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Enhanced performance of an InGaN–GaN light-emitting diode by roughening the undoped-GaN surface and applying a mirror coating to the sapphire substrate

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An InGaN–GaN light-emitting diode (LED) with a roughened undoped-GaN surface and a silver mirror on the sapphire substrate was fabricated through a double transfer method. It was found that, at an injection current of 20 mA, its luminance intensity was 100% larger than conventional LEDs. Its output power was 49% larger than conventional LEDs. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2199613]

Recently, epitaxial growth techniques have significantly improved the brightness and efficiency of light-emitting diode (LED). GaN-based LEDs are attractive devices for use in a variety of applications including traffic signals, full-color displays, backlighting in liquid-crystal displays, and miniprojectors.[1,2] However, the light extraction efficiency of GaN-based LEDs is limited by the large difference in refractive index between the GaN film and the surrounding air. According to Snell's law, light traveling from GaN to air travels only within a critical angle of 23°. The light reaching the surface beyond the critical angle will experience total internal reflection that will continue to be reflected within the LED until it is absorbed. One method of reducing the percentage of total internal light reflection is to create light scattering centers in the form of random texturing on the top of the *p*-GaN layer of the LED.[3–6] Another alternative is to utilize wafer-bonding and laser lift-off technologies to transfer the *n*-side-up textured surface of GaN-based LEDs onto Si substrates,[7] or bond various mirror systems between the GaN LED structures and the substrate.[8]

In this work, GaN LEDs with a roughened undoped-GaN surface and/or a silver (Ag) mirror on the sapphire substrate were fabricated using wafer-bonding and laser lift-off technologies. Their performances and light extraction efficiencies were also investigated.

Four kinds of LEDs were used in this study. As illustrated in Fig. 1, samples designated as "C-LED" were conventional LED without any surface-roughening treatment. Samples designated as "M-LED" and "R-LED" were LEDs with either a mirror system or roughened undoped-GaN surface between the GaN LED structure and sapphire substrate, respectively. The "RM-LED" was R-LED with a Ag mirror on the backside of sapphire substrate. The device processes of these LEDs were the same. The InGaN–GaN films were grown by low-pressure metal organic chemical vapor deposition (MOCVD) on a sapphire substrate. The LED structures consisted of a 0.4-μm-thick Mg-doped GaN, an InGaN–GaN multiple quantum well (MQW), a 2-μm-thick Si-doped GaN, a 2-μm-thick undoped GaN (*u*-GaN), and a buffer layer on sapphire substrate. A device mesa with chip size of $250 \times 450\ \mu\mathrm{m}^2$ was defined by an inductively coupled plasma (ICP) which removed the Mg-doped GaN and MQW until the Si-doped GaN was exposed. Then, the indium tin oxide (ITO) layer was deposited onto the *p*-GaN layer to form a *p*-side contact layer and a current spreading layer. The Cr/Au was deposited onto the ITO layer as *p*-side and *n*-side electrodes. The LED wafer was bonded to a host substrate with an adhesive layer. After bonding, the sapphire substrate was then removed by laser lift-off with a frequency-tripled Nd:YAG (yttrium aluminum garnet) laser at 355 nm.[9] The Ga residues were subsequently removed by a wet chemical etch using diluted HCl:H_2O (1:1) solution for 60 s. The *u*-GaN layer of the M-LED was polished to achieve a smooth surface and then coated with a Ag mirror. On the other hand, the *u*-GaN epilayer of the R-LED was treated with 45% KOH solution for 1 min at 100 °C to obtain a roughened *u*-GaN surface. Figure 2 shows the side-view scanning electron microscopy (SEM) micrograph of the undoped-GaN layer with the treatment of 45% KOH solution for 1 min at 100 °C. The SEM image was taken at an angle of 70° from the perpendicular direction of the etched surface. The sample was measured using atomic force microscopy

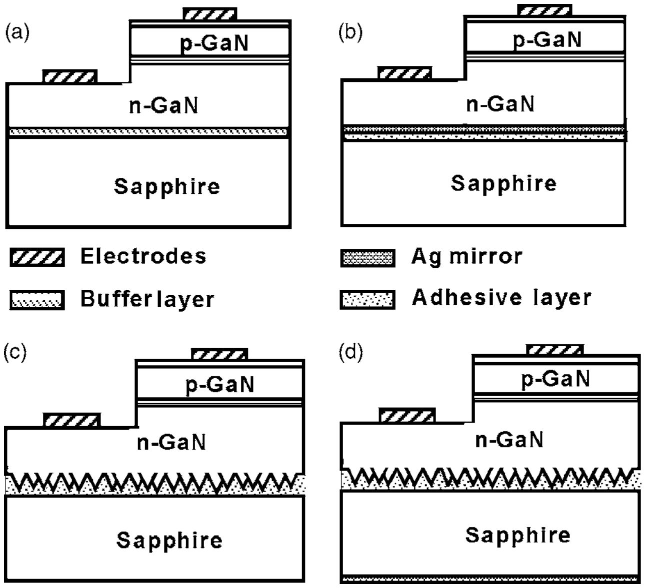

FIG. 1. Schematic diagrams of the (a) C-LED, (b) M-LED, (c) R-LED, and (d) RM-LED.

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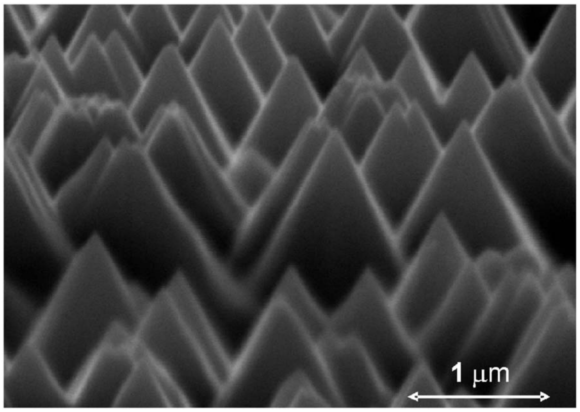

FIG. 2. Scanning electron micrograph of roughened undoped-GaN surface treated with 45% KOH solution for 1 min at 100 °C.

(AFM) to identify the degree of texturing. The root-mean-square (rms) roughness of the undoped-GaN layer was 146.7 nm. The heights and lengths of the GaN conelike islands were 700–950 and 600–900 nm, respectively.

These wafers were then bonded to a sapphire substrate with an adhesive layer that consisted of a polycyclic aromatic hydrocarbon (C_8H_6) composed of a benzene ring fused to a cyclobutene ring. The optical transparency of the adhesive layer was exceeding more than 90% across the visible spectrum. Wafers were annealed at 200 °C for 60 min with a comprehensive load of 10 kg/cm^2. The host substrate and glue layer were subsequently removed. To fabricate the RM-LED, a Ag mirror was coated on the backside of R-LEDs sapphire substrate. For comparison, the performances of these LEDs were fabricated from a single InGaN–GaN LED epitaxial wafer with a split wafer experiment.

Figure 3(a) shows the current-voltage (*I-V*) characteristics of the LEDs. It was found that the forward voltages of the M-LED, R-LED, and RM-LED were in the range of 3.4–3.5 V at 20 mA, which were similar to the C-LED, indicating that the transfer method did not degrade the performance.

Figure 3(b) depicts the effects of injection current on the luminous intensity of the LEDs. During the testing, LEDs were put onto a graphite plate with a collection angle of approximately 27°. The light intensities of M-LED, R-LED, and RM-LED were greater than that of C-LED. The light intensity of M-LED was greater than the C-LED by 58% at an injection current of 20 mA. Similar results have been reported by Wuu *et al.*[8] who fabricated GaN/mirror/Si LEDs using different mirror reflector materials such as Ag, Al, and Au. They found that the intensity strongly depended on the reflectivity of the mirror material. The LED with a Ag mirror achieved maximum luminance intensity as compared to other reflector materials. Therefore, in this study, Ag was chosen as a mirror material for the M-LED. The reflectivity of the Ag mirror was 96% at a wavelength of 470 nm.

The light intensity of R-LED was 242 mcd, which was 58% larger than the C-LED at an injection current of 20 mA. These results are similar to the conclusions drawn by Huh *et al.*[4] during their studies of microroughening the *p*-GaN surface. They produced microroughened *p*-GaN top surfaces using metal clusters as a wet etching mask and measured the light-output power of unpackaged LED chips from both the front side and the backside of the device. They found that the light-output power was increased on both sides. In comparison with the conventional LED, the light-output power of the microroughened top surface LED improved by 52.4% for the front side and by 30% for the backside. They believed that the microroughened surface structure improved the escape probability of photons due to the angular randomization of photons inside the LED structure, resulting in an increase of the light extraction efficiency of the LED.

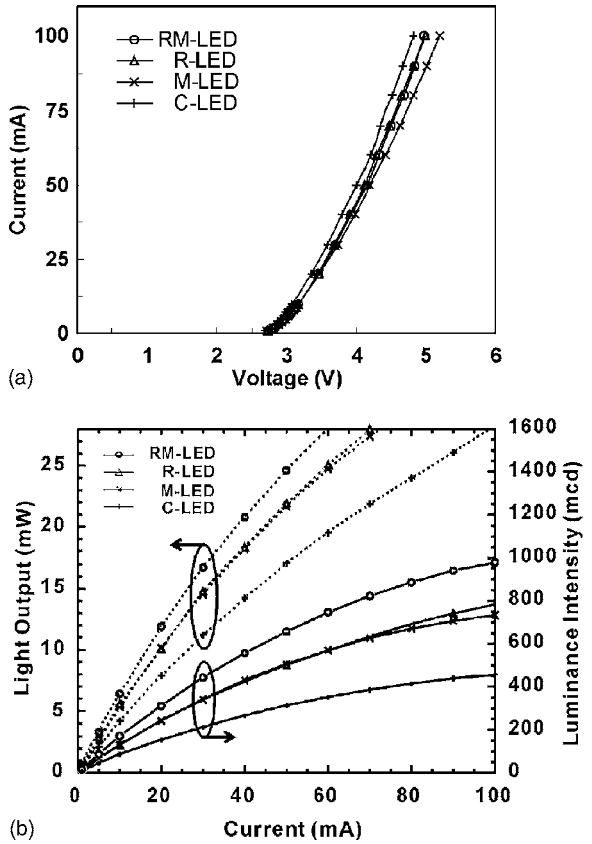

FIG. 3. (a) *I-V* characteristic of the LEDs and (b) the effects of injection current on the luminous intensity and the light output of the LEDs.

In this study, we fabricated a roughened undoped-GaN surface within the GaN LED layer instead of a microroughened *p*-GaN top surface. We also found that the light intensities of both sides were greatly enhanced. In contrast to the C-LED, the light intensity of the R-LED increased by 73% for the front side and by 53% for the backside at an injection current of 20 mA. The optical transparency of the adhesive layer was very important. If the adhesive layer were opaque, it would degrade the light intensity by absorbing the downward-traveling light. Furthermore, by adding a mirror to the backside of the R-LED to create a RM-LED structure, the light efficiency was enhanced by redirecting the downward-traveling light. As expected, the RM-LED provided the best performance with maximum light intensity of 312 mcd, which was 100% greater than the C-LED and 29% greater than the R-LED.

Figure 3(b) also indicates that the light intensity of RM-LED was greater than the M-LED, even though both LEDs had a Ag mirror. It is believed that the roughened surfaces of the RM-LED not only provided the photons multiple opportunities to escape the LED surface, but also redirected the photons which were originally emitted out of the escape cone, back into the escape cone [Fig. 4(b)]. In contrast, as illustrated in Fig. 4(a), the mirror of M-LED could only re-

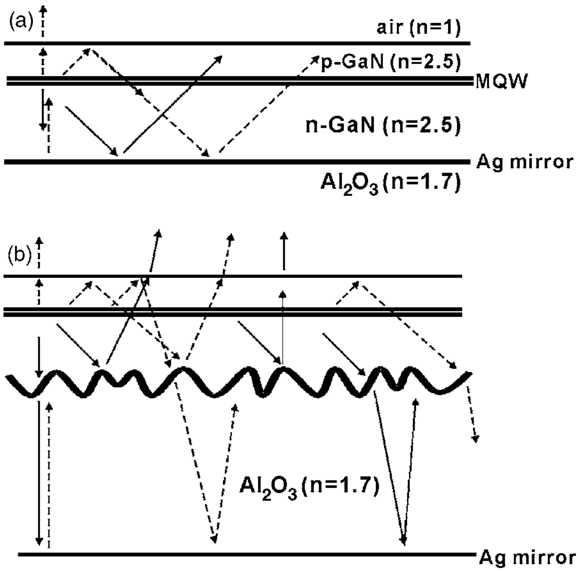

FIG. 4. Possible photon paths of the (a) M-LED and (b) RM-LED.

flect the downward-traveling light to the *p*-GaN surface, but not necessarily redirect the photons back into the escape cone. Hence, the RM-LED provided the best light intensity of 312 mcd, which was 29% larger than the M-LED.

The light output versus injection current curves for the LEDs were shown in Fig. 3(b). LEDs were measured in an integrating sphere and were not encapsulated during the electrical and optical measurements. It was found that the RM-LED achieved a maximum output power of 11.8 mW (at 20 mA), which was 49% larger than the C-LED, and 16% larger than the R-LED and the M-LED. The improvement of the light output was also due to the light scattering improvement and redirection of photons from the roughened undoped-GaN surface and the backside mirror on sapphire substrate.

In summary, a GaN RM-LED with a roughened undoped-GaN surface and a silver mirror on the sapphire substrate was fabricated. The forward voltage was in the range of 3.4–3.5 V at 20 mA, which was similar to the C-LED. This indicated that the transfer method did not degrade the performance of LED. At an injection current of 20 mA, the luminance intensity of the roughened LED was 312 mcd, which was 100% larger than that of the C-LED. Furthermore, the output power was 11.8 mW, which was 49% larger than the C-LED. The roughened undoped GaN of the RM-LED redirected the photons into the escape cone of the LED surface to improve the extraction efficiency of the LED. The backside mirror on sapphire substrate also played a critical role in reflecting the downward-traveling light back to the surface of the LED.

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[1] S. Nakamura, S. Senoh, N. Iwasa, and S. Nagahama, Jpn. J. Appl. Phys., Part 2 **34**, L797 (1995).
[2] H. X. Jiang, S. X. Jin, J. Li, J. Shakya, and J. Y. Lin, Appl. Phys. Lett. **78**, 1303 (2001).
[3] I. Schnitzer, E. Yablonovitch, C. Caneau, T. J. Gmitter, and A. Scherer, Appl. Phys. Lett. **63**, 2174 (1993).
[4] Chul Huh, Kug-Seung Lee, Eun-Jeong Kang, and Seong-Ju Park, J. Appl. Phys. **93**, 9383 (2003).
[5] Y. P. Hsu, S. J. Chang, Y. K. Su, S. C. Chen, J. M. Tsai, W. C. Lai, C. H. Kuo, and C. S. Chang, IEEE Photonics Technol. Lett. **17**, 1620 (2005).
[6] C. H. Liu, R. W. Chuang, S. J. Changb, Y. K. Su, L. W. Wu, and C. C. Lin, Mater. Sci. Eng., B **112**, 10 (2004).
[7] T. Fujii, Y. Gao, R. Sharma, E. L. Hu, S. P. DenBaars, and S. Nakamura, Appl. Phys. Lett. **84**, 855 (2004).
[8] D. S. Wuu, S. C. Hsu, S. H. Huang, C. C. Wu, C. E. Lee, and R. H. Horng, Jpn. J. Appl. Phys., Part 1 **43**, 5239 (2004).
[9] M. K. Kelly, O. Ambacher, R. Dimitrov, R. Handschuh, and M. Stutzmann, Phys. Status Solidi A **159**, R3 (1997).