Thin Solid Films 570 (2014) 293–297

Contents lists available at ScienceDirect

Thin Solid Films

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

Current steering effect of GaN nanoporous structure

Chia-Feng Lin [a,b,*], Jing-Hao Wang [a], Po-Fu Cheng [a], Wang-Po Tseng [a], Feng-Hsu Fan [a], Kaun-Chun Wu [a], Wen-Che Lee [a], Jung Han [b]

[a] Department of Materials Science and Engineering, National Chung Hsing University, Taichung 402, Taiwan
[b] Department of Electrical Engineering, Yale University, New Haven, CT 06520, USA

ARTICLE INFO

Available online 14 February 2014

Keywords:
InGaN
Nanoporous
Current steering effect

ABSTRACT

Current steering effect of InGaN light emitting diode (LED) structure was demonstrated by forming a high resistivity GaN nanoporous structure. Disk-array patterns with current-injection bridge structures were fabricated on InGaN LED devices through a focused ion beam (FIB) system. GaN nanoporous structure was formed around the FIB-drilled holes through a electrochemical (EC) wet-etching process on a n-type GaN:Si layer under the InGaN active layer. High emission intensity and small peak wavelength blueshift phenomenon of the electroluminescence spectra were observed in the EC-treated region compared with the non-treated region. The branch-like nanoporous structure was formed along the lateral etched direction to steer the injection current in 5 μm-width bridge structures. In the FIB-drilled hole structure, high light emission intensity of the central-disk region was observed by enlarging the bridge width to 10 μm, with a 5 μm EC-treated width, that reduced the current steering effect and increased the light scattering effect on the nanoporous structure. The EC-treated GaN:Si nanoporous structure acted as a high light scattering structure and a current steering structure that has potential on the current confinement for vertical cavity surface emitting laser applications.

1. Introduction

Gallium nitride materials have attracted considerable interests in the development of optoelectronic devices, especially for the InGaN-based light-emitting diodes (LEDs). LEDs have been intensively investigated for various applications such as backlights in liquid crystal displays, solid-state lighting sources, and deep-ultraviolet LEDs [1]. However, LEDs have lower light extraction efficiency because of the large refractive index difference between GaN (2.5) and air. Therefore, InGaN-based LEDs with the pattern-nanoporous p-type GaN:Mg surfaces [2], the inverted cone-shaped pillar structures [3], nanosphere lithography [4], roughened N-face GaN surface [5], patterned sapphire substrates [6], the inclined undercut GaN structure [7], and the laser treated pattern structures [8] were used to improve the light extraction efficiency. Hsu et al. [9] reported slice-type GaN LED fabricated by a focused ion beam (FIB) process. Park et al. [10] demonstrated that the doping selective etching was used to lift-off a GaN epitaxial layer. Zhang et al. [11] reported the nanoporous GaN layer for the liftoff process of GaN layers. Soh et al. [12] reported the InGaN LED on the GaN porous templates for quantum dots emission. Microcavity and current confinement are major structures to fabricate nitride-based vertical cavity surface-emitting lasers (VCSEL) [13,14]. It had been reported that oxidized AlInN interlayer lattice matched [15] and buried AlN current aperture [16] acted as the current-confinement structures for the VCSEL devices.

In this paper, InGaN LED structure with a nanoporous GaN:Si structure was fabricated through a electrochemical (EC) wet-etching process. N-type GaN:Si layer below the InGaN active layer was treated as a nanoporous structure that acted as a high light scattering structure and a high-resistivity current-steering structure. The meaning of current steering is about controlling and blocking the injection current into the center disk area with an InGaN active layer by forming the GaN nanoporous structure at the bridge structure. The disk-array patterns and the drilled-hole patterns on the same LED wafer have been designed to analyze the current steering effect of the InGaN devices fabricated through a focused ion beam microscopy system. The geometric morphologies and optical and electrical properties of the treated LED structures are analyzed in detail.

2. Experimental details

InGaN-based LED structures were grown on a C-face (0001) 2 in.-diameter sapphire substrate through a metalorganic chemical vapor deposition system. These LED structures consisted of a 30 nm-thick GaN buffer layer, a 3.0 μm-thick unintentionally doped GaN layer (background carrier concentration about 2×10^{16} cm^{-3}), a Si-heavy-doping 2.8 μm-thick n-type GaN layer (5×10^{18} cm^{-3}), a 0.15 μm-thick Si-light-doped n-type GaN layer (5×10^{17} cm^{-3}), 5 pairs of InGaN/GaN multiple quantum wells (MQWs) active layers, and a 0.25 μm-thick

* Corresponding author at: Department of Materials Science and Engineering, National Chung Hsing University, Taichung 402, Taiwan.
E-mail address: cflin@dragon.nchu.edu.tw (C.-F. Lin).

http://dx.doi.org/10.1016/j.tsf.2014.02.039
0040-6090/

magnesium-doped p-type GaN layer (5×10^{17} cm^{-3}). The active layers consisted of a 30 Å-thick InGaN-well layer and a 120 Å-thick GaN-barrier layer for the InGaN/GaN MQW LED structure. The dimensions of the chips were 300×300 μm^2 in size, and the mesa region was defined by the inductively coupled plasma etcher using Cl_2 gas. A 250 nm-thick indium tin oxide (ITO) film was deposited on the p-GaN layer as a transparent conductive layer. The disk-array patterns were fabricated on the mesa region of the ITO coated InGaN-LED structure between the n- and p-electrodes through a focused ion beam (FIB, JEOL JIB-4601F) microscopy system. The dimension of disk-array patterns consisted of an 8.3 μm-diameter disk pattern and a 9.0 μm-length bridge structure with a 3.3 μm-width as shown in Fig. 1(a). All the samples were immersed in a 0.5 M oxalic acid solution through a wet electrochemical (EC) etching process with an external dc bias voltage at +15 V for 2 min. An external dc bias was fixed at a positive 15 V applied on the dry-etched n-type GaN:Si layer surface as an anode contact without immersing in a 0.5 M oxalic acid solution, and a platinum electrode was used as the cathode for the wet etching process. The ITO layer on the LED structure was slightly etched without affecting the electrical property of the treated device structures. Then, the samples were slightly oxidized through the photoelectrochemical (PEC) oxidation process for 10 s treatment time illuminated by a 400 W-Hg lamp in deionized water [17] and the insulated GaOx layers were formed on the surface of GaN nanoporous structures. The Cr/Au (50 nm/2500 nm) metal layers were deposited as the n-type and the p-type metal contacts. In Fig. 1(b), the selected positions at disk, bridge, and sidewall regions were treated by the FIB system for the cross-sectional morphology analysis. After the EC etching and the PEC oxidizing processes, the nanoporous structure was observed on the sidewall of the FIB-drilled holes as shown in Fig. 1(c). The cross-sectional images of the disk pattern, the bridge region, and the sidewall region were observed in Fig. 1(d), (e), and (f), respectively. The surface morphologies of all LED structures were observed through a scanning electron microscope (JEOL, JIB-4601F). The electroluminescence (EL) spectra and the light output power were characterized through an optical spectrum analyzer. The light-intensity profiles of LED samples were measured by a beam profiler.

3. Results and discussion

The positions of the cross-sectional images were pointed out in Fig. 1(b). The FIB etching induced damage on the sidewall surface can be etched and removed through the EC etching process to form the nanoporous structure and the PEC oxidation process to form the GaOx layer on nanoporous GaN surface. In Fig. 1(c), the nanoporous structure was observed on the treated sidewall structure of the FIB-drilled patterns through the lateral EC process. The nanoporous structure formed on the 2.8 μm-thick GaN layer without top p-type GaN:Mg layer was

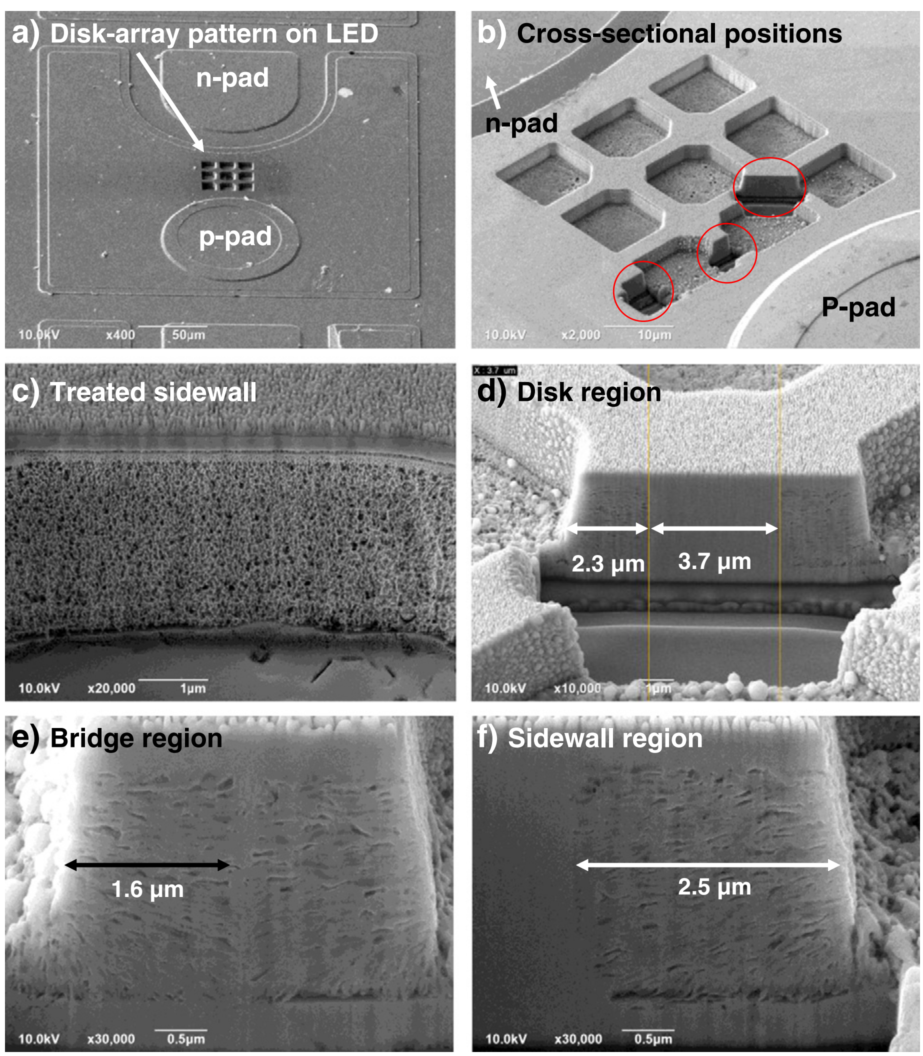

Fig. 1. The SEM micrographics of (a) the disk-array pattern on LED structure, (b) the analyzed positions fabricated by the FIB cutting process, and (c) the treated sidewall structure were measured. The cross-sectional SEM micrographics at (d) the disk region, (e) the bridge region, and (f) the sidewall region were observed in the EC-treated LED structure.