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# Flip-chip InGaN Light-emitting Diodes with an Integrated Microlens Array

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**Abstract:** The fabrication of hexagonally close-packed lens array on flip-chip bonded InGaN LED by nanosphere lithography is reported. A self-assembled monolayer of silica spheres with diameters of 1- $\mu\text{m}$  serves as an etch mask to be transferred onto the sapphire face of the LED to form hemispherical lenses. Without degrading electrical characteristic, the light output power of lensed LED is increased by more than one-quarter, compared with an unpatterned LED. The optical behavior of individual lenses and converging effect of lensed LED are by ray-tracing and confocal imaging.

## 1. Introduction

Typically, external optical components, such parabolic reflector and collimator, are utilized to implement on the top/bottom of the LED so as to condense the original Lambertian radiation pattern into narrow light beam with less divergence but such converging process indeed poses several challenges, such as poor heat dissipation, low efficiency and less flexibility with bulky packaging and luminaires. Monolithic integration of lens shaped geometry on transparent sapphire of flip-chip LED is a promising approach with its abilities of improving the light extraction and altering the emission behaviors [1, 2]. Tedious processes involving photolithography and thermal resist reflow step are employed to generate micro-lens structures of the order of microns [3]; we propose the fabrication of hexagonally close-packed (HCP) micro-lens array on a flip-chip bonded LED via nanosphere lithography (NSL) [4]. This self-assembly method of fabricating micro-lens array indeed offers several distinct advantages over conventional photolithographic technique: (i) NSL is the one-step, low cost and high yield approach to directly define large-area nano-patterns; (ii) compare with photo-/thermal- resist, silica spheres provide relatively high etch resistance (comparable to sapphire), resulting in larger height-to-diameter ratio of lens geometry and more pronounced surface curvature; (iii) inevitably, additional reflow step for reshaping the coated resist into pedestals introduces large spacing while the self-assembly method produces ultimate high-density of HCP hemispherical elements; (iv) NSL, with wide range of scalable sphere dimensions, overcomes the resolution limitation arising from optical diffraction limit. The monolayer of silica spheres acts as an etch mask for transferring pattern onto the sapphire substrate.

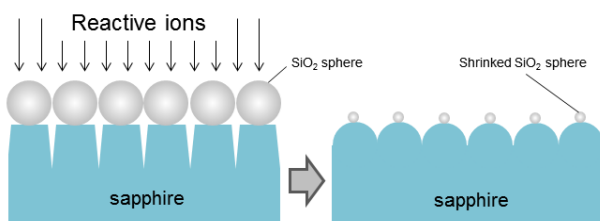


Fig 1 Process flow schematics for formation of microlenses.

## 2. Experimental details

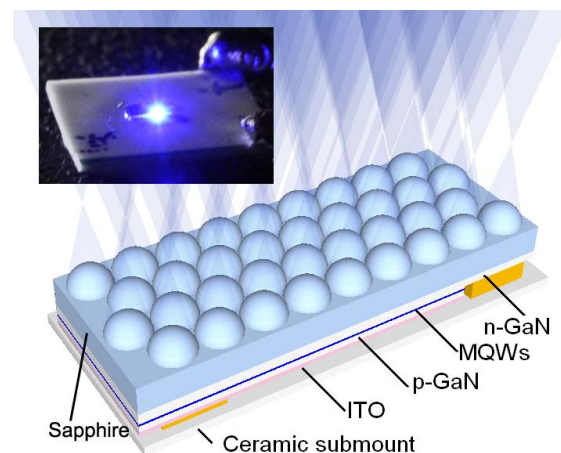


Fig. 2 Schematic diagram of device with integrated microlenses. An emitting device shown in the inset.

LED devices with mesa areas of  $500 \times 200 \mu\text{m}^2$  are fabricated by standard micro-fabrication processes on InGaN/GaN LED wafers grown on c-plane sapphire by MOCVD, with center emission wavelengths of  $\sim 440 \text{ nm}$ . Silica spheres with mean diameters of  $1 \mu\text{m}$  are coated evenly over the entire sapphire surface, self-assembly into an HCP pattern. The spheres, serving as etch masks, shrink both laterally and vertically during the pattern-transfer dry etch process, yielding hemispherical lens geometries, as depicted in Figure 1. The chips are flip-chip bonded onto a ceramic sub-mount, as illustrated in the schematic diagram of Figure 2. A microphotograph of an emitting device is shown in its inset.

## 3. Experimental results

The  $10 \times 10 \mu\text{m}$  planar AFM image shown in Figure 3(a) illustrates the HCP lens array patterned on sapphire substrate. The profiles of the lenses are shown in the cross-sectional AFM image of Figure 3(b). At a current of  $20 \text{ mA}$ , the forward voltages of the LEDs with and without lenses are  $3.41 \text{ V}$  and  $3.34 \text{ V}$  respectively; sapphire patterning does not deteriorate the electrical behavior. The measured L-I relation (not shown here)

also reveals the light output power of the LED with integrated microlenses is enhanced by 27.8 % at a current of 90 mA over an unlensed LED.

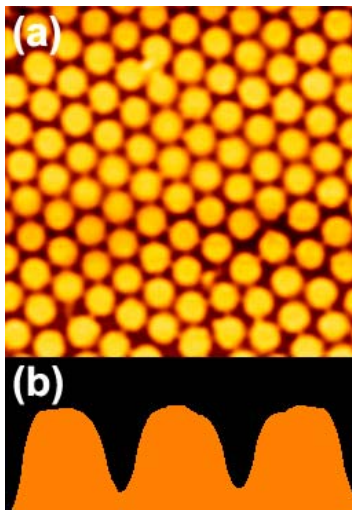


Figure 3 AFM image of microlenses formed on sapphire.

To study the effects of a microlens array to the emission characteristics of a flip-chip LED, ray-trace simulations have been performed using Tracepro, based on the model illustrated in Fig. 4(a). The simulated results predicts an enhancement of light extraction of about 40%; in reality the enhancement achieved was less than that by ~12% (from L-I data), attributed to non-ideal spherical profiles of the lenses, as well as surface roughness induced by the plasma etch process. Apart from light extraction, the microlenses play an important role in modifying the emission divergence of the device. Ray-trace simulation calculates the focal distance of the microlenses to be ~650 nm, close to the theoretical calculation of  $f = R/(n-1) = 665\text{nm}$ , where  $R = (h^2 + r^2)/2h$ . The ray-trace plot is shown in Figure 4(b). Experimental evidence of the convergence effect is provided by confocal imaging, a technique which has been demonstrated as a powerful tool for imaging the optical properties of micro-optical elements. Figure 4(c) shows a confocal scan of collimated light (from a 473nm DPSS laser) passing through the fabricated sapphire microlens array, obtained using a Carl Zeiss LSM700 confocal imaging microscope collected with a 150x objective with an N.A. of 0.95 [5]. The microlenses focus the laser beam to focal spots ~640 nm away from the apex of the lenses, consistent with calculated and simulated values. Confocal imaging provides real-time optical imaging with micrometer resolution, confirming the role of microlenses for improving the performance of LEDs, as well as reducing emission divergence for the spot-lighting effect. Angular emission plot for the lensed device is obtained by goniometry (not shown); the emission half-angle is found to be reduced by ~20° over a device without lenses, attributed to the optical characteristics of the microlenses.

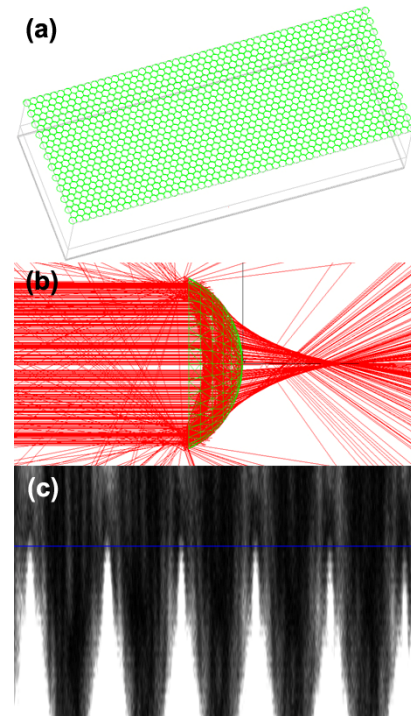


Fig. 4 (a) Model adopted for the ray-trace simulations. (b) Ray-trace plot depicting the focusing effect of a single microlens. (c) Focusing effects of several microlenses imaged using confocal microscopy.

#### 4. Conclusions

Hexagonally closed-packed microlenses have been fabricated onto the sapphire face of InGaN LEDs, which are flip-chip bonded to expose the lensed sapphire surface. The device is found to be superior to a conventional flip-chip LED with a planar sapphire surface with an enhanced light output of ~30% at 90 mA. Due to the focusing behavior of the lenses (with a calculated and measured focal length of ~650 nm), the emission divergence of the device is found to be reduced by 20° from angular emission measurements.

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#### References

- [1] H.W. Choi, C. Liu, E. Gu, G. McConnell, J.M. Girkin, I.M. Watson and M.D. Dawson, *Appl. Phys. Lett.* **84** 2253 (2004).
- [2] T. N. Oder, J. Shakya, J.Y. Lin and H.X. Jiang, *Appl. Phys. Lett.* **82** 3692 (2003).
- [3] H.W. Choi, E. Gu, C. Liu, C. Griffin, J.M. Girkin and M.D. Dawson, *J. Vac. Sci. Tech. B* **23**, 130 (2005).
- [4] W.Y. Fu, K.K.Y. Wong and H.W. Choi, *Appl. Phys. Lett.* **95**, 133125 (2009).
- [5] C. Griffin, E. Gu, H.W. Choi, C.W. Jeon, G. McConnell, J.M. Girkin and M.D. Dawson, *Appl. Phys. Lett.* **86**, 041111 (2005).