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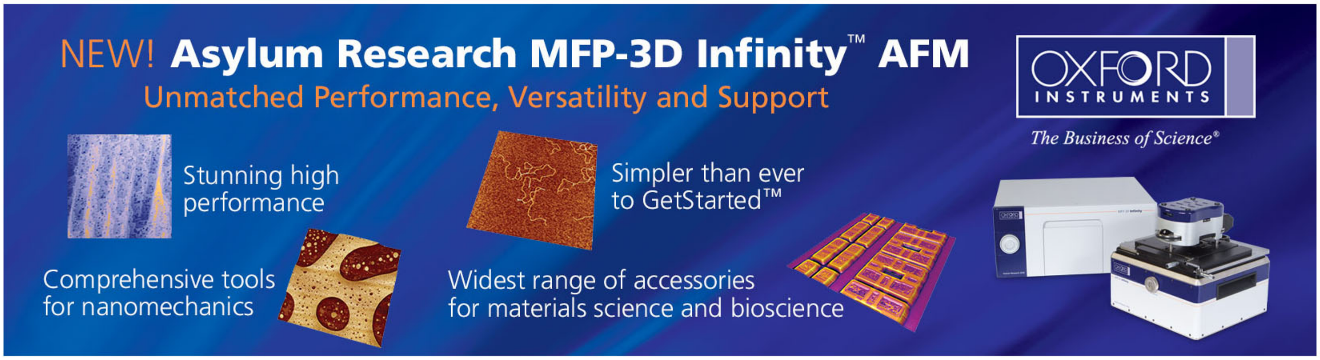

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APPLIED PHYSICS LETTERS **89**, 041116 (2006)

# Improved luminance intensity of InGaN–GaN light-emitting diode by roughening both the *p*-GaN surface and the undoped-GaN surface

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The InGaN–GaN epitaxial films were grown by low-pressure metal-organic chemical vapor deposition on a sapphire substrate, and then the light-emitting diode (LED) with double roughened (*p*-GaN and undoped-GaN) surfaces was fabricated by surface-roughening, wafer-bonding, and laser lift-off technologies. It was found that the front side luminance intensity of double roughened LED was 2.77 times higher than that of the conventional LED at an injection current of 20 mA. The backside luminance intensity was 2.37 times higher than that of the conventional LED. This is because the double roughened surfaces can provide photons multiple chances to escape from the LED surface, and redirect photons, which were originally emitted out of the escape cone, back into the escape cone. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2236462]

The epitaxial growth techniques have significantly improved the brightness and efficiency of light-emitting diode (LED).[1] Some techniques have been employed to reduce the dislocation density through epitaxial lateral overgrowth (ELO),[2,3] lateral epitaxial patterned sapphire (LEPS),[4,5] and $SiN_x$ interlayer[6] using a metal-organic vapor-phase epitaxy. These improvements have enabled LED to be widely applied to mobile phones, full-color displays, and lighting.[7] The LED operating in the wavelength region ranging from blue to green light has been employed by the InGaN–GaN alloy system grown on sapphire substrates. However, the efficiency of conventional LED is limited by their inability to emit all of the light that is generated from the active layer. According to Snell's law, light traveling from a GaN surface having a high index of refraction ($n=2.5$) to an air with a low index of refraction ($n=1.0$) that is only within a critical angle of 23° will cross the air. The light reaching the surface beyond the critical angle will not cross the air but will experience total internal reflection that continues to be reflected within the LED until it is absorbed. One method of reducing the percentage of total internal reflection light is to create light scattering centers in the form of random texturing on the LED's surface.[8] However, the thickness of the top layer *p*-GaN cladding is very thin. Consequently, it is not easy to control the dry etching depth and plasma damage to the *p*-GaN during the dry etching process. Some methods have been used to improve the light extraction efficiency by roughening the top surface[9–13] or the mesa sidewall[14] of LED. It could also utilize wafer-bonding technology to transfer *n*-side-up GaN-based LED on Si substrates with a hexagonal "conelike" surface on *n*-GaN.[15] All these studies described above were focused on a single roughened top surface of nitride-based LED. In this study, LED with double roughened surfaces was proposed. It was fabricated using surface-roughening, wafer-bonding, and laser lift-off technologies.

Three kinds of LED were investigated in this study. Their specifications and structures are schematically illustrated in Fig. 1. Samples designated as "CV-LED" were conventional LEDs without any surface-roughening treatment. Samples designated as "PR-LED" were LEDs with a *p*-GaN roughened surface, while "DR-LED" were LEDs with double roughened (*p*-GaN and undoped-GaN) surfaces. The basic processes of these LEDs were almost the same. The InGaN–GaN films were grown by low-pressure metal-organic chemical vapor deposition (MOCVD) on a sapphire substrate. The LED structures and growth temperature included a *p*-type Mg-doped GaN at 950 °C, an InGaN–GaN multiquantum well (MQW) with six pairs of InGaN (3 nm)/GaN (9 nm) at 800 °C, a 2-$\mu$m-thick *n*-type Si-doped GaN at 1050 °C, a 2-$\mu$m-thick undoped-GaN layer film at 1050 °C, and a buffer layer at 550 °C on the sapphire substrate. The major difference was that the thickness of the *p*-type GaN of CV-LED was 0.2 $\mu$m, which was thinner than that of PR-LED and DR-LED samples, 0.5 $\mu$m. This extra length of the *p*-type GaN layer was employed to create the roughened *p*-type GaN surface by lowering the epitaxy growth temperature.[13]

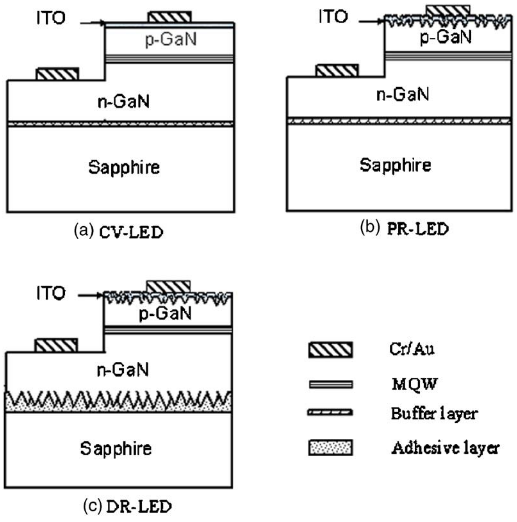

FIG. 1. Schematic diagrams of (a) CV-LED (without any surface-roughening treatment), (b) PR-LED (with roughened *p*-GaN surface), and (c) DR-LED (with double roughened surfaces).

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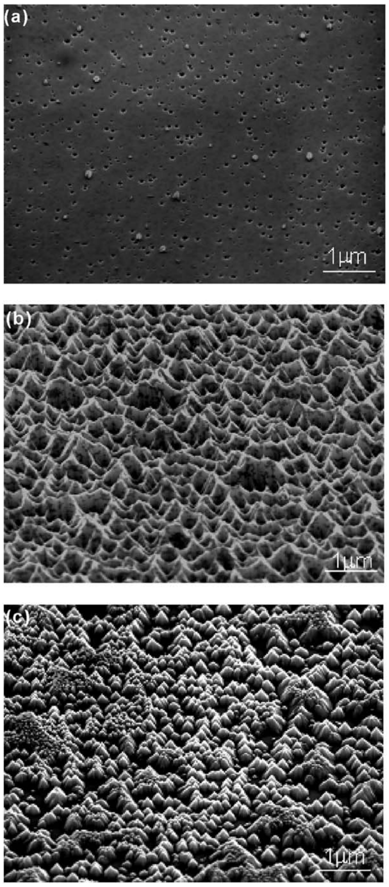

FIG. 2. Scanning electron micrographs of (a) $p$-GaN surface without any surface-roughening treatment, (b) roughened $p$-GaN surface, and (c) roughened undoped-GaN surface.

For the CV-LED and PR-LED, the device of $300 \times 300\ \mu\mathrm{m}^2$ dimension was defined by inductively coupled plasma (ICP) to remove Mg-doped GaN and MQW until Si-doped GaN was exposed. Then, the indium tin oxide (ITO) layer was deposited on the $p$-GaN layer ($\rho \sim 4\ \Omega\,\mathrm{cm}$) to form a $p$-side contact layer and a current spreading layer. Finally, Cr/Au was deposited onto the ITO layer and $n$-GaN layer as the electrodes. The structures were shown in Figs. 1(a) and 1(b), respectively.

As for the fabrication of DR-LED devices, PR-LED wafer was bonded to a host substrate covered with adhesive layer. The optical transparency of the adhesive layer was exceeding than 90% across the visible spectrum. It was then annealed at 200 °C for 60 min. After bonding, the sapphire substrate was removed by laser lift-off with a frequency-tripled neodymium-doped yttrium aluminum garnet laser at 355 nm.[16] The roughened undoped-GaN surface was obtained by treatment with 60 °C KOH solution for 1 min. The wafer was then bonded to sapphire substrate with an adhesive layer. Finally, the host substrate was removed. The structure of DR-LED was shown in Fig. 1(c).

Figure 2 shows the morphologies of LED surfaces. Clearly, the surface of CV-LED is much smoother than that of PR-LED. Their surfaces were measured using atomic force microscopy (AFM). The root mean square (rms) roughness of $p$-GaN surface without any treatment is only 11.8 nm, while that of roughened $p$-type GaN surface is 71.6 nm. As for the surface of the roughened undoped-GaN layers the surface was full with three-dimensional islands. The height and size of the GaN islands were 300–700 nm and 0.1–0.4 $\mu$m, respectively. The rms roughness of this undoped-GaN surface was 91.9 nm.

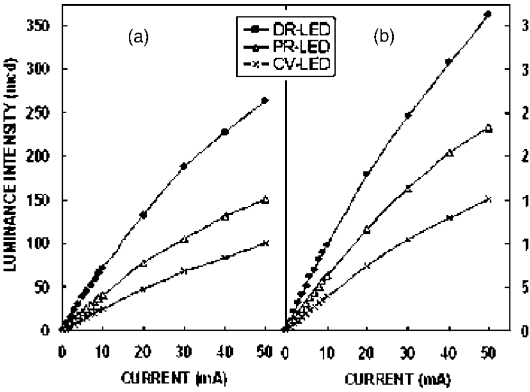

FIG. 3. Luminance intensity of three LED chips vs the forward injection current. (a) Intensity measured from the front side (topside through the transparent metal layer) of the LED chip. (b) Intensity measured from backside substrate side (through the sapphire/transparent glue/glass) of the LED chip.

The $I$-$V$ characteristics of the PR-LED and DR-LED exhibited normal $p$-$n$ diode behaviors with forward voltages about 3.3 V at 20 mA, which was similar to that of CV-LED (3.2 V at 20 mA). This similarity indicated that the surface-roughening process, wafer-bonding process, and laser lift-off process did not degrade the performance of DR-LED. To further investigate the influence of roughened GaN surfaces on light-output performance of LED chips, the luminance intensities of unpackaged LED were measured from both the front side (top side through the transparent ITO layer) and backside (substrate side through the sapphire/transparent glue/glass) of the device. The light intensities as a function of injected forward current are shown in Figs. 3(a) and 3(b), respectively. It is obvious that roughened surfaces of LED did enhance the luminance intensities.

Compared with that of the CV-LED chip, the light intensity of the PR-LED chip with a roughened $p$-GaN surface was increased by 60% for the front side and by 56% for the backside at an injection current of 20 mA. The reason why the greater increase in light intensity measured from the front side than from the backside is because the microroughened top surface for the front side was thought to give the photons multiple chances to escape from the LED to the surrounding air. These results are similar to the conclusions drawn by Hu *et al.*[4] in their studies on microroughening of the $p$-GaN surface. They measured the light-output powers of unpackaged LED chips from both front side and backside of the device. They also found that the light-output powers were increased on both sides, and the increase from the front side was also higher than that from the backside. Compared with that of the conventional LED chip, the light-output power for the LED chip with a microroughened top surface was increased by 52.4% for the front side and by 30% for the backside, respectively. Moreover, our increase in light intensities from both sides was higher than those obtained by Hu *et al.* This is because the rms roughness of our roughened $p$-type GaN surface is 71.6 nm, which is higher than that of the samples of Hu *et al.*, 6 nm.

As for the luminance intensity of our DR-LED, the light intensities from both sides were greatly enhanced. The front side luminance intensity was 133 mcd, which was 2.77 times

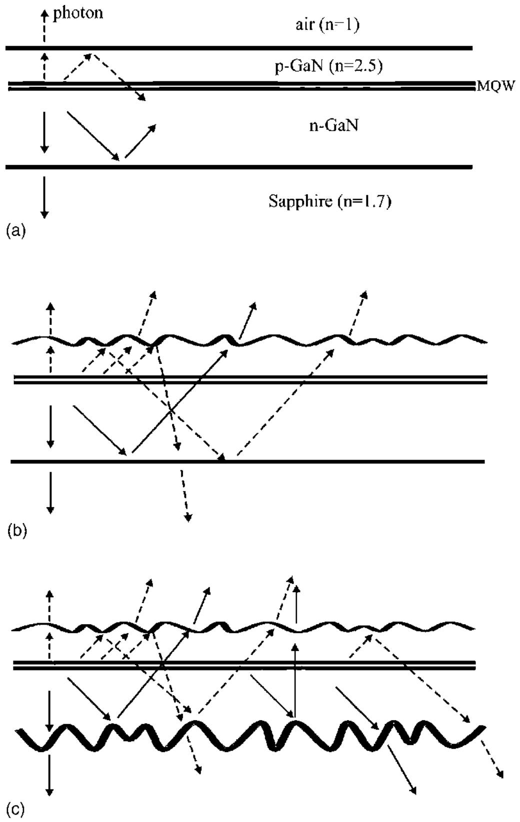

FIG. 4. Possible photon paths inside the structures of the (a) CV-LED, (b) PR-LED, and (c) DR-LED.

higher than that of the CV-LED, and 1.73 times higher than that of the PR-LED. As for the backside luminance intensity, it was 178 mcd, which was 2.37 times higher than that of the CV-LED and 1.52 times higher than that of the PR-LED. Clearly, this tremendous enhancement was caused by the roughened *p*-GaN surface and the roughened undoped-GaN surface. The increase in light intensity measured from the front side was still higher than that from the backside, even though the rms roughness of the roughened undoped-GaN surface (91.9 nm) was much higher than that of the *p*-type GaN surface (71.6 nm). This is because during bonding process, we might create interfacial defects at two bonded interfaces (GaN/adhesive layer and adhesive layer/sapphire). These defects have a negative effect on optical properties, and it is suggested that this might be the reason why the increase in backside luminance intensity was not as high as we expected. In addition, Fresnel losses resulting from the GaN ($n \sim 2.5$)/adhesive layer ($n \sim 1.5$) and adhesive layer ($n \sim 1.5$)/sapphire ($n \sim 1.7$) interfaces might also have a negative effect on the backside luminance intensity.

The light extraction efficiency in the GaN-based LED is limited mainly due to the difficulty for light to escape from high refractive index semiconductors. The key to enhance the escape probability is to give the photons multiple opportunities to find the escape cone.[3] As shown in Fig. 4, roughened surfaces not only can provide photons multiple chances to escape from the LED surface, but also redirect photons, which were originally emitted out of the escape cone, back into the escape cone. Figure 4(a) shows the possible photon paths for CV-LED without any roughened surface. For a PR-LED, the angular randomization of photons can be achieved by surface scattering from the roughened *p*-GaN surface, as shown in Fig. 4(b). Thus, the roughened surface structure can provide photons multiple chances to escape from the LED, and redirect photons back into the escape cone. A DR-LED device has two roughened surfaces, as shown in Fig. 4(c). Compared to the PR-LED, the extraroughened undoped-GaN layer can greatly increase the escape probability of photons, resulting in an increase in the luminance intensity of LED, as shown in Fig. 3.

In summary, DR-LED with double roughened (*p*-GaN and undoped-GaN) surfaces was investigated in this study. It was fabricated by surface-roughening, wafer-bonding, and laser lift-off technologies. It was found that surface-roughening, wafer-bonding, and laser lift-off processes did not degrade the performance of DR-LED. At an injection current of 20 mA, the front side luminance intensity of double roughened LED was 133 mcd, which was 2.77 times higher than that of the conventional LED, and the backside luminance intensity was 178 mcd, which was 2.37 times higher than that of the conventional LED. This is because the double roughened surfaces not only can provide photons multiple chances to escape from the LED surface, but also redirect photons, which were originally emitted out of the escape cone, back into the escape cone.

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