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Nitride-based LEDs with nano-scale textured sidewalls using natural lithography

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Abstract

This investigation describes the development of a InGaN/GaN light-emitting diode (LED) with textured sidewalls using natural lithography with polystyrene spheres (PSs) as the etching mask and dry etching the epitaxial layers of LEDs to achieve nano-scale textured sidewalls. The LED with textured sidewalls increased the output power of the InGaN–GaN multiple quantum well (MQW) LEDs by a factor of 1.3, indicating that the LED with nano-scale textured sidewalls had larger light extraction efficiency. The wall-plug efficiency of nitride-based LEDs was increased by 30% using textured sidewalls.

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

III-nitride wide band gap light-emitting diodes (LEDs) have recently attracted considerable interest due to their various applications, such as traffic signals, backside lighting in liquid crystal displays (LCDs) and illumination lighting by white light LEDs [1]. However, the external quantum efficiency of GaN-based LEDs is low because the refractive index of the nitride epitaxial layer differs greatly from that of the air. The refractive indexes of GaN and air are 2.5 and 1.0, respectively. Thus, the critical angle at which light generated in the InGaN–GaN active region can escape is approximately $[\theta_c = \sin^{-1}(n_{air}/n_{GaN})] \sim 23°$, which limits the external quantum efficiency of conventional GaN-based LEDs to only a few per cent [2, 3]. The light from LEDs can be enhanced either through the sample surface or through the sidewalls of the chip. Research into improving the light extraction efficiency (external quantum efficiency) and brightness in the LEDs [3–8, 10–16] has been intense. These processes all allow the photons generated within the LEDs to find the escape cone by multiple scattering from a rough surface. A similar concept can also be applied to chip sidewalls. In other words, more photons should be able to escape from LEDs with textured chip sidewalls compared to LEDs with conventional flat chip sidewalls.

By using a plasma-enhanced chemical vapour deposition SiO_2 layer as the etching mask, Chang *et al* successfully demonstrated a 10% output power enhancement for nitride-based LEDs with micron-scale wavelike textured sidewalls [8]. Due to the lithography limits of their instruments, they used a mask with a large period to fabricate micron-scale wavelike textured sidewalls. Further enhancement of the light output can be achieved if sidewall roughness can be reduced to the sub-micron or nano-scale range. Therefore, Deckman *et al* described the application of textured surfaces prepared using 'natural lithography' techniques which are currently being investigated [9]. Recently, Horng *et al* demonstrated the power enhancement of surface-textured indium–tin oxide (ITO)/GaN LEDs using a combination of natural lithography and dry etching techniques [10]. In this paper, nitride-based LEDs with nano-scale textured chip sidewalls were fabricated by natural lithography and dry etching techniques. As a result,

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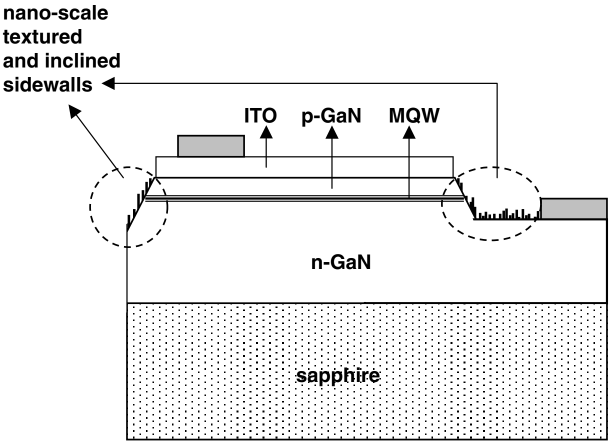

Figure 1. A schematic diagram of an InGaN–GaN MQW LED structure with nano-scale textured sidewalls.

the light output efficiency of an LED with nano-scale textured sidewalls was increased significantly compared with that of a conventional LED. Furthermore, the nano-scale textured sidewalls will not result in any degradation in the electrical properties of nitride-based LEDs.

The GaN-based LED samples were grown by metal–organic chemical vapour deposition (MOCVD) with a rotating-disk reactor (Emcore) on a *c*-axis sapphire (0001) substrate at a growth pressure of 200 mbar. The LED structure consists of a 50 nm-thick GaN nucleation layer grown at 550 °C, a 3 μm-thick Si-doped n-GaN buffer layer grown at 1050 °C, an unintentionally doped InGaN/GaN multiple quantum well (MQW) active region grown at 770 °C, a 50 nm-thick Mg-doped p-AlGaN electron blocking layer grown at 1050 °C, a 0.25 μm-thick Mg-doped p-GaN contact layer grown at 1050 °C, and a Si-doped n-$In_{0.23}Ga_{0.77}N/GaN$ short-period superlattices (SPS) structure. The MQW active region consists of five periods of 3 nm/7 nm-thick $In_{0.21}Ga_{0.79}N/GaN$ well layers and barrier layers. After annealing to activate Mg in the p-type layers, a 0.5 μm SiO_2 layer was then deposited on top of the LED samples by plasma-enhanced chemical vapour deposition (PECVD). Photolithography was subsequently performed to define the mesa mask pattern. The boundary of the SiO_2 mask (300 μm × 300 μm) and mesa edge is about 10 μm. A combination of natural lithography and dry etching techniques was used to form nano-scale textured sidewalls where the PSs were spun randomly onto the top as a natural mask around the boundary of the SiO_2 mask and mesa edge. The LED sample was then subjected to the inductively coupled plasma (ICP) process using the Cl_2/Ar mixture. A schematic diagram of the GaN LED structure with textured sidewalls is shown in figure 1(a). A 300 nm-thick ITO layer was subsequently evaporated onto the LED sample surfaces to serve as the upper contact at 300 °C. Since ITO is electrically conductive with a high transparency, we could achieve much larger light output from the LED surface [4, 10]. On the other hand, a Ti/Al/Ti/Au contact was deposited onto the exposed n-type GaN layer to serve as the n-type electrode. Finally, Ni/Au was deposited onto the p-type electrode. The wafers were then lapped down to about 90 μm. We then used scribe and break to fabricate InGaN–GaN LED chips. Figures 2(a) and (b) show the scanning electron microscopy (SEM) picture of the sidewall. It can be seen clearly that this device indeed has nano-scale textured sidewalls. The SEM images in figures 2(a) and (b) show that the nano-rod dimension and the density of the nano-scale textured sidewalls were approximately 200 nm and 2×10^9 cm^{-2}, and the height of the nano-rods was approximately 1.28 μm. The tilt of the sidewall can be greatly enhanced by the nano-roughness sidewall effect compared with conventional LEDs [17].

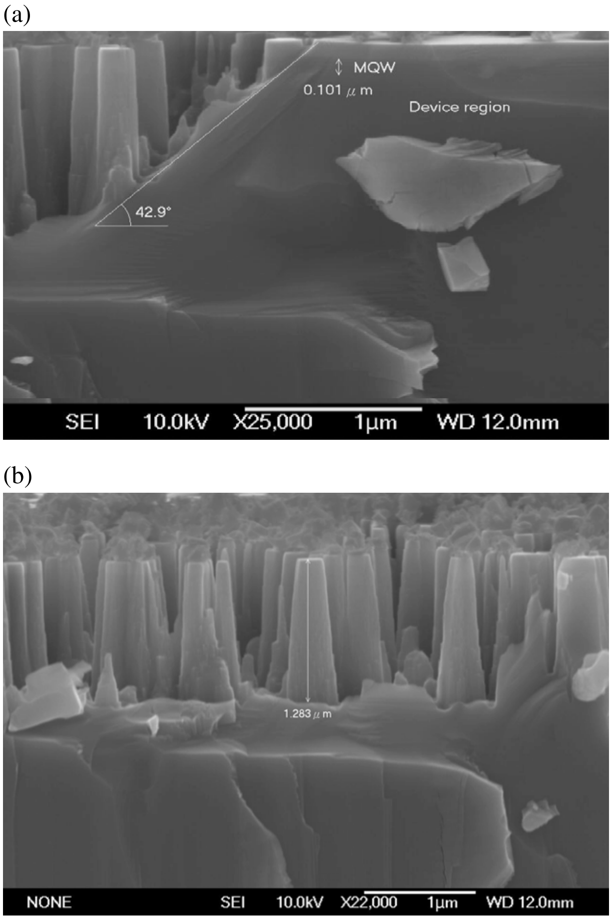

Figure 2. SEM images of an InGaN-GaN MQW LED structure with nano-scale textured sidewalls. (a) Cross-section of nano-scale textured sidewalls and (b) nano-rod density of nano-scale textured sidewalls.

A prime concern regarding these LED samples is their leakage current characteristics. Figure 3(a) shows the reverse I–V curves of the ITO/GaN LEDs with and without nano-scale textured sidewalls. The nano-scale textured sidewalls of LEDs did not induce a larger leakage current than that in the conventional LED. At a reverse voltage of −5 V, the leakage currents were approximately similar. Therefore, to avoid ITO being residual at a sidewall it is also very important to remove ITO at sidewalls to reduce I_R. Furthermore, it was found that the results indicate that the dry etching process does not adversely affect LED performance, because the plasma does not destroy the p-GaN layer. The forward voltages of the LED with nano-scale textured sidewalls and of the conventional LED were both approximately 3.42 V at a driving

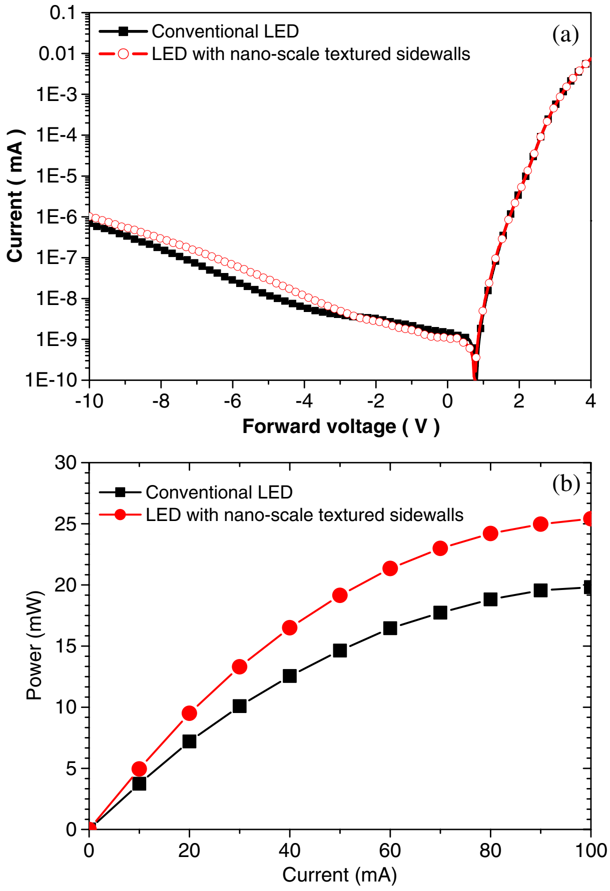

Figure 3. (a) Current–voltage (I–V) and (b) intensity–current (L–I) characteristics of a conventional LED and an LED with nano-scale textured sidewalls fabricated in this investigation.

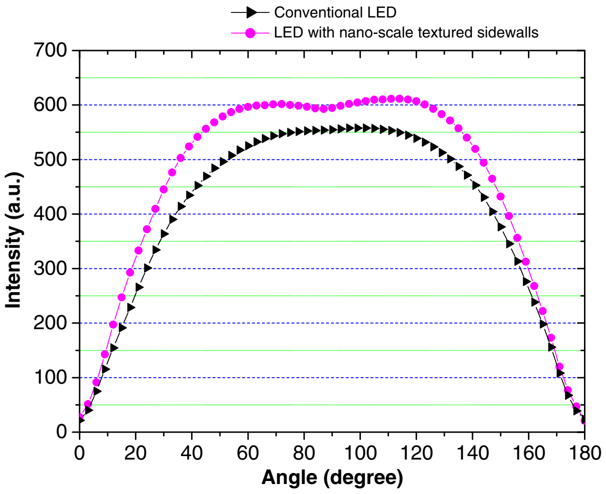

Figure 4. Light output patterns of the LED with nano-scale textured sidewalls and of the conventional LED.

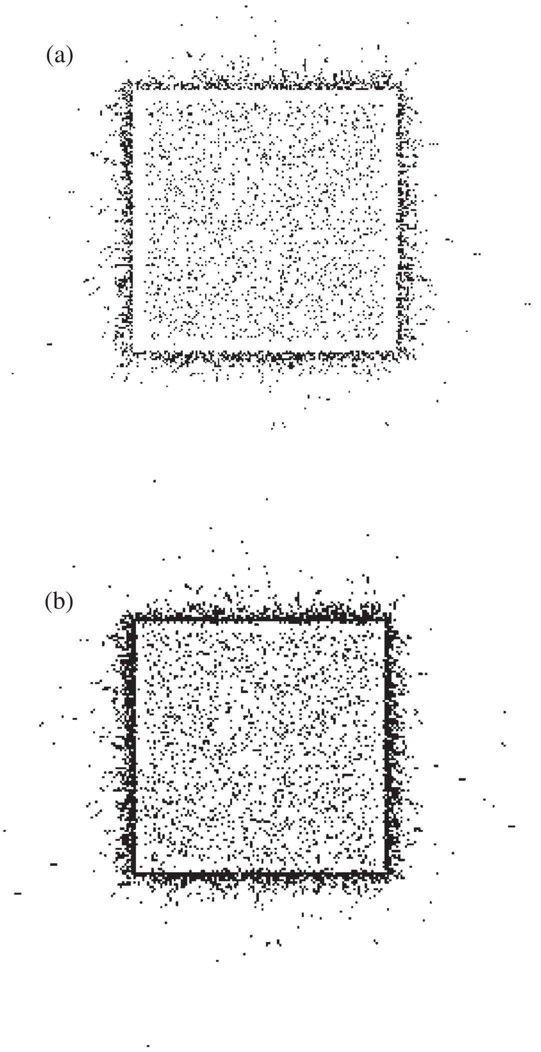

Figure 5. Top-view ray-tracing images of (a) the conventional LED and (b) the LED with nano-scale textured sidewalls.

current of 20 mA. Such an observation indicates that the nano-scale textured sidewalls will not result in any degradation in the electrical properties of nitride-based LEDs. Figure 3(b) shows the L–I characteristics of the LED with nano-scale textured sidewalls and of the conventional LED. At an injection current of 20 mA, the light output powers of the LED with nano-scale textured sidewalls and of the conventional LED were approximately 9.5 and 7.2 mW, respectively. The nano-scale textured sidewalls increased the output power of the InGaN–GaN MQW LEDs by a factor of 1.3, indicating that the LED with nano-scale textured sidewalls had larger light extraction efficiency. The wall-plug efficiency (output power/input power) was also calculated: it was 30% higher than that of the conventional LED at an injection current of 20 mA because of the enhanced light output power with nano-scale textured sidewalls.

To further investigate the influence of sidewall roughness on the light output performance of the LED chip, intensity distribution measurements were performed on a conventional LED and an LED with nano-scale textured sidewalls in figure 4. During these measurements, we injected a 20 mA dc current into these two different kinds of LEDs. It can be seen clearly that the LED with nano-scale textured sidewalls shows higher extraction efficiency with wider viewing angle compared to the conventional LED. The higher light extraction efficiency can be attributed to the increase in photon scattering from the sidewall roughness of the InGaN/GaN LED [8].

Further, the slight enhancement in the near-vertical direction can be attributed to the tilt angle of the sidewalls [17] and we simulated light propagation and reflection using the ray-tracing method provided by an advanced system analysis program (ASAP). For simplicity, we employed a two-dimensional model which is similar to GaN-based LED structures: the top mesa width is 300 μm and the depth is 1.3 μm, with a vertical sidewall and a 42° over-cut sidewall. Figures 5(a) and (b) show the top-view ray-tracing images of a conventional LED and an LED with nano-scale textured sidewalls. The result can also be greatly enhanced light extraction efficiency. Such an enhancement could give a larger probability for emission from the nano-scale textured sidewalls, and thus achieve even brighter LEDs.

In summary, InGaN/GaN LEDs with nano-scale textured sidewalls have been fabricated. By using PSs as the etching mask, the epitaxial layers of the LEDs were ICP etched to achieve nano-scale textured sidewalls. The LED with nano-scale textured sidewalls increased the output power of the InGaN–GaN MQW LEDs by a factor of 1.3, indicating that the LED with nano-scale textured sidewalls had larger light extraction efficiency. The wall-plug efficiency of nitride-based LED was increased by 30% using textured sidewalls.

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