Integration of 3D printed lens with InGaN light-emitting diodes with enhanced light extraction efficiency

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ABSTRACT

III-nitride based light-emitting diodes (LEDs) have great potential in various applications due to their higher efficiency and longer lifetime. However, conventional planar structure InGaN LED suffers from total internal reflection due to large refractive index contrast between GaN (n_{GaN} = 2.5) and air (n_{air} = 1), which results in low light extraction efficiency ($\eta_{extraction}$). Accordingly, various approaches have been proposed previously to enhance the $\eta_{extraction}$. Nevertheless, most of the proposed methods involve elaborated fabrication processes. Therefore, in this work, we proposed the integration of three-dimensional (3D) printing with LED fabrication as a straightforward and highly-reproducible method to improve the $\eta_{extraction}$. Specifically, 500-μm diameter dome-shaped lens of optically transparent acrylate-based photopolymer is 3D-printed on planar structure 500 × 500 μm^2 blue-emitting LEDs. Light output power measurement shows that up to 9% enhancement at injection current 4 mA can be obtained from the LEDs with 3D printed lens on top as compared to LEDs without the lens. Angle-dependent electroluminescence measurement also exhibits significant light output enhancement between angles 0 and 30° due to the larger photon escape cone introduced by the higher refractive index of the 3D printed lens (n_{lens} = 1.5) than the air medium as well as the enhanced light scattering effect attributed to the curvature surface of the 3D printed lens. Our simulation results based on 3D finite-difference time-domain method also show that up to 1.61-times enhancement in $\eta_{extraction}$ can be achieved by the use of 3D-printed lens of various dimensions as compared to conventional structure without the lens.

Keywords: Light extraction efficiency, InGaN light-emitting diodes, 3D printing, encapsulation, dome-shaped lens, finite-difference time-domain

1. INTRODUCTION

III-nitride based light-emitting diodes (LEDs) have been extensively employed in wide variety of applications including flat panel displays, traffic signals, automotive lighting and general illuminations, as the performance of the LEDs improve continuously[1,2]. Despite the tremendous progress in LED development, further enhancement of the external quantum efficiency (η_{EQE}) of LED, which is strongly dependent upon internal quantum efficiency (η_{IQE}), injection efficiency ($\eta_{injection}$) and light extraction efficiency ($\eta_{extraction}$), is essential in realizing next generation high-efficiency LEDs especially for solid-state lighting. Several challenges such as charge separation due to spontaneous and piezoelectric polarizations induced by the large lattice mismatch between GaN materials and the substrate, efficiency droop phenomena at high current injection, and large refractive index contrast between GaN and air medium, have been identified to obstruct the realization of high-brightness III-nitride LEDs[1–4]. In order to suppress the charge separation issues and to improve the $\eta_{injection}$, novel LED designs and growth methods have been proposed previously including band structure engineering to enhance electron-hole wavefunction overlap[5–8], surface plasmon coupled InGaN QWs to improve Purcell effect[9–12] and nonpolar/semipolar InGaN QWs growth to minimize the polarization field[13–15].

On the other hand, significant efforts have also been devoted in enhancing $\eta_{extraction}$ of InGaN LED[16–19]. According to Snell's Law, the critical angle (θ_c) for a photon to escape from GaN layer into air is about 24°. As a result, photons generated from conventional planar structure LEDs arrive at the GaN/air interface at angle larger than 24° will experience total internal reflection and get trapped inside the high refractive index (n) material. For a conventional planar GaN-based LED structure, the $\eta_{extraction}$ estimated theoretically from the equation $1/4n^2$, where n is the refractive

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index with $n_{GaN} = 2.5$, suggested that only ~4% of light generated in the active region can be radiated out from the InGaN/GaN LED device[20]. This relatively low light output power is inadequate for realizing high-efficiency solid state lighting. Accordingly, various LED designs such as surface roughening[16], patterned sapphire substrate[17], microstructure arrays[18] and photonic crystals (PhCs)[19] have been investigated with the intentions to enhance photon scattering effect and to increase the chances of photons entering the photon escape cone in the LED structure that can lead to enhancement in the $\eta_{extraction}$. Although all these proposed methods have reported substantial improvement in the LED performance, all of them involve elaborated fabrication processes, which add to the complexities in the LEDs fabrication.

Considering that the three-dimensional (3D) printing technology is getting more popular and more mature in electronics manufacturing, we are proposing the integration of 3D printing process with LED fabrication in this work as a straightforward and highly-reproducible method to improve the $\eta_{extraction}$ for the first time. Specifically, a 500-μm diameter dome-shaped lens is 3D-printed layer-by-layer, with layer thickness of 25 μm, using optically transparent acrylate-based photopolymer on planar structure 500 × 500 μm^2 blue-emitting LEDs. The light output power measurement results show that up to 9% enhancement in output power at injection current of 4 mA can be obtained from the LEDs with 3D printed lens on top as compared to conventional LEDs without the lens. The angle-dependent electroluminescence (EL) measurements also exhibit significant light output enhancement between angles 0 and 30° from the LEDs with 3D printed lens due to the larger photon escape cone introduced by the higher refractive index of the 3D printed lens ($n_{lens} = 1.5$) than the air medium as well as the enhanced light scattering effect attributed to the curvature surface of the 3D printed lens. From our simulation results based on 3D finite-difference time-domain (FDTD) method, up to 1.61-times enhancement in $\eta_{extraction}$ can be achieved from blue-emitting LEDs by the use of 3D-printed lens of various dimensions. In addition to enhancing the $\eta_{extraction}$, the 3D printed lens with refractive index of 1.5 can also serve as encapsulation layer for LED devices which can help to eliminate the additional manufacturing cost incurs from the separated LED encapsulation process. Since the use of 3D printing technology provides the flexibility in the lens design, where the lens dimension can be changed easily in the CAD file, as well as the convenience in experimenting with different materials, it is expected that the proposal of the integration of 3D printed lens with nitride-based LEDs could offer an alternative solution for realizing next-generation high-efficiency and high-brightness LEDs.

2. CHARACTERIZATION OF 3D PRINTED LENS

In order to 3D-print the lens, the CAD model of the lens is first prepared using Solidworks, and then the design is geometrically sliced into a series of 2D images that will be printed one on top of the next by Formlabs Form 2 3D printer using an optically transparent acrylate-based ultraviolet (UV) curable photopolymer. For each layer to be printed, a galvanometer scans a 405 nm laser beam over the region of the liquid resin to be cured, and between each laser curing cycle, a new layer of uncured resin is spread. The thickness of each layer is set to 25 μm. After the final layer is cured, the 3D printed lens is rinsed in isopropyl alcohol and then post-cured in UV curing over for approximately 30 minutes to improve the adhesion of the 3D printed lens onto the LED.

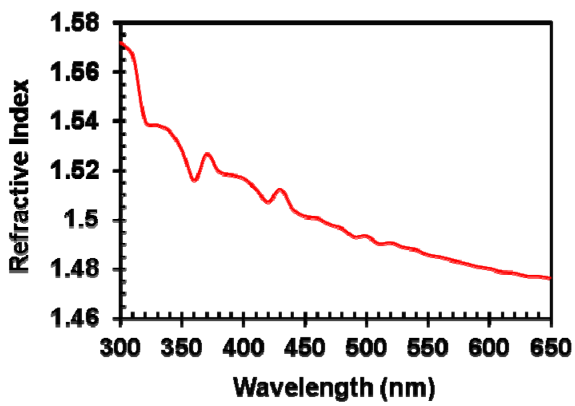

Figure 1. Refractive index of photopolymer as a function of wavelength.

First of all, a 1-mm thick square-shaped photopolymer with side length of 25 mm is 3D printed on a bare silicon wafer for the purpose of characterizing the refractive index of the photopolymer using Woollam VASE ellipsometer. As presented in figure 1, the refractive index of the photopolymer is ~1.5 at wavelength 450 nm. From the calculation based on Snell's Law, the θ_c for InGaN/GaN LED with the photopolymer on top can be increased to ~37°, which imply larger photon escape cone as compared to conventional planar LED structure without the photopolymer on top (θ_c ~24°). The presence of larger photon escape cone can help to extract more photons out of the LED structure, which in turn increases the likelihood of photons to escape into the air medium. In addition, the refractive index of 1.5 for the photopolymer is larger than silicone ($n_{\text{silicone}} \sim 1.3$), a common material used for LED encapsulation. Since larger refractive index material is desired for encapsulation layer, a well-design 3D printed lens using this photopolymer can also serve as encapsulation layer for LED devices, which can then eliminate additional cost incur from the separated fabricated processes for LED encapsulation.

Nonetheless, the use of material with larger refractive index than air medium on top of planar LED structure alone is not sufficient for enhancing the $\eta_{extraction}$. Correspondingly, the design of the 3D printed lens is essential to $\eta_{extraction}$ as it will impact the photons extraction from the LED device into the air medium. Figure 2 shows the two designs of 3D printed lens that has been test printed on dummy samples: (a) 5 mm diameter 3D printed dome-shaped lens with 2.5 mm dome height, and (b) 5 mm diameter 3D printed dome-shaped lens with 2.5 mm dome height on top of a cylinder base of 1.5 mm height. The 3D printed lens images presented in figure 2 clearly show the curvature shape and surface roughness of the 3D printed lens formed by the stacking layers, which are anticipated to result in enhanced photon scattering effect and lead to higher $\eta_{extraction}$.

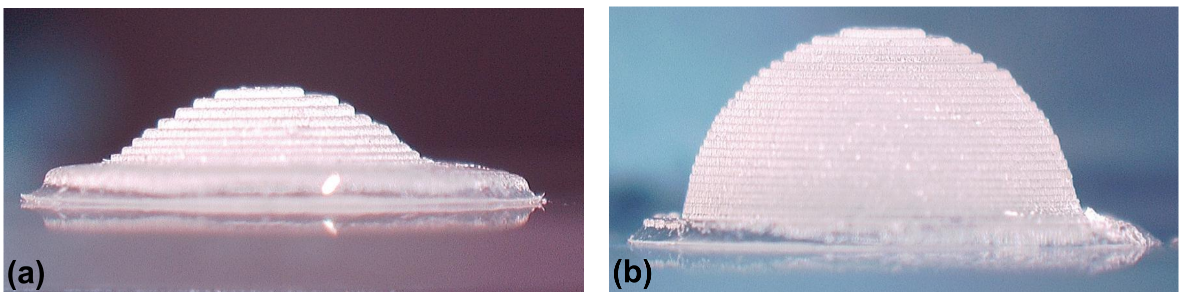

Figure 2. 3D printed lens on glass substrates with (a) 5 mm diameter dome with 2.5 mm dome height and (b) 5 mm diameter dome with 2.5 mm dome height on cylinder base of 1.5 mm height.

3. BLUE LEDS WITH 3D PRINTED LENS

As a proof of concept study, a dome-shaped lens of diameter 500 μm has been 3D printed on a 500 × 500 μm^2 blue LED device, as shown in figure 3(a). As can be seen from figure 3(a), the 3D printed lens of small dimension does not appear to be a perfect dome-shaped, as compared to 3D printed lens of large diameter depicted in figure 2. Further optimization of the 3D printing process is necessary in order to better control the dome-shaped for small diameter 3D printed lens. Figures 3(b) and 3(c) show the emission of blue LEDs with and without the 3D printed lens respectively at current injection of 4 mA. Due to the limitation of the microscope in focusing the LED with 3D printed lens, the comparison of emission brightness through visual inspection between the blue LEDs with and without 3D printed lens is not very distinct. Nevertheless, from the output power measurement results presented in figure 3(d), it clearly indicates output power enhancement for the LED with 3D printed lens as compared to LED without the lens. For example, up to ~9% enhancement in the output power can be obtained at current injection of 4 mA. Since the measurement of the light output power presented in figure 3(d) were performed by placing a Si detector at the top of the LED device, in which it only collects photons at the vertical direction, higher output power enhancement coming from angles is anticipated by the use of integrating sphere in the power measurement. As evidenced by the angle-dependent EL measurement presented in figure 3(e), higher light intensity can be measured from all angles, in particular, significant output enhancement can be observed at angles between 0 and 30°. The enhancement in the measured light output power is attributed to the larger photon escape cone by the use of photopolymer with refractive index of 1.5, and the enhanced light scattering effects introduced by the curvature and surface roughness of the 3D printed lens.

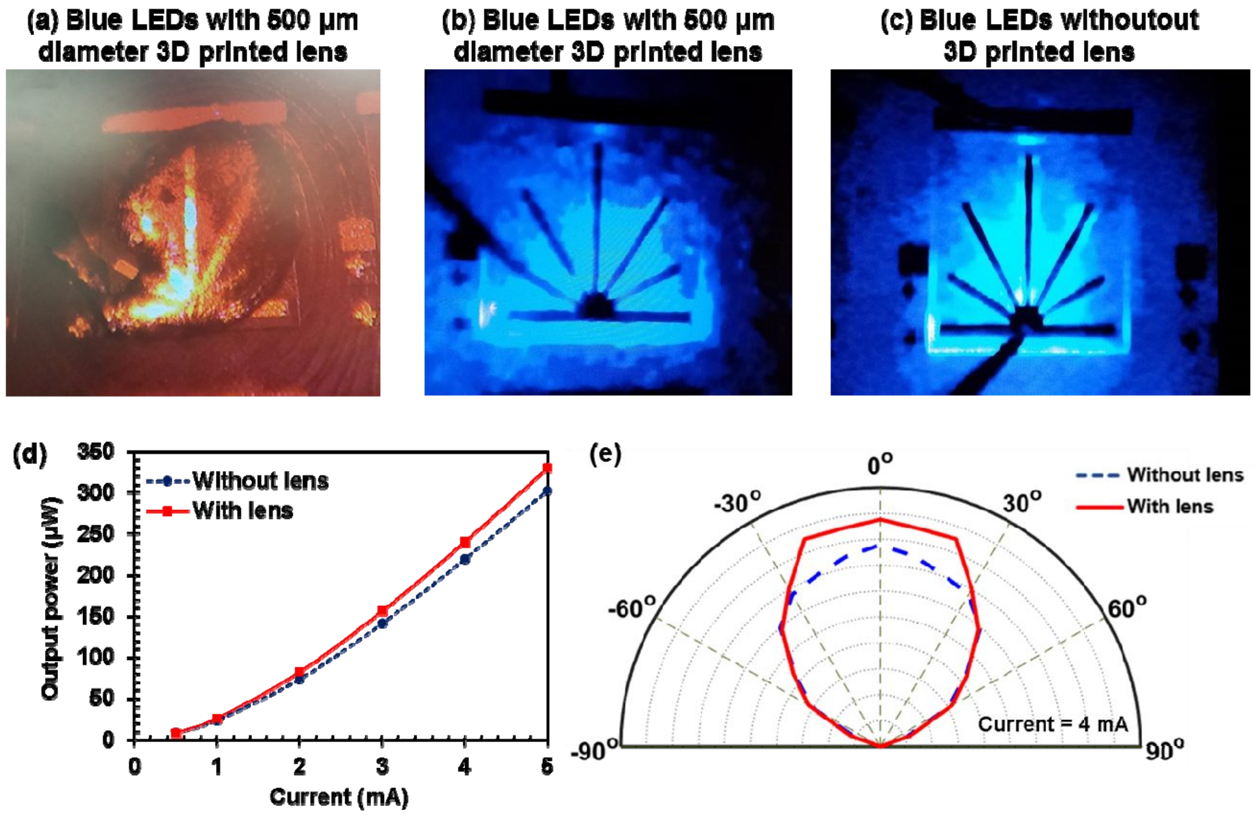

Figure 3. (a) 3D printed lens of diameter 500 µm on 500 × 500 µm ^{2} blue LED device, (b) emission from blue LED with 500 µm diameter 3D printed lens at current injection of 4 mA, (c) emission from blue LED without 3D printed lens at current injection of 4 mA, (d) output power measurement versus current injection for blue LEDs with and without 3D printed lens, (e) angle-dependent EL measurement for blue LEDs with and without 3D printed lens at current injection of 4 mA.

In order to investigate the effect of various lens designs on the $\eta_{extraction}$, 3D FDTD simulations[21], which rigorously solved Maxwell equations in time domain, have been performed for the two lens designs depicted in figure 2. The layer structure of the simulated LEDs emitting at 450 nm with 3D printed lens are illustrated in figures 4(a) and 4(f) where the height of the dome-shaped lens is labeled as *h* and the height of the cylinder base is labeled as *d*. The simulation domain is set to 5 × 5 µm^2 with non-uniform grid size (10 nm in the bulk and 2.5 nm at the edge[22]) so as to counterbalance the needs of intensive computation load and accuracy of the simulation results. The refractive index of the GaN, InGaN multiple quantum well (MQW), sapphire and 3D printed lens is set as 2.5, 2.6, 1.8 and 1.5 respectively with absorption coefficient of 10 cm^{-1} for GaN and 2000 cm^{-1} for InGaN MQW[5,22]. Perfectly matched layer boundary condition is applied to all the boundaries of the simulated structure. A single dipole source with emission wavelength 450 nm is placed at the center of the active region and a power monitor is placed at 200 nm away from the top of the simulated structure to monitor the light output power radiated out of the simulated device. Only transverse electric (TE)-polarized light (major electric field travels in the in-plane direction) is considered in this study since emission from InGaN-based active region has been reported to be primarily TE-dominant[23]. The $\eta_{extraction}$ is calculated as the ratio of the light output power measured by the power monitor to the total power dissipated by the dipole source in the active region while the $\eta_{extraction}$ ratio (η_{ratio}) is calculated by normalizing the $\eta_{extraction}$ obtained from the LED structure with 3D printed lens to the conventional LED structure without 3D printed lens.

The far-field radiation pattern for conventional LED structure without 3D printed lens is plotted in figures 4(b) and 4(g) where typical Lambertian radiation pattern with angular (θ) dependent and symmetrically azimuthal (ϕ) distribution has been expected. By integrating a 3D printed lens with refractive index of 1.5 on top of InGaN LED, the same

Lambertian radiation pattern can be observed from the simulated far-field radiation plots in figures 4(c)-4(e) and 4(h)-4(j), but with higher radiation intensity at the center region, which eventually contribute to larger $\eta_{extraction}$ than the conventional structure. From the η_{ratio} indicated in figures 4(c)-4(e) for LEDs with dome-shaped lens of various h, the enhancement in the $\eta_{extraction}$ is observed to increase when the dome height h is getting larger. Specifically, the η_{ratio} is calculated to increase from 1.35x to 1.61x when h changes from 0.6 µm [figure 4(c)] to 1.3 µm [figure 4(e)]. For the case of LEDs with dome-shaped lens on cylinder base, same phenomena can also be observed where the $\eta_{extraction}$ increases when the total height of the lens (h + d) is increasing. However, by comparing the radiation plots and η_{ratio} of figures 4(e), 4(i) and 4(j), it is obvious that d parameter has less effect than h parameter on the $\eta_{extraction}$, which imply that the curvature shape of the lens is more critical than the total height of the lens in enhancing the $\eta_{extraction}$. Basically the calculated η_{ratio} for LEDs with 1.3 µm total lens thickness increases from 1.32x at h = 0.3 µm, d = 1 µm [figure 4(i)] to 1.61x at h = 1.3 µm, d = 0 [figure 4(e)]. Another comparison is the LEDs with total lens thickness of 1 µm where the η_{ratio} with lens design of h = 0.5 µm, d = 0.5 µm [figure 4(h)] is only 1.42x while η_{ratio} for LEDs with lens design of h = 0.5 µm, d = 0 [figure 4(h)] is determined to be 1.58x.

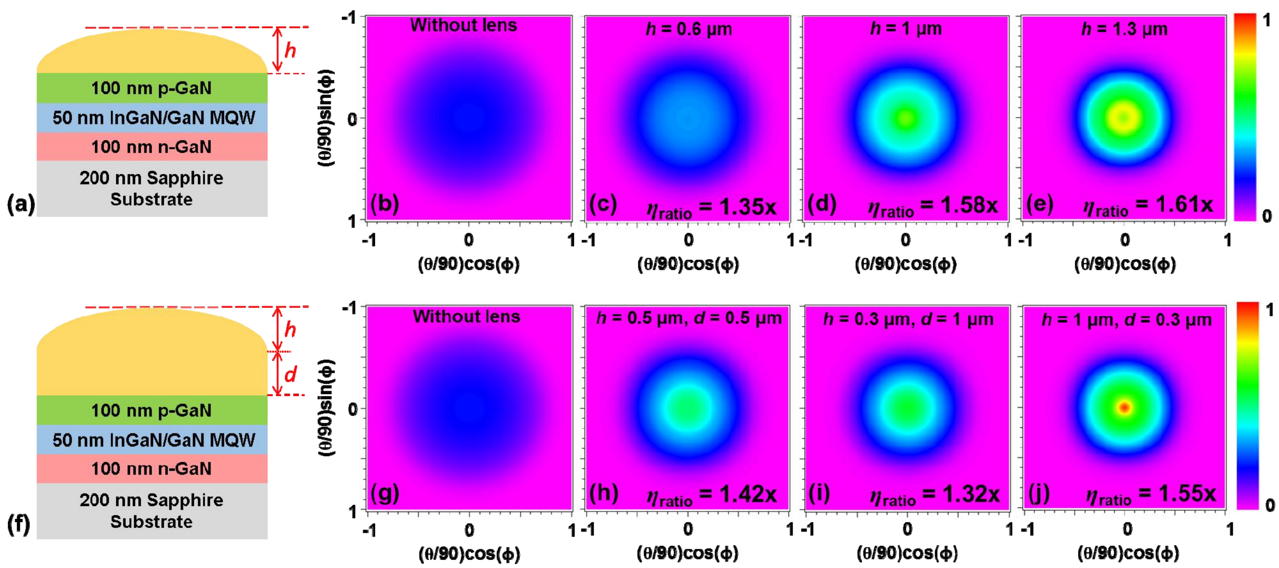

Figure 4. (a) Schematic side view of InGaN LED with dome-shaped lens; (b) far-field radiation pattern for conventional InGaN LED without lens; far-field radiation patterns for InGaN LEDs with dome-shaped lens of (c) h = 0.6 µm, (d) h = 1 µm, (e) h = 1.3 µm; (f) schematic side view of InGaN LED with dome-shaped lens on cylinder base; (g) far-field radiation pattern for conventional InGaN LED without lens; far-field radiation patterns for InGaN LEDs with dome-shaped lens on cylinder base of (h) h = 0.5 µm, d = 0.5 µm, (i) h = 0.3 µm, d = 1 µm, (j) h = 1 µm, d = 0.3 µm.

Based on the results obtained from the FDTD analysis, two conditions related to the lens design have been exemplified: 1) the use of 3D printed lens with higher refractive index (n_{lens} = 1.5) than air medium (n_{air} = 1) is resulting in larger photon escape cone in the GaN/lens interface that can help to extract more photons out of the LED structure, and 2) the curvature shape of the 3D printed lens, which can help to enhance the light scattering effect, is more critical than the total lens thickness in light extraction. These two design considerations can be tuned easily by the use of 3D printing technology as the parameter h and d can be changed by modifying the CAD file while the simplicity in changing the photopolymer type in the 3D printer enable the possibility of experimenting with different lens material of various refractive indexes. In addition, the use of 3D printed lens as encapsulation for LED devices can also achieve white color emission by mixing the photopolymer with phosphor, which remove the need of extended fabrication procedure.

4. CONCLUSION

In summary, the integration of 3D printed lens on blue LED has been proposed and investigated in this study. As a proof of concept study, a dome-shaped lens of diameter 500 µm with refractive index of 1.5 has been 3D printed on a 500 × 500 µm^2 blue LED device where ~9% enhancement in the light output power at current injection of 4 mA has been observed. The angle-dependent EL measurements have illustrated improved light intensity for all angles, in particular, significant output enhancement observed at angles between 0 and 30°, suggested the feasibility of using 3D printed lens to improve light extraction efficiency. In addition, the FDTD simulations of various lens dimension have verified that the curvature shape of the lens is an important design parameter that will impact the light extraction. Future work on optimizing the 3D printing process in order to better control the dome-shaped for small diameter 3D printed lens as well as the implementation of white LEDs with the integration of 3D printed lens on blue emitting LEDs are still on-going. It is anticipated that the proposal of the integration of 3D printed lens with nitride-based LEDs presented in this study could offer an alternative solution for realizing next-generation high-efficiency and high-brightness LEDs.

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