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2010 Semicond. Sci. Technol. 25 035008

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Two inch large area patterning on a vertical light-emitting diode by nano-imprinting technology

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Received 7 September 2009, in final form 2 December 2009
Published 29 January 2010
Online at stacks.iop.org/SST/25/035008

Abstract
A vertical light-emitting diode (LED) with a chip size of 500 × 500 μm² was fabricated by the laser lift-off (LLO) process of an InGaN-based blue LED wafer. After the LLO process, photonic crystal patterns by UV nano-imprint lithography were formed on the n-GaN top layer of the vertical LED over the entire area with a diameter of 2 inches. As the result of n-GaN patterning, light output power of the vertical LED with photonic crystals was increased by up to 44% compared to that of the vertical LED without a photonic crystal at a driving current of 1000 mA.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

GaN-based LEDs, especially high-power white light LEDs, have attracted increasing interest, due to their low power consumption, long lifetime and environmentally friendly nature. Due to the improvement in the efficiency of GaN-based LEDs, they can potentially be used as the light source in general lighting applications. However, the efficiency of these LEDs needs to be further improved before they can compete with other conventional light sources such as fluorescent lamp. The efficiency of LEDs is defined as the ratio of the amount of emitted photons to the electrical power input, which can be divided into two components, namely the ratio of the amount of generated photons to the electrical power input and the ratio of the amount of emitted photons to generated photons. The former is the internal quantum efficiency and it can be improved by the growth of lower defect density GaN crystals [1], higher p and n doping [2, 3], the formation of a better electrical contact [4] and so on. The latter is determined by the photon extraction efficiency and it can be improved by using a patterned sapphire substrate [5], the roughening and texturing of the GaN and ITO surface [6, 7] and the insertion of photonic crystal patterns into the LED structure [8] to suppress the total internal reflection of photons inside the GaN crystal. The overall performance of GaN-based LEDs can also be determined by measuring the heat dissipation, since the diode leakage current increases exponentially with increasing temperature.

Especially, for high-power, high-brightness LEDs, a large amount of current needs to be injected into the LED. However, the temperature of the diode increases rapidly and its performance decreases drastically with increasing injected current, the total power input is limited by the thermal dissipation of the LEDs. Due to the poor thermal conduction and electrically insulating properties of sapphire substrates, the dissipation of the heat generated by the p–n diode from the device to the outer environment is limited and the current cannot be injected directly through the sapphire substrate. By lifting off the GaN epi-layer from the sapphire substrate and transferring it to another substrate, which can transfer the heat effectively and is electrically conducting, the overall performance of GaN LEDs can be improved [9, 10]. Thus, such vertical LEDs are a very suitable structure for high-power high-brightness LEDs.

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Although the performance of vertical LEDs can be improved by providing them with better thermal dissipation, their photon extraction efficiency can be enhanced by the roughening of the GaN surface or the insertion of photonic crystal patterns on the GaN surface. In this paper, photonic crystal patterns were formed on the GaN surface of vertical LEDs. The pitch of the photonic crystal patterns ranged from 600 to 900 nm and the diameter of the holes ranged from 200 to 300 nm.

2. Experimental details

2.1. Fabrication of the vertical LED structure

A conventional GaN-based epitaxial wafer was grown on a (0001) oriented sapphire wafer by the metal organic chemical vapor deposition (MOCVD) process. After the growth procedure, 280 nm thick indium tin oxide (ITO) was deposited for a p-contact to the p-GaN. Next, the vertical LED structure was fabricated by the laser lift-off (LLO) process. The detailed structure of the LED wafer and fabrication process of the vertical LED device were described elsewhere [11]. The laser lift-off undoped GaN surface contains lift-off boundaries which consist of clusters of nano-sized pillars. However, roughness of most of the undoped GaN surface except lift-off boundary was negligibly small. Figure 1(a) and (b) are atomic force microscopy (AFM) images of the undoped GaN surface and the n-GaN surface after ICP etching, respectively. The RMS roughness of the undoped GaN surface is about 45.5 Å and that of the n-GaN surface is about 38.5 Å.

2.2. Patterning process of the n-GaN layer of vertical LEDs by nano-imprint lithography

The process flow for the GaN patterning is shown in figure 2. For the high throughput, low cost transfer of the nano-scale patterns, nano-imprint lithography was used. Since deep patterns were favored to maximize the effect of the photonic crystal patterns, a double layer consisting of 30 nm thick Cr and 100 nm thick SiO2 was deposited on the lifted-off GaN surface as an etch mask. Then, the UV nano-imprint process was applied to form the submicron-sized photonic crystal patterns. A polymer-based imprint stamp, which is flexible and transparent to UV, was used. Pattern transferring in the imprinting process is done by physical contact between a stamp and a substrate. Thus, uniformity of imprinted pattern largely depends on the flatness of a substrate. Surface flatness of a conventional LED wafer is poor. And some defects, originated from the LLO process, exist on the surface of the vertical LED. Thus, flexible and soft stamp should be applied for the imprinting process on a LED wafer to compensate poor flatness of a LED wafer. The polymer stamp was fabricated by UV NIL and hot-embossing processes. At first, polymer pattern was formed on a 4 inch glass wafer by UV NIL using Si master template at 10 atm and 10 min of UV exposure. Chemoptics™ NIP-K28 UV curable resin was applied for the UV NIL process. Next, the glass wafer with the polymer pattern was used for the hot-embossing process of polyvinyl chloride (PVC) sheet as a hot-embossing stamp. The hot-embossing process was performed at condition of 30 atm and 130 °C for 30 min. After the hot-embossing of PVC sheet, 10–20 nm thin SiO2 layer was deposited on the patterned PVC sheet and a hydrophobic self-assembled monolayer was coated on the SiO2 surface of the PVC stamp for anti-stiction treatment. The replicated 4 inch PVC stamp was then cleaved to 2 inch size. The details of the polymer imprint stamp can be found elsewhere [12]. Prior to the etching of the Cr and SiO2 mask layers, the imprint residual layer was cleared by oxygen-based plasma. The Cr layer was then etched by a chlorine-based plasma using the imprinted resist patterns as an etch mask and the SiO2 layer was continuously etched using the Cr layer as an etch mask. The underlying GaN was then etched with the Cr and SiO2 mask layers, in order to form deep photonic crystal patterns. The detailed etch conditions are described elsewhere [13]. After GaN etching, the remaining Cr and SiO2 layers were cleared by a BOE wet chemical etchant.

3. Results and discussion

A digital photograph of the patterned GaN vertical LED wafer and SEM micrographs of the nano-sized hole patterns formed
on the surface of the GaN layer are shown in figure 3. Photonic crystal patterns with periods ranging from 600 to 900 nm were formed with high fidelity on the 2 inch diameter vertical LED wafer. As shown in figure 3, the whole surface of the 2 inch diameter vertical LED wafer was divided into five sections and four different photonic crystal patterns were formed on the 4 sections of the wafer, while no pattern was formed on the fifth section to be used as a reference.

After n-GaN patterning, the GaN vertical wafer, metal n-pad was deposited on the n-GaN surface and all vertical LED devices were encapsulated with transparent Si gel. To analyze the effect of the photonic crystal patterns on the lifted-off GaN surface, the I–V characteristics and light output power with a conventional integration sphere were measured. In the case of I–V characteristics, shown in figure 4(a), no difference was observed among the GaN sections, patterned with the different photonic crystal structures. The operation voltage of the non-patterned LED device was 3.17 V and the operation voltages of the patterned LED devices were 3.17–3.19 V, at 350 mA. Leakage current of both the non-patterned and patterned LED devices was measure with 0.02 mA at a reverse bias of −5 V. This implies that the effect of the nano-imprint lithography and plasma etching processes, used to fabricate the photonic crystal patterns on the lifted-off GaN surface, on the leakage current can be ignored, since the thickness of the n-GaN layer is large enough. This result was attributed to the unique device structure of the vertical LED.

The effect of the GaN patterning on light output power at a forward current of 0–1000 mA is shown in figure 4(b). Compared to the optical output value of the un-patterned reference area, the optical output values of all four photonic crystal patterns, formed on the GaN surface, were increased by up to 44%. This can be explained by the fact that the photons emitted from the active layer interacted with the photonic crystal patterns on the GaN surface and, thus, the total internal reflection of the photons was effectively suppressed. Among patterned LEDs with different pitches, the patterned LED with pitches of 600 nm and 700 nm showed most increased output power. The pitch ranged from 600 nm to 900 nm of the photonic crystal pattern is suitable for enhancing the light extraction of a GaN blue LED [11]. No significant difference was observed among the four different photonic crystal patterns because the fill factor (the \( r/a \) ratio) of photonic crystals is small (\( \sim 0.2 \)). In order to achieve higher photonic crystal effect on light output and further increased output power, the fill factor of photonic crystals should be increased [14].

In the case where a photonic crystal pattern is formed on the thin p-GaN layer of conventional horizontal LEDs, the drastic degradation of the electrical characteristics was often
reported, due to the plasma damage to the p-GaN layer, while a stronger output power was detected, due to the enhancement of the photon extraction efficiency \[15, 16\]. And the thickness of the p-GaN layer was about 100–200 nm; the underlying multi-quantum well-active layer can easily be damaged during the plasma etching of p-GaN. However, since the thickness of the lifted-off GaN layer of the vertical LED is over a micron, the multi-quantum well-active layer was sufficiently protected from the plasma.

4. Conclusion

Sub-micron-sized photonic crystal patterns were formed on the surface of the GaN layer of a vertical LED over the entire area with a diameter of 2 inches using UV nano-imprint lithography and plasma etching. The operation voltage required driving a current of 350 mA and the reverse current of the diode at a reverse bias of \(-5\) V revealed that the nano-imprint lithography and plasma etching processes used to form the photonic crystal pattern do not cause any electric degradation. The light output power of the LED devices with photonic crystal patterns was increased by up to 44%, compared to that of the LED device without photonic crystal pattern at a forward current of 1000 mA.

Acknowledgments

This work is the outcome of a Manpower Development Program for Energy & Resources supported by the Ministry of Knowledge and Economy (MKE). This work is also supported by Seoul R&BD Program (NT080570).

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