Light extraction efficiency enhancement in light-emitting diodes with indium tin oxide nano-craters*

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Abstract: A simple and low cost method is described which improves extraction efficiency. The indium tin oxide (ITO) textured film was fabricated by using the self-assembly method and dry-etching. The surface morphologies and surface roughness were observed by using an atomic force microscope. The I–V characteristics, output power and polar radiation pattern of the LEDs with and without textured ITO were measured for comparison. Cylinders and craters were formed on the ITO surface after the etching, the height of which increased with etching time. The output power of the devices is proportional to the etching time. Total internal reflection of light on the ITO-GaN interface is reduced due to the appearance of cylinders and craters, and their increasing height. Thus, the output power is improved.

Key words: indium tin oxide; self-assembly; light-emitting diodes; textured surface

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1. Introduction

GaN-based light-emitting diodes (LEDs) have attracted considerable interest in recent years due to their huge demand and potential for various applications[1]. However, the majority of applications are currently hindered by the low light extraction efficiency and Lambertian-like radiation profile caused by the large difference in the refractive index between the LED die and the external medium[2, 3]. Most photons are trapped inside the LED device by total internal reflection (TIR) and converted to heat, which limits the external quantum efficiency of conventional LEDs to only a few percent[2] . Several methods has been studied to enhance external quantum efficiency and to reduce the total internal reflection. Using a textured surface has been demonstrated to be an effective technique[4]. It was studied that high light output power values in LEDs was achieved by using a textured surface[5−12]. Surface roughness was defined by processes such as indium tin oxide (ITO) with a textured surface[13−23], etching thin film[24, 25] and side-wall roughness[26]. However, such methods are complex and expensive. In this study, a new approach is developed to fabricate textured indium tin oxide (ITO) film by using a self-assembly method and dry etching. The advantage of the method is its simplicity and low cost. Meanwhile, the p-GaN layer is protected during the process.

2. Experimental methods

A conventional GaN LED structure was grown on a 2-inch patterned sapphire substrate by using metal-organic chemical vapor deposition (MOCVD). The epitaxial LED structure consists of a 1-μm-thick low-temperature grown GaN buffer layer, a 2-μm-thick undoped GaN layer, a 2-μm-thick heavily doped n-type GaN layer, 10 pairs of InGaN (3 nm)/GaN (12 nm) multiple quantum wells (MQWs) with a total thickness of 0.15 μm, and a 0.2-μm-thick p-type GaN layer. After a 300-nm-thick ITO transparent conductive layer was deposited on the wafer by an electron beam system, monodisperse polystyrene (PS) nanoparticles with a diameter of 1 μm were assembled into a closely packed monolayer on the ITO layer by using the self-assembly method. The GaN LED was divided into four parts: samples A, B, C, D. Inductively coupled plasma (ICP) etching was applied on samples B, C, D for 175, 250, 300 s, respectively. All the samples were then put into deionized water before polystyrene particles were moved by using an ultrasonic concussion bath. Sample A was not etched and used for comparison. Next, the LED mesa (1 $\times$ 1 mm^2) was obtained by standard lithography patterning followed by GaN etching in ICP to expose the n-type GaN layer. Finally, a metallization process was applied on the samples to form the p- and n-electrodes where Cr/Pt/Au (50/50/1500 nm) was deposited onto the ITO transparent conductive layer and the n-type GaN layer respectively by using an electron-beam evaporator. Schematics of the fabricating process are illustrated in Figs. 1(a)–1(d).

3. Results and discussion

Figure 2 shows the AFM images of ITO surface morphologies. The ITO and nanoparticles are etched with 0, 175, 250, 300 s, respectively. The surface roughness of samples A, B, C, D is 8.129, 37.629, 52.170, 58.778 nm, respectively. Cylinders were formed on the ITO surface during ICP etching, as shown in Fig. 2(d). When etching time was above 250 s, craters were

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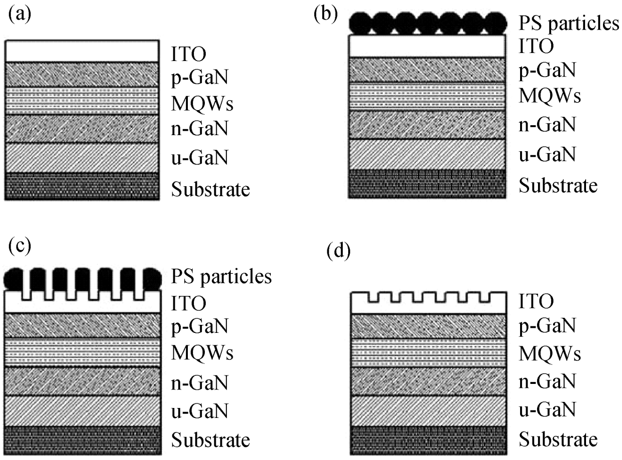

Fig. 1. Schematics of the fabricating process.

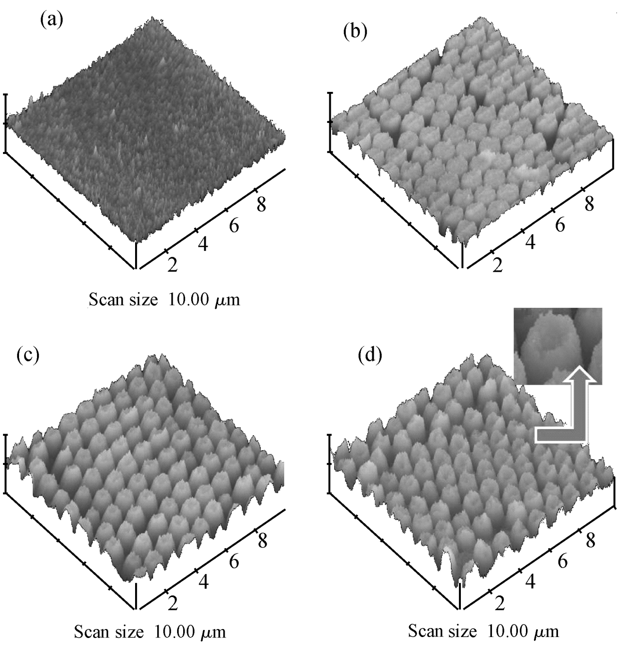

Fig. 2. AFM images of ITO surface morphologies. (a) Unetched. (b) 175 s. (c) 250 s. (d) 300 s.

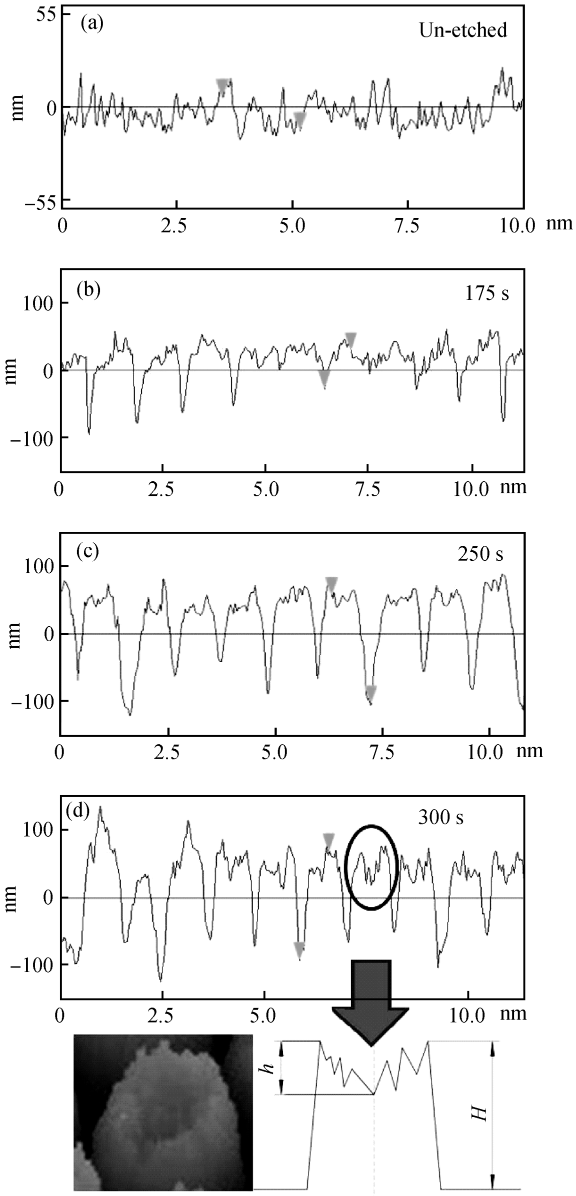

Fig. 3. Surface roughness of samples A, B, C, D. (a) Unetched. (b) 175 s. (c) 250 s. (d) 300 s.

found on the top of cylinders due to complete etching of the nanoparticles.

Figures 3(a)–3(d) represent the surface roughness of samples A, B, C, D, respectively. Figure 3(a) shows the curve for the shape cross sections of un-etched ITO. Cylinders can be seen on the surface of ITO after an etching of 175 s, as illustrated in Fig. 3(b). The cycle period is equal to the diameter of the nanoparticles. The height of the cylinders is in the range of 78 nm and 127 nm, due to non-uniform etching on the ITO surface. Sample C shown in Fig. 3(c) is etched for 250 s. The height of the cylinders is between 84 and 152 nm, which is higher than that of sample B. The height of craters that formed on the top of the cylinders is about 30 nm. The height distribution is more uniform than the samples discussed above. The height of sample D's cylinders is between 151 and 169 nm, which is higher than that of sample C and the height of the craters is about 40 nm.

Figure 4 shows the I–V characteristics of GaN-based-LEDs with a textured ITO layer under different etching conditions. The original ITO/GaN LED is also shown for reference purpose. The output power of the samples is also illustrated in Fig. 4. The GaN LEDs with textured ITO layers were etched for 175, 250 and 300 s, respectively. It has been found that the I–V characteristics of the samples treated under the three conditions described above and the sample with original ITO layer were almost the same. The forward voltages of these samples at 350 mA are 3.09, 3.082, 3.078, and 3.086 V for textured ITO layer etched for 175, 250, 300 s and conventional ITO/GaN, respectively. Such result indicates that the p-GaN surface has not been damaged during the ICP etching time and the output power is proportional with etching time. The output power of conventional ITO/GaN and textured ITO layer etched for 175, 250, 300 s at an injection current of 350 mA are 142.5, 149.5, 150.6, 160.9 mW, respectively. Therefore, the output

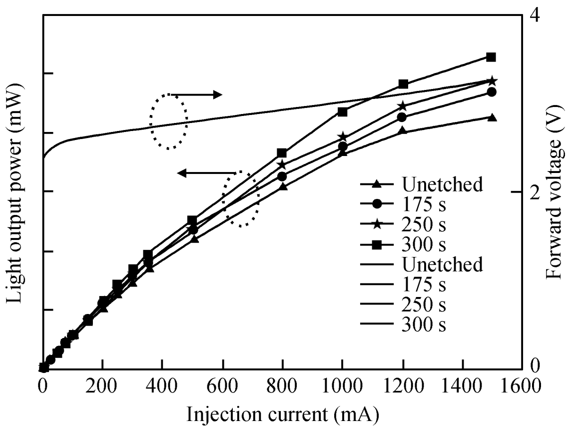

Fig. 4. $I-V$ characteristics and the output power of the four samples.

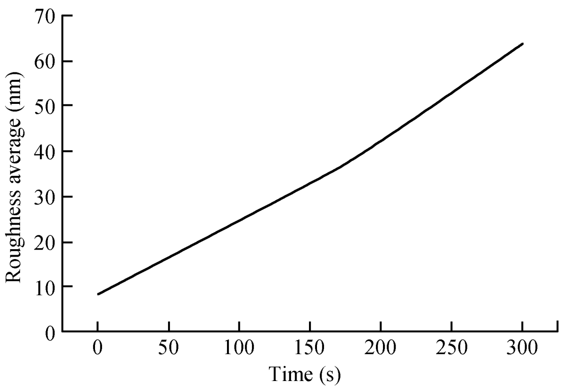

Fig. 5. Relationship between the surface roughness and the etching time.

power of ITO textured GaN LEDs etched for 175, 250, 300 s is 4.91%, 5.68% and 12.91% higher than that of the conventional ITO/GaN LEDs, respectively. This result indicates that higher light output intensity can be attributed to the reduction of the total internal reflection and an increase of surface light scattering induced by the formation of a textured ITO surface.

Figure 5 illustrates the relationship between the surface roughness and the etching time. The surface roughness of an ITO surface is vital to the output power of LED chips. The output power increases with an increase of surface roughness.

The polar radiation pattern of the conventional LEDs and the LEDs with textured ITO at different times are shown in Fig. 6. The polar radiation pattern of ITO etched LEDs is wider than that of the conventional LED. The device being etched with 300 s has the widest polar radiation pattern among them all. The light extraction from the LED-air interface has been improved significantly with the textured surface and it has been observed that higher output power can be obtained from the LEDs with textured surface. Therefore, the radiation profile is highly related to the etching depth of ITO.

The surface roughness and height of cylinders and craters have a great influence on the output power of LED chips. The output power increases with an increase of the parameters mentioned above. Total internal reflection of light at the ITO-GaN interface was reduced due to formation of cylinders and craters, which leads to an increase of the output power of devices. In

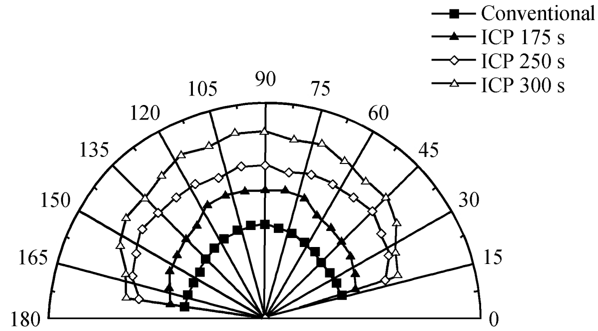

Fig. 6. Polar radiation pattern of the conventional LEDs and the LEDs with textured ITO at different times.

addition, the increment can be further improved by obtaining larger size self-assembly film and optimizing the uniformity of the PS particle distribution in the film.

4. Conclusion

In this study, indium tin oxide (ITO) textured film was fabricated by using the self-assembly method and dry-etching. The surface morphologies and surface roughness are observed by using an AFM. The $I-V$ characteristics, output power and polar radiation pattern were measured for comparison. Cylinders and craters were found on the ITO surface, the height of which increase with etching time. It has been found that the output power of the LEDs with textured ITO film is proportional to the parameters. Total internal reflection of light on the ITO-GaN interface is reduced due to the formation of cylinders and craters, and it can be further reduced with increasing height of the formed structure. The cylinders and craters provide more opportunities for photons to emit. Meanwhile, many rays that emerge at angles larger than the critical angle can also emit from the ITO-air boundary after numerous refractions. The numerous refractions are caused by the cylinders and craters on the ITO surface. Therefore, the output power of the devices can be improved.

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