

Research Article

Light Output Enhancement of InGaN/GaN Light-Emitting Diodes with Contrasting Indium Tin-Oxide Nanopatterned Structures

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Various nanopatterns on the transparent conducting indium tin oxide (ITO) layer are investigated to enhance the light extraction efficiency of the InGaN/GaN light-emitting diodes (LEDs). Triangular, square, and circular nanohole patterns with the square and hexagonal lattices are fabricated on the ITO layer by an electron beam lithography and inductively coupled plasma dry etching processes. The circular hole pattern with a hexagonal geometry is found to be the most effective among the studied structures. Light output intensity measurements reveal that the circular hole nanopatterned ITO LEDs with a hexagonal lattice show up to 35.6% enhancement of output intensity compared to the sample without nanopatterns.

1. Introduction

In recent years, InGaN/GaN light-emitting diodes (LEDs) have been used in many applications such as general white lightening, traffic signals, automobile head lights, and back light units of liquid crystal display [1]. Although InGaN/GaN LEDs are being commercially available, it is still necessary to further improve the light extraction efficiency and the internal quantum efficiency for the realization of the high-efficiency and high-power LEDs. There are many methods to improve the efficiency of the InGaN/GaN LEDs such as substrate design, metal reflection layer, distributed Bragg reflector, omnidirectional reflector, truncated-inverted-pyramid chip geometry, nanopatterning, transparent substrate, surface texturing, and laser lift off [2–10]. In addition, the surface texturing or patterning of a p-type transparent conducting layer has been demonstrated to be effective for enhancing light extraction efficiency [11–18]. In the previous works, Pan et al. conducted photolithography and dry etching to fabricate the InGaN/GaN LEDs with a 3 μm square surface-textured ITO [15]. With the textured ITO surface, they achieved 16% output power enhancement compared to the

planar ITO LEDs. Also, Chang et al. reported nitride-based LEDs with an ITO electrode, patterned by an imprint lithography and dry etching [11]. It was found that the LED output power for nanopatterned ITO LEDs with 0.85 μm holes was about 12 and 8% higher than that of the planar ITO LEDs and micropatterned ITO LEDs with 1.75 μm holes, respectively. Such a result suggested that submicron-sized holes can scatter light more effectively. It is thus worth investigating the nanopatterned structure and geometry on the ITO layer of the GaN-based LEDs for achieving the higher light extraction efficiency. Nanopatterning technique has attracted great attentions for more efficient light extraction from the LED structure and various methods are explored. Most of researches have been focused on the influences of periods and hole depths of the nanopatterns on the properties of the LEDs [11, 12, 18]. There are few studies on the light output enhancement by various geometry and shapes of the nanopatterned structure on the transparent conducting oxide layer of the LEDs. In this study, we report the light output analysis of the InGaN/GaN LEDs with varying geometric lattices and hole shapes fabricated on a transparent ITO layer.

2. Experiments

GaN-based LED structures were grown on sapphire substrates by metalorganic vapor phase epitaxy (MOVPE, AIX-TRON, G3 2600HT). For the growth of GaN, trimethylgallium (TMGa) and ammonia (NH_3) were used as the reactant sources for Ga and N, respectively. Silane (SiH_4) and bis(cyclopentadienyl) magnesium (Cp_2Mg) were used as n- and p-type dopants, respectively. A 30 nm thick GaN nucleation layer was grown on a sapphire substrate and followed by 2 μm thick undoped GaN buffer, 3 μm thick Si-doped n-GaN layer, InGaN/GaN multiple quantum wells (MQWs), and 0.15 μm thick Mg-doped p-GaN layer. The MQWs region consists of 3 nm thick InGaN wells and 10 nm thick GaN barriers.

To fabricate 1 mm² LED devices, mesa etching was carried out by a standard photolithography and inductively coupled plasma etching processes. A 200 nm thick ITO was deposited on top of the p-GaN surface as a transparent conducting layer using an electron beam evaporator, followed by annealing at 550°C under the N_2 flow for 4 min to obtain a good p-ohmic contact. After the deposition of Cr/Au for an n-type contact, chip isolation was carried out by a standard photolithography and inductively coupled plasma etchings.

Triangular, square, and circular hole nanopatterns with the square and hexagonal lattices are generated by Layout Editor (L-EDIT, TANNER), which is the gds file generation program. To create the nanopatterns on the ITO layer, the GaN-based LED wafer was coated with 400 nm thick ZEP-520A (ZEON), which is a positive-type electron beam resist. The square and hexagonal nanopatterned structures with various shaped holes including triangle, square, and circle were patterned using a 100 kV electron beam lithography machine (JBX9300FS of JEOL). After the electron beam exposure, electron beam resist was developed by dipping in ZED-N50 (ZEON), rinsed in isopropyl alcohol (IPA), and blown with a N_2 dry gun.

The samples then were etched by an inductively coupled plasma dry etcher (STS, MULTIPLEX LITE ICP System) using a Cl_2/CF_4 gas mixture. The electron beam resist on the etched LED wafer was removed by microwave asher (ULVAC, ENVIRO II) in the mixed O_2 and N_2H_2 gas conditions. Figure 1(a) schematically describes the diagram of the LED chip structure with a patterned ITO surface. The microscopic image of the top view of the fabricated LED chip with a nanopatterned ITO is shown in Figure 1(b). The patterned samples were examined by a field emission scanning electron microscopy (FE-SEM, HITACHI, S-4800). Electroluminescence (EL), current-voltage (I - V), and light output-current (L - I) measurements were carried out using an in-line LED tester (WITHLIGHT, OPI-150). The diameter of the photodetector and the distance between the photodetector and LEDs are 11 and 60 mm, respectively, in the EL measurement conditions.

3. Results and Discussion

The design parameters of the nanopatterns for an ITO layer are summarized in Table 1. The shapes of the nanopatterns consist of triangle, square, and circle with either square or

TABLE 1: The lattice and dimension of the nanopatterns fabricated on the ITO layer by an electron beam lithography.

Nanopatterns	Lattice	Pattern shape	X pitch (nm)	Y pitch (nm)	Pattern dimension (nm)
ST		Triangle	400	400	304
SS	Square	Square	400	400	200
SC		Circle	400	400	226
HT		Triangle	400	693	283
HS	Hexagonal	Square	400	693	186
HC		Circle	400	693	210

hexagonal lattices for comparison study of shape and geometry dependencies on the InGaN/GaN LEDs performances. We designed six different types of nanopatterns, which are square lattice triangular (ST), square lattice square (SS), square lattice circular (SC), hexagonal lattice triangular (HT), hexagonal lattice square (HS), and hexagonal lattice circular hole (HC). The coverage of nanopatterned area is fixed at 25% by controlling the length and pitch of the nanopatterns. The dimensions of the triangular, square, and circular holes are 304, 200, and 226 nm, respectively, with a 400 nm pitched square lattice. In case of the hexagonal lattice, X and Y pitches are 400 and 693 nm, respectively, and the dimensions of the triangular, square, and circular holes are 283, 186, and 210 nm, respectively. Scanning electron microscopy (SEM) images of the fabricated nanopatterns with varying hole-shapes and lattices are displayed in Figure 2. The etched depth of the ITO layer on the LEDs is 70 nm.

Figure 3 shows the injection current versus voltage (I - V) characteristics of the nanopatterned ITO LEDs. Under 20 mA current injection, it was measured that forward voltage for the conventional ITO LED is 2.95 V and that of the nanopatterned ITO LED with the ST, SS, SC, HT, HS, and HC hole structures is 3.03, 3.02, 3.02, 3.00, 3.01, and 2.99 V, respectively. It also reveals that the nanopatterned ITO electrode causes a slight increase of operating voltage. The slightly higher forward voltage could result from the dry etching damage to the ITO layer, which affects the sheet resistances and current spreading [13].

Figure 4 shows the light output versus injection current (L - I) characteristics of the nanopatterned ITO LEDs. The output power increased with the injection current and no intensity saturation was observed up to 100 mA for all the nanopatterned LEDs. It was also found that the highest output power is achieved from the nanopatterned ITO LED with an HC hole structure. For the 20 mA injection current, the LED output powers are 3.25, 3.61, 3.87, 4.03, 3.77, 4.03, and 4.40 mW for the conventional ITO LED, nanopatterned ITO LED with the ST, SS, SC, HT, HS, and HC hole structures, respectively. Table 2 summarizes the relative light output intensity increments of the samples with the different nanopatterns. The light output intensities of the nanopatterned ITO LEDs with the ST, SS, SC, HT, HS, and HC hole structures increase by 11.0, 19.1, 24.2, 16.2, 24.1, and 35.6%, respectively, compared to the one without

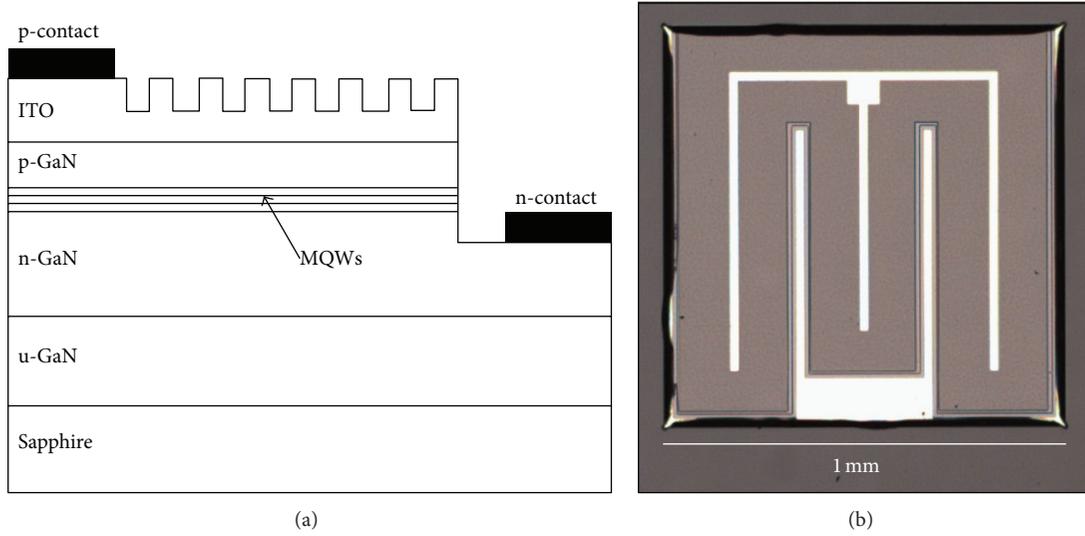


FIGURE 1: (a) Schematic diagram of the InGaN/GaN LED structure and (b) top-view microscopic image of the fabricated ITO LED chip with nanopatterns.

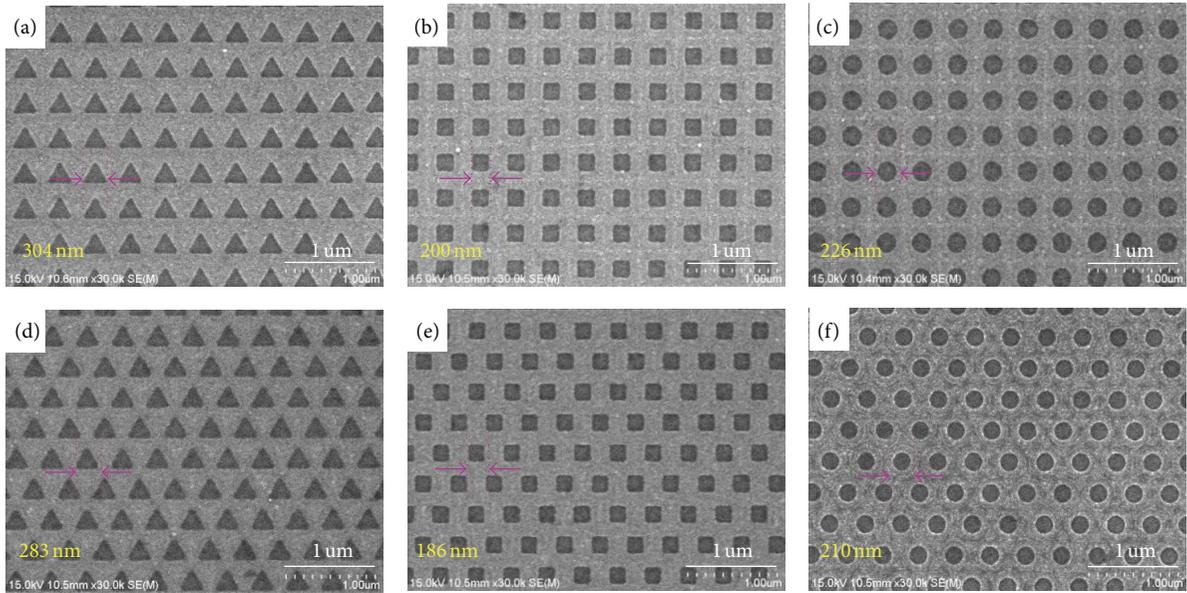


FIGURE 2: SEM images of the (a) triangular, (b) square, and (c) circular holes with the square lattice and (d) triangular, (e) square, and (f) circular holes with the hexagonal lattice on the ITO layer.

the nanopatterns. According to Snell's law, the critical angle of the total internal reflection at air/ITO interface is around 29° , assuming the refractive index of the ITO to be 2.06 at 437 nm wavelength. Thus, a significant amount of photon will be reflected at the sample surface for conventional ITO LEDs. The nanopatterned ITO layer results in the formation of large sidewalls, with which some of the reflected light may escape through the sidewall air/ITO interfaces, resulting in additional light extraction and, in turn, enhancement of the light output power. The more efficient relative light output intensity in the nanopatterned LEDs may be attributed to the improvement of the spontaneous Purcell emission rate [7].

TABLE 2: The relative light output increment of the InGaN/GaN LEDs with a nanopatterned ITO layer.

Lattice type	Relative increment of light output intensity (%)		
	Triangular holes	Square holes	Circular holes
Square	11.0	19.1	24.2
Hexagonal	16.2	24.1	35.6

As shown in Figure 4 and Table 2, circular hole pattern on the ITO layer is measured to be more effective in enhancing the light extraction efficiency than the square and triangular

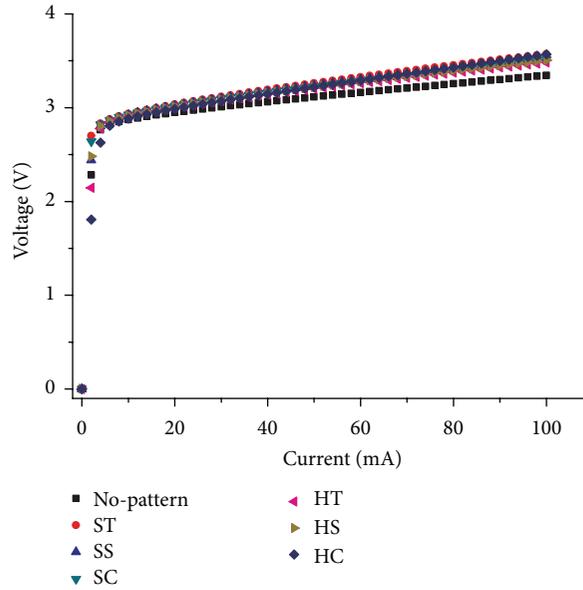


FIGURE 3: Voltage versus current characteristics of the nanopatterned ITO LEDs at room temperature.

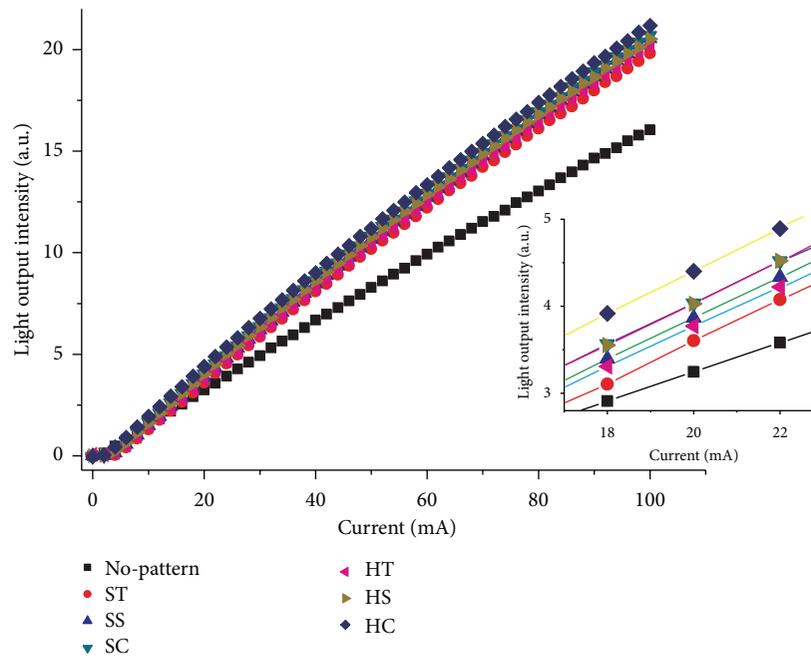


FIGURE 4: Light output versus injection current ($L-I$) characteristics of the nanopatterned ITO LEDs at room temperature. The inset shows light output versus injection current ($L-I$) characteristics at 20 mA injection current.

hole-patterns. Photons generated in the multiple quantum well (MQW) regions may escape more efficiently at the ITO/air sidewall interfaces through the circular hole patterns due to the unfolded side surface areas. Furthermore, the light output of the LEDs with the nanopatterned ITO with a hexagonal lattice is greater than those with the square lattice because the number of hole patterns per unit ITO area of hexagonal lattice is higher than that of square lattice.

Figure 5 shows the room temperature EL spectra of the nanopatterned ITO LED at 20 mA injection current. EL

intensities of the LEDs with the nanopatterned ITO layer are measured to be significantly increased compared to the one without the nanopatterns. The EL intensity of the nanopatterned ITO LEDs with the HC hole structures increases by 35.6% compared to the one without the nanopatterns. Our results for the HC structures with $0.21 \mu\text{m}$ holes show better EL intensity enhancement compared to the previously reported 12% EL enhancement from the nanopatterned ITO LEDs with $0.85 \mu\text{m}$ holes [11]. It could be attributed to the increment of the number of hole patterns per unit ITO area by

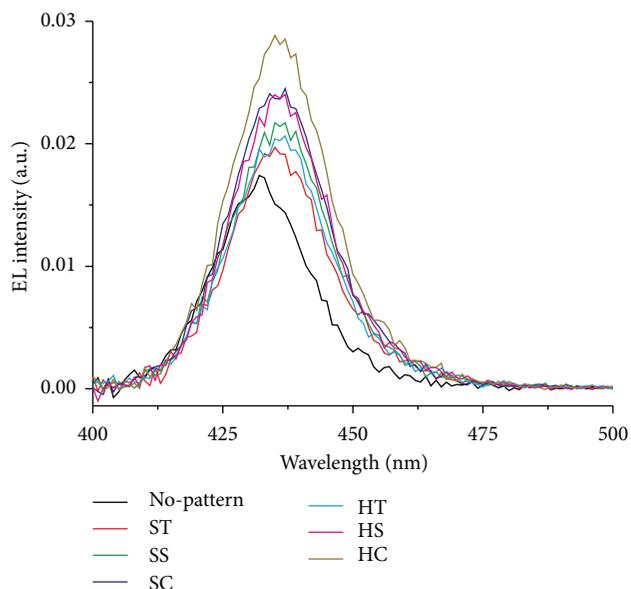


FIGURE 5: EL spectra of the nanopatterned ITO LEDs at room temperature.

the smaller hole pattern, which scatters light more efficiently than the larger hole pattern. The circular nanopatterned ITO LEDs with the hexagonal lattice show the highest enhancement of the EL intensity, consistent with the results from the light output intensity current measurements. The possibility of vertical penetration of photons at the ITO/air hole interfaces is enhanced by the increased surface areas of the circular hole patterns in comparison with the other square and triangular hole patterns. Furthermore, the EL intensity of the LEDs with the nanopatterned ITO with a hexagonal lattice is greater than those with the square lattice. Because the number of hole patterns per unit ITO area of the hexagonal lattice is larger than that of the square lattice, the circular nanopatterned ITO LEDs with the hexagonal lattice show the greatest EL intensity enhancement. The main EL emission peak of the nanopatterned ITO LEDs is measured to be red-shifted; for example, the main peak emission for the nanopatterned ITO LEDs with an HC hole structure was observed at 437 nm, while that of the conventional ITO LEDs was measured at 432 nm. It is known that the main EL emission peak of the InGaN/GaN LEDs with a nanopatterned ITO layer shifts to a longer wavelength compared to the non-patterned ITO LEDs due to the Joule heating effect [19]. This could be attributed to the increased surface areas of the patterned ITO layer, resulting in more heat dissipation through the increased surface.

4. Conclusions

Various nanopatterns have been fabricated on the transparent conducting ITO layer of the InGaN/GaN LEDs by the electron beam lithography and inductively coupled plasma dry etching process. It is found that the InGaN/GaN LEDs fabricated with the nanopatterned ITO layer produce a higher

light output power than the sample with the planar ITO electrodes. The circular hole pattern with a hexagonal geometry is found to be the most effective among the tested structures. The light output intensity of the hexagonal lattice with the circular hole patterns on the ITO layer of the InGaN/GaN LED showed an enhancement of 35.6% over that of the conventional LED with a planar ITO at 20 mA injection current.

Conflict of Interests

The authors declare no competing financial interests.

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