Solid-State Electronics 52 (2008) 1193–1196

Contents lists available at ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

Effect of the surface texturing shapes fabricated using dry etching on the extraction efficiency of vertical light-emitting diodes

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ARTICLE INFO

Article history:
Received 3 November 2007
Received in revised form 2 May 2008
Accepted 7 May 2008
Available online 20 June 2008

The review of this paper was arranged by Prof. E. Calleja

Keywords:
GaN
Dry etching
Light-emitting diode

ABSTRACT

On the surfaces of GaN-based light-emitting diodes (LEDs) having an n-side-up vertical electrode structure formed by the laser lift-off, various shapes of photoresist-patterned surface textures were formed by inductively coupled plasma etching and their effect on the light emission efficiencies was investigated. By the formation of various shapes of surface textures, the light output efficiency was increased from 37% to 45% compared to that without surface textures. The increase of light output efficiency was related to the increase of sidewall scattering, the decrease of reflected loss, and the decrease of cavity wall effect that occurs for the vertical LEDs by the increase of sidewall surface area.

1. Introduction

III-nitride wide band gap semiconductors have attracted great interest due to their applications for optoelectronic devices which are active in the blue and ultraviolet (UV) wavelength regions and for electronic devices capable of operation at high temperatures, high power levels, and in harsh environments [1,2]. GaN-based multi-quantum-well (MQW) light-emitting diodes (LEDs) are attractive devices for use in a variety of applications including traffic signals, full color displays, backlighting in liquid crystal displays, and miniprojectors [3,4]. However, the poor thermal and electrical conductivity of sapphire substrate used for the conventional GaN-based LEDs have hindered efficient heat dissipation and increased process complexity. In addition, the conventional GaN-based LEDs have anode and cathode made on the same side of wafer, which are lateral-type GaN-based LEDs, accordingly, a severe current crowding effect usually occurs, causing a higher forward voltage drop and lower internal quantum efficiency. The adverse effect of sapphire substrate thus imposes a limit on the high power applications of the conventional LEDs [5].

These days, vertical GaN-based LEDs fabricated by a laser lift-off (LLO) processing of the conventional lateral GaN-based LEDs are being investigated, which has an n-GaN side-up device structure instead of the conventional p-GaN side-up device structure, to decrease the current crowding effect by aligning the electrode structure vertically and to increase the thermal and electrical conductivity by removing the sapphire wafer [5–7]. On these n-side-up vertical GaN-based LEDs, to improve the external quantum efficiency, processes such as surface roughening and the deposition of transparent conductive oxide (TCO) are generally applied [8,9].

In this study, various shapes of surface texture were formed by photoresist patterning followed by dry etching using an inductively coupled plasma (ICP) on the n-side-up $300 \times 300\ \mu m^2$ vertical GaN-based LED fabricated by LLO processing, and the effect of various surface texturing shapes on the light-emitting characteristics of the LEDs was investigated.

2. Experimental

The samples used in this work were grown by metal organic chemical vapor deposition. The LED structure which has a dominant wavelength of 460 nm is composed of a buffer layer, a 0.5-μm-thick undoped GaN, a 2-μm-thick Si-doped n-GaN layer, an active region with five periods GaN–InGaN MQW layer, and a 0.15-μm- thick Mg-doped p-GaN layer deposited on the sapphire wafer. Before conducting the LLO process, a metal multilayer composed of Ni/Ag/Ni/Au was deposited to serve as an ohmic contact to p-GaN and a reflective mirror layer by using an e-beam evaporator and also an adhesive layer to the subsequent electroplated copper layer. And this p-side metal multilayer was annealed at 550 °C for 1 min in N_2 atmosphere using a rapid thermal annealing system.

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0038-1101/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.sse.2008.05.005

The LLO process was executed using a KrF excimer laser of 248 nm directing through the back of polished sapphire substrate. After the LLO process, gallium particles remaining on the undoped GaN layer on the separated GaN device layers were removed by using the HCl mixed with deionized water (1:2). And undoped GaN layer was removed by the dry etching using BCl_3 ICP until n-GaN is exposed. Then, various shapes of surface texture such as circle, donut, honeycomb, and waffle were formed on the n-GaN layer after the photolithographic patterning using AZ1512 photoresist (PR) followed by the dry etching using BCl_3 ICP. The dry etchings of GaN were carried out using a planar ICP etcher in 10mtorr BCl_3, 1400 W of inductive power, and -150 V of bias voltage. On the pad, n-GaN contact was formed and, to form n-type contact, a metal layer composed of Ti/Au was deposited followed by annealing at 350 °C for 2 min.

Fig. 1 shows the 3-dimensional shape of the vertical GaN-based LED structure formed in this study. On the side of p-GaN, in addition to contact metal, Ag layer was used to decrease the light absorption and to increase the reflectivity of the light emitted from the MQW active layer [10]. The thickness of PR was about 1.4 μm and, by using the BCl_3 ICP etching, 1 μm depth of surface textures was formed with the etch selectivity of GaN to PR as 1:2 ∼ 3. On the surface of n-GaN, as shown in Fig. 1, surface texture was formed and, depending on the PR mask features, different surface textures were formed.

The GaN etch depth was measured using a step profilometer (Alpha step 500, Tencor) and the etch profile of GaN was observed by field emission scanning electron microscopy (FE-SEM, S-4700 Hitachi). The light-emitting spectra of the GaN LEDs were measured using an optical emission spectrometer (OES, SC Tech) and the relative light output power was measured using a silicon photodetector.

3. Results and discussion

Fig. 2 shows the SEM etch profile of the surface textures formed on the n-GaN. Different shapes of surface textures such as circle, honeycomb, donut, and waffle were formed on the n-GaN surface as shown in the figure. By controlling the lithographic pattern profile, as shown in the figure, sloped etch profile instead of vertical etch profile was obtained. The diameter of the circle pattern was 4 μm and, for other shapes such as honeycomb, donut, and waffle, the differences between outer dimension and inner dimension was 2 μm. The calculated ratios of flat area to total area of the surface were 39%, 39.8%, 41.2%, and 44.7% for circle, honeycomb, donut, and waffle, respectively. The differences in the surface area ratio which is originated from the sidewall area will contribute in increasing the light amount escaped from the device inside.

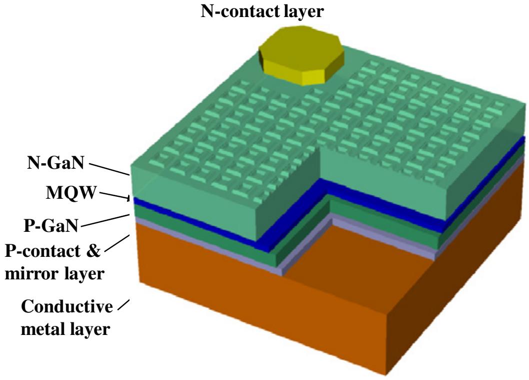

Fig. 1. A schematic diagram of a GaN-based vertical LED device structure with texturing used in this study.

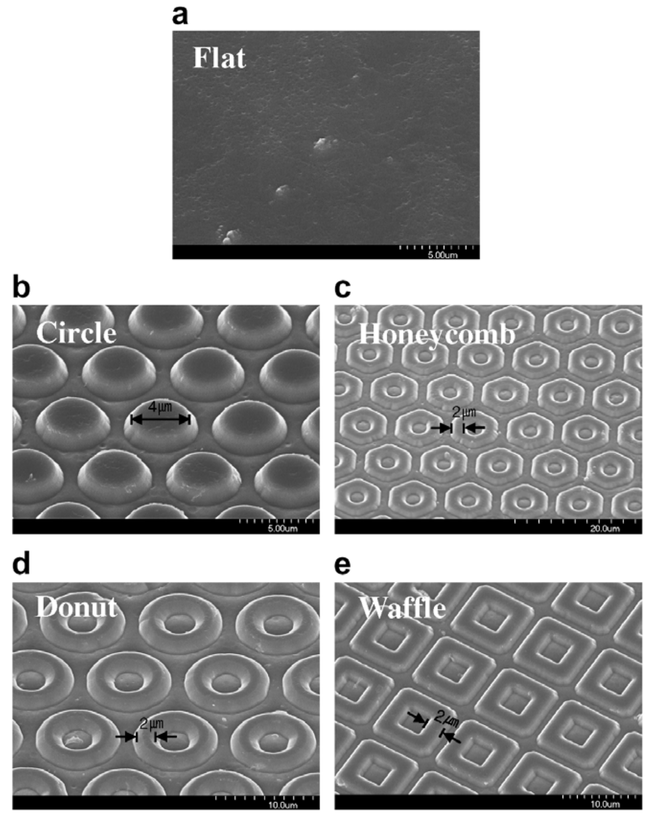

Fig. 2. SEM images of flat and various textured surfaces of n-GaN. (a) Flat, (b) circle, (c) honeycomb, (d) donut, and (e) waffle.

The improvement of the light output efficiency in the optical devices such as LED can be achieved, first, by maximizing the light emission efficiency inside of the device (internal quantum efficiency, η_{int}) and, second, by maximizing the light extraction efficiency outside of the device (external quantum efficiency, η_{ext}). Due to the enormous study in improving the quantum well device structure, it is known that it is difficult to improve the η_{int} further, and, therefore, most of current studies are concentrated in improving the η_{ext} by decreasing differences in the refractive index between the air and the device or by decreasing incident angle of the light emitted from the device to the interface between GaN and air though the surface roughening. The Snell's law describes the critical incident angle which the light emitted is reflected back to the device [11].

$$\theta_c = \sin^{-1}(n_{air}/n_{GaN})$$

When the refractive index of GaN ($n_{GaN} \approx 2.5$) [12] and air ($n_{Air} \approx 1$) is considered, 23.6° of critical angle is obtained. Therefore, by forming a surface roughening on the surface which makes the incident angle of the light larger than the critical angle, more light can be extracted and the increase of the surface area will also increase the light extraction efficiency. Figs. 3a and c show the optical microscopic pictures of the waffle-textured device before emission and after emission, respectively, and Figs. 3b and d show the pictures of the flat device before emission and after emission, respectively.

The emission current was maintained at 20 mA for both devices. As shown in the figure, all the devices had only one contact pad on the device surface because of the vertical device structure, and which minimized the decrease of emission area for the same device area. Also, the waffle-textured device showed higher emission than the flat device at the same emission current and, for the waffle-textured device, the sidewall area of the waffle showed higher emission compared to the flat area.

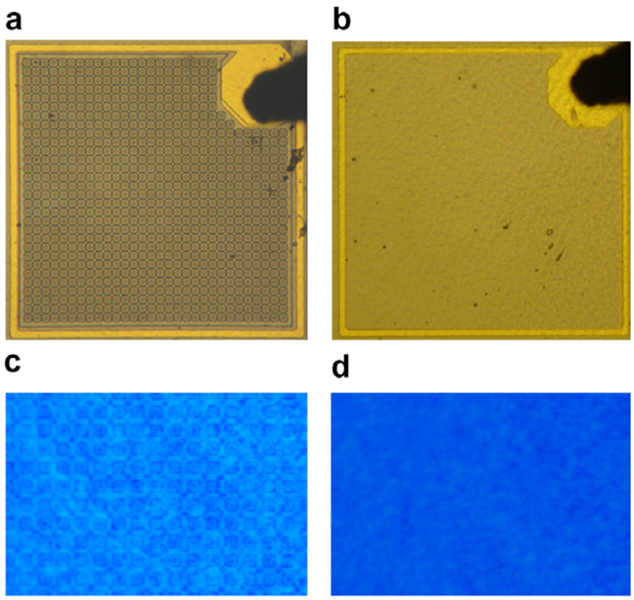

Fig. 3. Microphotographic view of GaN-based vertical LED devices. (a) and (c): waffle-textured surface, (b) and (d): flat surface. (a) and (b): before emission, (c) and (d): after emission.

The wavelengths of the light emitted from the variously textured devices were measured using OES for the same emission current of 20 mA and the results are shown in Fig. 4. As shown in the figure, the flat device showed multiple peaks while the textured devices showed a single peak even though the main peak wavelength of the light emitted from the devices was the same at 465 nm corresponding to blue color.

The formation of the multiple peaks is known to be from the interference effect caused by reflecting of the light between p-metal and air due to the cavity sandwich configuration of p-metal/GaN/air for the vertical device structure [11,13]. The lack of the multiple peaks for the surface textured devices is believed to be from the suppression of the resonance effect by decreasing of light intensity reflected at the interface between GaN and air. Also, as shown in the figure, the devices with textured surface such as circle, honeycomb, donut, and waffle-shaped surface showed higher emission intensity compared to the flat device.

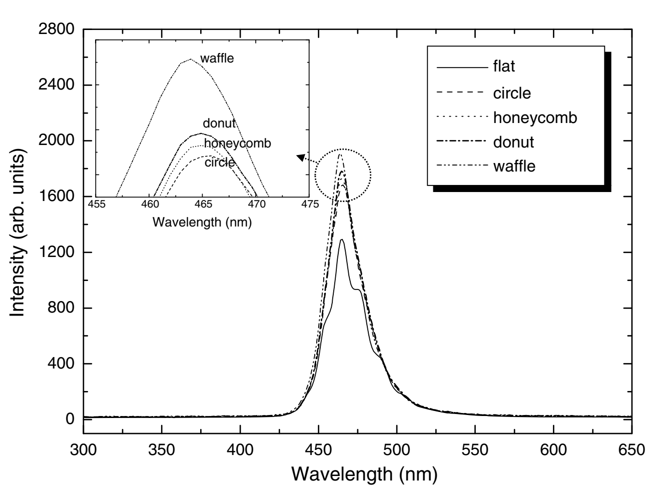

Fig. 4. Optical emission spectroscopy of GaN-based vertical LED devices with flat and various textured surfaces. Device current: 20 mA.

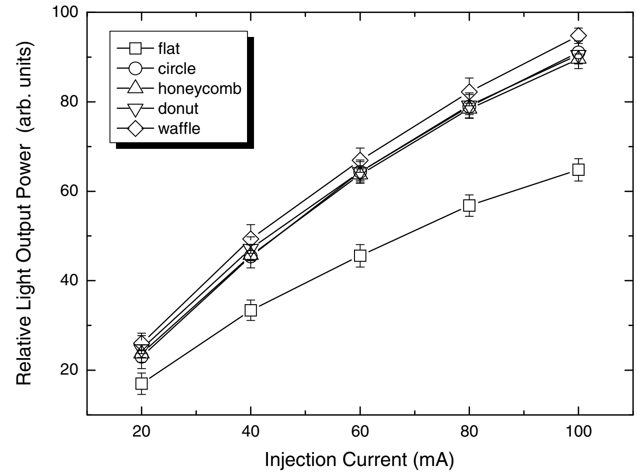

Fig. 5. Light output power measured at the top surface of GaN-based vertical LED devices with flat and various textured surfaces as a function of device current.

To compare the light emitted by the devices, the light output power of the devices was measured using a silicon photodetector and the result is shown in Fig. 5 for the flat device and the textured devices with the shapes of circle, honeycomb, donut, and waffle as a function of device current.

The light output power increased with increasing the device current and the light output power of the textured device was higher compared to that of the flat device similar to the result shown in Fig. 4. The textured devices showed the increase of light output in the sequence of circle, honeycomb, donut, and waffle similar to the increase of total area by the texturing. Also, the increased amount of light output which corresponds to 37 ~ 45% was similar to the increase percentage of total area (39 ~ 44.7%) by texturing the surface. Therefore, the increase of light emission for the textured devices was directly related to the increase of light-emitting surface area by texturing, which enables the decrease of light reflected at the surface by Snell's law.

4. Conclusions

The effect of surface roughening by texturing the n-GaN surface of the vertical GaN LED devices on the light-emitting properties of the devices was investigated. The texturing of the n-GaN surface was formed by ICP etching of n-GaN surface of the devices after the PR patterning with various shapes to have different flat/total surface ratios from 39% to 44.7%. The texturing the n-GaN surface increased the light output without changing the main light peak intensity. The increased light output was directly related to the increase of surface area of the devices by showing the increase of light output from 37% to 44.7% depending on the increase of surface area by texturing. Also, the surface texturing showed a single emission peak by removing the cavity resonance effect of the vertical LED devices showing multiple emission peaks caused by the reflection at the boundaries between p-metal/GaN/air.

Acknowledgment

This work was supported by the National Program for Tera-Level Nanodevices of the Korea Ministry of Science and Technology as a 21st Century Frontier Program.

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