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].

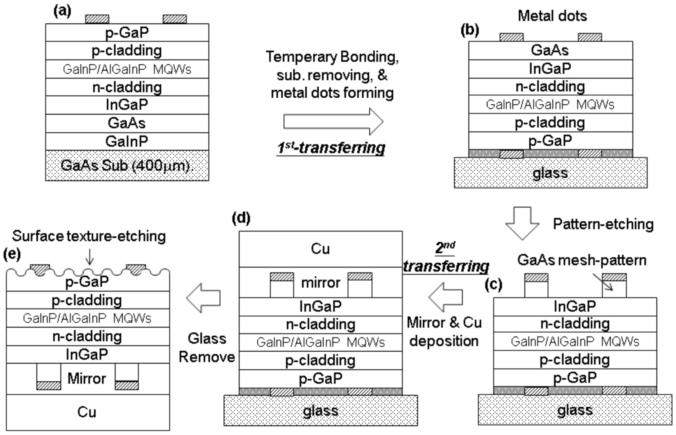


Fig. 2. Schematic diagrams of fabrication process for p-side up thin AlGaInP-based LED with dot-patterned n-GaAs contact layer and roughening p-GaP layer.

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.

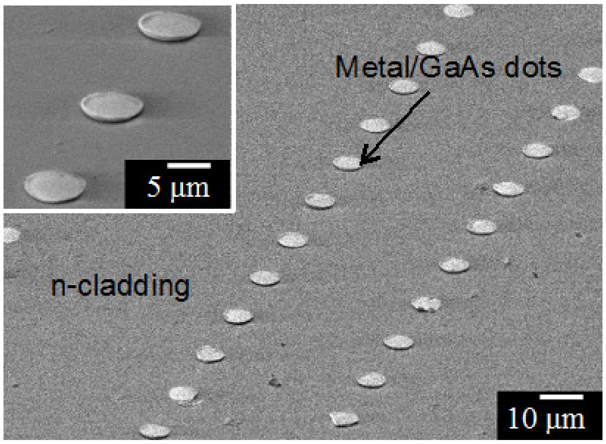
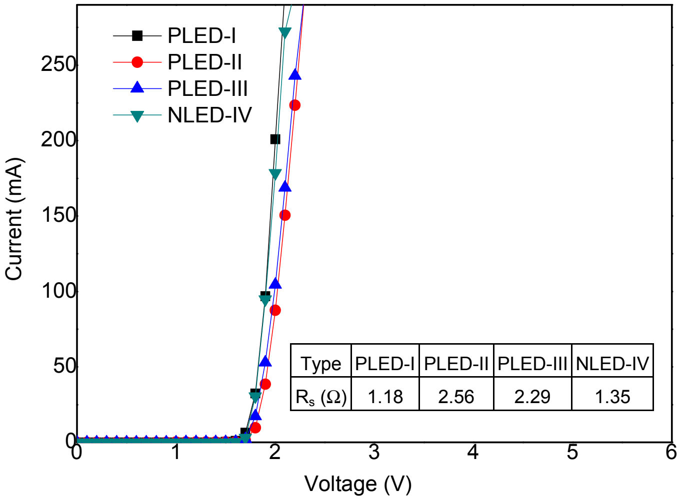


Fig. 3. Top-view FE-SEM image of dot-patterned GaAs on n-cladding surface for the thin AlGaInP-based LED after GaAs substrate removing.

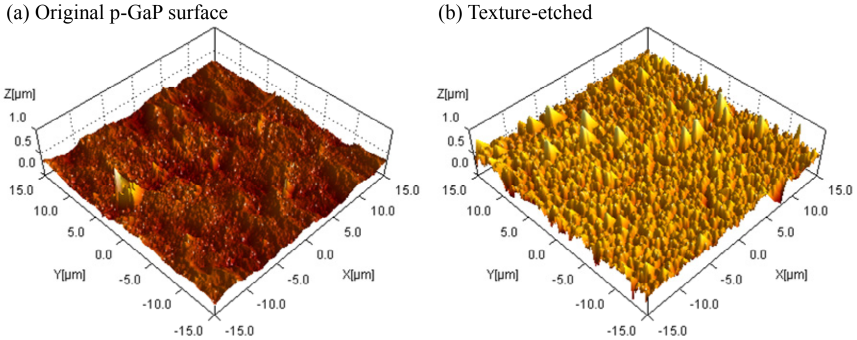
The I-V characteristics of these four types of AlGaInP LEDs were measured and shown in Fig. 4.The turn on voltages for these four LEDs are almost the same and about 1.7 V. The series resistances (Rs) are 1.18, 2.29, 2.56, and 1.35 Ω for PLED-I, PLED-II, PLED-III and NLED-IV, respectively. The series 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.



Type	PLED-I	PLED-II	PLED-III	NLED-IV
R_s (Ω)	1.18	2.56	2.29	1.35

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).

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.


(a) Original p-GaP surface

(b) Texture-etched

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.

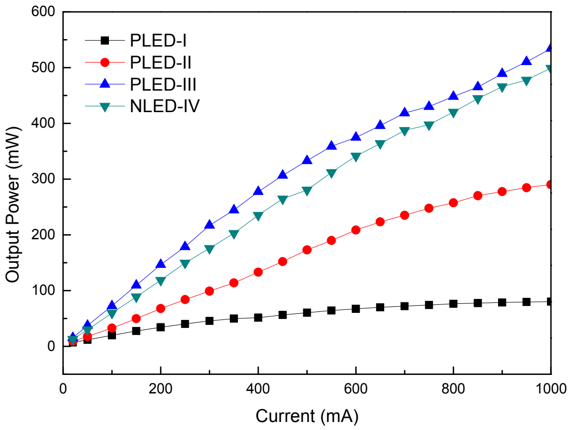


Fig. 6. Output powers of AlGaInP-based LEDs for PLED-I (line with square), PLED-II (line with circle), PLED-III (line with triangle), and NLED-IV (line with down triangle).

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.

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