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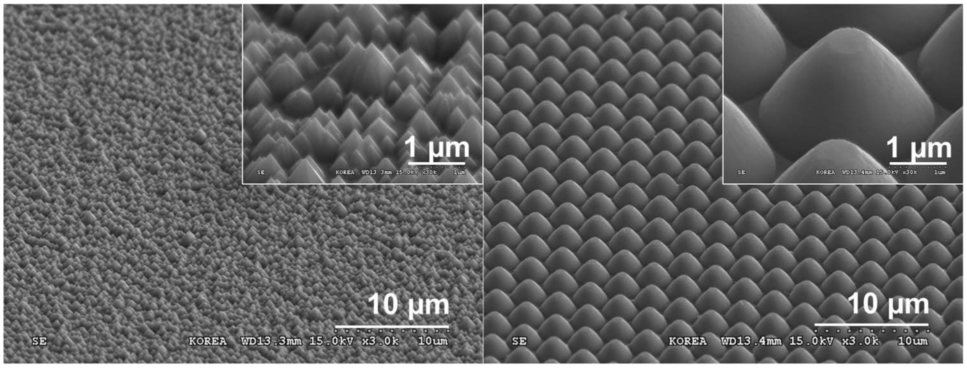

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High-Brightness Vertical GaN-Based Light-Emitting Diodes With Hexagonally Close-Packed Micrometer Array Structures

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Abstract: A high-brightness GaN-based vertical light-emitting diode (VLED) was demonstrated by introducing a large-area low-cost direct printing process. A hexagonally close-packed micrometer convex array was fabricated on the n-GaN top layer of the VLED by direct printing using a hydrogen silsesquioxane solution and subsequent inductively coupled plasma etching. To confirm that the enhancement of light extraction by this structure, a conventional wet-chemical-etched structure was also fabricated on the n-GaN top layer of the VLED, yielding randomly oriented pyramid structures on the layer. Both VLEDs showed much stronger electroluminescence emission than an unpatterned VLED. However, the micrometer convex array improved the light extraction significantly more than the random pyramid structure owing to its greater ability to enlarge the light escape cone, attributed to its 50°-tapered profile and large extraction area. After chip packaging with silicone encapsulation, the light output power of the micropatterned VLED was 11.4% and 106% greater than those of the wet-etched and unpatterned VLEDs, respectively, under a 350-mA drive current.

Index Terms: Light-emitting diodes (LEDs), microstructure fabrication.

1. Introduction

GaN-based light-emitting diodes (LEDs) have attracted tremendous interest for use in various industrial applications, including backlights for cell phones and liquid crystal displays, automotive lights, traffic signals, and full-color displays, owing to their long lifetime, low energy consumption, small size, and faster switching. Over the past decades, considerable research and development have yielded great improvements in the overall performance of GaN-based LEDs. However, next-generation applications such as general illumination, projection, and automotive headlights demand further improvements in their brightness, external quantum efficiency, and heat dissipation under a high injection current. Recently, n-type side-up vertical GaN-based LEDs (VLEDs) fabricated by laser lift-off (LLO) or chemical lift-off processes have been developed for high-power and high-efficiency applications [1]–[5]. In the VLED structure, n-GaN/InGaN multi-quantum well/p-GaN layers are placed on a highly reflective metal mirror that acts as a p-electrode and reflects light toward the top n-GaN layer. This LED structure shows promise for overcoming the limitations of conventional LEDs, which have a lateral current injection path, owing to its good heat dissipation and superior current spreading/injection. Nevertheless, the light extraction efficiency of VLEDs is fundamentally limited by total internal reflection originating from large difference in the refractive index between the GaN ($n \approx 2.5$) and air ($n = 1$) or a polymer encapsulant ($n = 1.4 \sim 1.6$), as in conventional LEDs. Most of the photons generated in InGaN multi-quantum wells are reflected back inside the LED structure, and only a few photons that proceed within the critical angle for total internal reflection can escape into air. Therefore, the light extraction efficiency can be greatly elevated by suppressing total internal reflection.

Various surface textures, such as surface roughening by alkaline-solution-based wet etching [6]–[8], photonic crystals [9]–[12], and nanorods [13], [14] have recently yielded enhanced light extraction efficiencies in VLEDs. Owing to the large thickness ($2 \sim 3\ \mu\text{m}$) and heavy doping concentration of the n-GaN top layer of the VLED, texturing methods that require dry or wet etching of the n-GaN can be applied to VLEDs without degrading their electrical properties [15], [16]. Additionally, the light extraction efficiency of the VLED can be effectively enhanced by combining highly reflective mirrors and light-extracting structures in the n-GaN layer [17], [18]. To commercialize the texturing methods in the LED industry, a large area, low cost, and large enhancement of light extraction are significant. Among these texturing methods, wet etching processes are well known as very effective methods of achieving highly enhanced light extraction at low cost over a large area. However, the irregular patterns produced by wet etching are still not optimal for light extraction in VLEDs. Photonic crystals are also known to be efficient structures for increasing the light extraction efficiency; however, they are difficult and expensive to fabricate. Moreover, the formation of a photonic band gap for strong coupling between photons and photonic crystals is difficult because the InGaN active layers cannot be penetrated by the photonic crystal owing to electrical degradations of the devices. Microlens arrays have been also established to enhance the light extraction efficiency of VLEDs [19]–[24]. Compared to photonic crystals, microlens arrays can be relatively easily fabricated on VLED structures using photolithography. However, these structures are several tens of micrometers in diameter and have low curvatures and low pattern density; thus, there is additional room for further enhancement of the light extraction.

In this paper, we fabricated a GaN-based micrometer convex array on blue VLED devices with a large area using simple, low-cost direct printing by spin-on-glass [25], [26] and inductively coupled plasma (ICP) etching processes to further increase the light extraction efficiency beyond that obtained by wet etching methods. Patterned sapphire substrates (PSSs) in particular are well known to be very effective for enhancing the light extraction efficiency of conventional LEDs, as well as the internal quantum efficiency. Therefore, we used a commercialized PSS that has a close-packed micro convex array as the template for the direct printing process. Further, we report the light extraction and electrical properties of three types of packaged VLED devices that have unpatterned (bare), wet-etched, and micropatterned n-GaN surfaces. Additionally, the optical powers of all the VLED devices are reported before and after final molding with silicone gel encapsulation.

2. Experimental Details

To fabricate an n-type side-up VLED, a typical GaN-based blue LED structure, consisting of 0.15 μm-thick Mg-doped p-GaN, five periods of InGaN multiple quantum wells, 4-μm-thick Si-doped n-GaN, and 2-μm-thick undoped GaN layers, was grown on a (0001)-oriented 2 inch sapphire substrate by a conventional metal organic chemical vapor deposition process. After the epitaxial layer was grown, a thin indium tin oxide layer was deposited on the p-GaN layer for a p-contact. Next, a VLED structure was fabricated by the LLO process using a KrF excimer laser (248 nm). Finally, the undoped GaN layer was then etched by an ICP system to expose the n-GaN layer. The details of the structure and fabrication process of the VLED device were described elsewhere [27], [28].

Two types of textures were formed on the n-GaN layer of the VLEDs by wet chemical etching and direct printing processes. The textured VLEDs with roughened n-GaN were fabricated by wet chemical etching using a heated KOH solution [27]. Next, the textured VLEDs with micropatterned

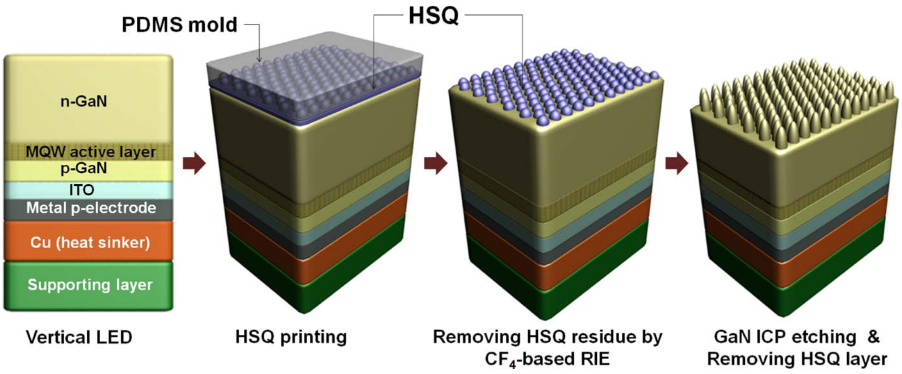

Fig. 1. The patterning process of the VLED with GaN-based micro-dome array using direct printing of HSQ and ICP etching.

n-GaN were fabricated by direct printing using the spin-on-glass solution hydrogen silsesquioxane (HSQ, Dow Corning) and subsequent ICP etching of n-GaN, as shown in Fig. 1. Before an elastomeric mold was made for use in the direct printing process, a thin SiO_2 layer was deposited on the PSS by sputtering, and then a hydrophobic self-assembled monolayer [29] was coated on the SiO_2 layer of the PSS as an anti-stick treatment. Next, a poly(dimethylsiloxane) (PDMS) solution containing a 10 : 1 mixture of Sylgard 184A and 184B (Dow Corning) was spread on the PSS at 80 °C for 1 h. After the PDMS was cured, the PDMS mold was detached from the PSS. To transfer the HSQ micropattern to the VLED, an HSQ solution diluted with methyl isobutyl ketone (MIBK) was spin-coated on the PDMS mold, and then the HSQ/PDMS stack was placed in contact with the n-GaN surface of the VLED at room temperature under a pressure of 5 atm for 5 min at vacuum ambient. After the printing process, the HSQ micropattern layer received UV ozone treatment to prevent reflow of the HSQ. Reactive ion etching using CF_4 plasma was then applied to remove the residual layer of the HSQ micropattern. To pattern the n-GaN layer, ICP reactive ion etching using N_2/BCl_3 plasma was performed on the n-GaN layer with the HSQ micropattern. Finally, the remaining HSQ was clearly removed by a buffered oxide etch solution.

After the texturing process of the VLEDs, a metal n-pad was formed on the VLED structures with bare, wet-etched, and micropatterned n-GaN layers. The VLED samples were then cut into 1 mm^2 chips and packaged into a standard chip on board. Further, their electrical and optical characteristics were analyzed.

3. Results

To achieve uniform pattern formation of the HSQ, an elastomeric PDMS mold that is highly permeable to chemical solvent was used in the direct printing process. Although most of the MIBK solvent in the HSQ solution is volatilized during spin-coating, some remains in the spin-coated HSQ solution layer on the PDMS mold. However, most of the remaining MIBK is absorbed into the high-permeability PDMS mold during direct printing, and then the HSQ pattern containing a small amount of MIBK is transferred from the PDMS mold to the n-GaN surface by detaching the mold from the VLED. If the MIBK is not effectively removed during the direct printing process, uniform pattern transfer is impossible because of the weak solidification of the HSQ and sticking between the HSQ and the PDMS. In addition, because the PDMS mold enables conformal contact, the HSQ pattern could be uniformly transferred over a large area. Fig. 2(a) and (b) show scanning electron microscope (SEM) images of the HSQ micropatterns on a bare GaN LED wafer. The micro-convex patterns with 1.2 μm in diameter, 3 μm in pitch, and 1.26 μm in height were uniformly fabricated on a large-area GaN surface. The slope of the HSQ micropattern profile in the inset of Fig. 2(b) was about 50°, which strongly affects the etch profile of the n-GaN layer. A residual layer of the HSQ micropattern about 100–150 nm thick was confirmed, as shown in the inset of Fig. 2(b), and was removed to expose the n-GaN layer by reactive ion etching using CF_4 plasma.

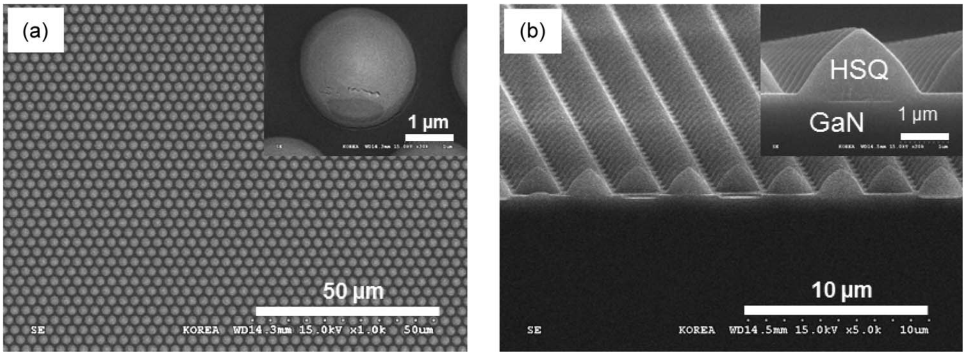

Fig. 2. (a) and (b) are top and tilted view of SEM micrographs of the HSQ micropatterns on bare GaN substrate, respectively. The insets of (a) and (b) indicate high magnification images of top and cross-sectional view of SEM micrographs of the HSQ micropatterns.

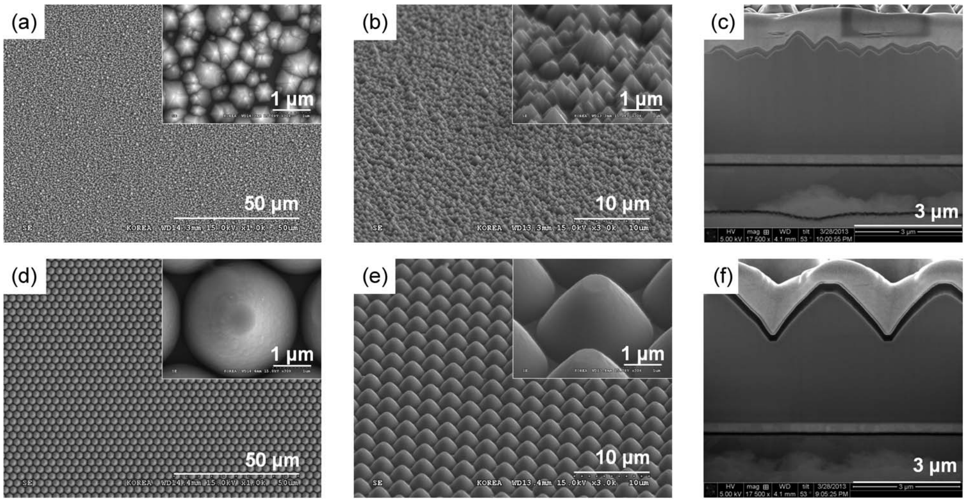

Fig. 3. (a) and (d) are top views of SEM micrographs of the wet etched n-GaN surface and patterned n-GaN surface of the vertical LED, respectively. Insets are its magnification. (b) and (e) are 70° tilted views of SEM micrographs of the wet etched n-GaN surface and patterned n-GaN surface of the vertical LED, respectively. Insets are its magnification. (c) and (f) are cross-sectional views of focus ion-beam SEM micrographs of the wet etched n-GaN surface and patterned n-GaN surface of the vertical LED, respectively.

Both of wet etched and micropatterned of n-GaN surface of VLED was confirmed by measurement of SEM. Fig. 3(a) and (b) show SEM images of top and 70° tilted views of the n-GaN textured by KOH wet etching. The crystallographic wet etching of GaN using the KOH solution formed hexagonal GaN pyramids with sizes ranging from 0.1 μm to 1.5 μm, as shown in the insets of Fig. 3(a) and (b). Fig. 3(c) presents a focused ion beam (FIB) SEM image of a 53° tilted view of the wet-etched VLED. The heights of the n-GaN pyramids range from 0.1 Km to 1 μm. After direct printing of the HSQ solution, the n-GaN layer masked with the HSQ micropattern was etched by ICP etching using N_2/BCl_3 plasma. Fig. 3(d)–(f) present SEM images of the micropatterned n-GaN layer. As shown in Fig. 3(d), the n-GaN layer was patterned with a hexagonally close-packed micrometer array over a large area by the direct printing and ICP etching processes. The inset of Fig. 3(d) shows that the upper side of the n-GaN micropattern is not etched by the ICP etching because of the residual HSQ layer. Compared to the HSQ micropattern, which is about 2.4 μm in diameter, the n-GaN micropattern is wider and has a diameter of about 3.1 μm because of over-etching of the n-GaN. Fig. 3(e) shows a 70° tilted SEM image of the n-GaN micropattern. The smooth surface of the n-GaN

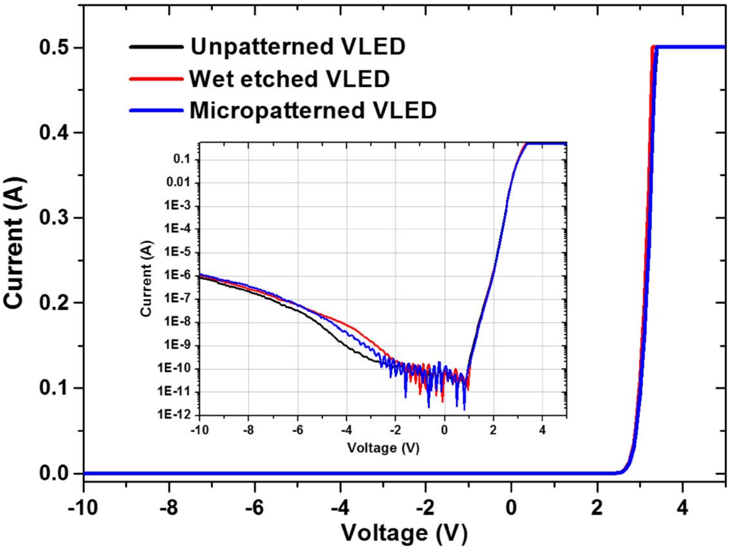

Fig. 4. The *I–V* characteristics of the unpatterned, micropatterned and wet-etched vertical LED devices. The inset shows the *I–V* characteristics on a logarithmic scale.

micropattern is confirmed in the inset of Fig. 3(e). Fig. 3(f) is a 53° tilted FIB-SEM image confirming a 1.8 *K*m etch depth and an etch profile with a 50° taper angle in the n-GaN micropattern. The profile of the HSQ micropattern is directly reflected in the n-GaN micropattern after ICP etching.

We measured the *I–V* characteristics of the unpatterned, wet-etched, and micropatterned VLED devices to analyze the effect of micropatterning and wet etching on their electrical properties. The forward voltages of all the VLED devices are between 3.23 V and 3.26 V under a 350 mA current, and the *I–V* curves of all the VLED devices are nearly indistinguishable, as shown in Fig. 4. The inset shows the *I–V* characteristics on a logarithmic scale; the reverse leakage currents of the wet-etched and micropatterned VLED devices are slightly larger than that of the unpatterned VLED device owing to surface leakage originating in the texturing. Nonetheless, these increments in the reverse leakage current are negligible compared to the overall electrical performance of VLED devices with a thick n-GaN layer. Therefore, the micropatterning process using direct printing and ICP etching, as well as the wet-etching process, can be used to enhance the light extraction efficiency of VLED devices without degradation of electrical property.

To confirm the effect of the textured n-GaN layer on light extraction in the VLED devices, we measured the electroluminescence (EL) spectra of the unpatterned, wet-etched and micropatterned VLED devices in an integral sphere under a 350 mA drive current, as shown in Fig. 5(a). The peak emission wavelengths of all the VLEDs ranged from 445 nm to 446 nm. Considerable wavelength shifts were not observed in the EL spectra of the wet-etched and micropatterned VLEDs because the InGaN multi-quantum-well active layers were not penetrated by the wet-etching and ICP etching processes. The integrated EL intensities of the wet-etched and micropatterned VLED devices were 164.1% and 194.8% higher, respectively, than that of the unpatterned VLED device. This result indicates that the textured n-GaN layers are very effective at suppressing total internal reflection inside the VLEDs. Specifically, the close-packed array of the micropattern is more helpful in suppressing the total internal reflection than the randomly textured structure obtained by wet etching. In our results, the EL intensity of the micropatterned VLED was 11.6% higher at the peak emission wavelengths than that of the wet-etched VLED.

To analyze the mechanism of these light extraction enhancements, we measured the far-field emission patterns of the unpatterned, wet-etched, and micropatterned VLED devices under a 350 mA drive current, as shown in Fig. 5(b). The EL intensities of the wet-etched and micropatterned VLEDs are much stronger than that of the unpatterned VLED in the −75° to 75° range, but the emission patterns of the two textured VLEDs differ in terms of the emission intensity at −45° to 45°. The

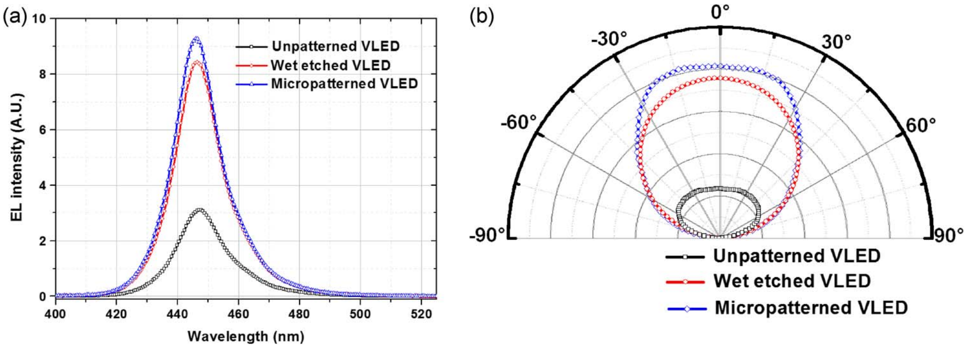

Fig. 5. (a) EL spectra and (b) far field emission patterns of the unpatterned, micropatterned and wet-etched vertical LED devices in an integral sphere at 350 mA.

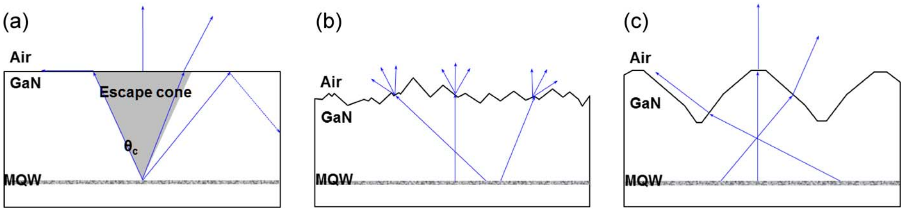

Fig. 6. Schematic drawings of (a) the unpatterned, (b) wet-etched, and (c) micropattterned VLED structures with light trajectories.

randomly textured n-GaN surface of the wet-etched VLED scattered the light in a nonspecific direction, producing a typical Lambertian emission pattern. In other words, the mechanism for the enhancement of light extraction by the randomly textured n-GaN surface is based mainly on light scattering, which hinders total internal reflection, as described in Fig. 6(b). In the micropatterned VLED, the enhancement of light extraction originates in the enlargement of the photon escape cone. As shown in Fig. 6(c), the n-GaN micropattern provides more opportunities for photons that proceed outside the critical angle to escape into air because of its 50° tapered profile and larger extraction area, compared to the flat n-GaN surface illustrated in Fig. 6(a). Moreover, the profile of the n-GaN micropattern is most helpful for extracting photons at -45° to 45°; thus, the EL intensity of the micropatterned VLED was stronger than that of the wet-etched VLED in this range.

We measured the optical power of unpatterned, wet-etched, and micropatterned VLED devices after molding process. Fig. 7(a) shows the light output powers, which were measured in an integral sphere, as a function of the forward injection current for the unpatterned, wet-etched, and micropatterned VLED devices packaged as standard chips on board with and without a silicone gel molding. Before the molding was applied, the light output powers of the micropatterned and wet-etched VLEDs were clearly higher than that of the unpatterned VLED, and the micropatterned VLED showed the highest light output power of the three, as in the EL spectra shown in Fig. 5(a). This effect on the light output power of the VLEDs was not changed after the silicone gel molding was applied to the chips, although the enhancement of the light output power by silicone encapsulation, which originates in the spherical curvature and intermediate refractive index (≈ 1.45) of the silicone, is different for each VLED. As a result, the light output power of the micropatterned VLED was 11.4% and 106% higher under a 350 mA drive current than that of the wet-etched and unpatterned VLEDs, respectively, after the molding was applied to the chip package. Fig. 7(b) shows the wall plug efficiency (WPE), which is defined as the ratio between the light output power and the electric input power, as a function of the forward injection current for the unpatterned, wet-etched, and micropatterned VLEDs with and without the silicone gel molding. The WPEs of the

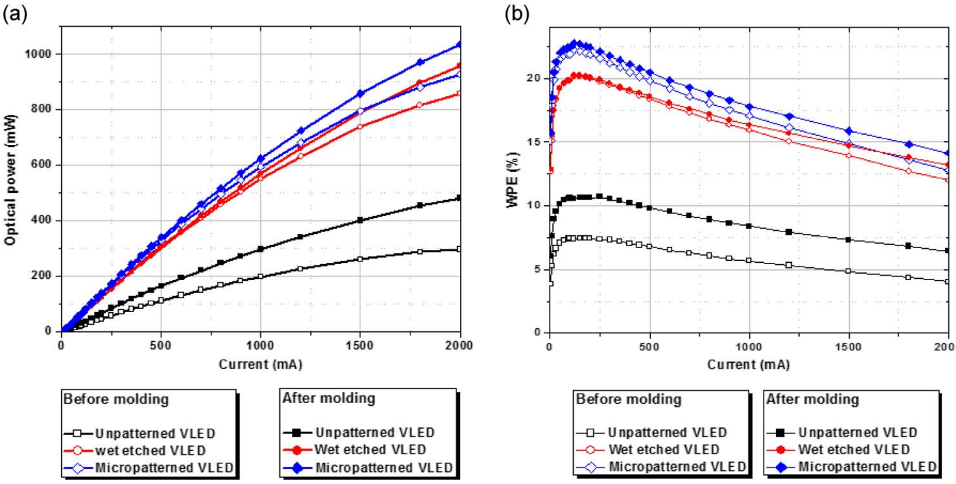

Fig. 7. (a) Optical power and (b) WPE of the unpatterned, micropatterned and wet-etched vertical LED devices before and after molding.

three VLEDs were dramatically increased until the forward current reached 150 mA and then decreased gradually because of the typical efficiency droop phenomena [30], [31] regardless of the presence of the silicone encapsulation. Among the three type of VLEDs, the micropatterned VLED showed the highest WPE under injection currents of 0 to 2000 mA, which can definitely be explained by its greatest light extraction enhancement.

4. Conclusion

In this paper, a simple large-area direct printing process was demonstrated to achieve high brightness GaN-based VLEDs. To enhance the light extraction of GaN-based VLEDs beyond that obtained by the conventional wet-etching method, a hexagonally close-packed micrometer array was formed on the VLED by direct printing and ICP etching processes. Measurements of the EL spectra and far-field emission patterns confirmed that the enlargement of the light escape cone by the micrometer array is more helpful for extracting light than light scattering by the random pyramid structure. After the VLEDs were packaged on a chip with silicone encapsulation, the light output power of the micropatterned VLED was enhanced by 11.4% and 106% under a 350 mA drive current in an integral sphere compared to those of the wet-etched and unpatterned vertical LEDs, respectively. Simultaneously, the WPE of the micropatterned VLED was maintained at higher values than those of the wet-etched and unpatterned VLEDs during gradual injection of a 2000 mA of forward current.

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