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Enhanced light output of GaN-based near-UV light-emitting diodes by using nanopatterned indium tin oxide electrodes

Hyun-Gi Hong[1], Seok-Soon Kim[1], Dong-Yu Kim[1], Takhee Lee[1], June-O Song[2], J H Cho[3], C Sone[3], Y Park[3] and Tae-Yeon Seong[4]

[1] Department of Materials Science and Engineering, Gwangju Institute of Science and Technology, Gwangju 500-712, Korea
[2] School of Electric and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250, USA
[3] Photonics Program Team, Samsung Advanced Institute of Technology, Suwon 440-600, Korea
[4] Division of Materials Science and Engineering, Korea University, Seoul 136-713, Korea

E-mail: tyseong@korea.ac.kr

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Abstract
We report on the enhancement of the light output of near-UV (298 nm) GaN-based light-emitting diodes (LEDs) by using nanopatterned indium tin oxide (ITO) p-type contact layers. One-dimensional (1D) and two-dimensional (2D) nanopatterns are defined using a TiO_2 nano-mask, fabricated by means of a surface relief grating technique. The LEDs fabricated with the 1D and 2D nanopatterned p-type electrodes produce higher output powers by 33–48% (at 20 mA) as compared to those fabricated with the unpatterned contacts. The pattern-induced improvement of the output power is described in terms of the formation of the sidewalls of p-type electrodes.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The realization of highly efficient GaN-based light-emitting diodes (LEDs) having high external quantum efficiency is of great technological importance for solid-state lighting applications [1]. Although for GaN-based LEDs internal quantum efficiency is relatively high enough, external quantum efficiency is still very low [2]. Low external quantum efficiency is mainly associated with high refractive indices (2.1–2.5 at 398 nm) of GaN-related materials and indium tin oxide (ITO) top contact layers, which result in a small escape cone for emitted light and so cause most of the light to experience total internal reflection. Thus, it is essential to enhance light extraction efficiency in order to increase external quantum efficiency.

Several methods, such as surface roughening of p-GaN and patterning of p-type contact layers, were introduced to enhance light extraction efficiency [3–7]. In particular, the contact layer patterning was known to be a promising technique for increasing light extraction. For example, Pan *et al* showed that the micro-sized patterning of ITO top electrodes results in an increase of output power (at 20 mA) up to 16% without the degradation of the electrical properties of the electrodes [5]. Wierer *et al* reported that the introduction of photonic crystal structures leads to the enhancement of the radiance of InGaN/GaN LEDs [6]. These patterning methods, however, require a very expensive equipment, such as e-beam lithograpy. For commercial application, a low fabrication-cost method is highly desirable. In this work, we used a surface relief grating (SRG) and dry etching technique to form one-dimensional (1D) and two-dimensional (2D) nanopatterns on the transparent p-type electrode layers of UV LEDs [8–10]. A Cu-doped indium oxide (CIO) (3 nm)/ITO (400 nm) scheme was used as a top p-contact layer because of its high transmittance of ∼90% at 398 nm and good ohmic behaviour [11]. It is shown that the 1D and 2D nanopatterning of the

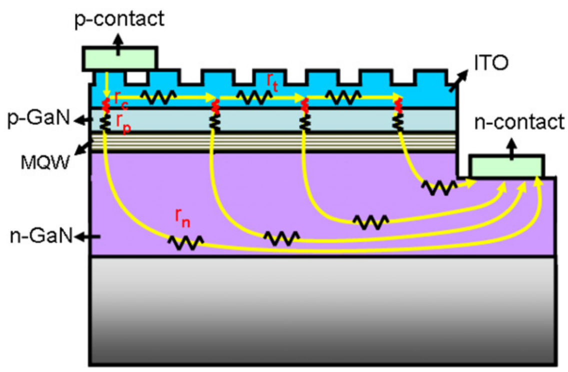


Figure 1. A schematic of the circuit of a LED with lateral injection geometry. r_t, r_c, r_p and r_n denote the lateral resistance components of the transparent electrode (ITO), the p-contact, the p-GaN and n-GaN, respectively.

CIO/ITO electrodes is very effective in enhancing the output power of the UV (398 nm) LEDs.

2. Experimental procedure

GaN-based UV (398 nm) LED structures were fabricated using metalorganic chemical vapour deposition (MOCVD). The LED structure comprised a GaN buffer layer, n-GaN, an InGaN/GaN multi-quantum well-active layer and p-GaN. Dry etching was used to form 300 × 300 μm^2 mesa-structures of LEDs. CIO (3 nm)/ITO (400 nm) p-type contact layers were deposited on p-GaN by e-beam evaporation [11]. After lift-off, the LEDs were annealed at 630 °C for 1 min in air. After fabricating full LED structures, the 1D and 2D nanopatterning processes were carried out. The details of the nanopatterning process will be published elsewhere [8]. To describe the process briefly, an azobenzene-functionalized polymer film PDO3 (poly (disperse orange 3)) (500 nm thick) was deposited on the LEDs by spin coating followed by drying. The 1D and 2D SRGs were fabricated on the polymer film by using an interference pattern of an Ar^+ laser beam at 488 nm. To fabricate 2D hexagonal hole-shaped SRGs, the samples were rotated by 60° after the first exposure process. After forming the SRGs, the 1D and 2D TiO_2 nano-masks were fabricated on the SRGs. A drop of Ti isopropoxide in 2-propanol containing HCl was placed on the SRGs and then immediately spun at room temperature. The spin-coated material was heat treated for 12 h through several steps (room temperature → 100 °C → 400 °C → 425 °C) to remove the polymer template and to avoid the cracking of the TiO_2 mask. Resultant ITO films with the TiO_2 masks were selectively etched using a dry etching process. Finally, the TiO_2 nano-mask was selectively removed by reactive ion etching in CF_4 plasma. Furthermore, for comparison, LEDs with 630 °C-annealed unpatterned CIO/ITO layers were also fabricated. Morphologies of the 1D and 2D nanopatterned LEDs were examined by scanning electron microscopy (SEM, Hitachi, S-4700). The current–voltage (*I*–*V*) characteristics of the LEDs were investigated using a parameter analyser (HP4155A). The output power and electroluminescence (EL) were also characterized. Figure 1 shows a schematic of the circuit of a LED with lateral injection geometry.

3. Results and discussion

Figure 2 shows SEM images of the 1D and 2D nanopatterned ITO surfaces. An unpatterned ITO layer (not shown) exhibited a very smooth surface with a root mean square (RMS) roughness of 3.1 nm. Furthermore, the unpatterned sample produced a sheet resistance of 43.28 Ω and transmittance of 90% at 398 nm. However, after etching, arrays of well-defined 1D line and 2D hexagonal hole-shaped nanopatterns were formed on the whole ITO surface, as shown in figures 2(*a*) and (*b*). The period and etch depth of the 1D and 2D nanopatterns are measured to be 500 nm and 100 nm, respectively.

Figure 3(*a*) shows the *I*–*V* characteristics of the LEDs with the CIO/ITO p-contact layers before and after nanopatterning. Both the 1D and 2D nanopatterned LEDs produce fairly similar *I*–*V* characteristics. Their forward voltages are, however, slightly higher than those of the unpatterned LEDs. For example, the unpatterned LEDs give a forward voltage of 3.69 V at 20 mA and a series resistance of 23.7 Ω, whereas the 1D and 2D nanopatterned LEDs produce 3.76 and 3.74 V at 20 mA, and 26 and 26.5 Ω, respectively. The slight increase of the forward voltages may be associated with a reduction of the surface area of the electrode (due to patterning), which is in contact with a probe tip for power supply.

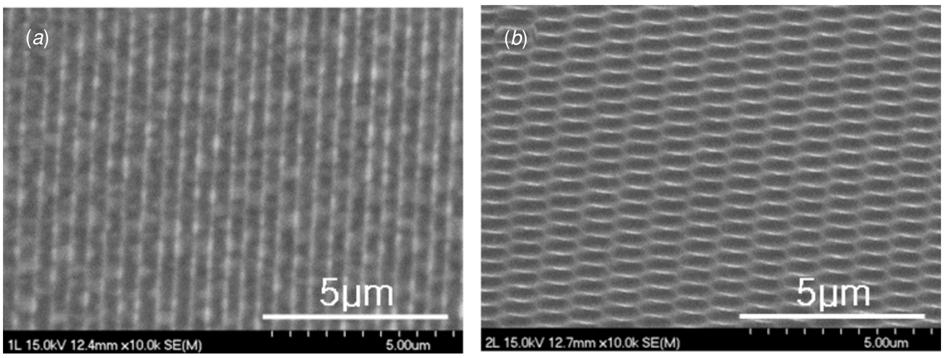
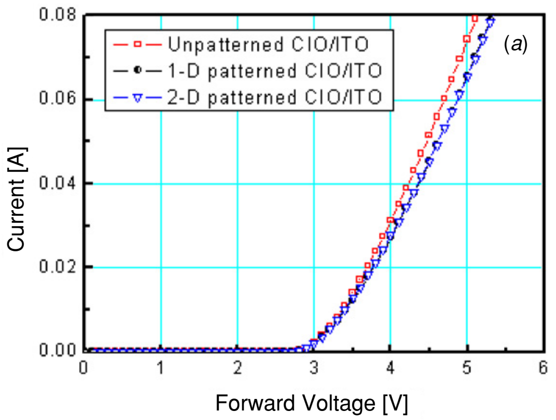


Figure 2. Plan-view SEM images of (*a*) 1D line-shaped and (*b*) 2D hexagonal-shaped nanopatterned ITO surfaces on LED structures.



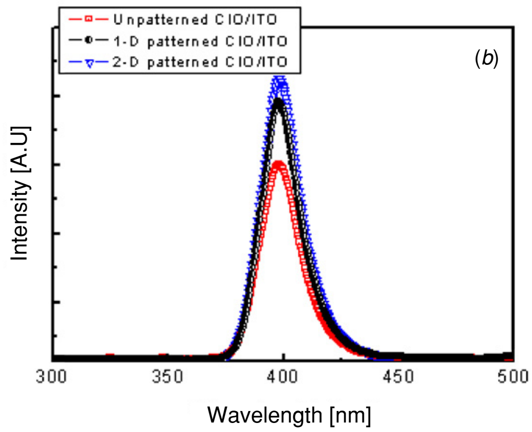


Figure 3. (*a*) The *I*–*V* characteristics and (*b*) EL data of LEDs fabricated with the 1D and 2D nanopatterned CIO (3 nm)/ITO (400 nm), and unpatterned CIO (3 nm)/ITO (400 nm) contacts.

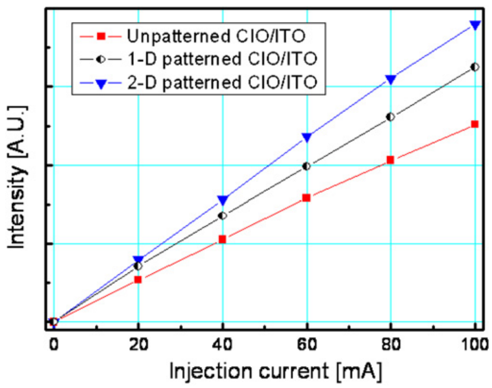


Figure 4. The light output–current (*L*–*I*) characteristics of LEDs fabricated with the 1D and 2D nanopatterned CIO/ITO, and unpatterned CIO/ITO contacts as a function of the forward drive current.

Electroluminescence was measured as a function of the wavelength at 20 mA. Figure 3(*b*) shows the EL data of the LEDs before and after nanopatterning. It is noted that irrespective of the nanopatterning process, the EL peak position (398 nm) of the LEDs remains unchanged and that among the three samples, the 2D nanopatterned LEDs produce the strongest EL.

Figure 4 shows the forward drive current dependence of the output–current (*L*–*I*) characteristics of the LEDs with the CIO/ITO p-contact layers before and after nanopatterning. It is evident that the light output powers of the LEDs with the 1D and 2D nanopatterned CIO/ITO contact layers are much higher than those of the unpatterned LEDs across the whole current range. For example, the output powers (at 20 mA) of the LED with the 1D and 2D nanopatterned p-type electrodes were improved by 33 and 48% as compared with those of the LEDs with the unpatterned electrodes, respectively. This shows that the nanopatterning of the electrode surface is a promising process for improving the performance of the LEDs.

It was shown that the light output of the 1D and 2D nanopatterned LEDs is increased by 33% and 48%, respectively. The improved performance can be attributed to the presence of nanopatterns, as shown in the SEM results (figure 2). Snell's law [12] shows that the critical angle (θ_{crit}) of total internal reflection is dependent on the refractive indices (n) of two different media. Based on the optical parameters of ITO and air, e.g. $n_{ITO} = 2.1$ and $n_{air} = 1$ at a wavelength of 398 nm, the θ_{crit} was calculated to be 28.4° with respect to the direction perpendicular to the surface for the ITO/air interface. For simplicity, we ignored n_{CIO} of a CIO interlayer between the ITO and GaN layers, since the CIO layer was broken into nanodots (5–45 nm in size). For the unpatterned sample, emitted light having incident angles smaller than $\theta_{ITO/air}$ of 28.4° can escape. However, the light outside the escape cone is reflected and so trapped inside the GaN region. For the nanopatterned sample, the patterning resulted in the formation of sidewalls [13, 14]. This can cause some of the internally reflected light outside the escape cone ($\theta_{ITO/air}$ of 28.4°) to escape through the sidewall ITO/air interface, resulting in additional light extraction. In addition, 2D nanopatterning produces more sidewalls as compared with 1D nanopatterning and so leads to higher output performance.

4. Summary and conclusion

We have introduced 1D and 2D nanopatterned p-type electrodes to fabricate high-performance UV LEDs. The use of the nanopatterned structures resulted in the enhancement of the LED output by 33–48% as compared with that of the unpatterned LEDs. The results imply that the nanopatterning technique could be a technologically promising process for the fabrication of high-brightness UV LEDs for solid-state lighting.

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