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# Nano-roughening n-side surface of AlGaInP-based LEDs for increasing extraction efficiency

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## Abstract

A chemical wet etching technique is presented to form a nano-roughened surface with triangle-like morphology on n-side-up AlGaInP-based LEDs fabricated by adopting adhesive layer bonding scheme. A simple and commonly used $H_3PO_4$-based solution was applied for chemical wet etching. The morphology of nano-roughened surfaces is analyzed by the atomic force microscope (AFM) and significantly related to the enhancement factor of the LED output power. The output power shows 80% increase after optimizing the nano-roughened morphology of n-side surface, as compared to the ordinary flat surface LED.

*Keywords:* Chemical wet etching; AlGaInP-based LEDs; Nano-roughening

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## 1. Introduction

With AlGaInP materials, high performance LEDs emitting light from the red to yellow-green part of the spectrum were made available. New level of high light-efficiency was achieved over this spectral regime, and as a consequence, new applications for LEDs including interior and exterior automotive lighting, traffic lights, full color displays, or display signs and billboards are in the process of being developed [1,2]. Given strong interest in epitaxial quality of AlGaInP materials in recent years, the internal quantum efficiency ($\eta_i$) of AlGaInP LEDs has reached near 100% [3]. However, the total light output from LEDs is rather low owing to the large refractive index of AlGaInP materials, most of the internally generated light suffer total internal reflection at the semiconductor–air interface. Thus, for obtaining high performance AlGaInP-based LEDs, it is significantly important to enhance the light extraction efficiency ($\eta_{\mathrm{extraction}}$). Considerable attention has been paid towards achieving this objective and successful methods including the inverted truncated pyramid, the lateral taper, the micro-reflectors, and the roughening surface have been realized [4–9]. Among them, roughening surfaces of LEDs significantly improves light extraction efficiency. However, previous studies aimed at generating the roughened surface morphology typically require complicated processes involving lithographic patterning and subsequent dry etching, or a high temperature annealing process. In our previous study, a simple, inexpensive, and feasible means of mass manufacturing n-side-up nano-roughened surface AlGaInP-based LEDs with triangle-like feature was demonstrated by using $H_3PO_4$-based solution for chemical wet etching [10]. In this report, an optimized nano-roughened morphology was obtained and investigated by variation of the etching time and an approximate 80% improvement in output power was observed, as compared to LEDs with flat surface.

## 2. Device fabrication

A schematic cross-section image of a AlGaInP LED with n-side surface roughening is shown in Fig. 1. The LEDs in this study were grown via low-pressure metal-organic chemical vapor deposition (MOCVD). The LED layer-structure comprised a 5 μm thick Si-doped n-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ layer

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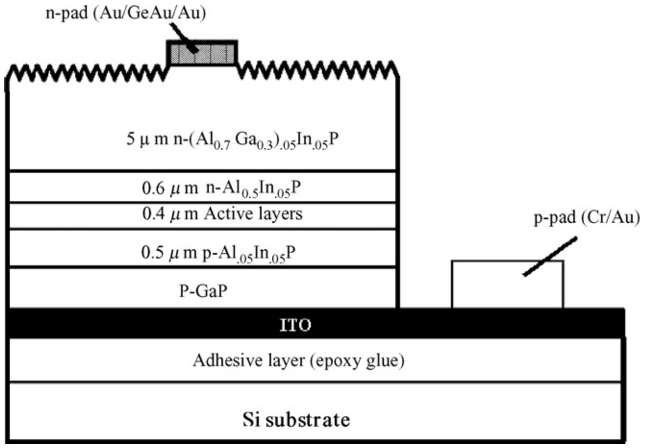

Fig. 1. Schematic cross-section of an AlGaInP LED with n-side surface roughening.

for surface roughening, a 0.6 μm Si-doped n-$Al_{0.5}In_{0.5}P$ cladding layer, a 0.4 μm undoped active layer region with 25 period $(Al_{0.3}Ga_{0.7})_{0.5}In_{0.5}P/In_{0.5}Ga_{0.5}P$ multiple quantum wells (MQWs), a 0.5 μm Mg-doped p-$Al_{0.5}In_{0.5}P$ cladding layer, a 1.2 μm Mg-doped p-GaP window layer and a 50 nm highly Mg-doped $p^+$-GaP layer to achieve ohmic contact. The details of the epitaxial structure are described elsewhere [10]. Thereafter, a 300 nm ITO current spreading layer was deposited on the surface of the $p^+$-GaP ohmic contact layer by e-beam evaporation. The LED wafer was flipped and bonded to a Si substrate with commercially available epoxy glue at a temperature of 80 °C. The n-type GaAs substrate was subsequently removed using a $NH_4OH$ based solution and the etching was stopped on the $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ surface roughening layer. Next, the n-contact composed of Au/GeAu/Au was formed on the exposed surface-roughening layer. In order to roughen the top of the surface, the etching solution of $H_3PO_4$:HCl:$H_2O$ = 5:1:2 was used at room temperature. The grown wafer was then partially dry etched by using inductively coupled plasma (ICP) until p-side ITO was exposed to define the emitting area and p-electrode. Finally, the Cr/Au were deposited as p electrode. The conventional LED sample with exactly the same epitaxial structure and process, but without n-side roughening, was also prepared for comparison. The Si substrate was lapped and polished down to about 170 μm. The wafer was cut into 300 μm × 300 μm chips and, then, packaged into TO-18 without epoxy resin for the subsequent measurement. 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.

## 3. 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:$H_2O$ = 5:1:2 for 20 s of etching time. According to Fig. 2, this solution etched the n-side surface of AlGaInP materials with triangle-like features, which tilt towards a specific direction associated with the lattice orientation and distribute uniformly. The formation of triangle-like features could be related to the surface polarity of AlGaInP since this nano-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. A similar phenomenon was also observed on GaN materials [11]. Shown in Fig. 3 are atomic force microscopy (AFM) images of n-side surface morphology of the AlGaInP LED with different chemical wet etching times. The etching times for (a)–(d) are 0 s, 10 s, 20 s, and 30 s, respectively. 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. According to Fig. 3(b)–(d), the dimension and the surface depth of the feature increase with etching time, indicating the smaller density of triangle-like features distributed under the longer period of etching time. The roughness of n-side surface markedly increased by using this $H_3PO_4$-based etching solution. Fig. 4 shows the measurement results of room temperature output power (*L–I* curve) with different etching time. The enhanced output power of roughened surface LEDs compared to flat surface LEDs at a forward 20 mA dc current is also inserted in this figure. Due to the higher thermal conductivity of Si compared to that of GaAs substrate, these devices are advantageous for high power

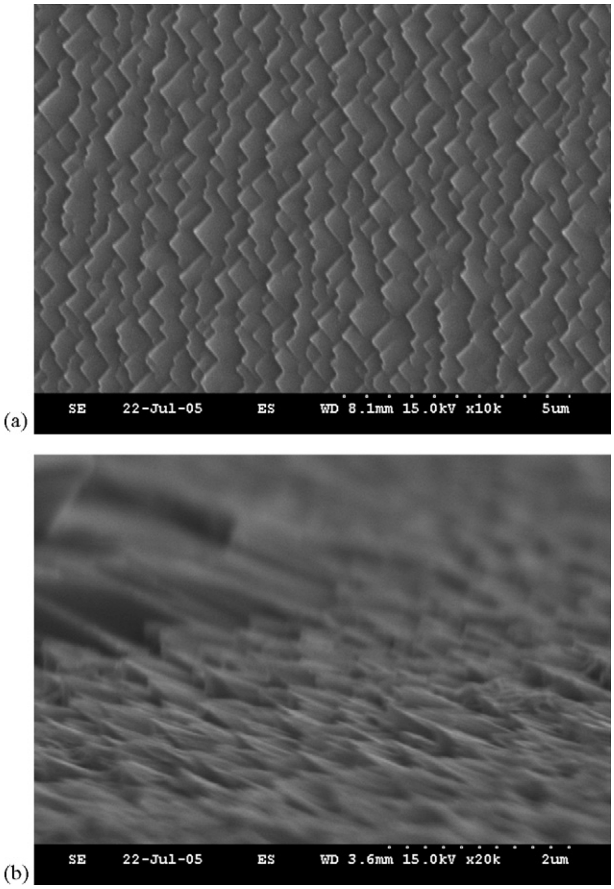

Fig. 2. SEM images of an n-side roughened-surface AlGaInP LED etched using $H_3PO_4$:HCl:$H_2O$ = 5:1:2 for 20 s of etching time. (a) Top view and (b) cross-section side views.

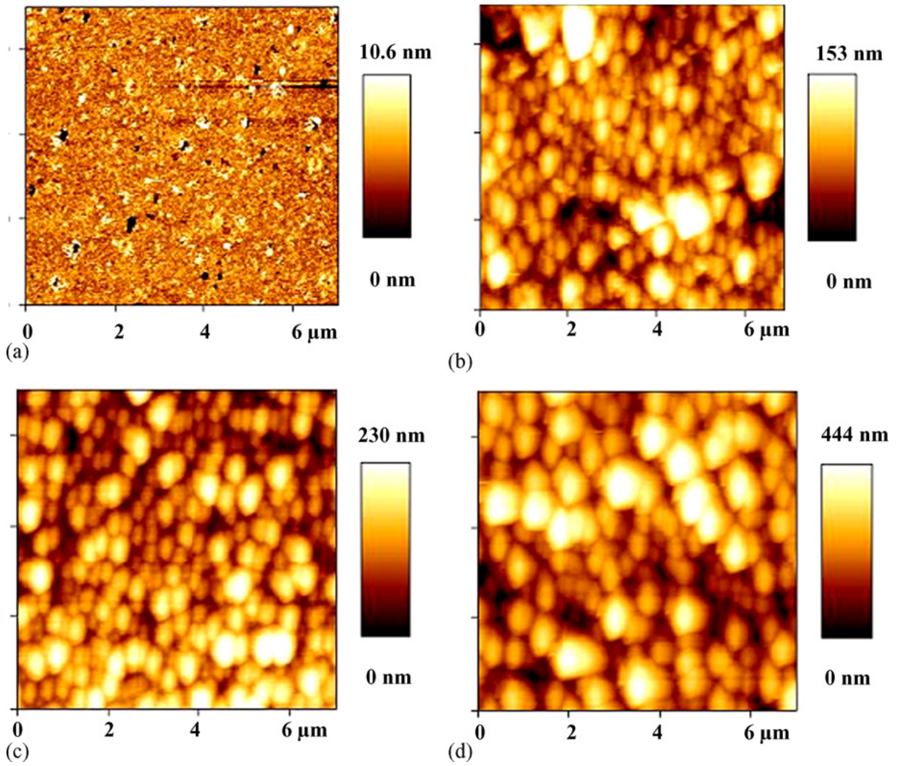

Fig. 3. AFM images of the n-side-up surface morphology of the AlGaInP LED with chemical wet etching time of (a) 0 s, (b) 10 s, (c) 20 s, and (d) 30 s.

operation. Except for the sample of etching time of 30 s, output power of other samples (flat surface, 10 s and 20 s etching times) increases with the driving forward current and exhibits no dropping behavior, in all our measurement conditions. Concerning the sample of etching time of 30 s, output power started to decrease after 90 mA. This could be attributed to its relatively poor current-spreading characteristic on the n-electrode. The 5 µm n-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$, serving for the surface roughening layer, became thinner with the increasing of the etching time, resulting in the relatively poor current spreading characteristic, that accompanied additional heat generation. For example, since the thickness of n-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ was decreased from the original 5 µm to about 3.5 µm by 30 s etching, an additional heat generation near the active region can decrease internal quantum efficiency, therefore, an early drop of output power was observed on the sample of etching time of 30 s. According to this figure, the optimized roughened surface morphology was obtained by using $H_3PO_4$:HCl:$H_2O$ = 5:1:2 for 20 s of etching time, and with a corresponding enhancement factor of output power of 1.8 at a drive current of 20 mA. The light output pattern of nano-roughened surface sample for 20 s of etching time is measured and shown in Fig. 5, where the chip is not encapsulated into epoxy. The light output pattern of the flat surface LED is also depicted for comparison. The angular dependences of emitted light were almost identical for these two devices. However, it

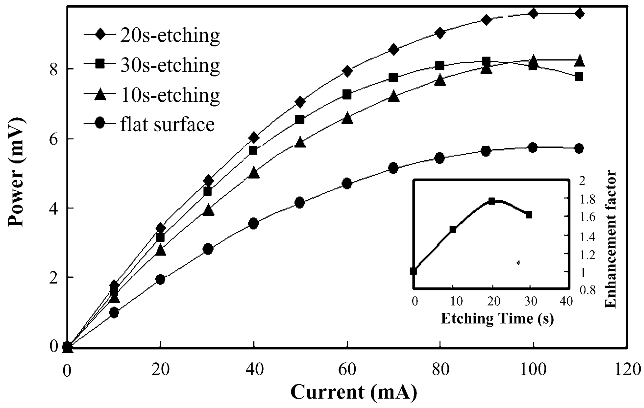

Fig. 4. The output power (*L–I* curve) as a function of the forward-bias current with different etching time. The inserted figure is the enhancement factor of output power of roughened surface LEDs compared to flat surface LEDs at a drive current of 20 mA.

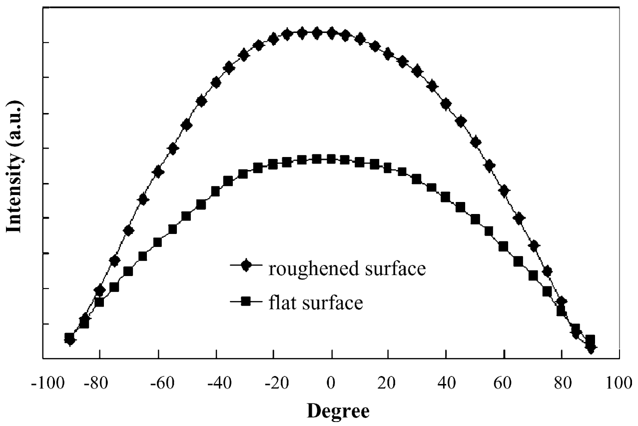

Fig. 5. Light output patterns of LEDs with and without surface roughening. The forward current was driven at 20 mA.

was found that the output of the LED with nano-roughened surfaces was larger, indicating the nano-roughened technique can effectively enlarge the output power without changing the optical pattern. Thus the original applications by adopting the ordinary AlGaInP-based LED with flat surface are also compatible with our nano-roughened n-side surface LEDs.

## 4. Summary

In summary, a feasible means of mass manufacturing AlGaInP-based LEDs with n-side nano-roughened surface is presented. The morphology of roughened surfaces by adopting the etching solution of $H_3PO_4$:HCl:$H_2O = 5:1:2$ with different etching times is investigated by the atomic force microscope (AFM). The light extraction of AlGaInP-based LEDs is strongly dependent on the roughened morphology. The optimized morphology of nano-roughened surfaces was obtained for 20 s of etching time, and with a corresponding enhancement factor of output power of 1.8 at a drive current of 20 mA. The simple technique to achieve a nano-textured surface is expected to be useful for realizing high brightness AlGaInP based LEDs.

## Acknowledgements

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