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Enhancement of the light output of GaN-based light-emitting diodes with surface-patterned ITO electrodes by maskless wet-etching

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Abstract

Wet-etching-induced surface patterning of p-type indium tin oxide (ITO) electrodes has been investigated to improve the light output of GaN-based light-emitting diodes (LEDs). Etching of as-deposited ITO layers in a buffered-oxide-etch solution results in the formation of a high density of randomly distributed sphere-shaped protrusions (250–1100 nm in size). LEDs fabricated with the 7 s-etched ITO electrodes yield higher light output (by 31.7% at 20 mA) compared with LEDs made with unpatterned ITO electrodes. The improvement is attributed to the increased light escape probability via the randomly distributed sphere-shaped protrusions formed on the electrode surfaces.

Keywords: GaN; LEDs; ITO; Surface patterning; Wet-etching

1. Introduction

To realize solid-state lighting by using highly efficient III-nitride based white light-emitting diodes (LEDs), the improvement of the light output is essential. One of the major barriers for such efficient LEDs is the internal total reflection of light trapped inside the devices, resulting in low extraction efficiency [1]. In order to enhance light extraction efficiency, various methods, such as photonic crystals [1], GaN surface roughening [2], and patterned sapphire substrates [3], have been used. In addition, the surface texturing [4,5] and the patterning [6,7] of transparent p-type electrodes have been also introduced and shown to be effective for improving LED efficiency. For example, Horng et al. reported that the output power of LEDs could be enhanced (by 28%) through the use of textured ITO window layers formed by a natural lithography technique [5]. However, these electrode texturing methods involve a dry-etching process, which could cause the degradation of the electrical properties of GaN-based LEDs [5]. Very recently, Leem et al. [6] showed that the light output could be enhanced up to 29% when ITO p-type electrodes are patterned by a combined technique of holographic lithography and two-step ITO deposition. Although this method obviates an additional dry-etching process, this process may not be suitable for a commercial device fabrication process. Thus, in this work, we have introduced a simple method for patterning ITO surface by means of a maskless wet-etching technique. It is shown that the method is simple and very effective for the patterning of as-deposited ITO layer surfaces. It is further shown that LEDs made with resultant patterned ITO electrodes produce the light output enhancement by about 30% as compared with unpatterned LEDs.

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2. Experiments

Near-UV LED structures (405 nm) consisting of a undoped GaN, Si-doped n-GaN, an InGaN/GaN multiple-quantum-well active layer, and Mg-doped p-GaN were grown on sapphire substrates by a metalorganic chemical vapor deposition system. To fabricate LED devices (300 × 300 μm^2 in size), mesa etching was carried out by inductively coupled plasma. Ti/Al n-type contact layers and ITO p-type contact layers were deposited by electron-beam evaporator. In particular, for p-type ohmic contacts, a thin Ag layer (3 nm) was introduced between ITO and p-GaN layer [8]. In order to form surface-patterned ITO layers, two different wet-etching processes were used. First, as-deposited ITO layers (500 nm) were dipped in a buffered-oxide-etch (BOE) solution diluted (1:10) with deionized (DI) water, followed by annealing at 600 °C for 2 min in air ambient (referred to here as "post-annealed ITO"). Second, as-deposited ITO layers were annealed at 600 °C for 2 min and then dipped in a diluted BOE solution (referred to here as "post-etched ITO"). The surface morphologies were examined by scanning electron microscopy (SEM) (Hitachi, S-4700) and atomic force microscopy (AFM) (PSI, Auto probe CP). Current–voltage (*I–V*) and light output–current (*L–I*) measurements were carried out using a parameter analyzer (HP 4155A) and Si photodiode (818-UV/CM) connected to an optical power meter, respectively.

3. Results and discussion

Fig. 1 shows a variation of the sheet resistances of ITO layers (500 nm) grown on the sapphire substrate as a function of the etching time. It is shown that the sheet resistance of the post-annealed ITO layers increases with increasing etching time. However, the sheet resistance of the post-etched ITO layers remains almost unchanged (or rather slightly decreases). It is also noted that the sheet resistances of the surface-patterned ITO layers are below 50 Ω/sq, implying that they could serve as current spreading layers for GaN-based top-emitting LEDs [9].

The insets of Fig. 1 shows AFM images of post-etched and post-annealed ITO layers. The post-etched ITO layer shows a smooth surface with a root-mean-square (RMS) roughness of 5.2 nm, whereas the post-annealed ITO layer reveals a significantly roughened surface with an RMS roughness of 81.6 nm. This indicates that the as-deposited ITO layers can be effectively roughened by wet-etching, which can be attributed to the different etching behaviors of as-deposited (amorphous) and annealed (polycrystalline) ITO surfaces [10].

Fig. 2a shows the *I–V* characteristics of near-UV LEDs fabricated with the surface-patterned ITO layers (500 nm) by the post-annealing method. A LED made with a smooth ITO layer (etched for 0 s) exhibits a forward-bias voltage of 3.57 V at 20 mA and a series resistance of 13.3 Ω. However, LEDs with the surface-patterned ITO layers (etched for 7, 10, and 12 s) produce forward-bias voltages of 3.61, 3.70, and 3.83 V at 20 mA and series resistances of 15.9, 18.4, and 22.6 Ω, respectively. The forward-bias voltages and series resistances of the LEDs with the surface-patterned ITO layers are somewhat increased,

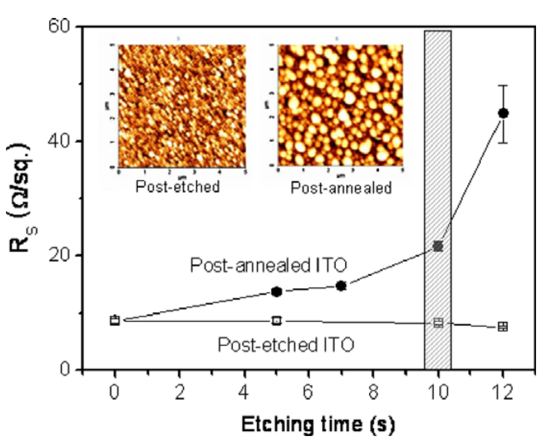

Fig. 1. Plots of the sheet resistances for the ITO layers as a function of the etching time. AFM images of the ITO layers are shown in the inset.

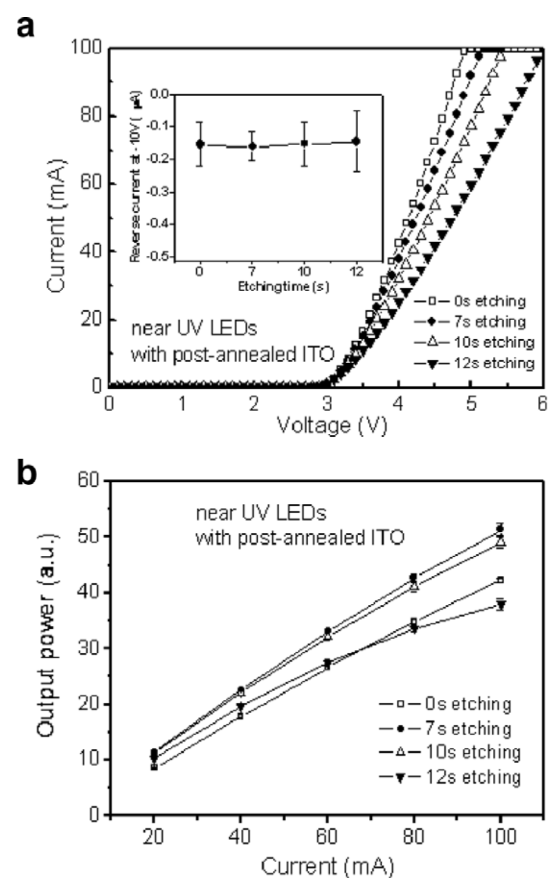

Fig. 2. (a) The typical *I–V* characteristics of near-UV LEDs fabricated with the post-annealed ITO electrodes. The inset shows a variation of reverse current at −10 V for the LEDs with the post-annealed ITO layers. (b) The light output–current (*L–I*) characteristics of LEDs fabricated with the post-annealed ITO layers.

which could be attributed to the increase of the sheet resistance caused by wet-etching of the ITO surface, as shown in Fig. 1. On the other hand, the reverse leakage currents of the LEDs (the inset of Fig. 2a) are almost unaffected by the wet-etching process. This indicates that the use of the wet-etching process can be effective in obviating any electrical degradation induced by a conventional dry-etching process [5].

Fig. 2b shows the output power of LEDs fabricated with the surface-patterned ITO layers. The light outputs (at 20 mA) of the LEDs with the ITO layers (etched for 7, 10, and 12 s) increase by 31.7%, 29.1%, and 19.2%, respectively, as compared with that of the LEDs with a smooth ITO layer (etched for 0 s). It is worth noting that the LED with a roughened ITO layer (etched for 7 s) produces the highest light output. However, the LED made with the 12 s-etched ITO layer gives much lower output power. This indicates that an optimum wet-etching time is 7 s, above which LED performance is degraded. It is worth noting that for LEDs made with the post-etched ITO (regardless of etch times of 0–12 s), their characteristics were found to be similar to that with the "post-annealed ITO" (etched for 0 s).

Fig. 3 shows SEM plan-view images of the surface-patterned ITO layers on p-GaN/QWs/n-GaN/sapphire substrates. The post-annealed ITO layer etched for 0 s reveals a smooth surface morphology (Fig. 3a). The ITO layers etched for 7 s and 12 s, however, exhibit significantly roughened surfaces, as shown in Fig. 3b and c. For the post-annealed ITO layer etched for 7 s, there are a number of sphere-shaped protrusions (250–550 nm in size) on the surface. The ITO layer etched for 12 s contains larger protrusions (500–1100 nm in size) as compared with the 7 s-etched ITO layer. It should be stressed that although the ITO electrodes went through a lift-off process, namely, the samples were ultra-sonicated in acetone, the sphere-shaped surface morphology remained stable and reproducible.

The enhanced light output performance of LEDs fabricated with the post-annealed ITO layers could be explained in terms of the increase of light escape probability. As shown in Fig. 3, the wet-etching caused the surfaces of the as-deposited ITO layer to get randomly patterned with sphere-shaped protrusions. This indicates that the wet-etching is an effective process for producing surface patterning without any masks. It was known that such irregularly patterned surfaces are more efficient in extracting light from devices [11]. Thus, the formation of randomly distributed sphere-shaped protrusions on the surface is responsible for the improved light output by 19.2–31.7% (at 20 mA). It was shown that the LEDs made with the ITO electrodes having sphere-shaped protrusions (250–550 nm in size) produce higher output power than the samples with larger protrusions (500–1100 nm in size). This indicates that there is an optimum size for maximum light extraction. It was known that the surface structure size much smaller than the wavelength of light serves as scatterers, while much larger structure sizes would reflect a large

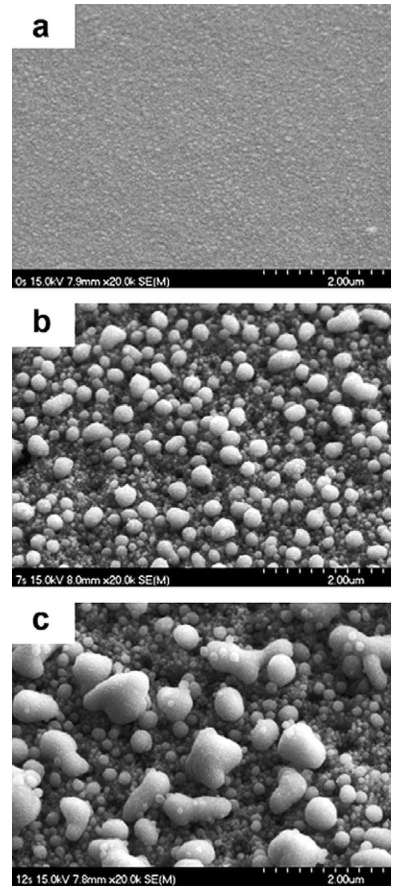

Fig. 3. SEM images obtained from (a) the post-annealed ITO layer (etched for 0 s), (b) the post-annealed ITO layer (etched for 7 s), and (c) the post-annealed ITO layer (etched for 12 s).

portion of light [12]. Thus, considering the wavelength of 405 nm for our LED samples, the 12 s-etched ITO layer with larger protrusions (500–1100 nm in size) may reflect a larger portion of the light instead of assisting light extraction and consequently could result in lower output power. In addition, this could be also attributed to the higher forward-bias voltage and series resistance of the 12 s-etched ITO layer, as compared with those of the 7 s-etched sample (Fig. 2).

4. Conclusion

We have demonstrated a simple maskless wet-etching technique for patterning as-deposited p-type ITO electrodes. It was shown that near-UV (405 nm) LEDs fabricated with surface-patterned ITO layers produce higher light output (19.2–31.7% at 20 mA) than the samples with unpatterned ITO electrodes. The enhanced output power was attributed to the improved light extraction caused by the formation of sphere-shaped protrusions on the ITO electrode surfaces. The result indicates that the wet-etching technique could be a potentially important process for patterning p-type ITO electrodes for the fabrication of high performance LEDs.

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