Solid-State Electronics 56 (2011) 8–12

Contents lists available at ScienceDirect

Solid-State Electronics

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

Output power enhancements of nitride-based light-emitting diodes with inverted pyramid sidewalls structure

Li-Chuan Chang [a], Cheng-Huang Kuo [b,*], Chi-Wen Kuo [a]

[a] Department of Optics and Photonics, National Central University, Jhongli, Taoyuan 32001, Taiwan
[b] Institute of Lighting and Energy Photonics, National Chiao Tung University, Guiren, Tainan 71150, Taiwan

ARTICLE INFO

Article history:
Received 3 November 2009
Received in revised form 31 August 2010
Accepted 27 October 2010
Available online 20 November 2010

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

Keywords:
GaN
Light-emitting diodes
Nitride
InGaN–GaN MQW
Metalorganic chemical vapor deposition

ABSTRACT

This study presents nitride-based light-emitting diodes (LEDs) with inverted pyramid sidewalls by chemical wet etching nitride epitaxial layers and investigates the chemical wet etching mechanism of inverted pyramid sidewalls. It is well known that chemical etching solutions such as KOH, H_2SO_4 and H_3PO_4, to selectively etch the N-face GaN but not the Ga-face GaN. In this study, the N-face GaN was exposed around the chip by laser scribing at the GaN/sapphire interface. These channels provided paths for the chemical etchant to flow and allow the etching solution to further contact with and etch the exposed bottom N-face GaN. Chemical etching of the chip sidewalls formed the inverted hexagonal pyramid shape with {10 −1 −1} facets. Findings show that inverted pyramid sidewalls enhance 20 mA LED output power by 27% for LEDs, with chemical etching of the chip sidewalls for 4 min, compared to the conventional LED. The larger LED output power is attributed to increased light extraction efficiency by inverted pyramid sidewalls.

1. Introduction

Researchers have recently developed high-performance optical devices, such as light-emitting diodes (LEDs) and laser diodes (LDs), using GaN-based materials grown on sapphire substrates [1,2]. For example, GaN-based blue and green LEDs have already been extensively used in full-color displays and high-efficiency light sources for traffic light lamps. UV emitters may have potential for fluorescence-based chemical sensing, flame detection, and possibly optical storage. These nitride-based LEDs are also potentially useful for solid-state lighting. To realize solid-state lighting, however, one needs to further improve the output efficiency of these LEDs.

Light extraction efficiency of the GaN-based LED is limited mainly by the large difference in refractive index between GaN film and the surrounding air. Snell's law determines the critical angle for photons to escape from the GaN film. This angle is crucially important for light extraction efficiency of LEDs. Since the refractive indices of GaN and air are 2.5 and 1, respectively, external quantum efficiency is limited to only a few percentages for conventional GaN-based LEDs. Several methods improve the output efficiency of nitride-based LEDs, such as textured surface [3–5], a highly transparent p-contact layer [6], proper substrate design [7], and flip-chip packaging [8]. Findings have shown enhancing light output by the light scattering layer (e.g., roughening the p-GaN or n-GaN surface, patterned substrate, etc.). With a light scattering layer, photons generated in the active layer will have multiple opportunities to find the escape cone [3–8]. Scattering from the roughened top surface of the LED or/and patterned substrate thus achieves angular randomizing of photons. A similar concept applied to the chip sidewalls could also enhance LED output intensity by the textured chip sidewalls of LEDs. Previously, using an inductively coupled plasma (ICP) etcher or photo electrochemical (PEC) etching process [9,10] could texture LED sidewalls. This research reports a more detailed study on the wet etching mechanism of inverted pyramid sidewalls and describes the characteristic of nitride-based LEDs with textured inverted pyramid sidewalls.

2. Experimental procedure

The blue InGaN/GaN MQW LEDs used in this study were all grown on c-face (0 0 0 1) 2-inch sapphire (Al_2O_3) substrates by a metalorganic chemical vapor deposition (MOCVD) system. The emission wavelength was 454 nm. Details of the growth procedures can be found elsewhere [11,12]. The samples consisted of a 30-nm-thick GaN nucleation layer, a 2-μm-thick undoped GaN (u-GaN) layer, a 2-μm-thick Si-doped GaN layer, an $In_{0.17}Ga_{0.83}N$/GaN multiple quantum well (MQW) active region, a 0.25-μm-thick

* Corresponding author. Tel.: +886 6 3032121x57798; fax: +886 6 3032535.
E-mail address: kuoch@mail.nctu.edu.tw (C.-H. Kuo).

0038-1101/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.sse.2010.10.024

planar Mg-doped GaN layer and a Si-doped n^+-InGaN/GaN (5 Å/5 Å) short-period superlattice (SPS) tunnel contact structure. The MQW active region consisted of six periods of 3-nm-thick $In_{0.17}Ga_{0.83}N$ well layers and 15-nm-thick GaN barrier layers. After growth, we first partially etched the surface of the samples to expose the n-type GaN layer. We then deposited a 250-nm-thick ITO film onto the LED surfaces by e-beam evaporation to serve as the p-contacts and subsequently deposited Cr/Au onto the exposed n-type GaN layer to serve as the n-type electrode. After the chip process, the experiment sequentially fabricated LEDs with inverted pyramid sidewalls. Fig. 1 schematically illustrates the proposed wet etching process of the inverted hexagonal pyramid sidewalls. A 2-μm-thick SiO_2 layer was deposited on top of the samples by a plasma-enhanced chemical vapor deposition (PECVD). The 2-μm-thick SiO_2 layer was used for protecting LED chip surface while etching the sidewalls of the LED chip by chemical etching. Laser scribing was subsequently performed to define the dimension of chip size and expose the GaN/sapphire interface, as shown in Fig. 1b. The deep valley between the two chips, formed by laser scribing, provided paths for the chemical etching etchant to flow and allow the etchant to further contact with and etch the exposed bottom N-face GaN (i.e., the GaN/sapphire interface). The samples were then placed into a H_2SO_4:H_3PO_4 = 3:2 solution to form inverted pyramid sidewalls and the temperature of solution was 250 °C. The LEDs with the wet etching process for 2 min, 3 min and 4 min, respectively, were labeled as LEDII, LEDIII and LEDIV. With increasing etching time, the inverted pyramid sidewalls became more obvious, as schematically illustrated in Fig. 1c–e. For comparison, a conventional LED without the wet etching process was also prepared. The conventional LED was labeled as LED I.

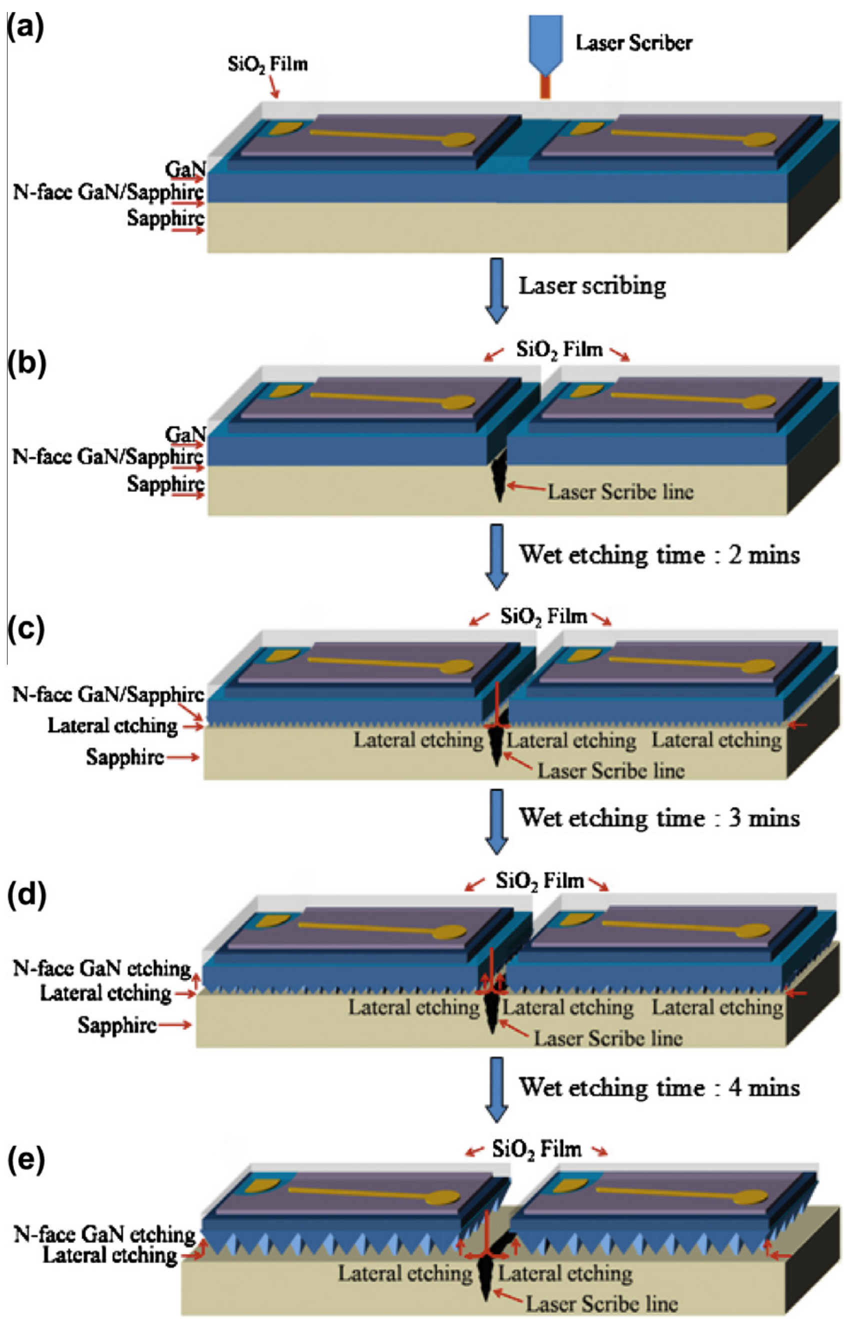

Fig. 1. Schematic diagram of fabrication of the inverted hexagonal pyramid sidewalls LED.