Nitride-Based Thin-Film Light-Emitting Diodes With Photonic Quasi-Crystal Surface

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***Abstract*—In this letter, the nitride-based thin-film light-emitting diodes (TFLEDs) with eight-fold photonic quasi-crystal (PQC) surfaces are proposed and demonstrated by a combination of wafer bonding, laser lift-off, and electron-beam lithography processes. By adopting a PQC surface, the light–output power (at 350 mA) of the PQC-TFLEDs exhibits 140% output power enhancement as compared with that of TFLEDs without a PQC surface.**

***Index Terms*—Electron-beam lithography, laser lift-off (LLO), photonic quasi-crystal (PQC), thin-film light-emitting diodes (TFLEDs), wafer bonding.**

I. INTRODUCTION

RECENTLY, tremendous progress has been achieved in GaN-based light-emitting diodes (LEDs). High-efficiency white LEDs made with blue LEDs and phosphors have received much interest because the replacement of incandescent, fluorescent, Hg and Xe lamps for general lighting, back lighting in large liquid-crystal displays, and vehicle head lamps could be realistic [1], [2]. Although the blue LEDs are commercially available, the performance of LEDs is still limited due to the poor thermal conductivity sapphire substrate and low light extraction efficiency. As a result, the replacement requires that LEDs should be more efficient and high power. At the present time, the thin-film LEDs (TFLEDs) were demonstrated to be one of the high potential light-emitting devices and promise even higher power operation due to their excellent thermal dissipation [3], [4]. In addition, the light extraction efficiency can be further enhanced by adopting a surface random roughening due to the random scattering from the roughened surface. Fujii *et al.* [5] reported a large enhancement of light–output power for TFLEDs using surface roughness formed by photoelectrochemical (PEC) etching. Kim *et al.* [6] also reported enhancement for light intensity of TFLED with "ball" shaped roughness fabricated by using dry etching compared to conventional laser lift-off (LLO) LED. However, the size effect and control of roughening fabricated by dry etching or PEC processes could encounter an additional problem, i.e., uneven surface roughening morphology, which is an important issue for the light output property. It could result in the uneven luminance intensity and decrease the process yield. As a result, in order to increase the light extraction efficiency and create a more even luminance intensity of TFLED, photonic crystals have been implemented on TFLEDs [7]. By employing the unique properties of photonic crystals as the photonic bandgap and the high density of leaky modes, the inhibit emission of guided modes or redirect trapped light can be utilized into the radiation modes, resulting in an enhancement in the light extraction from an LED [8]–[10]. Recently, the photonic crystal composed of a photonic quasi-crystal (PQC) lattice has attracted much interest. Quasi-crystals are structures with high-order rotational and line symmetries but without translation symmetries. It was found that PQCs with a higher level of symmetry exhibit unique light scattering [11], [12]. Thus it is expected that PQCs are promising for various applications on optical devices. In this work, in order to further extract the guided light out of the semiconductor material, a PQC has been utilized to enhance extraction efficiency of TFLEDs. Therefore, the LEDs incorporated with PQC on the light-emitting surface are expected to have a significant improvement on the extraction efficiency compared to that of TFLEDs without PQC. In this letter, the TFLEDs with a PQC surface were demonstrated for further enhancement of regular TFLEDs by a combination of wafer bonding, LLO, and electron-beam lithography. The electrical and optical properties of the TFLEDs with PQC surfaces will be reported.

II. EXPERIMENTS

The GaN-based LED wafers used in this study were grown by low-pressure metal–organic chemical vapor deposition onto c-face (0001) 2-in diameter sapphire substrates. The LED structure was comprised of a 40-nm-thick GaN nucleation layer, a 1.5-μm-thick undoped GaN layer, a 2.5-μm-thick Si-doped n-type GaN cladding layer, an unintentionally doped active region of 460-nm emitting wavelength with five periods of InGaN-GaN multiple quantum-wells, a 0.2-μm-thick Mg-doped p-type GaN cladding layer, and a Si-doped n-InGaN–GaN short-period superlattice structure. The fabrication process of TFLEDs on Si began with the deposition of a highly reflective ohmic contact stack (Ni–Ag), a diffusion barrier (Pt), and a bonding metal stack Ti–Pt–Au on the p-side of LED wafer. The metal coated wafer was then flipped and bonded onto a Ti–AuSn-coated p-type conducting Si wafer at 300 °C for 30 min. The wafer bonded sample was then subjected to the LLO process. A KrF excimer laser at a wavelength of 248 nm with a pulsewidth of 25 ns was used to remove the sapphire substrate. The incident laser was incident from the polished backside of the sapphire substrate onto the

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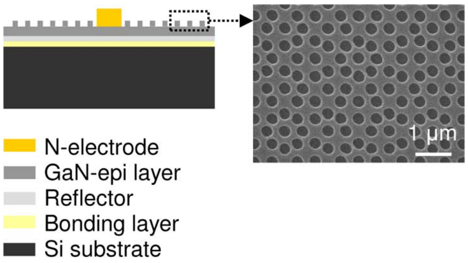

Fig. 1. Schematic drawing of PQC-TFLEDs and SEM image of PQC surface morphology.

sapphire–GaN interface to decompose GaN into Ga and N. After the sapphire substrate removing, the sapphire-removed samples were dipped into HCl solution to remove the residual Ga on the u-GaN. The details of the LLO process are described in [4]. Then the u-GaN was etched away to expose the n-GaN layer by an inductively coupled plasma (ICP) etcher and another ICP etch is used to define mesa of 1 mm × 1 mm. The PQC patterns were then formed on the n-GaN surface. Fabrication of PQC was illustrated as follows: A 50-nm-thick layer of SiO_2 was deposited and served as the hard mask on the n-GaN by plasma-enhanced chemical vapor deposition. The PQC pattern of circular holes was then defined by electron-beam (e-beam) lithography on the top of the hard mask layer. The lattice constant and air hole diameter of the PQC were chosen to be 520 and 320 nm, respectively. The PQC pattern was then transferred onto the n-GaN surface by dry etching using the main etch gases of chlorine and methane together with a radio-frequency power of 125-W ICP and 100-W reactive ion etching. The remaining SiO_2 was removed by dipping it in buffered oxide etch solution. Finally, a Ti–Pt–Au electrode was deposited as the n-type contact and the TFLEDs with PQC surface were obtained. The schematic drawing of the PQC-TFLED and scanning electron microscope (SEM) image of the PQC surface morphology is shown in Fig. 1.

III. RESULTS

The SEM micrograph of the PQC-TFLED's surface is shown in Fig. 2(a). The eight-fold PQC patterns were observed which consist of 320-nm air hole diameter and 520 lattice constant. Shown in Fig. 2(b) is a cross-sectional SEM micrograph of PQC patterns on the n-GaN surface. Notice that the depth of air hole is about 300 nm. Current–voltage (I–V) and intensity–current (L–I) characteristics of TFLED with and without PQC surfaces are shown in Fig. 3. It was found that the I–V curve of these devices were almost identical indicating that the TFLED and PQC fabrication processes would not result in any degradation in the electrical properties of PQC-TFLED. At a driving current of 350 mA, the forward voltages were about 3.19 V. According to the corresponding L–I characteristics, both types of TFLEDs show more linear characteristics up to 700 mA, which indicate a good thermal dissipation management for the TFLED's structure design. It is clearly observed that the light–output power of the PQC-TFLED was higher than that of the regular TFLED. This presents the fact that the light extraction from LED was definitely enhanced via the PQC on the top of the n-GaN layer. At a driving current of 350 mA, the output power of TFLED with and without PQC surfaces present 252 and 105 mW, respectively. It is noted that PQC-TFLED exhibits about 140% output power enhancement compared to that of TFLED without the PQC surface. To further investigate the optical influence of PQC on the light output of TFLEDs, the 3-D far-field radiation pattern of TFLED with and without PQC surfaces were also measured under the same output power condition for beam shape comparison. As shown in Fig. 4(a)–(b), the radiation patterns of TFLED with and without PQC surface present the regular Lambertian source emission. It is worth noting that the radiation pattern of PQC-TFLED is not very highly collimated because the lattice constant of the PQC is large enough to have many diffraction orders in the blue light regime resulting in light leakage along many directions. However, the radiation pattern of PQC-TFLED reveals a different beam-shaping effect. From the angular distribution radiation patterns of PQC-TFLEDs at a driving current of 350 mA, as shown in Fig. 5(a), most significantly, light extraction efficiency into the narrow cones was

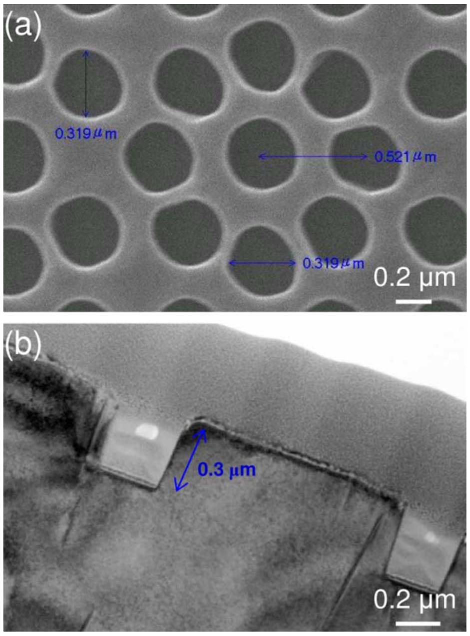

Fig. 2. SEM images of the etched top n-GaN formed by electron-beam lithography patterns using ICP etch process: (a) top and (b) cross sectional views.

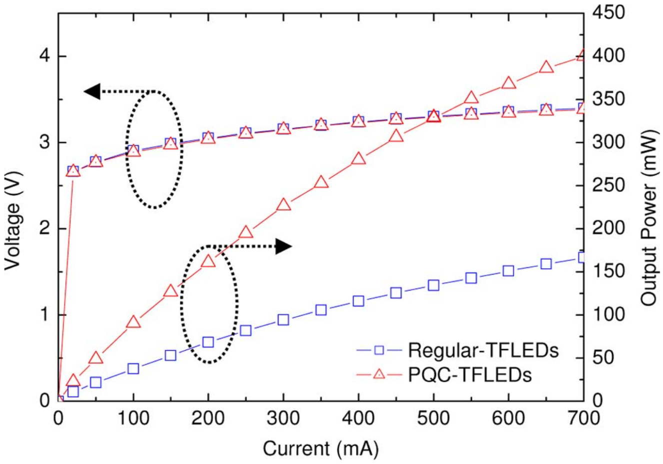

Fig. 3. L–I–V characteristics of TFLEDs with and without PQC surfaces.

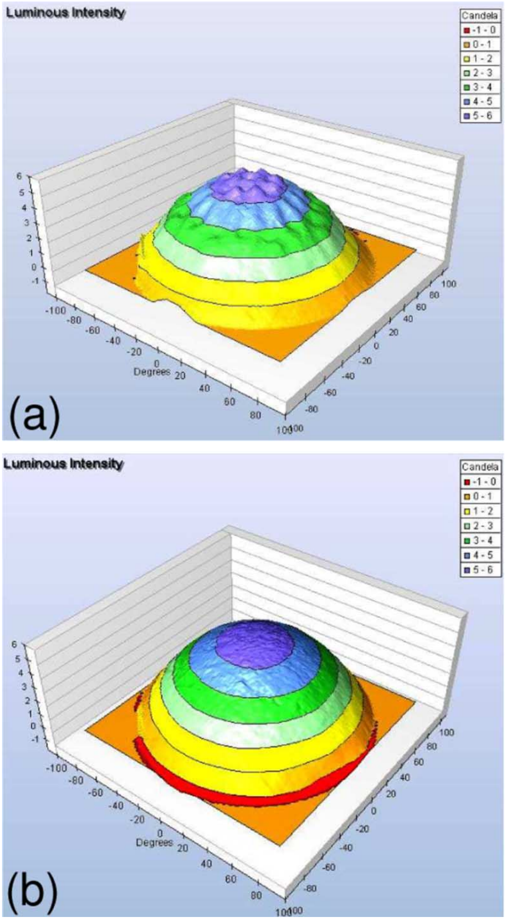

Fig. 4. Three-dimensional far-field patterns of (a) PQC-TFLED and (b) regular-TFLED.

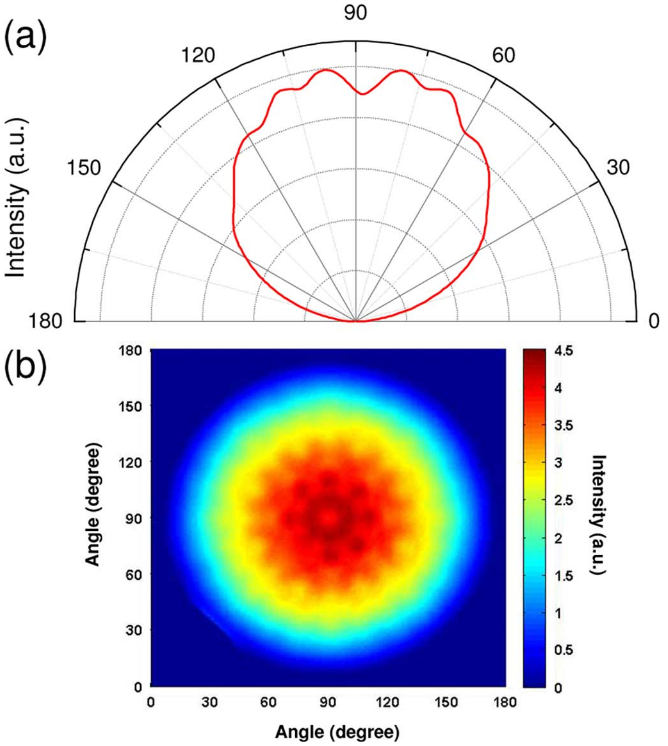

Fig. 5. (a) Angular distribution radiation patterns and (b) 3-D far-field patterns of a PQC-TFLED.

observed. The phenomena could be ascribed to the lattice symmetry PQC geometry pattern. Since the leakage bands located above the light cone have different leakage strengths, more light leaks in the symmetry direction. From the top-view of the 3-D far-field pattern, the light extraction along many diffraction directions is consistent with our earlier work [8], [13], as shown in Fig. 5(b).

IV. SUMMARY

A nitride-based TFLED incorporated with a PQC surface structure was investigated. The formation of the thin-film vertical-injection and PQC surface improves not only thermal dissipation management but the light extraction efficiency due to the lower series-resistance of the vertical-injection device structure and leaky modes of the PQC structure. By this novel device design, the PQC-TFLEDs (at 350 mA) exhibit about 140% output power enhancement compared to that of the TFLED without the PQC surface.

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