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Fabrication of nano-pillar array of surface Texture on GaN-based Light-Emitting Diode by Nanoimprinting Lithography

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1. Introduction

Presently, GaN-based LEDs are considered as the most promising candidate of light sources for the next generation solid state lighting. The various application of LEDs such as backlights for liquid crystal display (LCD) televisions and traffic signal lights. The light extraction efficiency of GaN-based LED is limited by difference in refractive index between GaN film and the surrounding air. According to Snell's law [1], the light extraction efficiency of GaN-based LEDs is limited that come from the large difference in refractive index between GaN with refractive index of 2.5 and air with refractive index of 1.0. The critical angle for the light from the InGaN–GaN active region escaped outward to ambient air is only about 23°. In order to avoid total internal reflection, the attempts of surface texture method[2-4] and insertion of two-dimensional(2D) photonic crystals have been studied.[5-7] However, any kinds of patterns with nano-scale feature can be formed by e-beam lithography or interference lithography and cannot be applied for mass production of LED devices. Comparing to above patterning technology, imprinting lithography is simpler and has higher throughout. Further, this technology has unique abilities in fabricating nanometer size and mass production[8-9]. In this study, Nanoimprinting lithography has been employed to fabricate polymeric nano-pillar array as nano-scale surface texture on GaN-based LEDs to improve the light extraction efficiency.

2. Experimental Method

InGaN/GaN MQW LEDs were grown on c-plane sapphire substrates by metalorganic chemical vapor deposition (MOCVD). Trimethylgallium (TMGa), trimethylindium (TMIn), and ammonia were used as Ga, In, and N sources, respectively. Bis(cyclopentadienyl) magnesium (Cp_2Mg) and disilane (Si_2H_6) were used as p- and n-type doping sources, respectively. We first performed the growth of 1-μm-thick undoped GaN buffer layer, followed by the growth of 1-μm-thick n-type GaN layer, five-pair InGaN/GaN MQW with the period thickness of 18 nm, and 0.2-μm-thick p-type GaN layer.

After the epitaxial growth, we deposited the transparent Indium tin oxide (ITO) film onto the surface and then deposited the contact electrodes of Cr/Pt/Au to promote carriers injection by E-Beam evaporator.

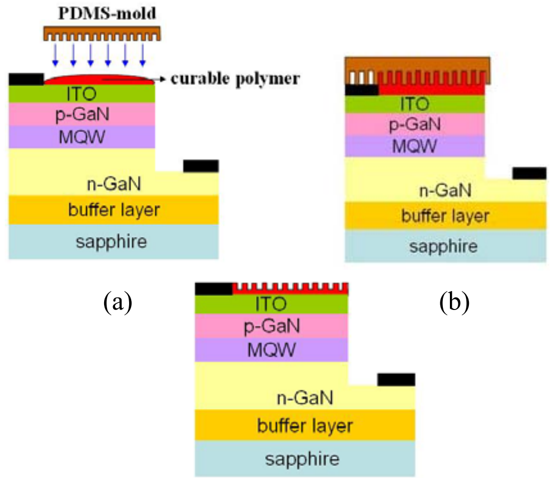


Figure1 The process of fabricated nano-scale surface texture on LED decice. (a)Dripped a drop of thermal curable epoxy on the surface of LED device before imprinting process. (b)The PDMS-mold was pressed with adequate force. (c) The PDMS-mold was removed after imprinting process and Epoxy cured.

The photonic crystal structure as the periodic surface texture onto ITO layer of above LED device was fabricated by nano-imprinting technology. The curable epoxy have employed as periodic surface texture material. A pattern with nano-pillar arrays of 200nm in diameter and 200nm in depth was fabricated on silicon as original mold by electron-beam lithography. And the pattern was transferred from original mold to the PDMS(polydimethyl siloxane) substrate to form nano-hole arrays so that the PDMS-mold has fabricated. Further, this PDMS-mold was employed to nano-imprinting process. The process was followed as figure 1(a)-(c). First, a drop of curable epoxy was dripped on ITO surface of LED device. The PDMS-mold was pressed adequate force onto this epoxy until the one spread whole of the surface as shown in figure 1(a) and 1(b). In order to thermal curing the epoxy, the temperatures of the device was raised to 100℃ by hot-player and hold 30 minutes to ensure polymerization for epoxy. Finally, after the temperature was cooling down to room temperature and the PDMS-mold was removed. The pattern with nano-pillar arrays was transferred to ITO surface as surface texture of GaN-based LED device from PDMS-mold, as shown in Figure 1(c).

The current-voltage (I-V) and light intensity-current (L-I) characteristics of the fabricated LED were measured by a Wei Min LED tester system (LED-628). The original Si-mold, PDMS-mold and the nano-pillar array of surface texture of LED device were observed by scanning electron microscopy (SEM) to ensure the fidelity of transferred pattern.

3. Results and Discussion

The periodic nano-pattern array has been observed from figure 2(a) and 2(b). The periodic nano-pillar array with 200nm in diameter and 400 nm in pitch were fabricated on the surface of LED device. And the depth nano-pillar was about 200nm approximately. From above SEM images, the fidelity of Si-mold compared to surface texture of LED was very high via twice imprinting process. And the expansion and compression of epoxy hasn't been observed. Thus, the polymeric thermal curable epoxy was suitable to be an etching barrier or be a material of transferred pattern with nano-scale feature in NIL.

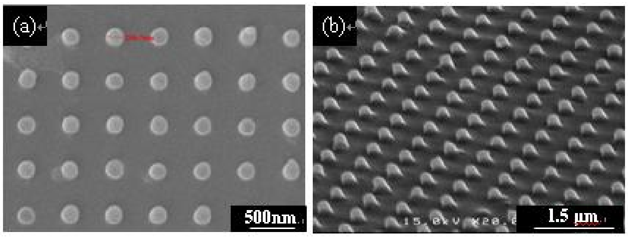
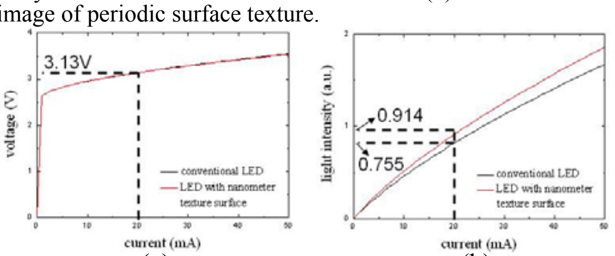


Figure 2. The SEM images of surface texture of LED device. (a) The surface texture of LED device with periodic nano-pillar arrays of 200nm in diameter was observed. (b) The tilt-45° SEM image of periodic surface texture.



(a) (b)

Figure 3 The (a)I-V, (b)L-I characteristics of conventional LED and the LED with nano-pillar array of texture surface.

The current-voltage (I-V) characteristics of conventional LED and the LED with nano-pillar array of texture surface were measured, as shown in Figure 3(a). The forward voltages of conventional LED and LED with nano-pillar array of texture surface at 20 mA of injection current both were 3.13 V. And their I-V curves were overlapped completely. We presumed that the electric characteristic of LED with polymeric nano-pillar arrays of surface texture compared to conventional LED was not affected by NIL process. And the damage of device was still induced from the imprinting action and the polymerization of epoxy during whole pattern transferred process.

The light intensity-current (L-I) characteristics of the conventional LED and LED with nano-pillar arrayof texture surface were measured, as shown in Figure. 3(b). The result revealed that the LED with periodic nano-pillar array has higher light intensity comparing to conventional LED device. Under forward bias, the light intensity of LED with nano-scale texture surface and conventional LED at 20 mA were 0.755 (a.u.) and 0.941 (a.u.), respectively. The reason of improvement of light intensity was considered that the nano-pillar array texture surface was helpful to enhance the light extraction efficiency. The escape probability of photons generated in the active layer of the LED can be enhanced by increasing the angular randomization of photons at the roughened surface [10]. In our result, the combination of the nano-pillar array of texture surface was able to disperse effectively the angular distribution of photons in the optical phase space, leading to a larger escape cone in the texture surface over the planar structure. And the angle should been increased for the light generated in the InGaN–GaN active region. However, the refractive index of epoxy is about 1.5 between ITO thin film and the ambient surrounding air. The larger difference in reflective index of interface boundary was reduced by fabricated this polymeric epoxy. From above reason, the light intensity of the GaN-based LED with polymeric nano-pillar array of surface texture was enhanced 24%, compared to conventional LED device.

4. Conclusions

In this study, the LED with periodic nano-pillar array of surface texture was fabricated by twice nano-imprinting technology with thermal curable exopy. The nano-pillar array was transferred completely to the surface of GaN-based LED from Si-mold. The higher fidelity of transferred pattern was reached by this process. In the current-voltage and the electroluminescence and characteristic, the forward voltage didn't been affected and the light intensity was enhanced 24%. Our result revealed that the pattern are of good replica of the related original mold after positive-negative-positive transfer step. Thus, to fabricate the surface texture with nano-scale pattern on the LED device is easier and inexpensive via nano-imprinting technique.

5. References

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