Increasing the Extraction Efficiency of AlGaInP LEDs via n-Side Surface Roughening

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***Abstract*—An n-side-up AlGaInP-based light-emitting diode (LED) with a triangle-like surface morphology was fabricated using the adhesive layer bonding technique, followed by wet etching to roughen the surface. The light output power of the roughened-surface LED was 1.6 times higher than that of a flat-surface LED at an injection current of 20 mA, i.e., a significant improvement attributed to the ability of the roughened surface to not only reduce the internal reflection between the rear mirror system and the semiconductor–air interface, but also to effectively scatter the light outside the LED device.**

***Index Terms*—AlGaInP, light-emitting diode (LED), surface roughening.**

I. INTRODUCTION

FOR THE spectral region from yellow to red, the quaternary AlGaInP materials grown on low-pressure metal–organic chemical vapor deposition (MOCVD) have proven to be the most reliable choice in many applications, including interior and exterior automotive lighting, traffic lights, full-color displays, or display signs and billboards [1], [2]. Given avid interest in epitaxial quality of AlGaInP materials in recent years, the internal quantum efficiency (η_i) of AlGaInP light-emitting diodes (LEDs) has reached near 100% [3]. However, the external quantum efficiency (η_{ext}) of AlGaInP LEDs is still low because the refractive index of the quaternary epitaxial layer significantly differs from that of the air. Approximately $1/(4n^2)$ of light from the active region can escape from the top and bottom of device, where n denotes the refractive index of semiconductor materials [4]. Thus, increasing the light extraction efficiency ($\eta_{\mathrm{extraction}}$) is essential to obtaining high-performing AlGaInP-based LEDs. Considerable attention has been paid toward achieving this objective [5]–[10]. Among them, roughening surfaces of LEDs significantly improve light extraction efficiency [7]–[10]. However, previous studies aimed at generating the roughened surface morphology often involve complex processes such as using the polystyrene sphere [9] or metal clusters [10] as a hard mask for either the following inductively coupled plasma dry etching or chemical wet etching. Inappropriate surface morphology due to the complex process will not increase the light extraction efficiency, yet damage the electrical or optical properties of the materials instead. This study describes a simple, inexpensive, and feasible means of mass manufacturing AlGaInP-based LEDs with n-side surface roughening. An n-side roughen-surface AlGaInP LED is obtained by adopting the adhesive layer bonding technique, followed by treatment with phosphoric acid $(\mathrm{H_3PO_4})$: hydrochloric acid $(\mathrm{HCl}) = 5 : 1$ for 40 s of etching. This etching solution is commonly used for wet etching AlGaInP-based materials [11]. Consequently, the light output efficiency of the AlGaInP LED with the n-side roughened surface is around 60% higher than that of a LED with a flat surface.

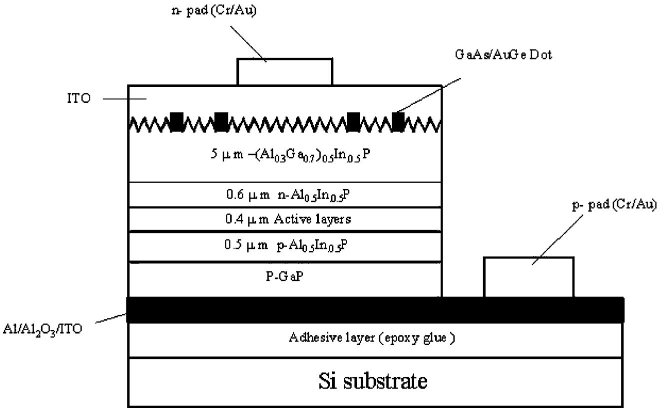

Fig. 1. Schematic cross section of a AlGaInP LED with n-side surface roughening.

II. DEVICE FABRICATION

Fig. 1 schematically depicts a cross section image of AlGaInP LED with n-side surface roughening. The LEDs used herein were grown via low-pressure MOCVD (Aixtron 2600 G) on a (100) n$^+$-GaAs substrate 15^0 off toward (111). The LED layer-structure comprised a 60-nm $\mathrm{In_{0.5}Ga_{0.5}P}$ etching stop layer, a 60-nm Si-doped GaAs ohmic contact layer, a 5-μm-thick Si-doped n-$(\mathrm{Al_{0.7}Ga_{0.3}})_{0.5}\mathrm{In_{0.5}P}$ layer for surface roughening ($n = 3 \times 10^{18}$ cm^{-3}), a 0.6-μm Si-doped n-$\mathrm{Al_{0.5}In_{0.5}P}$ cladding layer ($n = 5 \times 10^{17}$ cm^{-3}), a 0.4-μm undoped active layer region with 25 period $(\mathrm{Al_{0.3}Ga_{0.7}})_{0.5}\mathrm{In_{0.5}P}$–$\mathrm{In_{0.5}Ga_{0.5}P}$ multiple quantum wells, a 0.5-μm Mg-doped p–$\mathrm{Al_{0.5}In_{0.5}P}$ cladding layer ($p = 1 \times 10^{18}$ cm^{-3}), a 1.2-μm Mg-doped p-GaP window layer, and a 50-nm highly Mg-doped p$^+$-GaP layer ($p = 1 \times 10^{19}$ cm^{-3}) to achieve ohmic contact. Thereafter, a calculated reflection of about 90% rear mirror system composed of a 300-nm ITO current spreading layer, a 200-nm $\mathrm{Al_2O_3}$ low index layer, and a 200-nm Al metal layer were deposited in a sequential layer on the surface of the p$^+$-GaP ohmic contact

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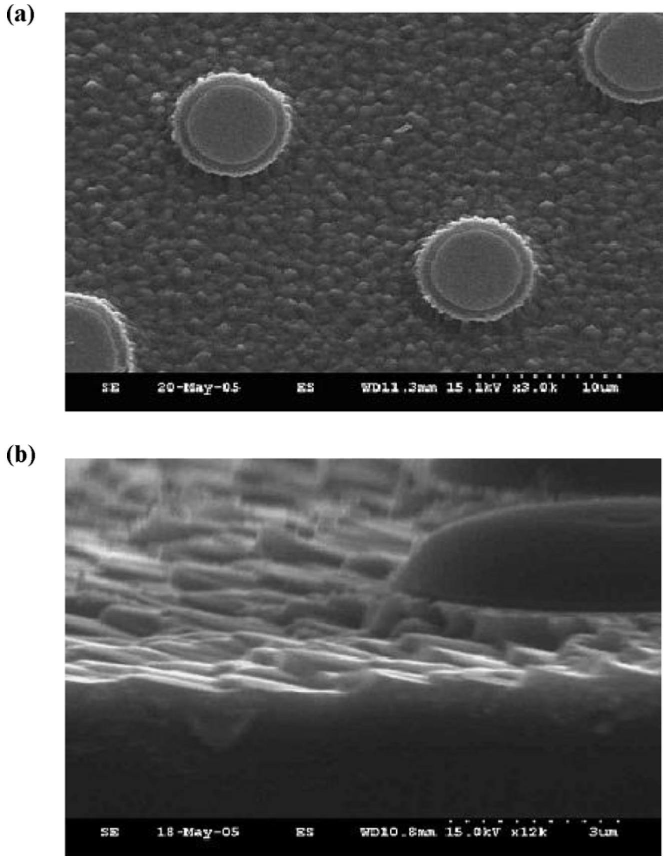

Fig. 2. SEM images of an n-side roughened-surface AlGaInP LED etched using $H_3PO_4 : HCl = 5 : 1$. (a) Top view and (b) cross section side views.

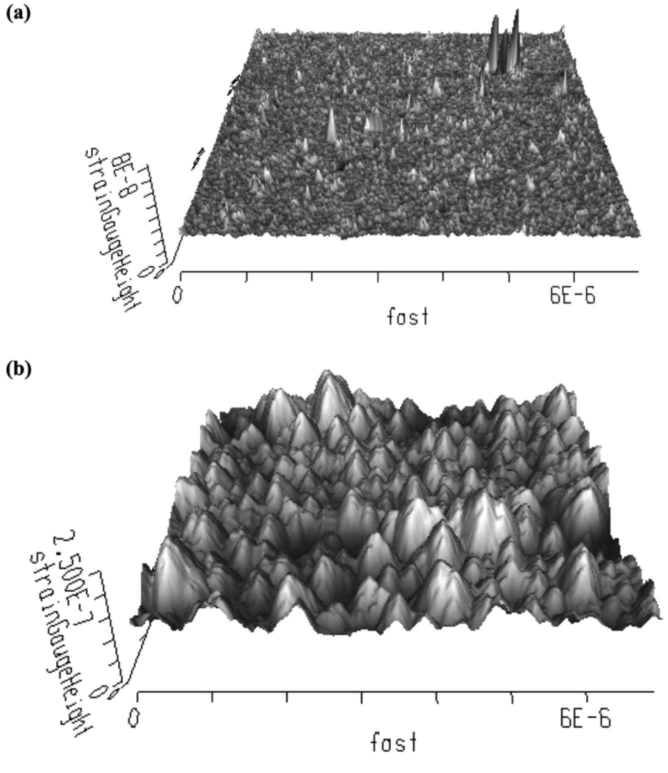

Fig. 3. AFM images of the n-side-up surface morphology of the AlGaInP LED. (a) Flat n-side surface LED image. (b) N-side roughened-surface LED image.

layer by e-beam evaporation. The LED structure and Si substrate carrier were then brought into contact with commercially available epoxy glue at an operating temperature of 80 °C. The n-type GaAs substrate was subsequently removed using a NH_4OH-based solution, and then the etching was stopped on the $In_{0.5}Ga_{0.5}P$ etching stop layer. After $In_{0.5}Ga_{0.5}P$ etching stop layer was removed via wet etching, 10-m AuGe alloy was deposited on the top of 60-nm Si-doped GaAs ohmic contact layer. The dot patterns composed of 60-nm GaAs and 10-nm AuGe alloy with a diameter of 7 μm were defined by standard photolithography and wet etching. The etching solution of $H_3PO_4 : HCl = 5 : 1$ was then used at 25 °C for 40 s of etching to roughen the outside region of dot patterns. Next, the ITO was deposited on the top of the device, enabling a current injected from n-electrode to effectively spread through ITO current spreading layer into the GaAs–AuGe dots because ohmic contact is made with ITO current spreading layer. The grown wafer was partially dry etched until p-side ITO was exposed to define the emitting area and p-electrode. Finally, the Cr–Au were deposited as n and p electrodes, respectively. The Si substrate was lapped and polished down to about 170 μm. The wafer was cut into $300 \times 300\ \mu m^2$ chips, and then packaged into TO-18 without epoxy resin for the subsequent measurement. The conventional LED sample with exactly the same process, but without n-side roughening, was also prepared for comparison. The n-side surface roughness of LEDs was measured by tapping mode atomic force microscope (AFM). Finally, the light output power of the LEDs was determined using an integrated sphere with a calibrated power meter.

III. RESULTS AND DISCUSSION

Fig. 2 shows scanning electron micrograph (SEM) images of the top and cross section side views of the AlGaInP LED after $H_3PO_4 : HCl = 5 : 1$ for 40 s of etching time. According to Fig. 2(b), the roughened surface morphology of the n-side-up AlGaInP-based LED displays a triangle-like feature, which tilts toward a specific direction associated with the lattice orientation. This feature could be related to the surface polarity of AlGaInP since this roughening feature can only be observed through wet etching only on the n-side-up surface of AlGaInP material after the GaAs substrate is removed. Our laboratory is currently investigating the detailed mechanism of forming the roughened surface. Fig. 3(a) and (b) illustrates the AFM images that describe the surface morphology change of the AlGaInP LED during surface roughening. Fig. 3(a) reveals that the flat n-side surface LED has a root-mean-square (rms) roughness of 0.8 nm, as well as a surface depth of approximately 3 nm. Some peak signals in this figure were induced by particles that could be eliminated. The surface of flat n-side surface AlGaInP LED was smooth. Fig. 3(b) illustrates an n-side roughened-surface AlGaInP-based LED AFM image rms roughness of 29.5 nm and a surface depth of approximately 150 nm. According to this figure, the roughness of n-side surface markedly increased by using the etching solution of $H_3PO_4 : HCl = 5 : 1$ for 40 s of etching time. Fig. 4 shows the electroluminescence (EL) spectra from a flat-surface LED (real line) and a roughened-surface LED (dotted line) under a forward driving current of 20-mA dc at room temperature. The spectrum of the flat n-side surface LED had a multipeak emission, implying that the radiated light from the active region resonates within

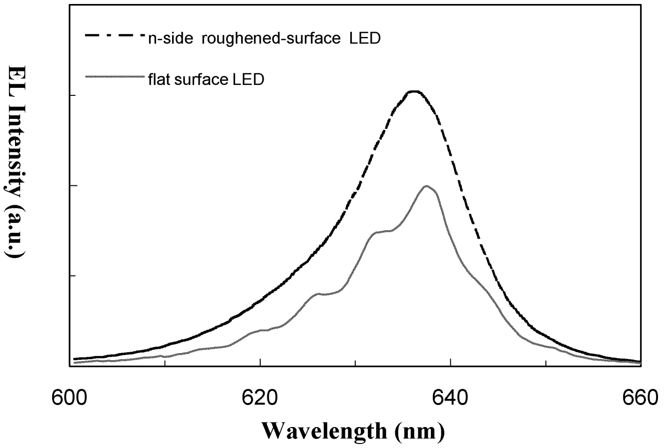

Fig. 4. Room-temperature EL spectra under a forward driving current of 20 mA from flat-surface and roughened-surface AlGaInP LEDs.

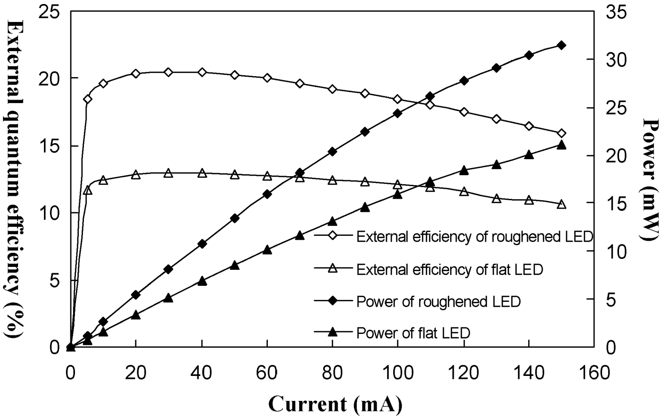

Fig. 5. L–I curve and external quantum efficiency of flat-surface and roughened-surface AlGaInP LEDs as a function of the forward-bias current.

the AlGaInP cavity sandwiched between the rear mirror system ($Al–Al_2O_3$–ITO) and the air. However, no longitudinal mode was detected on the n-side roughened-surface LED. Additionally, its EL intensity was roughly 54% larger than that of the flat n-side surface LED, indicating that the roughened n-side surface effectively scattered the light, resulting in effective suppression of the resonance and enhancement of the light extraction. Fig. 5 shows the measurement results of room-temperature output power (L–I) curve and external quantum efficiency of flat-surface and roughened-surface LEDs as a function of the forward-bias current. The data were obtained from the same device with and without $H_3PO_4 : HCl = 5 : 1$ etching, explaining why any factor causing this difference except the surface morphology would be neglected. The L–I curves of both devices show the linear features under our measurement condition of the driving current up to 150 mA. Owing to the higher thermal conductivity of Si compared to that of GaAs substrate, these devices are advantages for high-power operation. The light output powers at 20 mA of the flat-surface and roughened-surface LEDs are 3.4 and 5.4 mW, respectively. In contrast, the output power for a flat-surface LED and the 40-s etched surface LED, this roughening treatment with triangle-like surface morphology improved the light output power by an approximate factor of 1.6. While the current dependent external quantum efficiency is similar in flat-surface and roughened-surface LEDs, the external quantum efficiency of the roughened-surface LED is about 1.6 times higher than that of the flat-surface LED up to 150 mA. The above results suggest that the two devices have nearly the same internal quantum efficiency. Moreover, the main enhancement of the external quantum efficiency of the roughened-surface LED is due to the enhanced light extraction efficiency via the triangle-like surface morphology. Importantly, while the external quantum efficiency is still low for the roughened-surface LED studied here, the comparison is being made on the overall intensity enhancement using the roughening treatment.

IV. CONCLUSION

This study presents a feasible means of mass manufacturing AlGaInP-based LEDs with n-side surface roughening. The extraction efficiency of AlGaInP-based LEDs is increased by roughening the n-side surface using $H_3PO_4 : HCl = 5 : 1$ for an etching time of 40 s. In addition to effectively suppressing the internal reflection, the roughened surface increased the likelihood of photons inside the LED escaping, thus increasing the output power by approximately 60%.

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