Light Extraction Efficiency of GaN-based LEDs with Non-periodic and Periodic Sub-wavelength Structures

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Antireflective non-periodic and periodic sub-wavelength structures (SWSs) are fabricated on indium tin oxide (ITO) layers deposited on p-GaN layers of GaN-based green light-emitting diodes (LEDs). The light output powers of the LEDs using non-periodic and periodic SWSs are increased by 18% and 39% at a 20-mA input current, respectively, compared to LEDs with flat ITO layers. Periodic ITO SWSs show a larger enhancement of output power because they have more effective profiles of the graded refractive index. The output power of periodic SWS LEDs is improved in all angular directions, indicating that the improved output power is attributed to lower total internal reflection and lower Fresnel reflection.

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I. INTRODUCTION

GaN-based light-emitting diodes (LEDs) are attractive devices for use in a variety of applications, including traffic signals, full-color displays, backlighting for liquid-crystal displays, and solid-state lighting. The rapid development of epitaxial growth techniques has significantly improved the internal quantum efficiency of LEDs. However, the light extraction efficiency of GaN-based LEDs is limited by the large refractive index difference between the GaN film (n = 2.5) and the surrounding air (n = 1). Therefore, various methods have been proposed to increase the light-extraction efficiency, including conductive reflection layers [1,2], photonic crystals [3–6], patterned substrates [7–10], and textured surfaces [11–16].

When the angle of incidence of the light is greater than the critical angle, total internal reflection (TIR) occurs at the interface between GaN and air. If the angle of incidence is smaller than the critical angle, TIR does not occur, but Fresnel reflection still occurs. For example, TIR is not observed at a normal incidence angle, but 18% of the light is reflected back to the LED because of Fresnel reflection [17], which results in a decrease in the light-extraction efficiency of the LED.

An antireflective sub-wavelength structure (SWS) is a promising candidate for high-efficiency LEDs because of its excellent antireflection properties [18–23]. The light extraction efficiency of LEDs was recently reported to be increased by using non-periodic SWSs fabricated on hexagonally patterned microstructures [18]. The antireflective SWSs are tapered feature with a gradient refractive index. When the grating period is smaller than the wavelength, all higher-order diffracted fields are evanescent, and only the zero-order field propagates [24,25]. The SWSs can, therefore, be regarded as a homogeneous medium with an effective refractive index. The effective refractive index is determined by the filling factor of the grating and the groove media. This means that the peri-
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The light extraction efficiency depends on the period and the height of the SWS [21–23,26]. However, because no studies have reported on the effect of non-periodic and periodic SWSs on the performance of LEDs, we studied the effects of non-periodic and periodic ITO SWSs on the light extraction efficiency of LEDs.

II. EXPERIMENTS AND DISCUSSION

LEDs with a green emission at 525 nm were grown on c-plane sapphire substrates by using metalorganic chemical vapor deposition (MOCVD). The green LEDs consisted of a nucleation layer, a 2-μm-thick Si-doped GaN layer, multiple quantum wells (MQWs) with 5 periods of undoped 2-nm-thick InGaN wells and undoped 8-nm-thick GaN barriers, and a final Mg-doped p-GaN layer with a thickness of 0.2 μm. A hole concentration of $3 \times 10^{17}$ cm$^{-3}$ was obtained after thermal annealing of the p-GaN layer. A 400-nm-thick ITO layer, as a transparent conducting layer, was deposited on the p-GaN layer by using electron-beam evaporation, followed by thermal annealing at 500 °C for 1 min in ambient air. Figures 1(a) and (b) schematically illustrate the process used to fabricate the LEDs with non-periodic and periodic ITO SWSs, respectively. A SiO$_2$ layer with a thickness of 200 nm was used as an etch mask for both the non-periodic and the periodic ITO SWSs. It was reported previously that the height of the ITO nano-cones should be greater than 0.4 times the wavelength to minimize reflection. If the height becomes comparable to or higher than the above condition, the reflectance still maintains its minimum value [27]. As shown in Fig. 3, the average heights of the non-periodic and the periodic ITO SWSs are 228 nm and 250 nm, respectively, and these are higher than the 210 nm that corresponds to 0.4 times a wavelength of 525 nm. This indicates that the height difference of the ITO SWS in this study is not crucial to the reflectance of the ITO SWS. To fabricate LEDs, we etched the p-GaN layer by using an inductively coupled plasma (ICP) etching process with Cl$_2$/CH$_4$/H$_2$/Ar source gases until the n-GaN layer was exposed for use as a n-type ohmic contact. Green LEDs with a size of 300 × 300 μm$^2$ were fabricated using the non-periodic and the periodic ITO SWSs as a transparent current layer but also an antireflection coating. A Cr/Au film with a thickness 50 nm/150 nm was deposited as a n- and p-pad electrode by using e-beam evaporation.

Figure 1(a) shows the process used to fabricate the non-periodic ITO SWSs. First, a 7 nm-thick Ni layer was deposited on the SiO$_2$ layer by using electron-beam evaporation. The Ni layer was then annealed by using a rapid thermal annealing (RTA) process at 500 °C for 5 min under a nitrogen atmosphere. The self-assembled agglomeration process produced nano-scale Ni islands on SiO$_2$.

Figure 2 shows a scanning electron microscope (SEM) image of the Ni islands on SiO$_2$. The SiO$_2$ layer with a random Ni mask was etched by reactive ion etching (RIE) to form SiO$_2$ pillars on the ITO layer. Finally, the ITO layer with the SiO$_2$ pillar mask was etched by using an ICP-to fabricate the non-periodic ITO SWS, as shown in Fig. 3(a). ITO etch parameters such as the...