up AlGaInP-based LED, schematically. LEDs employed in this work are grown on n-type GaAs substrates by MOCVD. The structure is consisting of a p-GaP window layer, p-cladding AlGaInP, GaInP-AlGaInP MQWs, n-cladding AlGaInP, n^+-GaAs contact layer, and a GaInP etching stop layer. AuBe/Au metal layers are deposited on p-GaP window layer followed by thermal annealing to form p-contact [Fig. 2(a)]. Then, LEDs are first bonded to glass carriers using polymer-based adhesive, called 1st-transferring. The absorbing GaAs substrates are then removed by dipping into NH_4OH and H_2O_2 blended solution. GaInP as an etching-stop protects the thin GaAs layer (about 50 nm) from the chemical damage. Next removal process is performed using H_3PO_4:HCl solution to remove GaInP layer. Patterned metal dots (AuGeNi) are deposited on the surface of GaAs using thermal evaporating system followed by standard lithography process, as shown in Fig. 2(b). GaAs is then wet chemical etched by employing NH_4OH and H_2O_2 blended solution, as shown in Fig. 2(c). For the second transferring process, a thick mirror layer (Ag), seed layer (Au), and electroplated Cu substrate are deposited onto the n-side surface to serve as rear-contact and also permanent substrate shown in Fig. 2(d). Then, the temporary glass substrate is removed and p-GaP window layer is roughened. A texture-etching process is carried out to roughen the p-GaP surface for increasing the output light using nano-sphere lithography technique and inductively coupled plasma reactive ion etching [Fig. 2(e)]. Here, p-GaP nanopillars with diameter of 300-320 nm and depth of 550-650 nm are obtained, which can provide the optimized light extraction [15]. Finally all samples are cut into 1010 × 1010 μm^2 separated chips and packaged by epoxy resin. In order to evaluate the effects of dot-patterned GaAs contact layer and roughening p-GaP window layer on the LED performance, the following three types LEDs are fabricated using the same epilayers. PLEDs-I are p-side up thin film

AlGaInP LEDs with GaAs contact layer and flat p-GaP surface. PLEDs-II are p-side up thin film AlGaInP LEDs with dot-patterned GaAs contact layer and flat p-GaP window. PLEDs-III are p-side up thin film AlGaInP LEDs with dot-patterned GaAs contact layer and texturing p-GaP window. Moreover, the commercial n-side up thin film AlGaInP LEDs are also used for comparison, named as NLED-IV here. The similar structure has been published [16].

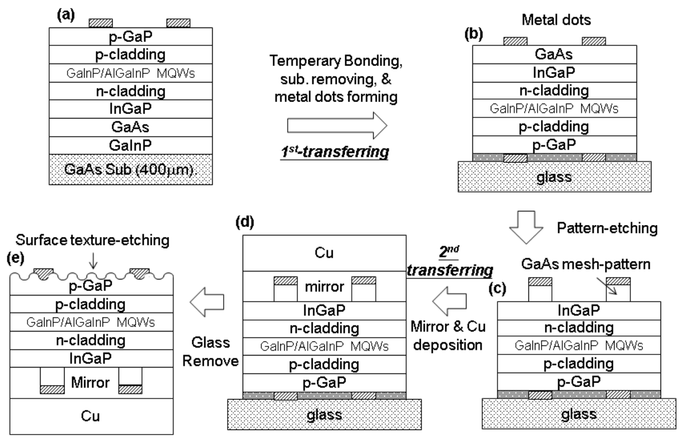

Fig. 2. Schematic diagrams of fabrication process for p-side up thin AlGaInP-based LED with dot-patterned n-GaAs contact layer and roughening p-GaP layer.

A field-emission scanning electron microscope (FE-SEM) and an atomic force microscope (AFM) are used to examine the dot-patterned of n-GaAs contact layer and surface roughness of p-GaP window layer, respectively. The current-voltage (I-V) characteristics are measured by a Keithley model 2400 sourcemeter at room temperature under ambient conditions. Furthermore, the output power-injection current characteristics (L-I) of LED samples are measured at the same conditions using an integrated sphere detector (diameter of 50 cm) and the measured deviation was around 5%. Moreover, each optoelectronic characteristic result shown in this research was obtained from the average data measured 50 samples.

3. Results and discussion

To fabricate p-side up thin AlGaInP LEDs with vertical electrode metal contacts, the n-Ohmic contact fabrication is the main issue. In this study, AuGeNi is deposited on n^+-GaAs to obtain the n-Ohmic contact. However, the n^+-GaAs is an high absorbing layer for the transmitting light. To overcome this problem, the dot-patterned GaAs layer is fabricated. After the optimization, the radius of each dot is 3 μm diameter and the distance between two successive dots is 13 μm. The top-view image of patterned GaAs dots on n-cladding surface after wet chemical etching is shown in Fig. 3 observed by an FE-SEM with tilt angel of 60°. The Ohmic contact area is about 28055 μm^2 which is only 2.7% of the bottom mirror. It means that 97.3% of emitting area directly contact to the Ag mirror.

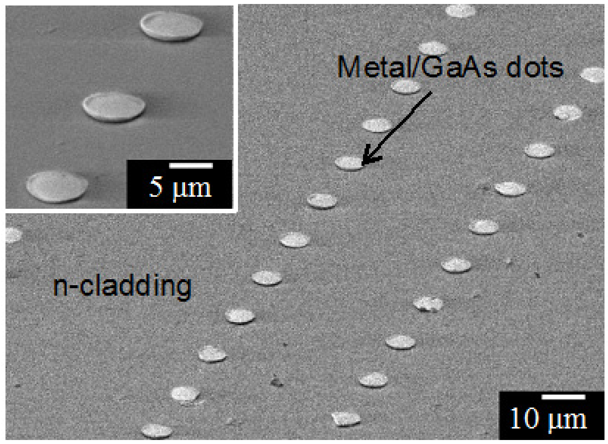

Fig. 3. Top-view FE-SEM image of dot-patterned GaAs on n-cladding surface for the thin AlGaInP-based LED after GaAs substrate removing.

The I-V characteristics of these four types of AlGaInP LEDs were measured and shown in Fig. 4.The turn on voltages for these four LEDs are almost the same and about 1.7 V. The series resistances (Rs) are 1.18, 2.29, 2.56, and 1.35 Ω for PLED-I, PLED-II, PLED-III and NLED-IV, respectively. The series resistance of PLED-I is the smallest one due to the AuGeNi Ohmic contact metal directly touching to whole n-GaAs layer. The NLED-IV presents the second small series resistance because the wafer bonding metal is directly contacted to the whole p-GaP layer. As concerning the n-GaAs dot pattern contact to the mirror for PLED-II and PLED-III, the series resistances are very close and a little higher than that of PLED-I and NLED-IV. These results suggest that dot-patterned GaAs with only 2.7% cover area can provide a good Ohmic contact for low resistance even under the high current injection.

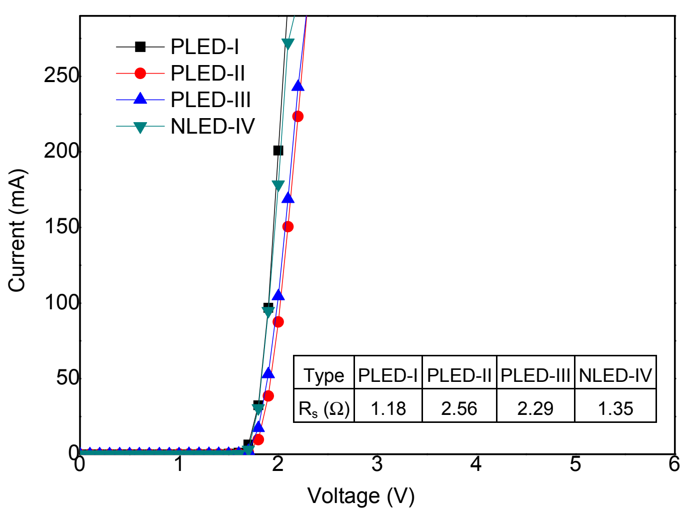

Fig. 4. I-V curves of AlGaInP-based LEDs for PLED-I (line with square), PLED-II (line with circle), PLED-III (line with triangle), and NLED-IV (line with down triangle).

#190249 - $15.00 USD Received 8 May 2013; revised 14 Jul 2013; accepted 30 Jul 2013; published 14 Aug 2013

P-side up thin film AlGaInP LEDs preserve the p-GaP window layer function. However, the optical refractive index of p-GaP is very high (about 3.19). In order to improve the light extraction, the surface of p-GaP should be roughened. The images of before and after texture-etched p-GaP surfaces are presented in Figs. 5(a) and 5(b), respectively. The averages thickness of rough surfaces for as-deposited and texture-etched p-GaP measured by AFM is 11.6 and 206 nm, respectively.

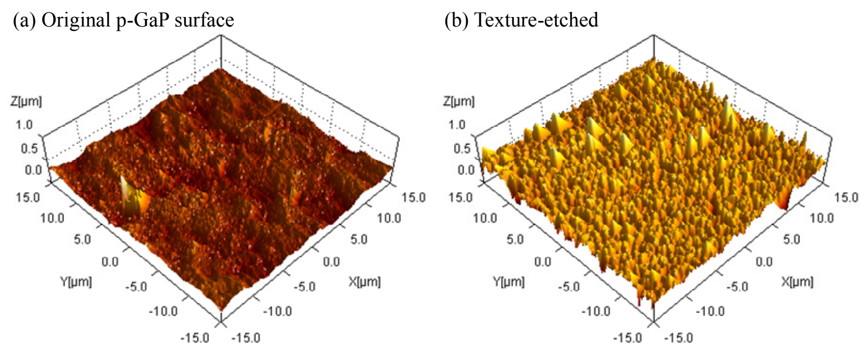

Fig. 5. AFM images of (a) original and (b) textured p-GaP surface for the thin p-side up AlGaInP-based LED.

Figure 6 represents the output power as function of injection current of these four kinds of thin-flim AlGaInP LED. Under an injection current of 350 mA, the light output powers are 50, 114, 245 and 202 mW for PLED-I, PLED-II, PLED-III, and N-LED-IV, respectively. It is found that PLED-I presents the worst performance in output power for various injection currents. It is attributed to the light emitted toward the mirror is absorbed by the bottom GaAs contact layer. Moreover, some light toward the surface is dramatically total internal reflected toward the active layer due to the high refract index p-GaP layer. It is worthy to note that the GaAs contact layer fabricated into the dot-patterned, the light absorption can be dramatically alleviated. The output power (at 350 mA) can be increased from 50 mW (PLED-I with GaAs contact layer) to 114 mW for the PLED-II with GaAs dot-patterned layer. There is about 1.28 times output power increasing due to the area of absorbing GaAs contact layer reducing to 2.7% of the bottom mirror.

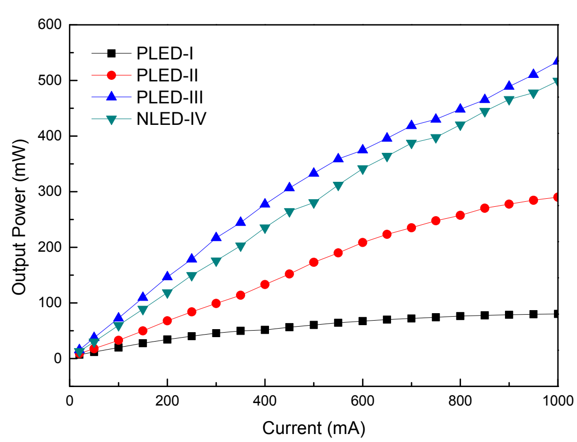

Fig. 6. Output powers of AlGaInP-based LEDs for PLED-I (line with square), PLED-II (line with circle), PLED-III (line with triangle), and NLED-IV (line with down triangle).

Furthermore, the output power is increased from 114 mW (PLED-II with flat p-GaP layer) to 245 mW for PLED-III with roughening p-GaP window layer. There is 115% output power extracted from the p-GaP window layer. Obviously, the window layer roughening can contribute more light to escape from the LED structure. The combination of bottom mirror and roughening window layer can extract light from 50 mW to 245 mW under the 350 mA current injection. The best wall plug efficiency is about 35.6% for the PLED-III. Current crowding arising from lateral electrodes structure does not occur in the new p-side up thin-film AlGaInP LEDs with vertical type electrodes. Therefore, there is no power saturation as the current increasing up to 1A as compared with p-side up thin-film AlGaInP LEDs with lateral type electrodes [13].

Table 1. Efficiencies of four types LEDs. Internal quantum efficiency (IQE) is considered to be 90% for all thin-film LEDs.

at 350mA	PLED-I	PLED-II	PLED-III	NLED-IV
Vf (V)	2.03	2.3	2.34	2.20
Output Power (mW)	50	114	245	202
WPE(%)	7	14	30	26
EQE (%)	7.2	16	35.6	29
Extraction (%)	8	17.8	39.5	32.22

The efficiencies (Wall plug (WPE), external quantum (EQE), and light extraction) of four types LEDs are summarized in Table 1. The overall light extraction efficiencies (Extraction) are 8, 17.8, 39.5, and 32.22% for PLED-I, PLED-II, PLED-III, and NLED-IV, respectively. Internal quantum efficiency (IQE) is considered to be 90% for all LEDs. From the analysis, obviously, the p-side up AlGaInP with high reflector bottom mirror and roughening top p-GaP surface can provide the highest light extraction of 39.5%. It is also higher than that of N-side up thin-film AlGaInP LEDs.

4. Conclusion

In this work, p-side up AlGaInP-based LEDs with dot patterned GaAs Ohmic contact and surface texture-etched p-GaP window are fabricated via epilayer transferring process. Dots patterned GaAs films are fabricated on the n-side of main LEDs structure to serve as an n-type Ohmic contact layer between n-type AlGaInP and mirror. The emitting light surface of p-GaP window is further texture-etched as a roughen surface to increase the light extraction.

The p-side up devices with dot-patterned structure and surface texturing present the highest output power of 245 mW than traditional n-side up devices (202 mW) and p-side up devices with non-patterned GaAs contact layer (50 mW) under same injection current of 350 mA. Additionally, WPE and extraction of 30 and 39.5% are obtained, respectively. These are promising results for further development of high power AlGaInP-based LEDs.

Acknowledgments

This work is supported by the Southern Taiwan Science Park, Hsinchu Taiwan Science Park and National Science Council of the Taiwan, Republic of China under Contract Nos. 101CE06, 101A108 and NSC 100-2221-E005-092-MY3.