Materials Science in Semiconductor Processing 31 (2015) 209–213

Contents lists available at ScienceDirect

Materials Science in Semiconductor Processing

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

Improving performance of high-power indium gallium nitride/gallium nitride-based vertical light-emitting diodes by employing simple n-type electrode pattern

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ARTICLE INFO

Available online 12 December 2014

Keywords:
Vertical LED
n-electrode
GaN
Ohmic contact

ABSTRACT

In this work, simple n-type electrode structures were used to enhance the electrical and optical performances of fully packaged commercially mass-produced vertical-geometry light-emitting diodes (VLEDs). The forward bias voltage of the VLED with a Y-pattern electrode increased less rapidly than that of VLEDs with a reference electrode. The VLEDs with the reference and Y-pattern electrodes exhibited forward voltages of 2.93 ± 0.015 and 2.89 ± 0.015 V at 350 mA and 3.77 ± 0.015 and 3.53 ± 0.015 V at 2000 mA, respectively. The VLEDs with the Y-pattern electrode resulted in a higher light output than the VLEDs with the reference electrode with increase in the drive current to 2000 mA. The emission images showed that the VLEDs with the Y-pattern electrode exhibited better current spreading behavior and lower junction temperatures than the VLEDs with the reference electrode. With increase in the current from 350 to 2000 mA, the VLEDs with the Y-pattern electrode experienced a 39.4% reduction in the wall plug efficiency, whereas the VLEDs with the reference electrode suffered from a 43.3% reduction.

1. Introduction

The applicability of indium gallium nitride/gallium nitride-based light-emitting diodes (LEDs), which are expected to replace incandescent and fluorescent lighting lamps, is determined by crucial factors, such as a large chip area and high driving current. For such LEDs, effective heat dissipation is very important because the heat generated at a high drive current of 350 mA can accelerate the aging degradation of the LEDs. In this view, vertical LEDs (VLEDs) from which light is extracted through the top n-type GaN [1–9], have been extensively investigated. These VLEDs have been fabricated by different lift-off methods, such as laser lift-off (LLO) [1–8] and chemical lift-off (CLO) [9,10]. For example, Lee et al. [1] investigated the light-extraction of 465 nm GaN-based VLEDs using double diffuse surfaces (i.e., a top transmitted diffuse surface and a bottom diffuse omnidirectional reflector). It has been shown that the VLEDs with a double diffused surface exhibit 56% and 236% higher light output powers than VLEDs with a single side diffused surface and conventional LEDs, respectively. Consequently, the VLEDs yielded a calculated external quantum efficiency of ~40%. Lin et al. [2], while investigating the performance of a large area (chip size $= 1 \times 1$ mm^2) vertical conductive GaN–mirror–Cu VLED fabricated by laser lift-off and electroplating techniques, showed that the luminance intensity (at 20 mA) and the light output power (at 500 mA) of the VLEDs were ~2.7 times and twice as large as the values exhibited by conventional lateral

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http://dx.doi.org/10.1016/j.mssp.2014.11.043
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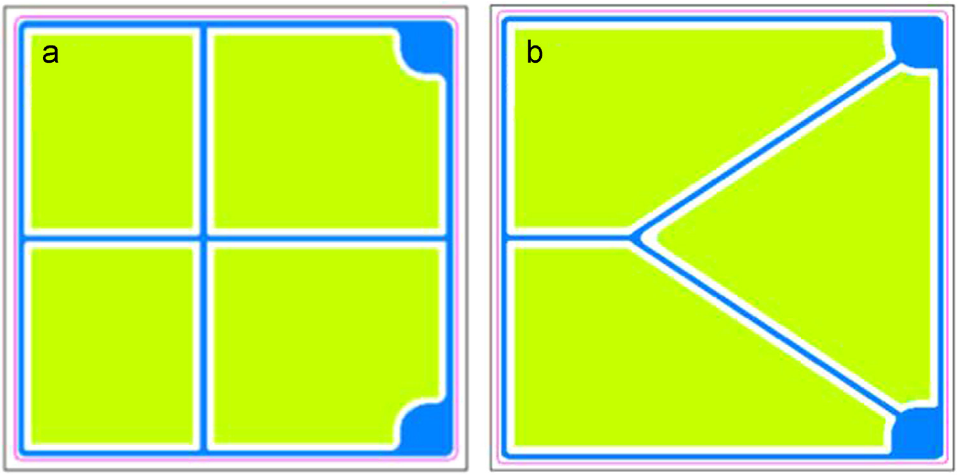

Fig. 1. The schematic of the two-dimensional plan view diagrams of InGaN/GaN-based VLEDs (chip size = 1450 × 1450 μm^2, the width of the n-electrode = 15 μm) with (a) reference and (b) Y-pattern n-type electrodes.

LEDs, respectively. Lee et al. [3] investigated the wafer-level fabrication of GaN-based VLEDs (1 × 1 mm^2) using a multi-functional bonding material system and showed that packaged VLEDs produced an operating voltage of 3.35 V at 350 mA. The operating voltages and the reverse currents at −5 V insignificantly increased after 1800 h. The light output power of these LEDs degraded by only ~2% of the initial value after 1800 h. The investigation of the optical performance of GaN-based VLEDs on a metal alloy by Chu et al. [8] showed that VLEDs with low operating voltages and serial dynamic resistances can be fabricated. Furthermore, the VLEDs demonstrated excellent heat dissipation capabilities compared to conventional LEDs. A high-power white VLED with an efficiency of 120 lm/W could be fabricated by a combination of use of reflectors, surface engineering, and optimization of the n-GaN layer thickness. Lin et al. [9] reported that a CLO in combination with a truncated triangle stripe patterned sapphire substrate is effective in the fabrication of InGaN-based VLEDs. In this work, free-standing LED structures with an electroluminescence emission spectrum at 453 nm by CLO could be achieved, demonstrating the potential created by replacing the LLO process by the CLO process in VLED fabrication. Ha et al. [10] investigated the optical and electrical performances of VLEDs fabricated by the CLO process using a selectively etchable CrN layer, which served as a buffer layer for the growth of GaN LEDs and was consequently removed by selective chemical etching. The VLED showed a low series resistance of 0.65 Ω, required a low operation voltage of 3.11 V at 350 mA, and exhibited excellent heat dissipation efficiency. As stated previously, various types of fabrication processes (e.g., use of double diffuse surfaces and better mirrors) have so far been used to enhance the output power of GaN-based VLEDs. In this work, to increase the light output performance of VLEDs, we employed a simple n-type electrode with a Y pattern instead of a mesh pattern. This method is advantageous because of the absence of any additional steps required for the fabrication of the VLEDs in comparison to conventional mass-production processes. Thus, in this paper, we propose a simple and an effective process to improve the output performance of mass-produced VLEDs. We investigated the effects of use of n-type electrodes with different patterns on the electrical and optical characteristics of VLEDs prepared by the LLO process. We specifically investigated the use of different patterns of n-electrodes to enhance the light extraction and current spreading.

2. Experimental procedure

A metalorganic chemical vapor deposition system was used to grow the InGaN/GaN-based epilayer stacks on (0001) sapphire substrates for the blue (450 nm) VLEDs. The VLED epilayer stacks consisted of a 30 nm-thick GaN nucleation layer, a 1.5 μm-thick undoped GaN layer, and a 5 μm-thick Si-doped n-GaN layer, in addition to an active region with four periods of InGaN/GaN multi-quantum wells (MQWs), 50 nm-thick Mg-doped AlGaN, and a 70-nm-thick Mg-doped p-GaN layer. The device fabrication was carried out using the following protocol. First, the samples were immersed into a sulfuric acid hydrogen peroxide solution (H_2SO_2:H_2O_2 = 2:1) for 10 min and rinsed in running deionized (DI) water and blow dried with N_2. After the cleaning process, a SiO_2 current blocking layer was deposited by plasma chemical vapor deposition. An Ag/Ni reflective layer was then deposited on the p-GaN layer by RF-magnetron sputtering. A bonding metal alloy, consisting of Au, Sn, and Cu, was then deposited on the reflector by a dual e-beam system. After completing the LED structures, the whole wafer (6 in.) was bonded to the sapphire wafer by thermal compression at 300 °C. The LLO process was then performed using a KrF excimer laser to separate the LED structures from the sapphire substrate to expose the undoped GaN epilayer to air [3,11]. The undoped GaN was etched away to expose the n-GaN layer by inductively coupled plasma (ICP) and wet chemical etching. A heated KOH solution was used to roughen the n-GaN surface [12]. A Cr/Al/Ti/Au film (n-contact) was deposited onto the n-GaN surface. Finally, a SiO_2 passivation layer was deposited by plasma chemical vapor