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Improvement of GaN-based LED with SiO_2 photonic crystal on an ITO film by holographic lithography

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GaN-based light-emitting diode (LED) with SiO_2 photonic crystals (PCs) structure made by holographic lithography on an indium-tin-oxide (ITO) film was fabricated. The PCs made on SiO_2 but an ITO film both improves the light extraction efficiency of the GaN-based LED and prevents the sheet resistance increasing of the ITO film from the dry etching damage. It was found that the forward voltage at 20 mA of the GaN-based LED with SiO_2 PCs on an ITO film was 1.9% higher than the GaN-based LED with a planar ITO film only. The output power of GaN-based LED with SiO_2 PCs on an ITO film at 20mA was 17.1%, 26.5% and 125.3% higher than that of the GaN-based LEDs with the planar SiO_2/ITO, planar ITO or Ni/Au surface layers, respectively.

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1 Introduction In the recent years, GaN based wide band-gap compound semiconductors have attracted lot attention as the commercial productions of light-emitting diodes (LEDs) [1]. The GaN based LEDs have been extensively used in the variety of applications such as full color display, optical communication, traffic light, and daily lighting. The external quantum efficiency is important for high brightness GaN based LEDs, however the external quantum efficiency is limited by the total internal reflection of the generated light, because of the large difference in refractive index between the semiconductor and air. There are lots theses concentrated on the increment of external quantum efficiency. Roughening the top surface is an efficient method to enhance the light extraction efficiency of the GaN-based LEDs [2-4]. The rough surface of the GaN-based LEDs is easy to be fabricated by partially etching the top p-type GaN layer. However, it is hard to prevent the surface plasma bombardment effect and control the etching depth so that the rough surface fabricated by etching the planar surface may cause the damage of the p-type GaN layer. It is reported that the light extraction efficiency of the GaN-based LEDs can be improved by fabricated a textured indium-tin oxide (ITO) transparent contact layer on the p-type GaN layer. Some studies revealed that the textured patterns could be fabricated by the photolithography and natural lithography on ITO layer, respectively [5]-[6]. Fabricating the textured ITO can both increase the light extraction efficiency of the GaN-based LEDs and prevent the damage of top p-type GaN layer, but it still increases the sheet resistance of the ITO layer. The holographic lithography is an application of the monochromatic laser beam interference, and achieves a mass production of the large area 2D photonic crystals (PCs) array pattern [7]. In this study, the silicon dioxide (SiO_2) textured by holographic lithography with a 2D PCs pattern was applied to enhance the light extraction efficiency and prevent the damage of the ITO and p-type GaN layers.

2 Experimental

The blue GaN multiple quantum well (MQW) LED wafer with peak wavelength of 470 nm was used in this study. The wafer was grown on c-face sapphire by the metal-organic chemical vapor deposition (MOCVD). The struc-

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ture consisted of a GaN nucleation layer, a 4 μm thick Si doped n-GaN cladding layer, a 0.1 μm InGaN-GaN MQW active layer, a Mg doped p-AlGaN cladding layer, and a Mg doped p-contact layer. The GaN epi-wafer was cleaned with HCl:H_2O (1:1) solution. A 3 nm Ni layer was deposited by the electron beam evaporation system on the p-GaN layer with a 350 ^oC heat treatment under oxygen flowed for 30 min in the chamber immediately. The Ni layer was oxidized by the heat treatment and form the

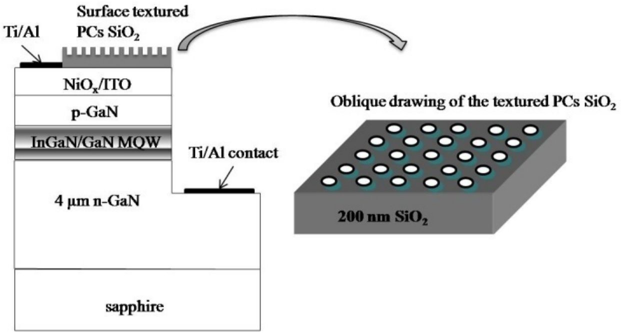

Figure 1 The schematic structure diagram of the surface SiO_2 textured GaN-based LED.

NiO_x served as an ohmic contact layer to the p-GaN. Then the chamber was set to 300 ^oC and then a 200 nm ITO layer was deposited in the same oxygen ambient. A dimension of 300 x 300 μm^2 LED mesa pattern was etched with a reactive ion etching (RIE) to a depth of 1-μm until the n-type GaN layer was exposed, and the Ti/Al (50 nm/200 nm) deposited by electron beam evaporation was employed for the n-electrode and both p-type and n-type bonding pads. Subsequently, a SiO_2 (200 nm) layer was deposited by a plasma enhanced chemical vapor deposition (PECVD) onto the ITO layer. A textured photoresist PCs pattern was fabricated by the holographic lithography method on the surface of SiO_2/ITO/NiO_x/LED layers, and the SiO_2 was etched by the RIE in the SF_6/Ar ambient. The period and diameter of the PCs photoresist mask were 500 nm and 400 nm as the two-dimensional array, respectively. After the RIE dry etching, the remained photoresist was removed by acetone and the GaN-based LED with a textured PCs SiO_2 surface was obtained. Standard GaN-based LEDs with planar-SiO_2/ITO/NiO_x, ITO/NiO_x and Ni/Au as the surface contact layers were also prepared for the comparisons.

3 Results and discussion The textured SiO_2 PCs surface layer was fabricated by the holographic lithography and dry etching methods. Fig. 1 shows the schematic structure diagram of the GaN-based LED with SiO_2 PCs layer. In Fig. 2, the top view of SiO_2 PCs textured surface was observed by the scanning electron microscopy (SEM) and the photograph is shown. The shape of the holographic lithography PCs pattern was designed as circles array originally, but after the lithography and dry etching process, the shape became ellipses. This could be attributed to the con-

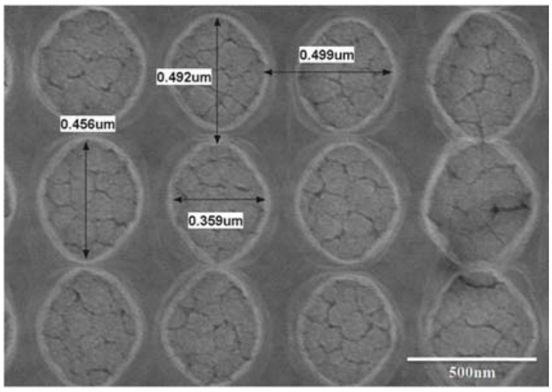

Figure 2 SEM photograph of surface textured PCs SiO_2 layer by holographic lithography.

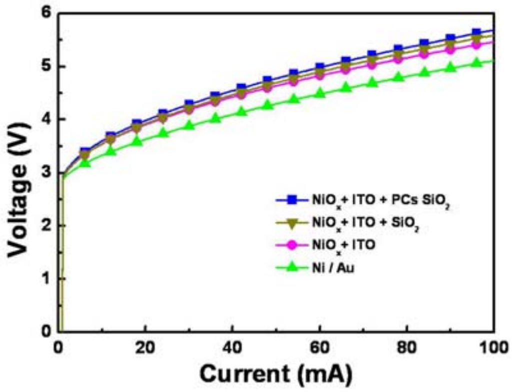

Figure 3 Current-voltage characteristics of GaN-based LEDs with textured PCs-SiO_2/ITO, planar-SiO_2/ITO, ITO and Ni/Au surface.

dition of the multi-direction laser interference exposure was not optimized in the holographic lithography process. Figure 3 shows the forward voltage-current characteristics of the GaN-based LEDs with textured PCs-SiO_2/ITO, planar SiO_2/ITO, ITO and Ni/Au surface top layers measured at room temperature. The forward voltages of LEDs with the textured PCs-SiO_2/ITO, planar-SiO_2/ITO, ITO and Ni/Au surface layers at 20 mA are 3.98, 3.92, 3.91 and 3.63 V, respectively. The textured PCs SiO_2 on ITO surface GaN-based LED exhibits the similar forward voltage characteristic as the planar-SiO_2/ITO and ITO surface LEDs at 20 mA. Figure 4 shows the current-output power characteristics of the four different surface layers GaN-based LEDs. In Fig. 4, it is found that the output power of the GaN-based LED with textured PCs-SiO_2/ITO surface layer is 17.1%, 26.5% and 125.3% higher than that of the LEDs with the planar-SiO_2/ITO, ITO or Ni/Au surface layers, respectively. The output power of the GaN-based LED with planar-SiO_2/ITO surface is 8.2% higher than that of the LED with ITO surface because the refractive indices of the prepared SiO_2 and ITO films are around 1.5 and 1.7,

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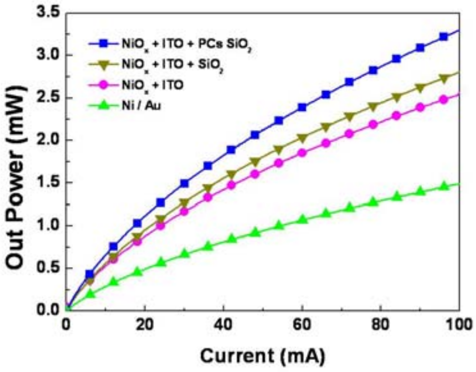

Figure 4 Current-output power characteristics of GaN-based LEDs with textured PCs-SiO_2/ITO, planar-SiO_2/ITO, ITO and Ni/Au surface.

respectively. Therefore, the lower refractive index of the SiO_2 film than ITO would enlarge the total reflection angle and increase the probability of the light escaping from the semiconductor surface. Compared with the planar-SiO_2/ITO surface GaN-based LED, the roughened surface of the textured PCs-SiO_2/ITO LED could further improve the light extraction efficiency because of the surface roughness structure; however, the low refractive index of the SiO_2 film diminishes the effect of the surface roughness. Consequently, it is found that the output power of the GaN-based LED with surface textured PCs-SiO_2/ITO layer is enhanced by the textured surface PCs structure and the low refraction index compared to that of the LEDs with planar-SiO_2/ITO, ITO or Ni/Au surface layers, and the current-voltage characteristics of the LEDs with textured PCs-SiO_2/ITO, planar-SiO_2/ITO and ITO surface layers are almost the same.

4 Conclusion The GaN-based LED with textured PCs SiO_2 on ITO layer fabricated by the holographic lithography and dry etching methods were investigated. The LED with textured PCs SiO_2 on ITO surface exhibited the improvement of the light extraction efficiency and a negligible increment of the forward voltage. The surface textured PCs SiO_2 on ITO layer both increases the output power and protects the ITO and p-GaN layers from the surface damage in the dry etching roughening process.

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