GaN-LED’s on Nano-etched sapphire substrate by metal-organic chemical vapor deposition

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ABSTRACT

385nm InGaN/GaN based light emitting diodes (LEDs) were fabricated on a nano-patterned sapphire substrate formed with nano-imprint lithography technique by metal organic chemical vapor deposition (MOCVD). The characteristics of the LEDs were evaluated by atomic force microscopy (AFM), cathodoluminescence (CL), I-V and Electroluminescence (EL) method. The output power of the LEDs on nano-patterned sapphire at forward current with 20mA was 40% higher than that of LEDs grown on non-patterned sapphire substrate.

1.INTRODUCTION

GaN-based LEDs has been widely developed in the applications for solid state illumination and lighting. However, the external quantum efficiency of GaN-based LEDs is generally low. Because the light originated in active layer is totally reflected at GaN/sapphire and GaN/air interface over the critical angle due to the large refractive index of GaN($n_{\lambda=385nm}$=2.8)[1], which is lager than those of sapphire and air.

There are many reports for the improvement of light extraction efficiency for LED. Fujii et al. reported that the output power was improved by roughening the top surface of a LED [2]. In this case, the roughened top surface of the LED scatters the emitted light and the output power was increased.

However, There are few reports about the LED grown on nano-patterned sapphire substrates. In this work, we investigated the characteristics of the LEDs on the nano-patterned sapphire substrates. If the size of nano-patterns structure is shorter than the wavelength of the light, the light feels this structure to be a layer with the refractive index of the middle value of sapphire and GaN. When the depth of this structure is deeper than $\lambda/4n$, the light repeats reflection and transmission at each boundary face. As a result, total output power of rear side would be enhanced. And we also evaluated the effect of GaN epitaxial growth on nano-patterned sapphire substrate.

2.EXPERIMENT

The GaN-based LEDs structures used in this experiment were grown on a nano-patterned sapphire substrates by MOCVD technique. The LEDs structures were consisted of a low temperature GaN buffer layer, 10μm-thick undoped GaN layer, n-type GaN layer, GaN/InGaN active layer and p-type GaN layer, as shown in Fig.1. Several kinds of samples, which sapphire substrates had various size of nano-patterned structure, and non-patterned sapphires, were prepared.

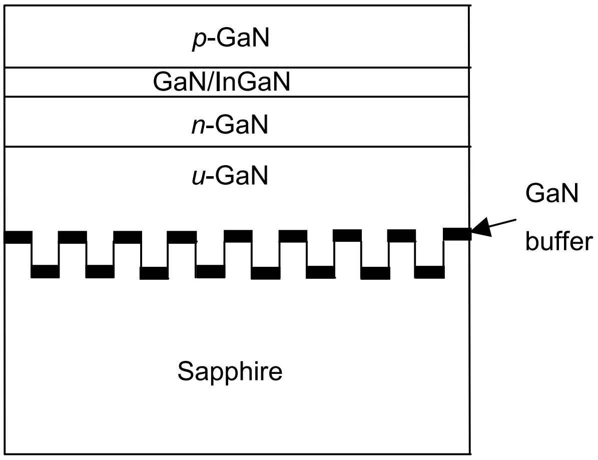

Fig.1 LED structure used in this experiment.

By using nano-imprint lithography technique, nano-structures over 2inchϕ area on the sapphire surface were patterned. As shown in Fig.2, the patterned substrates were made with 5 steps as follows. (1)replicating of nano-patterns by the resin on top of sapphire, (2)removing of backlog of resin using reactive ion etching (RIE) with O_2, (3)etching of sapphire using RIE with BCl_3 [3] and (4)removing of resin using RIE with O_2. The resin has resistance for the etching with CF_4 and BCl_3. Figure3 shows the schematic structures of replicated nano-patterns. All column depths of the replicated nano-patterns are 150nm, and the each diameter were (1)250nm and (2)200nm. The pitch of the columns has twice of each the diameter.

The surface morphology of the sample was observed by AFM. Cathodoluminesence was used also for evaluation of the crystalline quality of the samples. Electrical experiment was performed the examination of the output power of the LEDs.

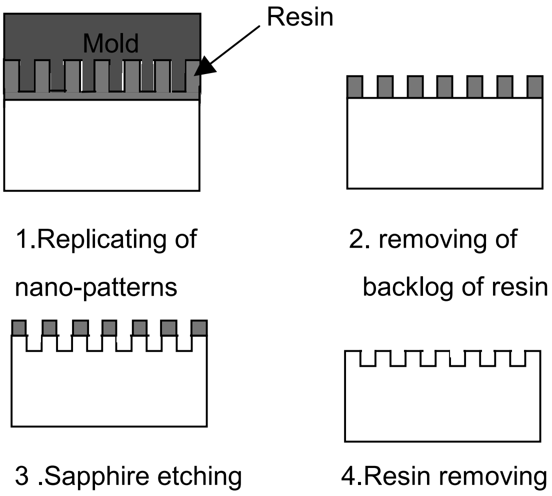

Fig.2 The method of nano-patterns fabrication by using nano-imprint lithography.

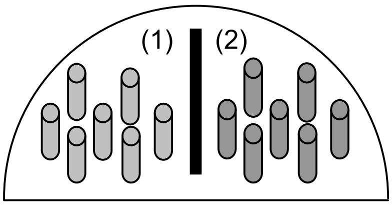

Fig.3 Nano-patterns structure.

3.RESULTS AND DISCUSSIONS

Figure 4 (a) and (b) show AFM images of resin on sapphire surface after nano-imprinting. In Fig.4 (a), the depth, the diameter and the pitch of columns were 130nm, 250nm and 500nm, respectively. In Fig.4 (b), the values were 140nm, 200nm and 400nm, respectively.

AFM images of etched sapphire surface after removing resin are shown in Fig.5 (a) and (b) for the samples with 500nm and 400nm column pitch, respectively. In Fig.5 (a), the column of the depth was 77nm and that of Fig.5 (b) was 71nm. Etching depth of the sapphire was deeper than 43nm, which is calculated by $\lambda/4n$ at λ=385nm and n=2.2. The diameters and pitches of each sapphire were not changed while sapphire etching by RIE. These results suggest that nano-patterned sapphire surface was successively formed by nano-imprint lithography technique.

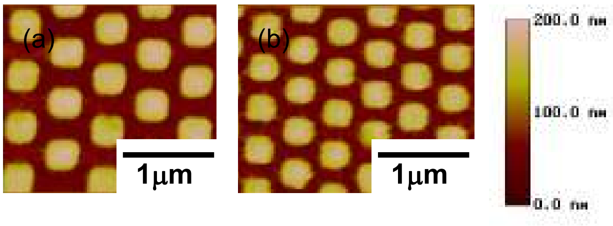

Fig.4 AFM image of top surface replicated nano-patterns. (a) 500nm pitch and (b) 400nm pitch.

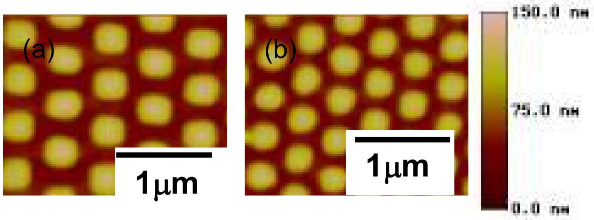

Fig.5 AFM image of etched sapphire surface after removing SiO_2. (a) 500nm pitch and (b) 400nm pitch.

CL images for the sample with the GaN 10μm-thick on non-patterned, 500nm pitch nano-patterned and 400nm pitch patterned sapphire are shown in Fig.6 (a), (b), and (c). Figure 7 shows the pit densities, calculated from the CL images in Fig.6. The pit densities of GaN grown on the non-patterned, 500nm pitch and 400nm pitch sapphire substrate was 1.09μm^{-2}, 0.96 μm^{-2} and 0.85 μm^{-2},respectively. The pit densities for GaN grown on 400nm pitch sapphire had the lowest value. This result suggests that crystalline quality for the sample with 400nm pitch nano-patterned sapphire was better than that of non-patterned and 500nm pitch nano-patterned sapphire.

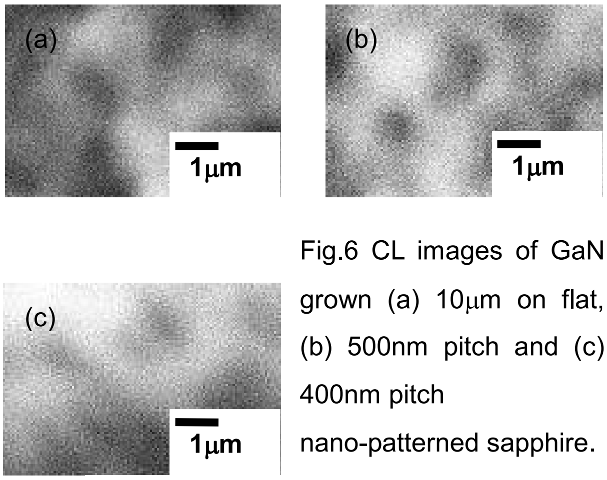

Fig.6 CL images of GaN grown (a) 10μm on flat, (b) 500nm pitch and (c) 400nm pitch nano-patterned sapphire.

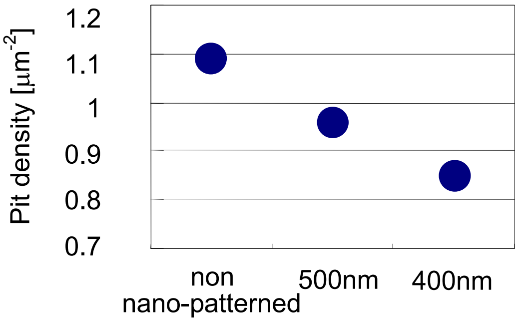

Fig.7 CL pit densities of each sapphire.

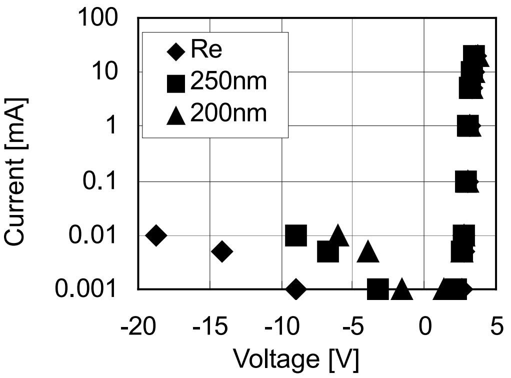

Fig.8 I-V characteristics.

Figure 8 shows I-V characteristics of each LED. In the region of reverse bias voltage, LED fabricated on non-patterned sapphire had the largest break down voltage. Therefore the crystalline quality would be degraded by introduction of nano-patterned sapphire substrate.

The results of EL experiment from the LED fabricated on non-patterned, 500nm pitch nano-patterns and 400nm pitch nano-patters sapphire at forward current of 20mA are shown in Fig.9. In case of LED samples fabricated on 500nm pitch and 400nm pitch nano-patterned sapphire, the 40% enhancement of output power compared to non-patterned sapphire was observed. Even though the crystalline quality of nano-patterned sapphires was degraded, the output power enhanced. The reason for this enhancement of output power would be (1)dislocation densities of LEDs fabricated on nano-patterned sapphire is less than that of LED fabricated non-patterned sapphire, which is confirmed by the results of CL experiment, (2) the light extraction from backside is increased through nano-patterned layer. The much increase of output power is expected by improvement of crystalline quality.

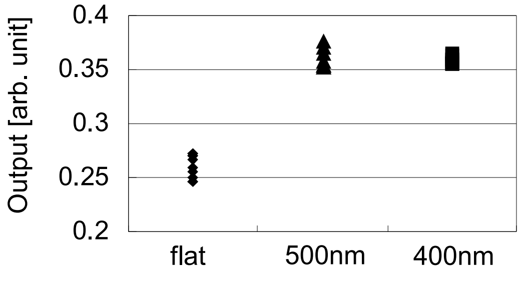

Fig.9 Electroluminescence of each LED @20mA.

4.CONCLUSION

We fabricated the LEDs on sapphire substrates nano-patterned sapphire substrates with the different pitch size by nano-imprint lithography and MOCVD technique. We measured surface morphology, pit densities and output power of these LEDs. The nano-imprint lithography technique is able to form nano-patterns over 2inchϕ size wide area. The extraction efficiency of backside increases using nano-patterned sapphire substrate. When LEDs were fabricated on 500nm pitch and 400nm pitch nano-patterned sapphire substrates, the CL pit density was improved. The output power was 40% lager than that of non-patterned sapphire substrate.

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