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Short Communication

Optimization of the nanopore depth to improve the electroluminescence for GaN-based nanoporous green LEDs

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A B S T R A C T

GaN-based nanoporous green LEDs with different pore depth have been fabricated by using anodic aluminum oxide (AAO) as dry etching mask. The experimental results show that the electrical properties of the nanoporous LEDs with different pore depths are similar, but for the optical properties, the LEDs with nanopores extended to the p-GaN layer exhibits the best performance, if increase the depth to MQWs or decrease to the ITO layer will both decrease the light output power (LOP). By calculating the light extraction efficiency using three-dimensional (3D) finite-difference time-domain method, the decrease of the light output is mainly attributed to the reduced light extraction efficiency when the pore depth stop at ITO transparent layer instead of p-type layer, while if the depth reach the MQWs, the deterioration of the QWs which is caused by dry etching damage will play an important role. This optimization would give a valuable guidance to the surface structure design for nanostructured GaN-based LEDs, such as surface roughening, photonic crystal, or top-down fabricated surface-plasmon enhanced LEDs.

1. Introduction

GaN-based light emitting diodes (LEDs) have experienced considerable development as a promising light source for the next-generation solid-state lighting [1–3]. However, due to the large difference of refractive index between GaN ($n=2.5$) and air ($n=1$) or plastic packaging ($n=1.5$), most of light generated in LED will be trapped by total internal reflection and cannot be extracted to the outside [4]. Considering the refractive indices of GaN and air, the critical angle for the light escape cone is about 23°, and approximately only 4% of the internal light can be extracted from a surface. In order to avoid this problem, various advanced optical designs have been proposed such as surface patterning [4–10], photonic crystal (PhC) [11–13], and reflectors [14,15]. Among these methods, patterning the LEDs surface into nanoporous structure can effectively improve the light extraction efficiency of LEDs, and have attracted a lot of attention [5–7]. However, the surface nanoporous structure needs to be controlled carefully to achieve a high light extraction efficiency, at the same time without the deterioration of internal quantum efficiency (IQE) or electric performance. Specifically, increasing the pore depth will enhance the light scattering effect and the light extraction efficiency [4], but the side effect is that this method will deteriorate the crystal quality of p-GaN and/or QWs caused by the damage during the dry/wet etching in the surface-patterning process [16,17], leading to the deteriorated light output power, leakage current or plug-wall efficiency. It is necessary

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to systematically study the influence of pore depth on the optical and electrical performance of the GaN-based LEDs.

Here, we experimentally and theoretically studied the influence of pore depth on the photoelectric properties of the GaN-based green LEDs, and optimized the pore depth to improve the electroluminescence (EL) enhancement. The surface nanoporous structure was achieved by using anodic aluminum oxide (AAO) as dry etching mask, the different pore depths extended to the ITO current spreading layer, p-GaN layer or QWs layer, respectively. The experimental results show that the largest EL enhancement is achieved when the nanopores extended to the p-GaN layer, but further increase of the pore depth will decrease EL intensity due to the deterioration of the QWs caused by dry etching damage, and the reduction of depth will also lead to a decrease of the EL intensity caused by the reduced light extraction efficiency.

2. Experimental methods

The green LED epilayer was grown on a 2 in. (0 0 0 1) sapphire substrate at a low temperature on the GaN buffer layer using metal–organic chemical vapor deposition (MOCVD). The structure consists of a 2 μm undoped GaN layer, a 2 μm n-GaN layer, a ten-period InGaN/GaN MQWs and a 200 nm Mg doped p-GaN layer. Afterwards, the LED devices were processed as follows: first, the surface region of the p-GaN layer was partially etched by an inductively coupled plasma-etching process (ICP) using $Cl_2/BCl_3/Ar$ gases to expose the n-GaN layer, then a 120 nm indium tin oxide (ITO) layer was deposited as a transparent current-spreading layer on the p-GaN layer followed by the evaporation of Cr/Pt/Au (30/100/1500 nm) on both the n-GaN layer and the ITO current-spreading layer as electrode by e-beam evaporation. After that, a 300 nm thick anodic aluminum oxide (AAO) membrane with a period of 400 nm was transferred to the LED chip wafer. The details of the transfer method have been reported elsewhere [18]. Then the LEDs were fabricated to be nanoporous by using the AAO membrane as the ICP etching mask. A gas mixture of $Cl_2/BCl_3/Ar=40/5/5$ sccm was used with the chamber pressure kept at 4 mTorr. The ICP power and rf power were set at 300 W/15 W. Three different pore depths were achieved by controlling the etching time: the first pore depth was 120 nm, which was stopped at the ITO layer, the corresponding LED is named 'ITO patterned LED'; the second pore depth was 210 nm, which extended into the p-GaN layer, the corresponding LED was named 'p-GaN patterned LED'; the third was 330 nm, which went through the p-GaN layer and arrived at the QWs region, the corresponding LED named 'QWs patterned LED'. After ICP etching, the residues of AAO template were removed by dilute NaOH solution. These three device structures combined with the plane LED control sample are shown in Fig. 1.

After lapping and polishing the substrate down to 200 μm, the wafers were cut into individual LED chips by scribing and breaking. Then, the chips were mounted and wire-bonded onto LED packages without silicone encapsulation. The electrical and optical properties of the LEDs were measured by Keithley 2400 and Labsphere/CSLMS-2021.

3. Results and discussion

Fig. 2(a) and (b) shows the scanning electron microscopy (SEM) top view images of an AAO template and the corresponding nano-patterned ITO–GaN surface, respectively. The diameters of the nanopores were mainly distributed at 360 ± 30 nm and 260 ± 30 nm for the AAO template and the ITO–GaN surface, respectively. The small pore diameter on ITO–GaN surface was caused by the re-deposition of ICP etching residues on the pore wall of the AAO template. The pore duty ratio of the textured ITO layer was 27%. Fig. 2(c)–(e) shows the SEM cross-section images of ITO patterned LED, p-GaN patterned LED and MQWs patterned LED, respectively. The interface of ITO/p-GaN and p-GaN/MQWs can be clearly observed. For the ITO patterned LED, the pores are just stopped at the ITO layer, with the depth of about 120 nm; for the p-GaN patterned LED and MQWs patterned LED, the pores reached into p-GaN layer and MQWs layer, with a depth of 210 nm and 330 nm, respectively.

The electroluminescence (EL) spectra and light output power of the LEDs with different pore depths at 20 mA are

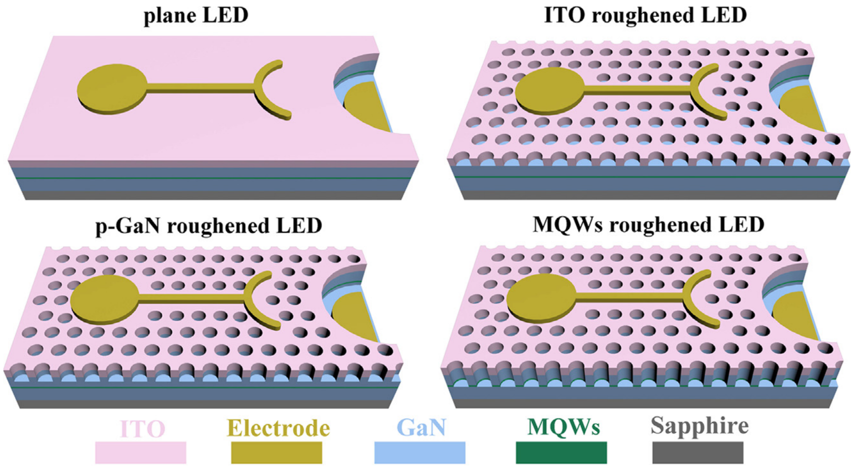

Fig. 1. Device structures of the LEDs with different pore depths, including plane LED, ITO patterned LED, p-GaN patterned LED and MQWs patterned LED. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)