High-Performance GaN-Based Vertical-Injection Light-Emitting Diodes With TiO_2–SiO_2 Omnidirectional Reflector and n-GaN Roughness

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***Abstract*—We have designed and fabricated a new type of GaN-based thin-film vertical-injection light-emitting diode (LED) with TiO_2–SiO_2 omnidirectional reflector (ODR) and n-GaN roughness. The associated ODR designed for LED operation wavelength at 455 nm was integrated with patterned conducting channels for the purpose of vertical current spreading. With the help of laser lift-off and photo-electrochemical etching technologies, at a driving current of 350 mA and with chip size of 1 mm × 1 mm, the light–output power and the external quantum efficiency of our thin-film LED with TiO_2–SiO_2 ODR reached 330 mW and 26.7%. The result demonstrated 18% power enhancement when compared with the results from the thin-film LED with Al reflector replace.**

***Index Terms*—Flip-chip, light-emitting diode (LED), omnidirectional reflector (ODR).**

RECENTLY, high-brightness GaN-based LEDs has become a strong candidate for applications such as outdoor displays, traffic signals, LED-backlit liquid crystal displays, and direct-view large-area signage [1]. However, to address next-generation applications of projectors, automobile headlights, and high-end general lighting, further improvement on optical power and light extraction efficiency are required. The thin-film LED structure is a recent development and shall be a good candidate for enhancing the light extraction efficiency of GaN-based LEDs [2]. To fabricate a desired thin-film LED structure, the sapphire substrate is usually removed using an excimer laser [3], and the exposed n-doped GaN is photo-electrochemically roughened [4]. An N-metal electrode is deposited on the roughened n-GaN, and the cathode connection is performed by means of a wire bond. The resulting LEDs have vertical device structures where p-GaN has been deposited with metal and bonded to another semiconductor substrate serving as an anode.

Most vertical device structures require reflectors to improve the extraction efficiency of LED and light emitted downward toward the substrate must be reflected upward in order to contribute to useable light output. High refractive metallic mirrors like Ag or Al have been used for this purpose [5]. Although those metallic mirrors can efficiently reflect light at arbitrary angles and polarizations, they are somewhat lossy in the visible regime [6] and have reliability problems at the interface with semiconductor due to degradation or electro-migration. As a result, dielectric mirrors, such as distributed Bragg reflectors (DBRs) [7] have been used to solve those problems. However, only light of a given polarization impinging near the normal direction to the DBR structure can be effectively reflected. Total reflection of light with arbitrary polarization and incidence angle onto a periodic structure can be realized with the existence of a complete photonic bandgap (CPBG) at the wavelengths of interest [8]. A one-dimensional (1-D) periodic dielectric structure possessing this characteristic is known as an omnidirectional 1-D photonic crystal (PhC). Therefore, compared with a DBR mirror, a substantially higher reflectance can be achieved. In our previous work, we have demonstrated enhancement in the extracted light intensity for a GaN-based LED with p-side up and flip-chip configuration incorporated with an ODR composed of alternate layers of TiO_2 and SiO_2 [9], [10]. To achieve ultrahigh brightness for GaN-based LEDs, a thin-film vertical-injection LED (VLED) structure incorporated with an ODR is demonstrated in this letter.

The schematic cross-sectional representations of the structures of InGaN–GaN VLEDs we proposed are shown in Fig. 1(a) with an Al mirror and Fig. 1(b) with an ODR composed of TiO_2–SiO_2 multilayer stake. The prepared GaN LED wafer 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 0.15-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 superlattice (SPS) structure. The MQW active region consists of five periods of 3-nm/7-nm-thick $In_{0.21}Ga_{0.79}N$–GaN quantum-well layers and barrier layers. By performing a split-wafer experiment, the original InGaN–GaN MQW LED wafer with backside polished sapphire substrate was cleaved into the size of 1.5×1.5 cm^2. A transparent conducting layer composed of indium–tin–oxide (ITO) with thickness 300 nm was first deposited onto the p-GaN surface of the wafer by electron beam evaporation for current

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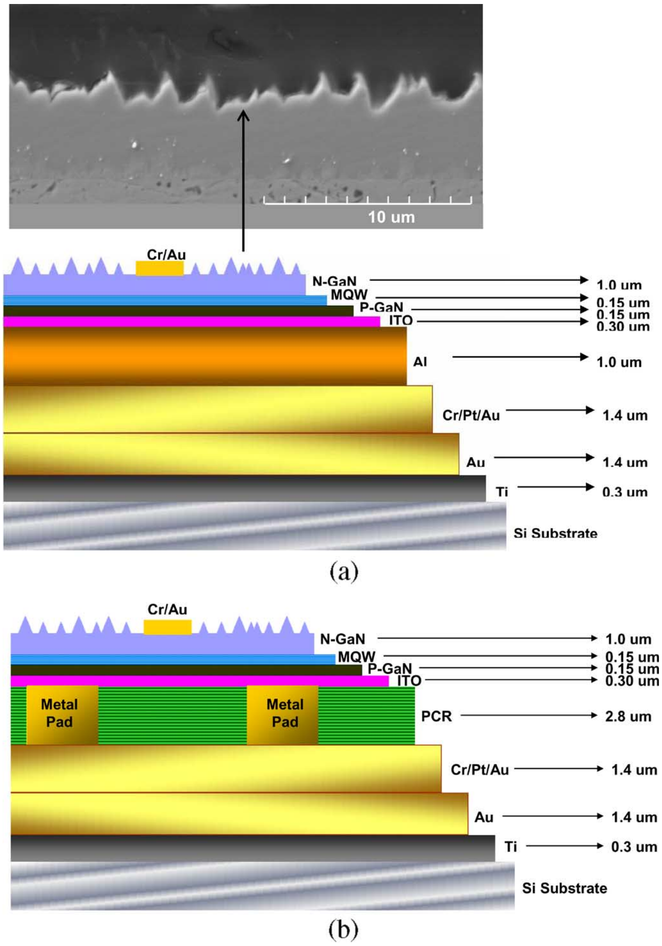

Fig. 1. Schematic diagram of a VLED structure (a) with Al mirror and roughness (b) TiO$_2$–SiO$_2$ ODR and roughness. Inset in (a) shows the SEM image of surface roughness with PEC process.

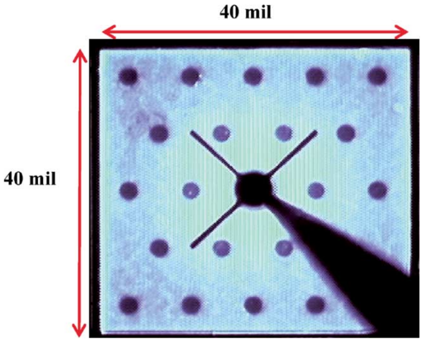

Fig. 2. Plain view photomicrograph of the LED with TiO$_2$–SiO$_2$ ODR in operation.

spreading. For the VLED structure with an ODR, since the ODR is nonconducting, we need to integrate some conducing channels inside the ODR to contact with ITO for vertical current spreading. The procedure was described as follows. First, an array of line of resistance posts with diameter 50 μm and height 7 μm, defined by the standard photolithographic process and formed on an ITO surface. Second, the designed ODR was directly deposited on the defined post array by electron beam evaporation. Third, those posts were moved away by a lift-off procedure. Finally, the forming holes inside the ODR were filled with Cr–Pt–Au to serve as conducing channels or p-GaN metal contacts. We also deposited a layer of Au with thickness of 1.4 μm on the ODR surface for proceeding with the wafer bonding process. For the VLED structure with an Al mirror, the sample was prepared rather straightforwardly by depositing an Al layer with thickness of 1 μm on the ITO surface and a Au layer with thickness of 1.4 μm on the surface of the forming an Al layer. Both types of samples were then bonded onto a Ti–Au-coated p-type conducting Si substrate by a commercial SUSS SB6e wafer bonder with a bonding temperature of 340 °C and a bonding pressure of 17 kg/cm^2 for 140 min. After that, the wafer-bonded samples were taken to undergo the laser lift-off process. A KrF excimer laser at wavelength of 248 nm with a pulsewidth of 25 ns was used to remove the sapphire substrate. The incident laser with a beam size of 1.2 mm × 1.2 mm was incident from the polished backside of the sapphire substrate onto the sapphire–GaN interface to decompose GaN into Ga and N$_2$. In this process, the beam size of the KrF laser was larger than our desired size (1 mm × 1 mm) of LEDs. Therefore, the laser irradiation on the interface of sapphire and GaN was uniform. After the sapphire substrate was removed by the excimer laser, the sapphire-removed samples were dipped into H$_2$SO$_4$ solution to remove the residual Ga on the n-GaN. In order to thin out the revealed n-GaN, the whole sapphire-removed samples were etched by inductively coupled plasma reactive ion etching and the associated mesas were etched further down to the ODR interface for single-chip isolation. To further increase the light extraction efficiency, the n-GaN surfaces of the samples were roughened through a photo-electrochemical (PEC) etching of the n-GaN surface using a UV lamp and a dilute aqueous solution of KOH [11]. The voltage bias was fixed at a positive 10 V on the n-GaN surface, and exposure under 400-W Hg lamp illumination. Then the oxide layer was removed in a diluted HCl solution $(\text{HCl:H}_2\text{O} = 1:1)$. Finally, a patterned Cr–Au electrode were deposited on n-GaN as the n-type contact layer.

The designed ODR is composed of 14 pairs of TiO$_2$–SiO$_2$ that were evaporated onto an ITO layer by an E-beam evaporator [10]. For the detailed band structure calculation and geometry design, refer to [10]. Fig. 2 shows a plane photomicrograph view of our thin-film VLED with the designed ODR in operation. The hexagonal array of dark holes made of Cr–Pt–Au are the fabricated conducting channels and located just below the ITO layer. We can clearly observe that those conducting metal holes are rather absorptive compared with the ODR. This result is consistent with the prediction on the superior reflectance of the ODR over its counterpart of metal mirrors.

Fig. 3(a) shows the forward current–voltage (I–V) curves for the thin-film VLED with ODR and the one with Al mirror. It was found that the measured forward voltages under injection current 350 mA at room temperature for the LED with TiO$_2$–SiO$_2$ ODR and the LED with Al mirror were approximately 3.52 and 3.46 V, respectively. The slightly higher forward voltage of the LED with TiO$_2$–SiO$_2$ ODR than that with Al mirror can be attributed to additional thermal processes during the ODR deposition. We believe that ITO/SPS layer interfacial mixing could result in a higher specific contact resistance and hence could raise the LED operation voltage. In addition, the current spreading via the conducting channels inside the ODR could cause the forward voltage to be slightly higher.

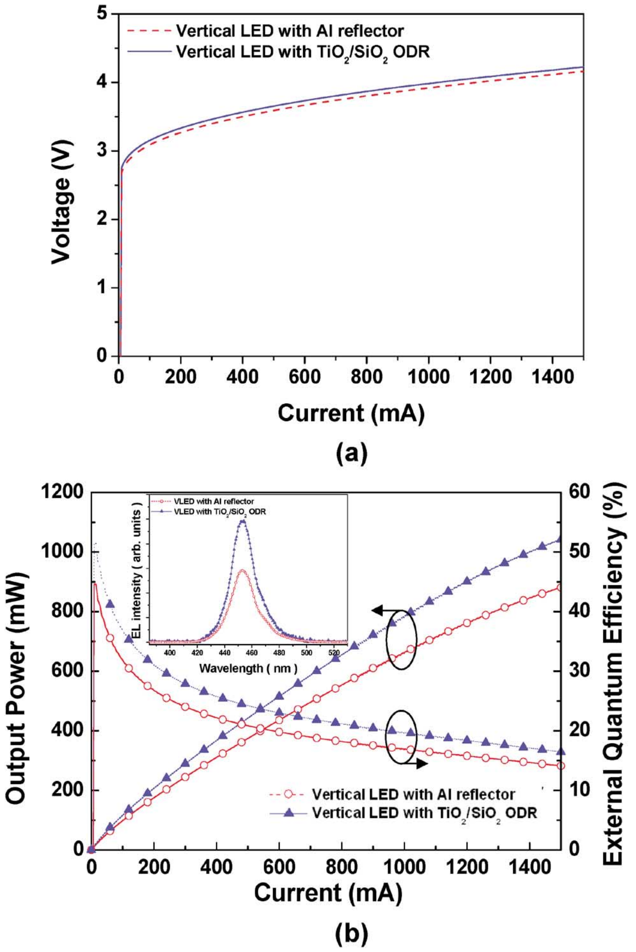

Fig. 3. (a) I–V and (b) intensity–current (L–I) and EQE versus forward dc current for the LED with TiO_2–SiO_2 ODR and roughness, and for the LED with Al reflector and roughness fabricated in this letter. The inset shows the room-temperature EL spectrums at a driving current of 350 mA.

Fig. 3(b) shows light–output power and external quantum efficiency (EQE) versus forward dc current for the LED with TiO_2–SiO_2 ODR and the one with Al reflector are taken continuous-wave. At an injection current of 350 mA, the light–output power of the LED with TiO_2–SiO_2 ODR and the LED with Al reflector were approximately 330 and 279 mW, respectively. The LED with TiO_2–SiO_2 ODR increased the output power by a factor of 1.18, indicating that TiO_2–SiO_2 ODR had higher reflectance and better light extraction efficiency than Al mirror. The EQE varies in a similar manner as the output power with forward dc current. The EQE of the LED with TiO_2–SiO_2 ODR is 1.16 times higher than that of the LED with Al reflector under all our measurement conditions. According to Fig. 3(b), at a driving current 350 mA, the EQEs for the LEDs with TiO_2–SiO_2 ODR and the one with Al reflector are 26.7% and 23.0%, respectively. The inset of Fig. 3(b) shows the typical room-temperature electroluminescence (EL) spectra of InGaN-based LEDs with TiO_2–SiO_2 ODR and InGaN-based LEDs with Al reflector at a driving current of 350 mA; it shows that the InGaN-based MQW emission peaks of those two devices are both located at 455 nm. However, the EL intensity of the LEDs with TiO_2–SiO_2 ODR was larger than that of the LEDs with Al reflector.

In summary, GaN-based thin-film VLEDs with TiO_2–SiO_2 ODR and n-GaN roughness were designed and fabricated. At a driving current of 350 mA and with a chip size of 1 mm × 1 mm, the light–output power and the EQE of the LED with TiO_2–SiO_2 ODR reached 330 mW and 26.7%, which were increased by 18% and 16%, respectively, when compared with the results from the LED with Al mirror. Our work brings out a new structure with superior performance for the next generation of high-brightness InGaN–GaN LEDs.

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REFERENCES

[1] E. F. Schubert and J. K. Kim, “Solid-state light sources becoming smart,” *Science*, vol. 308, pp. 1274–1278, 2005.
[2] S. J. Chang, C. S. Chang, Y. K. Su, C. T. Lee, W. S. Chen, C. F. Shen, Y. P. Hsu, S. C. Shei, and H. M. Lo, “Nitride-based flip-chip ITO LEDs,” *IEEE Trans. Adv. Packag.*, vol. 28, no. 2, pp. 273–277, May 2005.
[3] C. F. Chu, F. I. Lai, J. T. Chu, C. C. Yu, C. F. Lin, H. C. Kuo, and S. C. Wang, “Study of GaN light-emitting diodes fabricated by laser lift-off technique,” *J. Appl. Phys.*, vol. 95, pp. 3916–3922, 2004.
[4] T. Fuji, Y. Gao, R. Sharma, E. L. Hu, S. P. DenBaars, and S. Nakamura, “Increase in the extraction efficiency of GaN-based light-emitting diodes via surface roughening,” *Appl. Phys. Lett.*, vol. 84, pp. 855–857, 2004.
[5] J. K. Kim, T. Gessmann, H. Luo, and E. F. Schubert, “GaInN light-emitting diodes with $RuO_2/SiO_2/Ag$ omni-directional reflector,” *Appl. Phys. Lett.*, vol. 84, pp. 4508–4510, 2004.
[6] Y. Fink, J. N. Winn, S. Fan, C. Chen, J. Michel, J. D. Joannopoulos, and E. L. Thomas, “A dielectric omnidirectional reflector,” *Science*, vol. 282, pp. 1679–1682, 1998.
[7] Y. S. Zhao, D. L. Hibbard, H. P. Lee, K. Ma, W. So, and H. Liu, “Efficiency enhancement of InGaN/GaN light-emitting diodes with a back-surface distributed bragg reflector,” *J. Electronic Mater.*, vol. 32, pp. 1523–1526, 2003.
[8] J. D. Joannopoulos, R. Meade, and J. N. Winn, *Photonic Crystals: Molding the Flow of Light*. Princeton, NJ: Princeton Univ. Press, 1995.
[9] C. H. Lin, J. Y. Tsai, C. C. Kao, H. C. Kuo, C. C. Yu, J. R. Lo, and K. M. Leung, “Enhanced light output in InGaN-based light-emitting diodes with omnidirectional one-dimensional photonic crystals,” *Jpn. J. Appl. Phys.*, vol. 45, pp. 1591–1593, 2006.
[10] C. H. Lin, C. F. Lai, T. S. Ko, H. W. Huang, H. C. Kuo, Y. Y. Hung, K. M. Leung, C. C. Yu, R. J. Tsai, C. K. Lee, T. C. Lu, and S. C. Wang, “Enhancement of InGaN–GaN indium–tin–oxide flip-chip light-emitting diodes with TiO_2–SiO_2 multilayer stack omnidirectional reflector,” *IEEE Photon. Technol. Lett.*, vol. 18, no. 19, pp. 2050–2052, Oct. 1, 2006.
[11] C.-F. Lin, Z.-J. Yang, J.-H. Zheng, and J.-J. Dai, “High-efficiency InGaN light-emitting diodes via sidewall selective etching and oxidation,” *J. Electrochem. Soc.*, vol. 153, no. 1, pp. G39–G43, 2006.