Microelectronic Engineering 88 (2011) 3164–3167

Contents lists available at ScienceDirect

Microelectronic Engineering

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

Enhancement of light output power of GaN-based vertical light emitting diodes by optimizing n-GaN thickness

Hwan Hee Jeong [a], Sang Youl Lee [a,c], Kwang Ki Choi [a], June-O Song [a], Jung-Hee Lee [b], Tae-Yeon Seong [c,*]

[a] Department of Light-Emitting Diode Business, Chip Development Group, LG Innotek, Paju 413-901, South Korea
[b] School of Electronic and Electrical Engineering, Kyungpook National University, Taegu 702-701, South Korea
[c] Department of Materials Science and Engineering, Korea University, Seoul 136-713, South Korea

ARTICLE INFO

Article history:
Received 19 April 2011
Received in revised form 10 June 2011
Accepted 25 June 2011
Available online 30 June 2011

Keywords:
Vertical light emitting diode
GaN
Light output

ABSTRACT

The light output and electrical characteristics of GaN-based vertical light emitting diodes were investigated as a function of n-GaN thickness. The forward voltage increases from 3.34 to 3.42 V at an injection current of 350 mA as the n-GaN thickness decreases from 5.0 to 2.0 μm. Even at a high injection current of 2.0 A, LEDs with 2.0 μm-thick n-GaN reveal stable forward characteristics which are comparable to those of LEDs with 5.0 μm-thick n-GaN. All the samples exhibit almost the same reverse current up to approximately −8 V. The output power increases with decreasing n-GaN layer thickness. For example, LEDs with 2.0 μm-thick n-GaN yield about 12% higher light output power as compared to LEDs with 5.0 μm-thick n-GaN. Their light output power continuously increases without saturation as the injection current increases up to 1 A. The n-GaN thickness dependence of the electrical characteristics is described and discussed.

1. Introduction

High output power GaN-based light emitting diodes (LEDs) are very important for applications such as backlight in liquid crystal displays, automotive lighting, and solid-state [1–3]. In particular, vertical LEDs have been shown to be light-emitting devices for high brightness operation due to their excellent thermal dissipation and low operation voltage [4–7]. There are two principal approaches for the enhancement of GaN-based LED efficiency: the first is to increase internal quantum efficiency (IQE), which is determined by crystal quality, epitaxial layer structure and p-doping, and the second is to increase light extraction efficiency. Presently, the IQEs of GaN-based LEDs achieved by various groups are fairly high and so it may be very difficult to further improve the IQEs. On the other hand, the light extraction efficiency of LEDs is still relatively low and thus needs to be further increased. Thus, with the aim of the improvement of the light extraction efficiency, different methods such as surface roughening, inclined side wall, and diffused mirror techniques have been widely investigated [8–13]. In this work, in order to enhance the light output power by increasing light extraction, we investigated the electrical characteristics of GaN-based vertical LEDs as a function of n-GaN thickness which were fabricated by means of a multifunctional bonding material system consisting of a thick Cu diffusion barrier and a bonding layer. It is shown that as the GaN thickness increases from 2.0 to 5.0 μm, the forward voltage at an injection current of 350 mA decreases from 3.42 to 3.34 V. All the vertical LEDs give almost the same reverse current up to −8 V. The light output power increases by ~12% as the n-GaN thickness decreases from 5.0 to 2.0 μm.

2. Experimental procedure

GaN-based epilayer stacks for vertical-type configuration LEDs were grown on (0 0 0 1) sapphire substrate by means of a metallorganic chemical vapor deposition system. The LED epilayer stacks consisted of a 30-nm-thick GaN nucleation layer, a 1-μm-thick undoped GaN layer, and a 5-μm-thick Si-doped n-GaN layer, an active region with seven periods of InGaN/GaN multi-quantum wells (MQWs), 0.1-μm-thick Mg-doped AlGaN, and a 0.2-μm-thick Mg-doped pGaN layer. The device fabrication steps were as follows: first, the samples were immersed into a mixture of H_2SO_4:H_2O_2 (2:1) solutions for 10 min to remove metallic ingredient on the sample surfaces and then rinsed in running deionized (DI) water. Before lithography, the samples were ultrasonically degreased using acetone, methanol, and DI water for 5 min each per step followed by drying in a N_2 stream. After the cleaning process, a square mesa structure (1×1 mm^2) was fabricated using an inductive coupled plasma (ICP) etcher for electric current isolation. The ICP process was used to etch away the p-GaN, MQWs, and n-GaN to expose the sapphire surface. A

* Corresponding author.
E-mail addresses: hhjeong@lginnotek.com (H.H. Jeong), tyseong@korea.ac.kr (T.-Y. Seong).

0167-9317/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.mee.2011.06.020

SiO_2 passivation layer was deposited by a plasma-enhanced chemical vapor deposition system. Before the deposition of reflectors, SiO_2 current blocking layers (CBLs) were defined by photoresistor patterning on the p-GaN surface using the standard photolithographic and wet-etching processes, where the vertical centers of the CBLs and the n-pad electrodes were aligned (Fig. 1) [14]. After that, an ITO (50 nm) contact layer and an AgCu (200 nm) (2 at.% Cu) reflective layer were deposited on the p-GaN layer by radio frequency magnetron sputtering and electron beam (E-beam) systems, respectively, which were subsequently annealed at 650 °C and 400 °C for 1 min, respectively. Then, 50-nm-thick Ti adhesion and 1-μm-thick Cu layers were deposited onto the AgCu reflective layer by E-beam. A bonding metal alloy consisting of Au, Sn and Cu was deposited on the Ti/Cu layer by a dual E-beam system. This was followed by the deposition of a Ti layer onto the p-Si wafer to where the Ti metal was used as an ohmic contact layer. After completing the LED structures, the whole wafer (2 in.) was bonded to the Si wafer by thermal compression at 300 °C. A laser lift-off (LLO) process was then performed using an ArF excimer laser operated at a wavelength of 193 nm to separate the sapphire substrate from the structure, where an undoped GaN epilayer was exposed to air. The undoped GaN was etched to expose the n-GaN layer by wet chemical etching and ICP. As shown in Fig. 1, the thickness of the n-GaN layer was controlled to be 2.0, 3.0, 4.0, and 5.0 μm by ICP etching. Then, the n-GaN surface was roughened by a heated KOH solution. A Cr/Al/Ti/Au film (n-contact) and a Ti/Au film (p-contact) were deposited onto the roughened n-GaN surface and the back surface of the p-Si wafer, respectively.

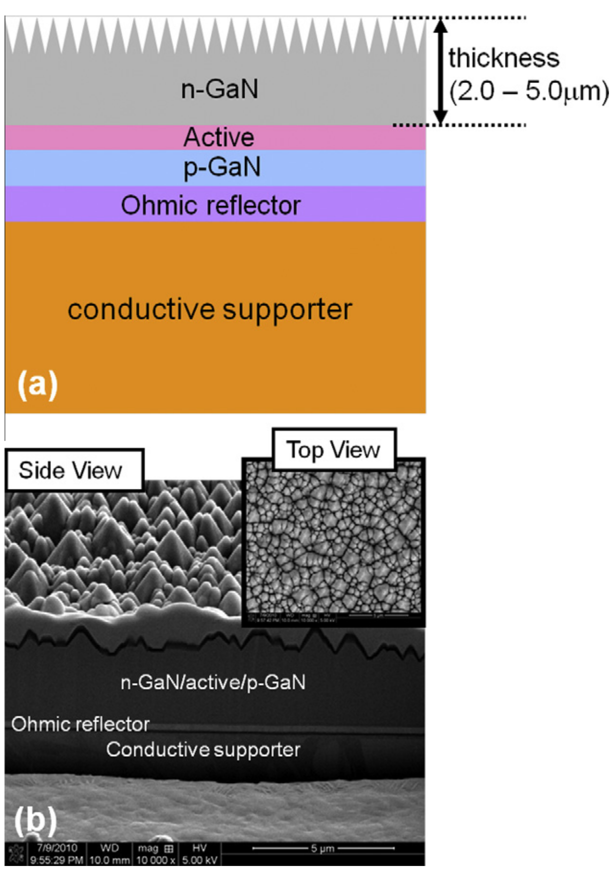

Fig. 1. (a) The schematic diagram of GaN-based vertical LEDs and (b) scanning electron microscope (SEM) images of a vertical LED chip.

3. Results and discussion

Fig. 1 illustrates the schematic diagram of GaN-based vertical LEDs and scanning electron microscope (SEM) images of a vertical LED chip. To investigate the optical and electrical characteristics as a function of the thickness of an n-GaN layer (through which the photons emitted from the active area are extracted), the LED chips were encapsulated into standard LED lamps. Vertical LEDs with GaN thicknesses of 2.0, 3.0, 4.0, and 5.0 μm were referred to herein as 'LED-2.0', 'LED-3.0', 'LED-4.0', and 'LED-5.0', respectively. Fig. 1(b) reveals a plan-view SEM image of a roughened surface of LED-4.0, showing hexagonal pyramids. The SEM examinations showed that regardless of the n-GaN thicknesses, all the samples exhibited almost the same surface morphological characteristics with the similar sizes and densities of the pyramids.

Fig. 2 shows the typical forward current–voltage (*I*–*V*) characteristics of vertical LEDs as a function of the n-GaN thickness. At low injection currents below 100 mA, all the samples show almost the same forward voltages. However, at high injection currents above 350 mA, the forward voltage increases with a decrease in the n-GaN thickness. For example, the forward voltages of LED-2.0, LED-3.0, LED-4.0, and LED-5.0 were measured to be 3.42, 3.38, 3.36, and 3.34 V, respectively, an injection current of 350 mA. It is noteworthy that although the n-GaN layer thickness decreases down to 2.0 μm, the samples do not suffer from a drastic increase in the forward voltage even at a high current of 1.0 A. The fact that the samples with the thinner GaN layers produced higher forward voltages could be explained in terms of a decrease in the lateral cross-section area for current flow. In other words, as the n-GaN thickness decreases, the contribution of spreading current (I_S) to total electric current (I) becomes dominant over vertical current (I_V) [15]. The series resistance of LED-2.0, LED-3.0, LED-4.0 and LED-5.0 was measured to be 0.644, 0.596, 0.520, and 0.503 Ω, respectively. This thickness dependence is consistent with the forward behaviors.

Fig. 3 shows the forward voltage–current (*V*–*I*) characteristics of vertical LEDs as a function of the n-GaN thickness. Unlike LED-5.0, LEDs with thin n-GaN layers (e.g., LED-2.0) are generally envisaged to experience serious electrical degradation or failure. However, all the samples reveal stable *V*–*I* characteristics even at a high injection current of 2.0 A. This could be attributed to the use of the conductive supporter which serves as heat dissipater and current spreader.

Fig. 4 exhibits the typical reverse electrical characteristics of vertical LEDs as a function of the n-GaN thickness. All the samples

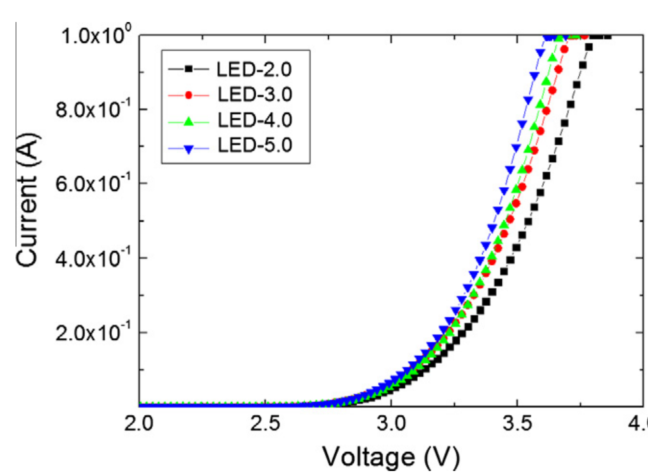

Fig. 2. The typical forward current–voltage (*I*–*V*) characteristics of vertical LEDs as a function of the n-GaN thickness.