# Nitride-based light emitting diodes with indium tin oxide electrode patterned by imprint lithography

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The authors propose a simple, low cost, and mass producible imprint lithography method to texture indium tin oxide (ITO) contact layer of nitride-based light emitting diodes (LEDs). Under 20 mA current injection, it was found that forward voltages were 3.24, 3.25, and 3.24 V while the LED output powers were 11.7, 12.6, and 13.3 mW for the conventional ITO LED, ITO LED patterned with 1.75 $\mu$m holes, and ITO LED patterned with 0.85 $\mu$m holes, respectively. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2753726]

Instead of conventional Ni/Au, one can use transparent indium tin oxide (ITO) as current spreading layer for GaN-based light emitting diodes (LEDs).[1] Indeed, it has been demonstrated that ITO LEDs are much brighter than Ni/Au LEDs. To further improve LED output intensity, one can texture the LED surface.[2,3] Previously, Pan *et al.* used standard photolithography and dry etching to fabricate InGaN–GaN LEDs with surface-textured ITO.[4] With the textured surface, they achieved 16% output power enhancement, as compared to planar ITO LEDs. However, they also found that 20 mA forward voltage increased from 3.46 to 3.56 V, probably due to dry etching induced damages. Leem *et al.* used laser holographic lithography (LHL) to pattern ITO LEDs and achieved 29.6% output power enhancement.[5] However, the LHL method is complex and difficult for mass production. Very recently, Cheng *et al.* applied imprint lithography to define ITO stripes and fabricated organic LEDs.[6] Compared with conventional photolithography, imprint lithography is simple, low cost, and mass producible.[7] In this study, we apply imprint lithography to texture ITO LEDs. Detailed process steps and the properties of the fabricated LEDs will also be discussed.

Samples used in this study were all grown on sapphire substrates by metal organic chemical vapor deposition.[8,9] After the growth, we evaporated a 230-nm-thick ITO layer onto the sample surface. We then performed imprint lithography to pattern the ITO layer. Detailed proceeding steps for imprint lithography are shown in Fig. 1. We first spin coated a polymethyl methacrylate (PMMA) layer on top of the ITO (i.e., step 1). We then placed a patterned hot mold onto the dried polymer film (i.e., step 2). By applying a high pressure, we heated the sample to above the glass transition temperature ($T_g$) of the polymer (i.e., step 3). The sample and the mold were then cooled down to room temperature to release the mold (i.e., step 4). We then used an inductively coupled plasma etcher with short oxygen-based plasma to remove the residual PMMA layer (i.e., step 5) and transferred the pattern onto PMMA (i.e., step 6). Subsequently, we used dilute hydrochloric acid (HCl) to partially etch the exposed ITO. Finally, we used acetone to remove the PMMA on the patterned ITO layer. We used a standard fabrication process to partially etch the epitaxial layer away and then deposited the contact electrodes. The epitaxial wafers were lapped down to 100 $\mu$m. We then used scribe and break to fabricate 350 $\times 350$ $\mu m^2$ InGaN–GaN chips. Two circular patterns were used for imprint lithography. The hole diameter and the spacing between holes of the first pattern were 1.75 and 1 $\mu$m, respectively. For the second pattern, the hole diameter and the spacing between holes were 0.85 and 0.5 $\mu$m, respectively. For comparison, conventional LEDs with planar ITO contact were also fabricated. Figure 2(a) shows a scanning electron microscope (SEM) micrograph of the proposed

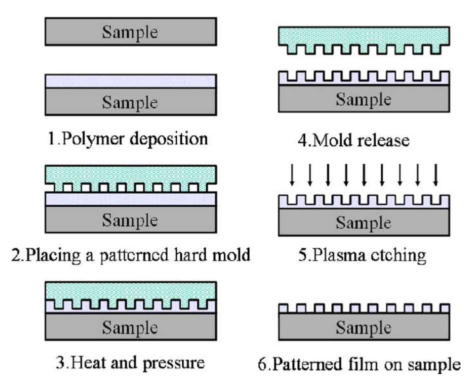


FIG. 1. Detailed proceeding steps for the imprint lithography.

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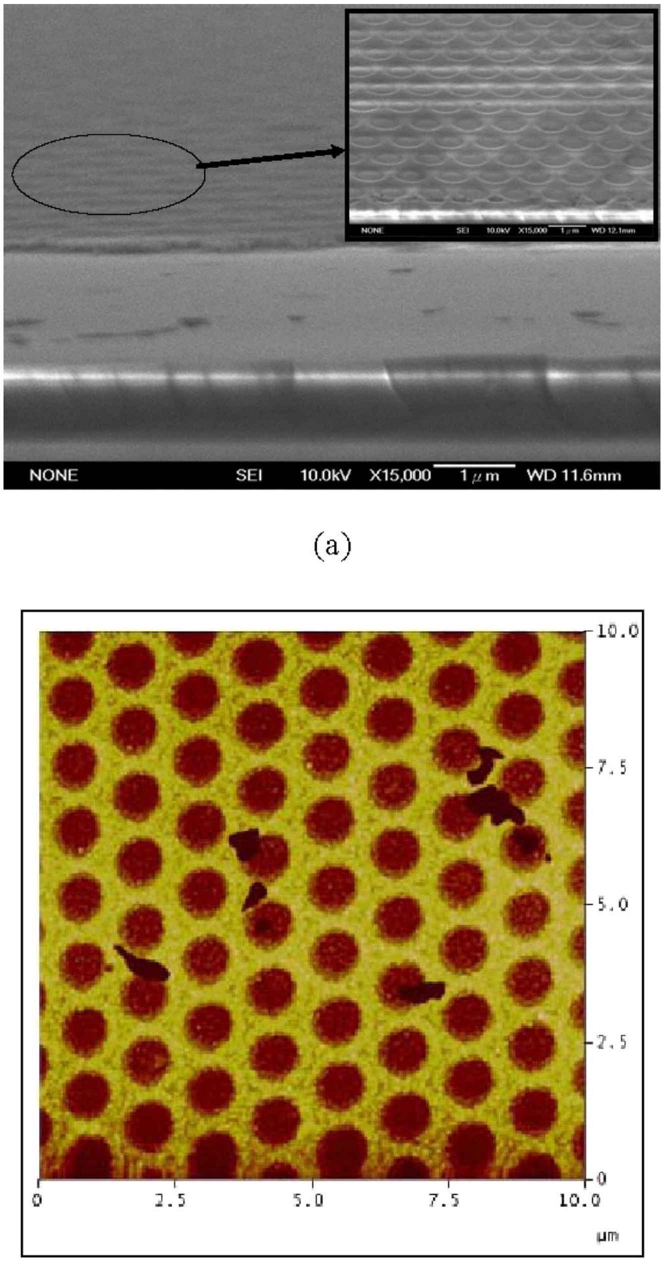


(a)

(b)

FIG. 2. (a) SEM micrograph and (b) AFM image of the patterned LED with 0.85 $\mu$m hole diameter and 0.5 $\mu$m spacing. The inset shown in the upper right corner of (a) shows an enlarged SEM micrograph.

LEDs while the inset shows an enlarged SEM micrograph. Figure 2(b) shows an atomic force microscope (AFM) image of the imprinted ITO LED with the second pattern. It can be seen clearly that the pattern was accurately transferred onto the ITO electrode. It was also found that the hole etching depth was around 90 nm which is much smaller than the original ITO thickness. This suggests that we can still achieve good current spreading.

Figure 3 shows 20 mA electroluminescence (EL) spectra of the fabricated LEDs. It was found that the EL peak positions of these three LEDs all occurred at 453 nm with the same full width at half maximum of 22 nm. It was also found that EL intensities observed from the two imprinted ITO LEDs were both larger than that observed from conventional planar ITO LED. This could be attributed to the enhanced light extraction efficiency of the textured surface.[2,3] Furthermore, it was found that EL intensity observed from ITO LED with 0.85 $\mu$m holes was larger than that observed from ITO LED with 1.75 $\mu$m holes. Such a result suggests that submicron sized holes can scatter light more effectively. Figure 4 shows measured intensity-current-voltage ($L$-$I$-$V$) characteristics of the fabricated LEDs. Under 20 mA current injection, it was found that forward voltages were 3.24, 3.25, and 3.24 V for the conventional ITO LED, ITO LED patterned with 1.75 $\mu$m holes, and ITO LED patterned with 0.85 $\mu$m holes, respectively. The almost identical forward voltages can be attributed to the same epitaxial layers used in these devices. It also indicates that imprint lithography will not degrade the electrical properties of the LEDs. It was also found that output power increased with the injection current and no intensity saturation was observed up to 100 mA for all these three LEDs. Furthermore, it was found that we achieved the largest output power from the ITO LED patterned with 0.85 $\mu$m holes, followed by the ITO LED patterned with 1.75 $\mu$m holes while the output power of the conventional ITO LED was the smallest. With 20 mA injection current, it was found that the LED output powers were 11.7, 12.6, and 13.3 mW for the conventional ITO LED, ITO LED patterned with 1.75 $\mu$m holes, and ITO LED patterned with 0.85 $\mu$m holes, respectively. In other words, we can achieve 12% by using the simple imprint lithography to pattern 0.85 $\mu$m holes on the ITO electrode. It is known that refractive indices of GaN, ITO, and air were 2.5, 2.1, and 1, respectively. According to Snell's law, the critical angles of total reflection at ITO/GaN interface and air/ITO interface are around 57° and 28°, respectively. Thus, a significant amount of photon will be reflected at the sample surface for conventional ITO LEDs, as shown in Fig. 5(a). With the textured ITO surface, photons generated in the multi-

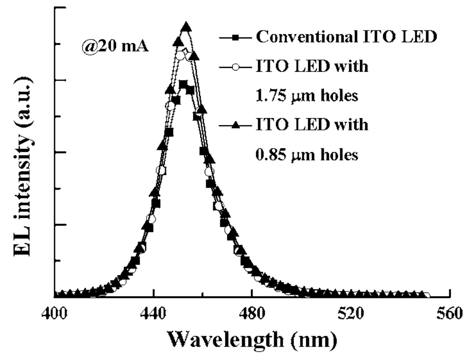


FIG. 3. 20 mA EL spectra of the fabricated LEDs.

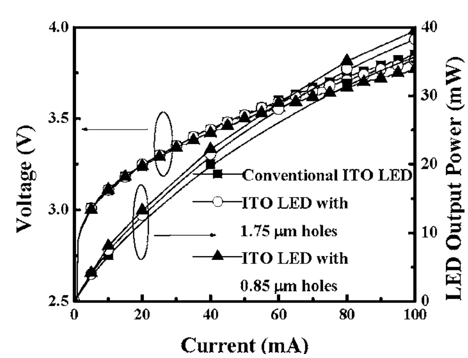


FIG. 4. Measured $L$-$I$-$V$ characteristics of the fabricated LEDs.

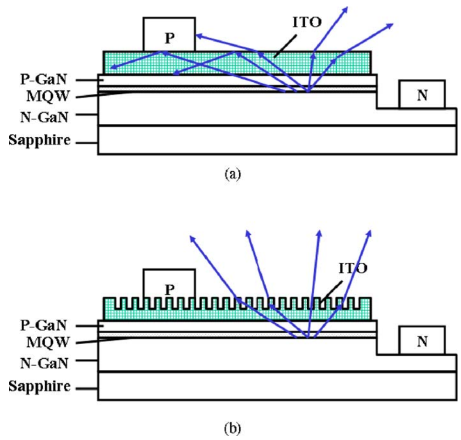


FIG. 5. Schematic drawings of (a) conventional ITO LED and (b) LED with imprinted ITO electrode.

quantum-well region should experience multiple scattering at the sample surface and could escape from the device easily,[3] as shown in Fig. 5(b). Thus, we can achieve larger output powers from the LEDs with imprinted ITO electrode. It should be noted that no optimization was performed in the current study. By optimizing the initial pattern on the mold and the etching depth or adopting a two dimensional photonic crystal structure,[10] we should be able to further enhance the LED output power.

In summary, we propose a simple, low cost, and mass producible imprint lithography method to texture ITO contact layer of nitride-based LEDs. It was found that we achieved 12% enhancement in LED output power by patterning the ITO layer with 0.85 $\mu$m holes. It was also found that imprint lithography will not degrade the electrical properties of the fabricated LEDs.

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