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Fabrication and characteristics of thin-film InGaN–GaN light-emitting diodes with TiO_2/SiO_2 omnidirectional reflectors

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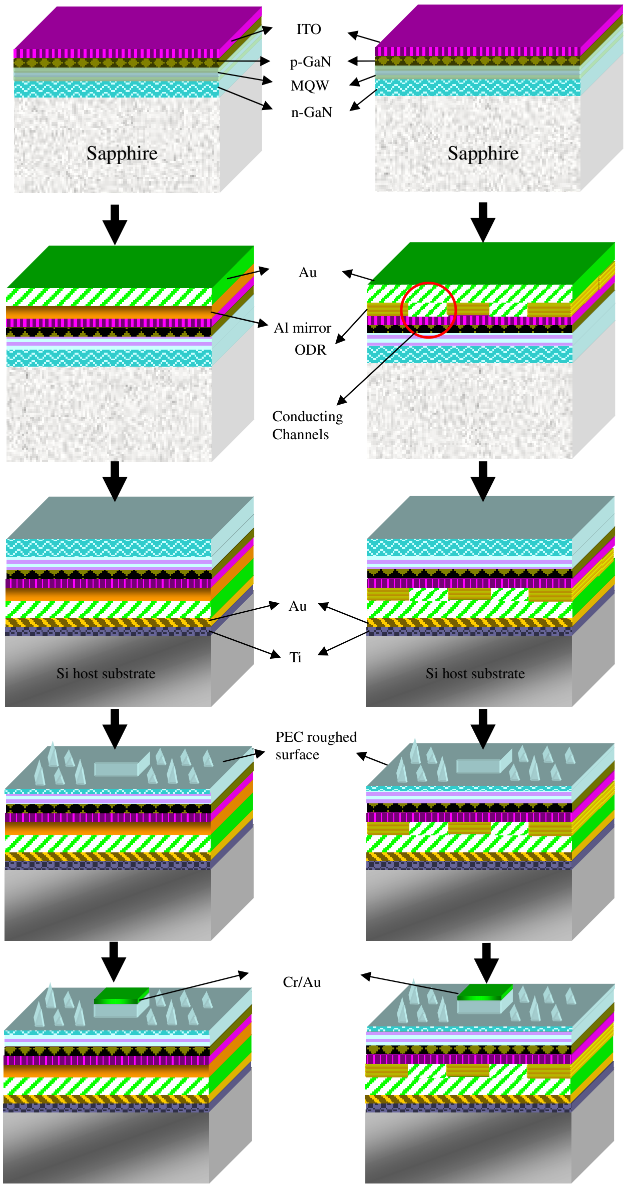
Abstract
In this paper, a novel GaN-based thin-film vertical injection light-emitting diode (LED) structure with a TiO_2 and SiO_2 omnidirectional reflector (ODR) and an n-GaN rough surface is designed and fabricated. The designed ODR, consisting of alternating TiO_2 and SiO_2, layers possesses a complete photonic band gap within the blue region of interest. The arrays of the conducting channels are integrated into the TiO_2/SiO_2 ODR structure for vertically spreading the current. Assisted by the laser lift-off and photo-enhanced chemically etched surface roughening process, the light output power and the external quantum efficiency of our thin-film LED with a TiO_2/SiO_2 ODR (at a driving current of 350 mA and with chip size of 1 mm × 1 mm) reached 330 mW and 26.7%, increased by 18% and 16%, respectively, compared with the results from the thin-film LED with an Al mirror. By examining the radiation patterns of the LEDs, the optical output power mainly increased within the 120 deg cone due to the higher reflectance of the TiO_2/SiO_2 ODR within the blue regime.

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

Introduction

Direct wide-bandgap gallium nitride (GaN) and other III–nitride-based semiconductors have attracted much attention for potential applications such as outdoor displays, exterior automotive lightings, backlight for various handheld devices, printers, liquid crystal display TVs and rear projection TVs [1, 2]. Recently, the high brightness GaN-based light-emitting diode (LED) has shown good performance for those applications. However, further improvement on the optical output power and light extraction efficiency is necessary for the next generation applications such as projectors, automobile headlight and general lightings. The thin-film LED structure shows great enhancement of the light extraction efficiency due to combining the processes of laser lift-off (LLO) to remove the sapphire substrate by an excimer laser and photo-electrochemical (PEC) etching to rough the exposed n-GaN surface. An N-metal electrode of the thin-film LED is deposited on the roughened n-GaN surface and the cathode connection is performed by means of a wire bond. The p-GaN surface of the LED in such a vertical structure is metalized and bonded to another semiconductor substrate such as Si wafers to serve as an anode. Such a structure shall be a good candidate to satisfy the next generation requirement and several groups have demonstrated excellent performance on light output power with high injection current [3–6].

The vertical structure LED with better extraction efficiency and higher light output is mainly because of the embedded reflector. The reflector on the bottom can reflect the downward emitting light upward towards the emitting substrate effectively to contribute to the useable light and enhance the light extraction efficiency. Metallic materials with high refractivity such as Ag or Al have been used for this purpose [7]. The metallic mirror indeed shows good reflectivity for arbitrary angles and polarizations but they are somewhat lossy in the visible regime [8]. In addition, the metallic mirror also has reliability problems at the interface with a semiconductor due to degradation or electromigration. In particular, a recent work indicated that the absorption by metallic mirrors becomes more severe as the thickness of the device is reduced [9]. As a result, dielectric mirrors, such as distributed Bragg reflectors (DBRs) [10] have been widely used to solve those problems. Compared with metallic counterparts, DBRs have many advantages, such as very low optical loss, high reflectance and high mechanical robustness [11]. 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 band gap (CPBG) at the wavelengths of interest [12]. A one-dimensional periodic dielectric structure possessing this characteristic is known as an omnidirectional one-dimensional photonic crystal (1D PhC). By selecting appropriate thickness of the dielectric layers, there is no allowed photon propagation state for wavelengths within the CPBG. Such an omnidirectional reflector (ODR) made from the designed 1D PhC can totally reflect the light with wavelengths within the CPBG at any incidence angle and polarization. Therefore, compared with DBRs, a substantially higher reflectance can be achieved by ODRs. 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 [13, 14]. An ultra-high brightness thin-film vertical-injection LED with the ODR composed of TiO_2 and SiO_2 and a PEC roughened surface is demonstrated and achieved in this paper.



(*a*) (*b*)

Figure 1. Fabrication flowchart of n-side surface roughness vertical-injection LED structures (*a*) with the Al mirror, and (*b*) with the ODR composed of TiO_2/SiO_2.

Device fabrication

The InGaN/GaN vertical-injection LED samples were grown by metal organic chemical vapour deposition with a rotation disc reactor (Encore) on a *c*-axis sapphire (0 0 0 1) substrate at a growth pressure of 200 mbar. The prepared InGaN/GaN vertical-injection 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 super lattice (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 wafers with a backside polished sapphire substrate were cleaved to the size of 1.5×1.5 cm^2. These LED samples were separated into two sets for different process procedures, with Al mirrors and ODRs.

As shown in figure 1(*a*), the first set of samples was the InGaN/GaN vertical-injection LED with an Al mirror. A transparent conducting layer composed of indium-tin-oxide (ITO) with a thickness of 300 nm is first deposited onto the p-GaN surface by electron beam (E-beam) evaporation. The ITO layer had a high transparency (>95% at 460 nm) and high electrical conductivity for current spreading. For the vertical-injection LED structure with an Al mirror, the sample was prepared by depositing the Al layer with a thickness of 1 μm by E-beam evaporation on the ITO surface. Then an Au layer with a thickness of 1.4 μm was deposited onto the surface of the forming Al layer for the purpose of bonding with the silicon

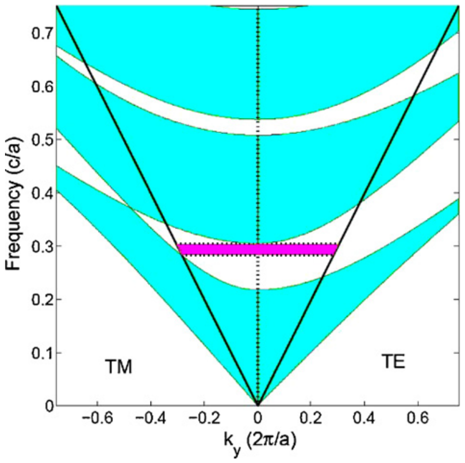
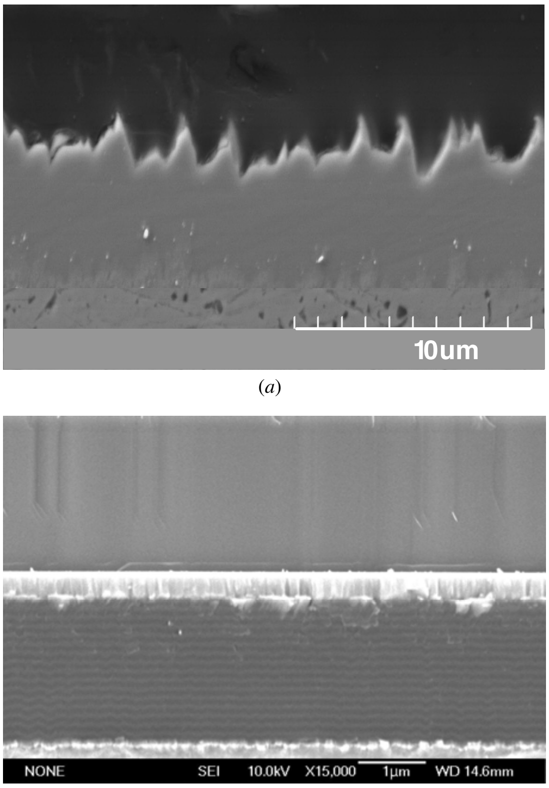


Figure 2. Photonic band diagram of a 1D PC composed of TiO_2 and SiO_2 multi-layers. Refractive indices and layer thickness are assumed to be 2.52, 56 nm for TiO_2 and 1.48, 77 nm for SiO_2, respectively. The red and white regions represent the allowed and forbidden photon states. The lines in the diagonal directions identify the edges of the light cone. The region with red area of the CPBG represents an omnidirectional reflection region.

wafer. As shown in figure 1(*b*), the second set of samples was the vertical-injection LED structure with an ODR. Conducting channels were integrated inside the ODR to contact with ITO for vertical current spreading. An array of lift-off resist (LOR) posts with diameter 50 μm and height 7 μm was first defined by a standard photolithographic process on the ITO surface. Second, the designed ODR of the TiO_2/SiO_2 multilayer stake was directly deposited onto the defined post array by E-beam evaporation. Third, those posts were moved away by a lift-off procedure. Finally, a thick layer of Cr/Pt/Au of 1.4 μm was deposited by E-beam evaporation and the formed 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 a thickness of 1.4 μm on the ODR surface for proceeding the wafer bonding process.

LED samples with Al mirrors and ODRs were then bonded onto a p-type conducting Si substrate (with the bonding metal of 0.7 μm Ti and 1.4 μm Au) 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 underwent the LLO process. A KrF excimer laser with a beam size of 1.2 mm × 1.2 mm at a wavelength of 248 nm with a pulse width of 25 ns and the incident laser fluence of 300 mJ cm^{-2} was used to remove the sapphire substrate [15]. In order to thin out the revealed n-GaN, the whole sapphire-removed samples were etched by inductively coupled the plasma reactive ion etching (ICP-RIE) system (SAMCO ICP-RIE 101iPH) and the associated mesas were etched further down to the ODR interface for isolating the individual chip. To further increase the light extraction efficiency, the n-GaN surfaces of the samples were roughened through PEC etching by using an UV lamp and the dilute aqueous solution of KOH [16]. Finally, a patterned Cr/Au electrode was deposited onto the n-GaN surface as an n-type contact layer.



(*a*)

(*b*)

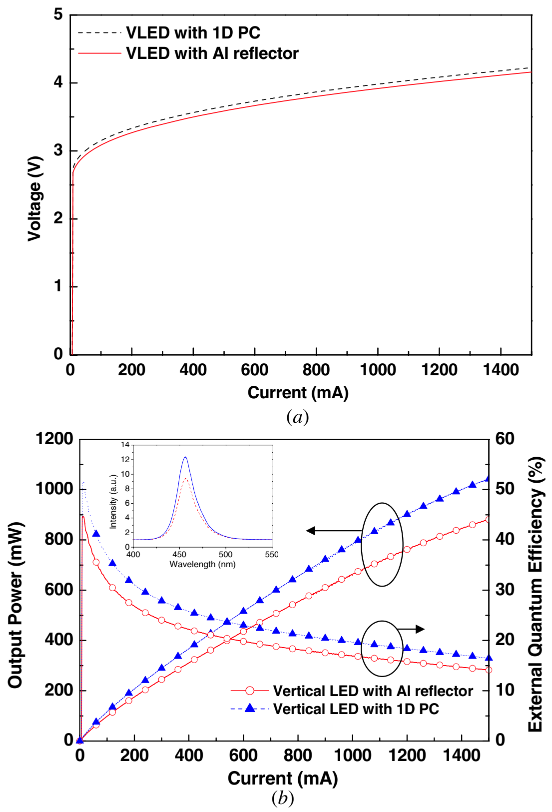
Figure 3. (*a*) SEM images of the roughened surface by PEC process. (*b*) Cross-sectional SEM images of the vertical-injection LED with TiO_2/SiO_2 multi-layers.

Result and discussion

Figure 2 shows the band structure of the ODR composed of TiO_2 and SiO_2 with different dielectric layer thicknesses using the transmission-line method [17]. The reflective indices of TiO_2 and SiO_2 are 2.52 and 1.48, respectively. We found that the optimal CPBG is at frequencies between 0.282 c/a and 0.304 c/a (the red region shown in figure 3), and at thicknesses of 0.421a and 0.579a, respectively for the TiO_2 and SiO_2 layers where c and a are the speed of light and the lattice constant. In this paper, we chose the lattice constant $a = 133$ nm to give a CPBG centred at 455 nm. Thus the TiO_2 and SiO_2 layers have a thickness of 56 nm and 77 nm respectively and the ODR has a CPBG between 437 nm and 472 nm. When the desired ODR composed of TiO_2 and SiO_2 is fabricated on the GaN LED with a peak emitting wavelength of 455 nm, it will show very a high reflectance for the wavelength falling within the emitting spectrum of the LED.

Figure 3(*a*) shows the SEM images of the roughened surface after the PEC roughening process on the n-GaN material. The roughened surface can enhance the external quantum efficiency since the total internal reflection was destroyed by the roughened surface. Figure 3(*b*) shows the cross-sectional SEM image of the ODR incorporated in our thin-film InGaN/GaN LED. The designed ODR composes of 14 pairs of TiO_2/SiO_2 layers evaporated onto the ITO layer by an E-beam evaporator.

Figure 4(*a*) shows the forward *I*–*V* curves of the thin-film vertical-injection LED with the TiO_2/SiO_2 ODR and



(*a*)

(*b*)

Figure 4. (*a*) Current–voltage (*I*–*V*) and (*b*) intensity–current (*L*–*I*) and external quantum efficiency versus forward dc current of the LEDs with a TiO_2/SiO_2 ODR and with an Al reflector. The inset shows the room temperature EL spectra at a driving current of 350 mA.

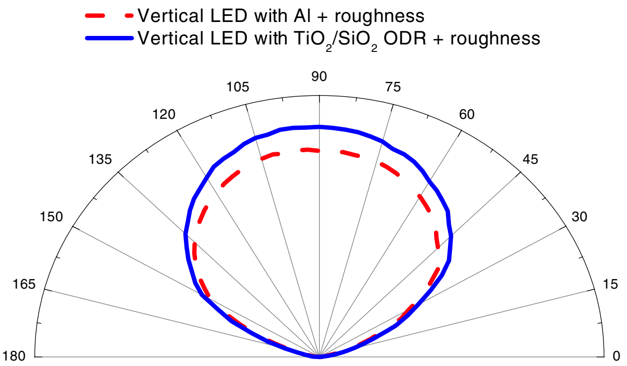


Figure 5. Comparison of the radiation patterns in air between LEDs with a TiO_2/SiO_2 ODR and with an Al mirror, respectively.

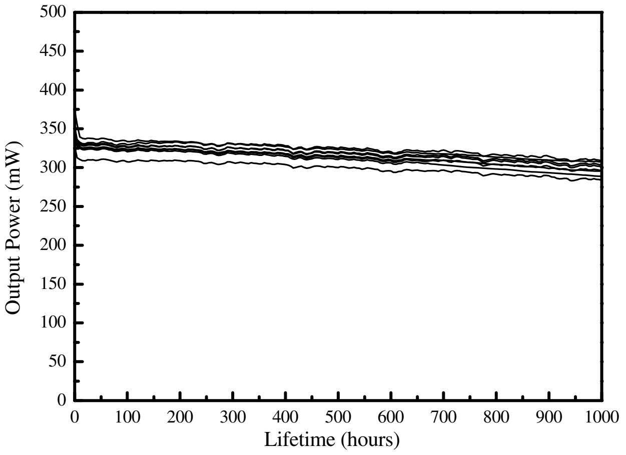


Figure 6. The life test results of the LEDs with TiO_2/SiO_2 ODRs under the condition of a 350 mA driving current and 55 °C ambient temperature.

with an Al mirror. The forward voltage of LED with a TiO_2/SiO_2 ODR is slightly higher than that of LED with an Al mirror. The measured forward voltages under an injection current of 350 mA at room temperature for the LEDs with a TiO_2/SiO_2 ODR and with an Al mirror are approximately 3.52 V and 3.46 V, respectively. The slightly higher forward voltage of the LED with a TiO_2/SiO_2 ODR than that with an Al mirror can be attributed to additional thermal processes during the ODR deposition. We believe that the ITO/SPS layer's interfacial mixing can result in a higher specific contact resistance and hence can raise the LED operation voltage. In addition, the current spreading via the conducting channels inside the ODR can cause the forward voltage slightly higher. Figure 4(*b*) shows light output power and external quantum efficiency versus applying forward dc current for the LEDs with a TiO_2/SiO_2 ODR and with an Al mirror. At an injection current of 350 mA, the light output power of the LED with a TiO_2/SiO_2 ODR and the LED with an Al mirror are approximately 330 mW and 279 mW, respectively. The LED with a TiO_2/SiO_2 ODR increased the output power by a factor of 1.18, indicating that LED with a TiO_2/SiO_2 ODR has higher reflectance and better light extraction efficiency than that with an Al mirror. The current-dependent external quantum efficiency is similar to the case of the output power versus the forward dc current. The external quantum efficiency of the LED with a TiO_2/SiO_2 ODR is 1.16 times higher than the LED with an Al mirror under all our measurement conditions. According to figure 4(*b*), at a driving current of 350 mA, the external quantum efficiencies for the LED with a TiO_2/SiO_2 ODR and with an Al mirror are 26.7% and 23.0%, respectively. The inset of figure 4(*b*) shows the typical room temperature EL spectra of InGaN-based LEDs with a TiO_2/SiO_2 ODR and an Al mirror at a driving current of 350 mA. We can see that the InGaN-based MQW emission peaks of those two devices are both located at 455 nm. However, the EL intensity of the LED with a TiO_2/SiO_2 ODR is larger than that of the LED with an Al mirror since the LED with an ODR has a higher external quantum efficiency.

We also measured the light output radiation patterns of the thin-film InGaN/GaN LED with an ODR and the LED with an Al mirror at a driving current of 350 mA (figure 5). It can be seen that the LED with the TiO_2/SiO_2 ODR shows a higher optical power within 120 deg cone than that of the LED with an Al mirror. This enhancement is attributed to the higher reflectance of our ODR within the blue regime when compared with that of an Al mirror.

During life test, nine thin-film InGaN/GaN LEDs with ODRs and PEC roughness were encapsulated and mount on a heat sink. All LEDs were driven by 350 mA current injection at a 55 °C ambient temperature. As shown in figure 6, after 1000 h, good ageing behaviour was observed except for a small decrease of the output power in the initial few hours. It also shows that the output power of the thin-film InGaN/GaN LED with ODR and PEC roughness only decreased by 7–11% and indicates that the structure is a reliable and promising method for device production.

Conclusion

In summary, the thin-film InGaN/GaN vertical-injection LED with a TiO_2/SiO_2 ODR and n-GaN PEC roughness process is 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 external quantum efficiency of the LED with a TiO_2/SiO_2 ODR reache 330 mW and 26.7%, increased by 18% and 16%, respectively, compared with the results from the LED with an Al mirror. The radiation pattern of the LED with a TiO_2/SiO_2 ODR shows a higher optical power within 120 deg cone due to the higher reflectance of the designed ODR within the blue regime than those LEDs of Al mirrors. The life time test indicates that the structure is reliable and promising for device production.

Acknowledgments

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