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Use of Anisotropic Laser Etching to the Top n-GaN Layer to Alleviate Current Crowding Effect in Vertical-Structured GaN-Based Light-Emitting Diodes

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With advantages of low power consumption, long lifetime, fast operation response, and environmental protection, etc, light emitting diodes (LEDs) have been widely applied in various fields, such as display and optical communication. GaN-based LEDs with high output power which can easily lead LEDs to produce white light by using a yellow YAG:Ce phosphor, which have very high potential for serving an alternative for general lighting in the near future. Until now, many efforts have been intensively studied for use in full color outdoor LED displays, LED lighting, etc, including structure design, process scheme of vertical device, and replacing sapphire substrate with suitable conducting one for large-area high-power GaN-based LEDs.

In this work, a concave-surface with a graded transparent conducting layer (TCL)/n-GaN layer structure on the top of Vertical-conducting Metal-substrate GaN-based LEDs (VM-LEDs) to enhance current spreading and improve light emission uniformity was presented and discussed. The key processes in realization of the concave surface structure including the use of an anisotropic etching to form a surface epilayer with its thickness decreasing from the edge to the center (far from contact pad) and the deposition of a TCL onto the concaved surface of the etched surface epilayer were described. Such a structure allows the current path at the edge of the device has a higher resistance in the epilayer, which would be totally balanced out by the resistance arising from the longer path in the TCL for the current flowing in the center region. The equalization in the resistances of all the possible current conduction paths thus improves the light emission uniformity of the LED.

Figure 1 illustrates the concept behind the proposed device structure in alleviating current crowding in VM-LEDs. For the two arbitrary conduction paths shown in Fig. 1(a) for a regular VM-LED with a flat n-GaN/TCL structure (referred to as sample A), the series resistance along path 2 is always larger than that along path 1 (i.e. $R_2+R_{TCL} > R_1$). Accordingly, the current density along the path far away from contact electrodes should be much less than that along the path under the contact electrodes. As a result,

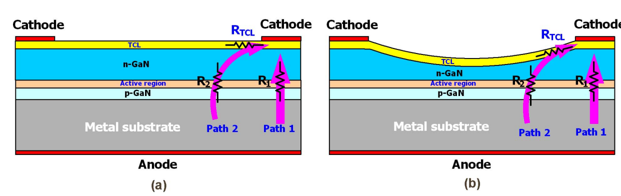

Fig. 1 Schematic cross section of (a) a regular VM-LED with a flat TCL/n-GaN structure (sample A)
and (b) VM-LED with a grade TCL/n-GaN structure (sample B)

light emission in the periphery region of the device would be much darker than that under or near the contact pad region. As for the device with Schottky IZO/n-GaN current blocking and a mesa surface n-GaN/TCL structure shown in Fig. 1(b) (referred to as sample B), the current blocked by the Schottky IZO/n-GaN region under the cathode contact pad would be forced to spread outward, hence light emission in the active region beneath the cathode can be effectively reduced. In addition, once the top n-GaN layer was properly mesa etched and the thickness and resistivity of the TCL layer has been optimized, the overall difference in series resistances for the two possible conducting paths could be minimized due to a relatively smaller thickness therein, hence the series resistance R2 is relatively smaller than that of sample A and a finite difference in resistance, •R(=R_1–R_2), exists. A good balance of series resistances could be realized (i.e., $R_2+R_{TCL}\approx R_1$) and improvement in the uniformity of current distribution can be expected. It is worth noting that, for mass production consideration, the anisotropic laser etching can be replaced by inductive-coupling plasma (ICP) mesa etching. Under the circumstance, the use of multiple ICP mesa etching to form a multiple-step-like periphery region on the top n-GaN layer, the same concept in equalized series resistance of any current path can be equally applied and uniform light emission can be obtained.

For a feasibility study on the proposed scheme, the distribution of current and light emission of sample A and B were analyzed using ISE-TCAD.

The chip size of the sample A and B are of 1000 μm × 1000 μm. The doping concentration and thickness of the top n-GaN layer are 5×10^{18} cm^{-3} and 3 μm, respectively. The n-GaN layer has a concave surface with an etching depth ranging from 0 to 1.7 μm along the edge to the center.

Figure 2 shows the calculated current density distribution across the active region of sample A and sample B devices under a forward bias of 4 V. The corresponding light emission distribution in the active region of the samples was shown in the figure. It is evident that, as compared to sample A, a considerable improvement in current distribution and fairly good uniformities in light emission of the sample B was obtained. It also clearly indicates that the current and light emission in the central of light emission area is as well as those near those under cathode contact pad.

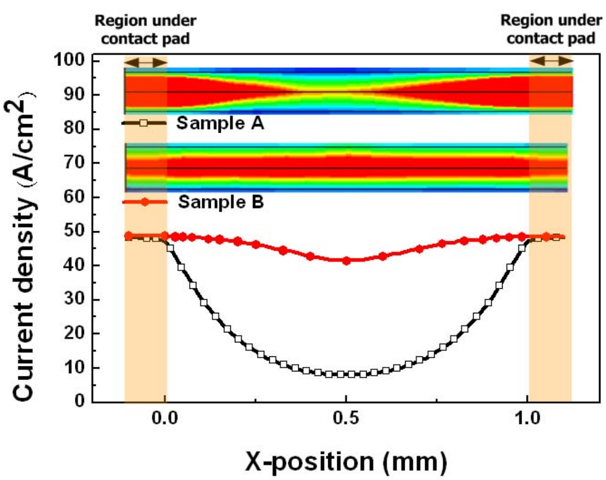

Fig. 2 Calculated current density distribution across the active region of sample A and B at 4 V. The calculated special light emission in the active region of the samples was also shown. Hues of red, orange, yellow, green, and blue indicate the relative

In experiments, the InGaN multiple-quantum-well (MQW) LED structures were grown on c-plane 2-inch sapphire substrates by metalorganic chemical vapor deposition. The LED structure comprises a buffer layer, a 0.5-μm -thick undoped GaN layer, a 3-μm-thick Si-doped n-GaN cladding layer, an undoped 5-period GaN/InGaN MOW, a Mg-doped p-cladding layer, and a 0.15-μm-thick Mg-doped GaN layer. Before conducting the patterned-LLO process, an oxidized Ni (2.5 nm)/Au (4.5 nm) layer was deposited to serve as an ohmic contact to p-GaN. Then a Ti (15 nm)/Al (400 nm)/Ti (100 nm)/Au (200 nm) multilayer was deposited as a reflective mirror layer and also an adhesive layer to the subsequent electroplated nickel layer. The electroplating process was performed under a DC current of around 1.7 A with a stable plating solution kept at about 55℃ for 90 min. A nickel layer with a thickness of about 50 μm was obtained. A 248 nm KrF excimer laser with a single pulse of 38 ns in width and energy of 850 mJ/cm^2 was directed through a copper mask to the back of the transparent sapphire substrate. The absorption of laser energy at the GaN/sapphire interface causes local heating and decomposition of the GaN. After the laser irradiation process the sample was then heated to about 40℃ and the electroplated-Ni adhered GaN epilayer was then separated from the sapphire substrate.

After the epilayer transfer process, the sample was subjected to ICP etching to remove the top u-GaN layer and then a chemical etching using 6-mol-KOH solution at 60℃ for 10 s to remove possible damaged regions caused by the ICP process.

After that, anisotropic laser etching process was followed. Without sacrificing the light extraction rate and to incorporate the width of contact ring, a diameter of 800 μm for the anisotropic etching region was used.

Figure 3 shows the schematic diagram of anisotropic laser etching, which the same KrF excimer laser with relatively lower energy of 400 mJ/cm^2 was directed through a special design copper mask onto the surface of n-GaN epilayer which was rotated at constant speed. Accordingly, the amount and depth of laser beam irradiation on the n-GaN layer and the subsequent decomposition of GaN was different radically. As a result, a concaved n-GaN epilayer with thickness decreasing from edge to center was obtained.

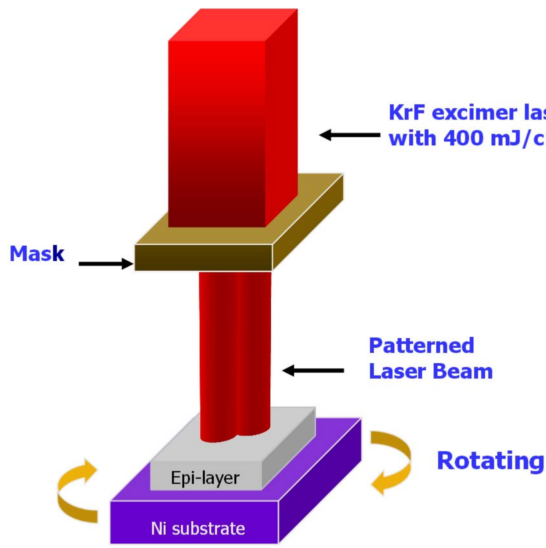

Fig. 3 Schematic diagram of the set-up for anisotropic laser etching

To further improve the contact properties and remove the possible Ga residues, chemical treatments with dilute HCl:H_2O (1:1) solution for 8 s were carried out on the etched n-GaN layer. Based on experimental results which reveal that the contact of Indium-Zinc-Oxide (IZO) to n-GaN layer is Schottky, before the Indium-Zinc-Oxide (IZO) films depositing, a layer Ti of 2.5 nm thickness should be deposited on the top n-GaN layer to form ohmic contact as shown in Fig. 4. IZO was deposited by using radio-frequency magnetron sputtering system to associate ohmic contact Ti serving as a transparent conductive layer (TCL). The IZO film was deposited by RF sputtering. An IZO target which comprises with 90%wt In_2O_3 and 10%wt ZnO in Ar ambient was used. Our experimental results indicate that IZO

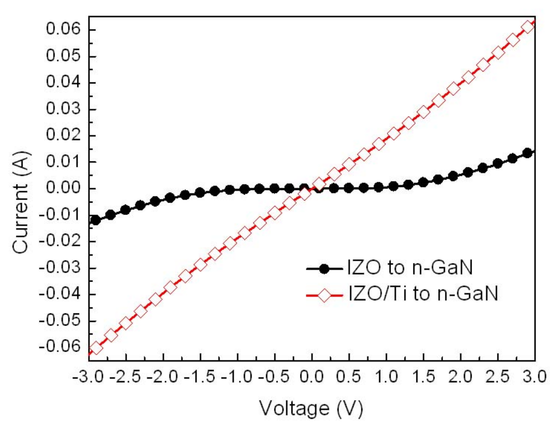

Fig. 4 The measured I-V characteristics of IZO (300 nm) and IZO(300 nm)/Ti (2.5 nm) contact to n-GaN layer.

films with thicknesses in the range of 100•500 nm have a transparency ≥ 80% in the visible light spectrum and a resistivity in the range of 8×10^{-5} - 12.1×10^{-4} Ω-cm.

Essentially, there is a trade-off between the series resistance (i.e., the resistance along the current path) and transparency of the IZO film, the thickness of an IZO film is very crucial for its application to a TCL. An optimum design among the series resistance, transparency, and light extraction is required. Based on our experimental results, the use of the 300-nm-thick IZO TCL in LEDs would have the best result in light output improvement. After IZO(300 nm)/Ti(2.5 nm) film being deposited onto the graded concave-surface n-GaN to form a TCL/n-GaN structure, then, a Cr (15 nm)/Al (200 nm)/Cr (15 nm)/Au (800 nm) metal system was deposited and patterned as a cathode contact ring.

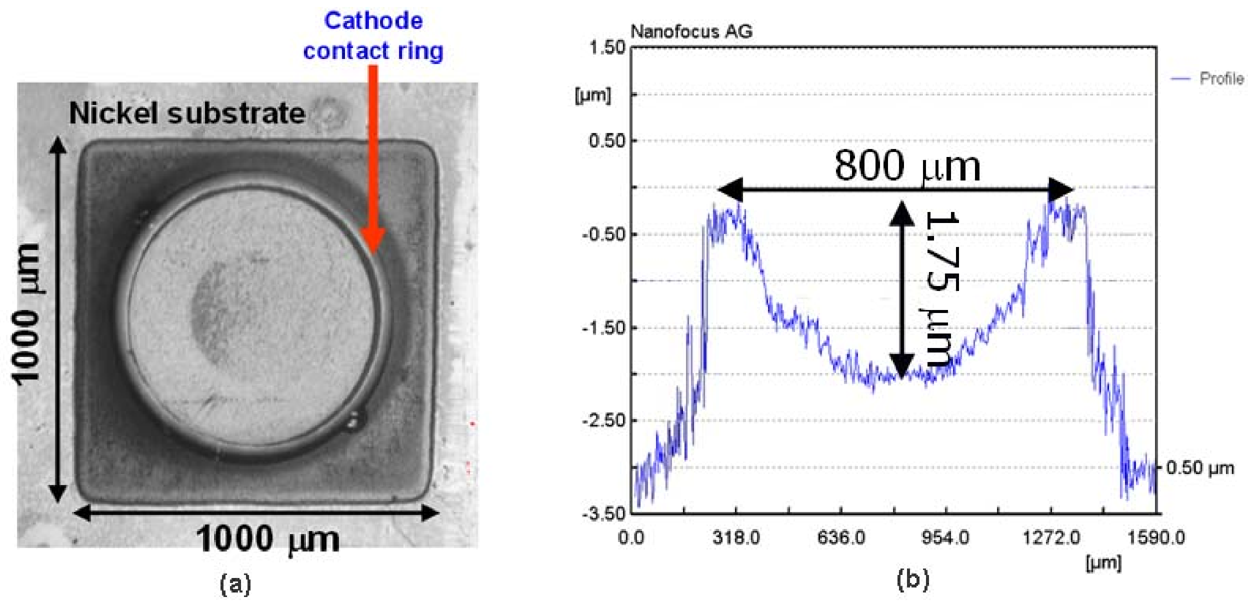

Fig. 5 Surface morphology of proposed device measured by 3D Confocal Microscopce (nanofocus): (a) OM photograph of top-view, (b) 1-D surface profile

Figure 5 shows the top view picture of a fabricated sample obtained from optical microscope. As is evident from the figure, a concave surface on the n-GaN layer with a diameter of around 800 mm and an etching depth of about 1.75 mm at the center were formed.

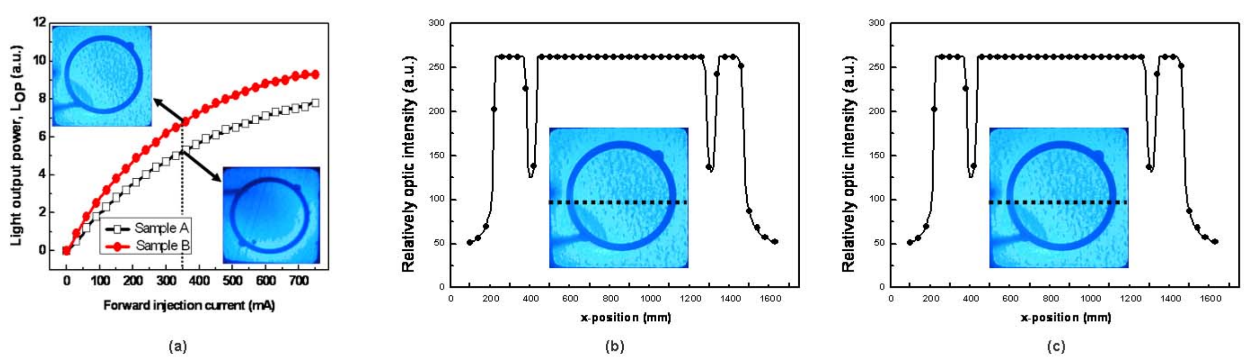

Fig. 6 (a) A comparison of LOP-I characteristics. The inset shows photos of light emission from proposed device and VM-LED at 350 mA. The relative light output intensity along the dashed lines shown on photo of (b)VM-LED with graded TCL/n-GaN structure, a

Note that devices without anisotropic etching (i.e., regular VM-LEDs) were also fabricated for comparison. Comparable current-voltage (I-V) characteristics with a typical forward voltage drop of about 3.45 V at 350 mA were obtained (not shown). Figure 6(a) illustrates typical experimental light output power-current (LOP-I) characteristics of VM-LED and VM-LED with graded concave TCL/n-GaN structure. The inset of the figure also shows the photomicrograph of the two samples at 350 mA of injection current. The corresponding light emission patterns were obtained and analyzed, as shown in Fig. 6(b) and (c), by using a near-field microscope with a charge-couple device and a video analyzer (Beam-View Analyzer, Coherent) linked to a computer. The relative light output intensity measured along the dashed lines indicates that the light emission distribution of VM-LED with graded concave TCL/n-GaN structure has a better uniformity than that of regular VM-LED. Though the graded concave-surface TCL/n-GaN structure has not yet been subjected to optimization, experimental results based on more than 50 samples reveal that, as compared to that of regular VM-LED, typical improvement in LOP by about 38-26% @ 350 mA has been obtained. From the light emission patterns, one also can see that the light emission uniformity of VM-LEDs with graded concave TCL/n-GaN has been significantly improved.

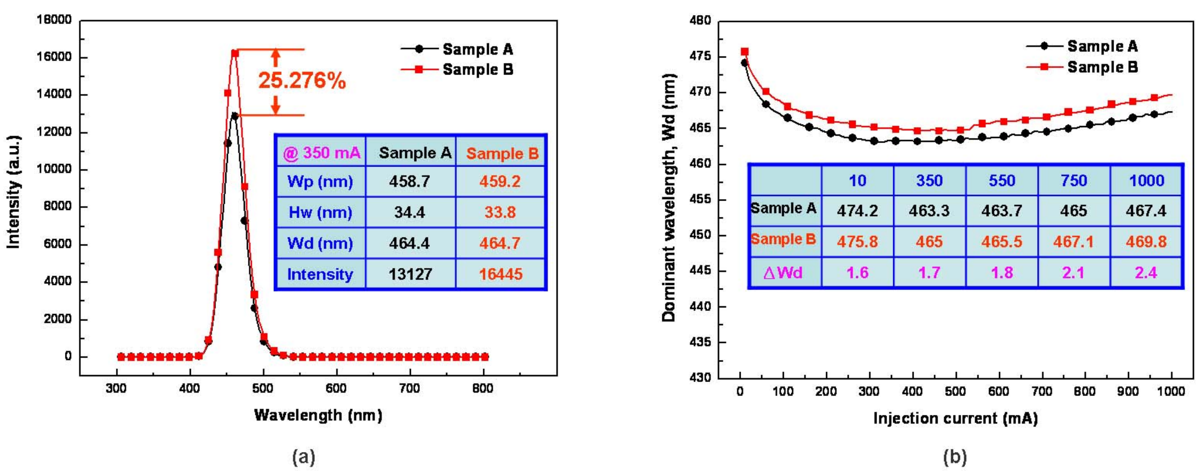

Fig. 7 (a) The Electroluminescence (EL) spectrum obtained from regular VM-LED and VM-LED with graded TCL/n-GaN under the injection current of 350 mA at room temperature. (b) The dependence of dominant wavelength on the injection current.

Figure 7(a) shows the Electroluminescence (EL) spectrum obtained from regular VM-LED (sample A) and VM-LED with graded concave TCL/n-GaN (sample B). The measurement was conducted under the injection current of 350 mA at room temperature. The EL spectrum shows the peak wavelength (λp) locating at around 464.7 nm without multipeaked emission and a full-width at half maximum (FWHM) of about 33.8 nm.

Figure 7(b) demonstrates the dependence of the dominate wavelength (λd) on the injection current for sample A and B. For the current range of 0~500 mA, λd decreases with increasing the injection current. Such a blue shift could be ascribed to the band filling effect of localization energy states [11]. Note that the sample A and B are almost with the same blue shift of dominant wavelength. It implies that the anisotropic laser etching process almost did not cause any damage on GaN epilayer structures. For the high injection current region (>500 mA), red shift mainly caused by thermal effect was observed for both devices. Note that sample A also behaves very similarly to the sample B. Further improvement in LOP can be expected by optimizing the anisotropic etching process, maximizing the area of series resistance balance region, or using a graded convex-surface TCL/n-GaN layer structure. Detailed study on the optimum design of concave- and convex-surface TCL/n-GaN layer structure is now still underway.

In conclusion, the use of an anisotropic laser etching to realize a concave-surface graded TCL/n-GaN structure to enhance current spreading of VM-LEDs has been presented. Theoretical calculations indicate that the effect of the concave-surface graded TCL/n-GaN structure strongly depends on the curvature and material parameters thereof. Using an anisotropic laser etching, VM-LEDs with a concave graded surface TCL/n-GaN layer structure of 800 •m in diameter with a depth of 1.7 •m at the center have been successfully fabricated. Typical improvement in light output power by about 38-26% at an injection current of 350 mA as compared to that of regular VM-LEDs has been obtained. It is expected that the proposed anisotropic etching to the top n-GaN layer would provide an effective way in enhancing current spreading in larger-area high-power vertical-structure GaN-based LEDs.