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Enhanced Light Output of Vertical GaN-Based LEDs with Surface Roughening Using IZO Nano Roughened

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1. Introduction

Recently, many attempts have been made to develop high-efficiency and high-power GaN-based light-emitting diodes (LEDs) for backlight, traffic display, and even solid-state lighting [1]. Efforts to enhance the light extraction efficiency of conventional GaN-based LEDs, by means of vertical-conducting structure LED (VLED) and surface texturing have been reported [2-3]. A roughened surface could interfere with the total-internal-reflection effect and facilitate photons to find the escape cone for extraction from the LED devices. Over the past years, the use of polystyrene spheres (PSs), acting as either an etching mask or a lift-off layer to form pillars and holes, respectively, to produce nano-roughening or patterning LED surface to reduce the TIR effect has been demonstrated [4-5]. It retains simplicity and cost effectiveness for without using costly equipments or inserting extra lithographic masking steps into established fabrication processes.

In this study, to further improve the EQE of regular VLEDs, effect of nano-roughening onto indium-zinc oxide (IZO) transparent conducting layer (TCL) using PSs as a patterned mask were studied. Comparisons of electrical and optical properties of VLEDs with different thickness of the nano-roughened IZO TCL were presented and discussed.

2. Experiments

Figure 1 illustrates the fabrication process of the proposed VLED structure. In experiments, the samples were cleaned with dipping into H_2SO_4:H_2O_2 (3:1) solution for 5 min, immersing in boiling acetone and isopropanol for 5 min to remove the surface oxide and rinsing in running deionized water. Prior to Ni-electroplating process, annealed-Pt/Al/Pt as a highly reflective ohmic contact layer and a Cr/Ti/Au metal system as an adhesive layer were deposited on p-GaN layer by E-beam evaporator sequentially (Figure 1(a)). An 80-μm-thick nickel substrate was formed by electroplating under a constant current of 1.7 A for 120 min. Through the use of quartz mask to define both size and shape of KrF excimer laser beam (248 nm) and the LLO process was performed at a reactive energy of 850 mJ/cm^2 (Figure 1(b)).

After the removal of the sapphire substrate, the exposed buffer layer (u-GaN) was removed by the inductively coupled plasma (ICP) dry-etching system. For device isolation, ICP dry-etching was conducted to etch the sample all the way down to the nickel substrate with SiO_2 mask, having device size of 1 mm×1 mm and cutting-way width of 90 μm (Figure 1(c)). It was followed by the deposition of Ti/IZO layers on the surface of top n-GaN as TCL [6]. After that, the PSs were dispersed on the IZO surface using a combination of tilting and spin-coating. To reduce the diameters of the PSs to form a suitable patterned mask, the coated sample was subsequently loaded into an ICP chamber to etch the spheres under RIE power of 250 W and the O_2 flow of 20 sccm (Figure 1(d)). Second sputtering-deposition of IZO film process with three different thicknesses of 300, 600, and 1000 nm was perform to fill the space between neighboring PSs. The PSs were then removed by using a high-temperature stripper to form a nano-roughened IZO top-layer (Figure 1(e)). Finally, a passivation layer and metal pad of Cr/Al/Cr/Au were deposited on the exposed IZO/n-GaN layer (Figure 1(f)).

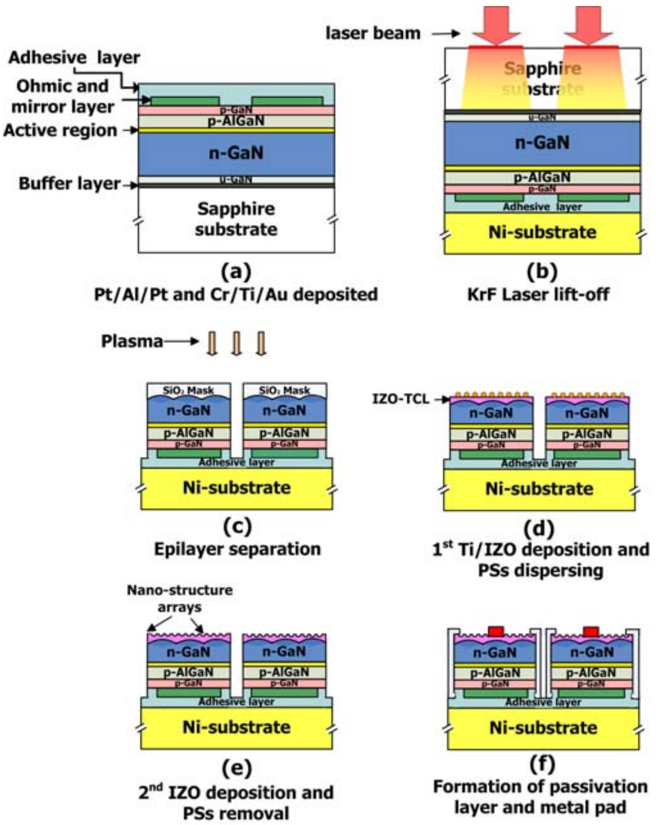

Fig. 1 Key fabrication processes of VLED with nano-roughened top-surface by IZO nanowells.

3. Results and Discussion

Figure 2 shows the transparent properties of the Ti/IZO as a function of the IZO thickness in the 454-466 nm wavelength spectra. It shows the average transmittances of the 300-nm-thick IZO case are maintained above 84%. The current-voltage (I-V) characteristics of the IZO (300 nm)/Ti(1.5 nm)/n-GaN and IZO(300 nm)/n-GaN contact are shown in the inset of Fig. 2. It reveals that the IZO/n-GaN contact has a Schottky behavior; however, the Ti/IZO contact to the n-GaN layer exhibits a good ohmic performance with a specific contact resistance of 9×10^{-5} Ω-cm^2.

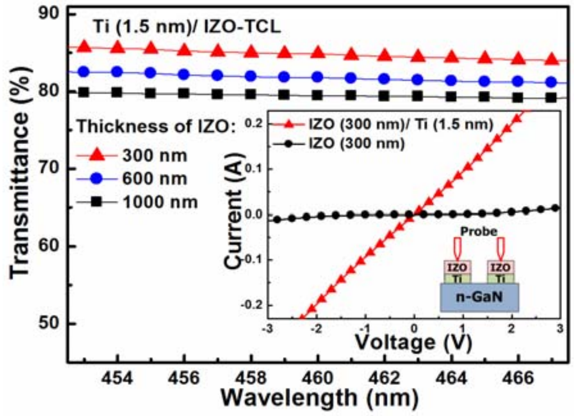

Fig. 2 The transmittance and I-V of properties of IZO TCL.

Figure 3 shows the scanning electron microscopy (SEM) images of the top surface morphology of the proposed VLED prepared at various stages of the surface-roughening process. It is seen that, as shown in Figure 3(a), PSs on the top IZO film were self-assembled into ordered monolayer array in hexagonally close-packed structure due to the lateral capillary effect. Figure 3(b) show the monolayer of PSs after O_2 plasma treatment. An average shrinkage in the PSs diameter from 400 nm to a value of around 300 nm was obtained, while the surface of the underlying IZO layer was intact. Figure 3(c) shows the image of the surface after the second IZO deposition, revealing the space between neighboring PSs was filled firmly. After the removal of PSs, a nano-textured IZO film with 280 nm holes was formed on the top-surface of VLED as shown in Figure 3(d).

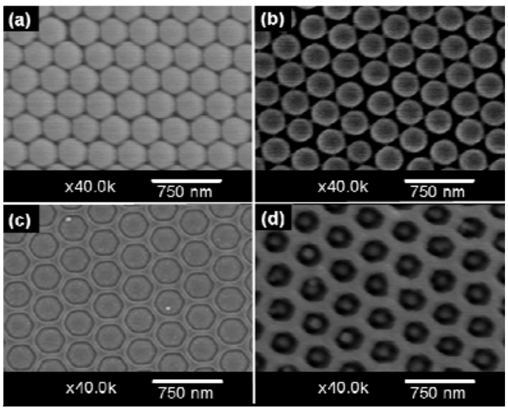

Fig. 3 Surface morphologies of VLED with IZO nano roughened structure at key fabrication stages: (a) As-spun nano-spheres on the IZO layer atop device; (b) Sample after O_2 plasma treatment; (c) Second IZO-deposition process; and (d) Sample after the formation of surface periodic IZO nano-wells.

The comparison of I-V and Lop-I characteristics of the fabricated various VLEDs with different IZO thickness designs were shown in Figure 4. Under an injection current of 350 mA, the forward voltages (V_f) of various VLEDs with IZO layer of 300, 600, and 1000 nm thicknesses were about 3.41, 3.38, and 3.37 V, respectively. Such a significant reduction in V_f for VLED with thicker IZO is mainly attributed to effectiveness in decreasing spreading resistance along the horizontal direction of the IZO film, thus enabling a relatively much less current crowding effect. However, Lop-I characteristics evident that the VLED with IZO layer of 300 nm has additional improvement in Lop of about 18.2% and 26.8% at 350 mA as compared to VLEDs with IZO layer of 600 and 1000 nm thicknesses, respectively, which can be attribute to improved its transmittance. In essential, because of the tradeoff between the sheet resistance and transparency of the IZO TCL, there exists an optimum thickness of around 300 nm for the IZO TCL employed in the VLED with the epilayer structure mentioned above.

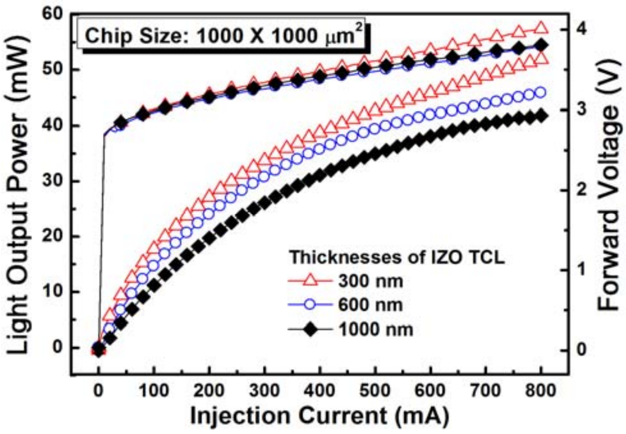

Fig. 4 Comparisons of I-V and L-I characteristics between various fabricated VLEDs.

4. Conclusion

In conclusion, surface texturing the IZO layer of 300-nm-thickness atop high-power VLEDs using PSs technologies were presented. Enhancement in Lop by 18.2% and 26.8% at 350 mA as compared to VLEDs with IZO TCL of 600 and 1000 nm thicknesses, respectively, has been achieved. It is expected that the proposed IZO TCL nano roughened structure through the use of PSs technologies could be further enhance the Lop of high power GaN-based LEDs for SSL in the near future.

Acknowledgments

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