Integration of Non-Lambertian LED and Reflective Optical Element as Efficient Street Lamp

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Abstract: A cost effective, high throughput, and high yield method for the increase of street lamp potency was proposed in this paper. We integrated the imprinting technology and the reflective optical element to obtain a street lamp with high illumination efficiency and without glare effect. The imprinting technique can increase the light extraction efficiency and modulate the intensity distribution in the chip level. The non-Lambertian light source was achieved by using imprinting technique. The compact reflective optical element was added to efficiently suppress the emitting light intensity with small emitting angle for the uniform of illumination intensity and excluded the light with high emitting angle for the prevention of glare. Compared to the conventional street lamp, the novel design has 40% enhancement in illumination intensity, the uniform illumination and the glare effect elimination.

OCIS codes: (220.4830) Optical systems design; (350.3950) Micro-optics; (230,3670) Light-emitting diodes ; (220,4000) Microstrucuter fabrication ; (220,2945) Illuminaiton design

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1. Introduction

Light-emitting diodes (LEDs) have various favorable characteristics, such as high flux efficiency and reliability, low power consumption, long life, and environmental friendly [1,2]. Moreover, LEDs have been extensively applied in several practical applications, such as backlight light source of flat panel, mobile projector, street lighting, traffic signal, automotive lighting, and general lighting [1,2]. However, the external quantum efficiency of LED is still restricted by the refractive index difference between GaN (n = 2.5) and that of air (n = 1.0). Most of photons generated from the multi-quantum well (MQW) layer, cannot escape from GaN due to the total internal reflection (TIR). The trapped photons were absorbed by the GaN active layer and then converted into heat. Fortunately, the external quantum efficiency of GaN-based LEDs can easily be improved by suppressing the total internal reflection. The methods which can enlarge the escape opportunity of photon inside GaN substrate included the surface roughness [3], the photonic crystals [4], the pattern sapphire substrate [5] and the imprinting technique [6,7]. Those methods introduced a relative roughness interface between air and LED chip so that the effect of TIR was suppressed. Currently, the most of street lamp light source are fluorescent lamps. The fluorescent lamps are power consuming, low efficiency, short life time and most of them contain mercury that is harmful to the environment. The advanced LED chip light source not only has advantages mentioned above, but also can be integrated with solar cell to be an environmental street lamp [8]. The solar cell can charge during daytime, and then the full charged solar cell becomes a power supply for night lighting.

Furthermore, the far-field pattern of LED chip was also a limit in various illumination applications. The characteristic of LED luminous intensity distribution was a rapid decay with the emitting angle. For most lighting application, a secondary optical element was a common method adopted to modulate the intensity distribution [9,10].

The secondary optical element applied on street lamp had two important issues. The first was that bring sufficient and uniform illumination on the illuminated surface. The second was that the high angle (larger than 80 degree) luminous intensity suppression for the elimination of glare effect [11]. In order to satisfy the lighting issues of street lamp, secondary optics elements played an important role for LED far-field pattern modulation [11]. The most important secondary optics element of a street lamp was an aspherical lens [11]. However, the aspherical lens introduced three disadvantages. First: the tooling cost was expensive because the fabrication cost of aspherical lenses was expensive. This disadvantage introduced an impact to the light source module cost. Second: the aspherical lens was a refractive optical element, so that Fresnel loss occurred at each surface penetrated by emitting light of the aspherical lens. Generally, the optical loss was 8% without for an aspherical lens without anti-reflection coating process. Third: the aspherical lens possessed large volume for the high power lens ability and result in the lower fabrication tolerance.

In this paper, we demonstrated a novel idea that can satisfy the both demands of street lamp. The imprinting technique was introduced after chip process to increase the light extraction efficiency of LED and modulate the intensity distribution in chip's level. Furthermore, a corresponding optical element was also designed for advanced utilization of the imprinted LED chip intensity distribution. This optical element adopted in this paper was a compact reflective surface which cannot only shape the terminative intensity distribution but also to prevent the loss of light after penetrating the different interface. Most important of all, both imprinting technique and the reflective surface were cost effective, high throughput, impact size, and high yield.

2. Imprinting and chip process

The fabrication process of surface textured LEDs by imprinting technology included the following steps, the mold fabrication, the imprinting and the chip process. Before the embossing process, the master molds were fabricated by conventional photo-lithography and

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anisotropic wet etching on Si chips. Pattern of the master stamp was a hole array with 4.5um in diameter and 5um in period.

The GaN wafer used in this paper was grown by metal organic chemical vapor deposition (MOCVD) technology. The GaN film was grown on the 2-inch diameter and (001) orientation sapphire surface. The peak wavelength of the GaN wafer was 460nm. The LED chip process included mesa etching, transparent conductive layer (TCL) deposition and pad deposition. The mesa was defined by ultra-violet lithography for a 300 × 300 μm^2 area and etched by inductively coupled plasma (ICP) in the depth of 800 nm. After mesa area etching, the TCL indium-tin oxide (ITO) with 180 nm thickness was deposited onto the top of mesa area for current spreading, and then the Cr/Au with thickness 50/200 nm was deposited by E-gun evaporator onto both p- and n-GaN surface for electrode pad.

The surface texture imprinting onto TCL process flow chart is shown in the Figs. 1. In the Fig. 1(a), the spin on glass (SOG) was spun onto LED chip surface in 3000 rpm and then a soft bake 120 °C, 90 seconds for solution evaporation. The thickness of as-spinning SOG was about 500 nm. In Fig. 1(b), the LED chip was sent into imprinting equipment. The imprinting pressure was 1100 Newton and the chamber temperature was maintained at 200 °C for 3 minutes. After the sample cooling to the room temperature, the mold and chip were separated as shown in Fig. 1(c), and then the LED chip was etched for exposing the pad area as shown in Fig. 1(d). After pad exposure the LED chip was wire bonding packaged.

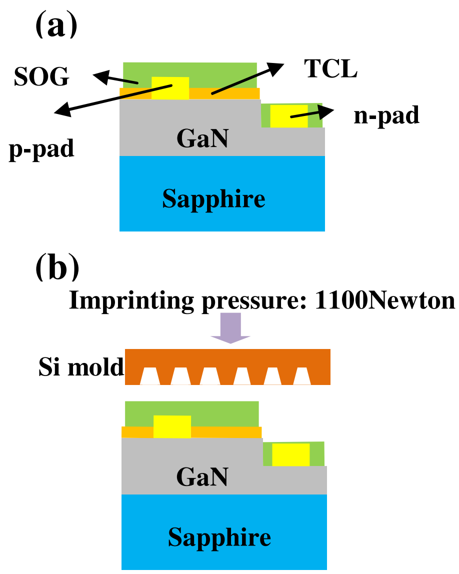

Fig. 1. The flow chart of imprinting process (a) The SOG layer spun onto the surface of LED chip (b) The imprinting process in chamber (c) The LED chip just separated from Si mold (d) The LED chip after removing SOG recover the pad area. (not to scale)

The optical microscope (OM) and atomic force microscopy (AFM) pictures of imprinted SOG structure are shown in Figs. 2(a) and (b) for the top view of OM picture and the tilt view of AFM picture. The dimension scheme is shown in the Fig. 2(c). The side wall angle of this cylinder structure was 17°, the height was 260 nm, the top width was 2.8 µm and the bottom width was 4.5 µm.

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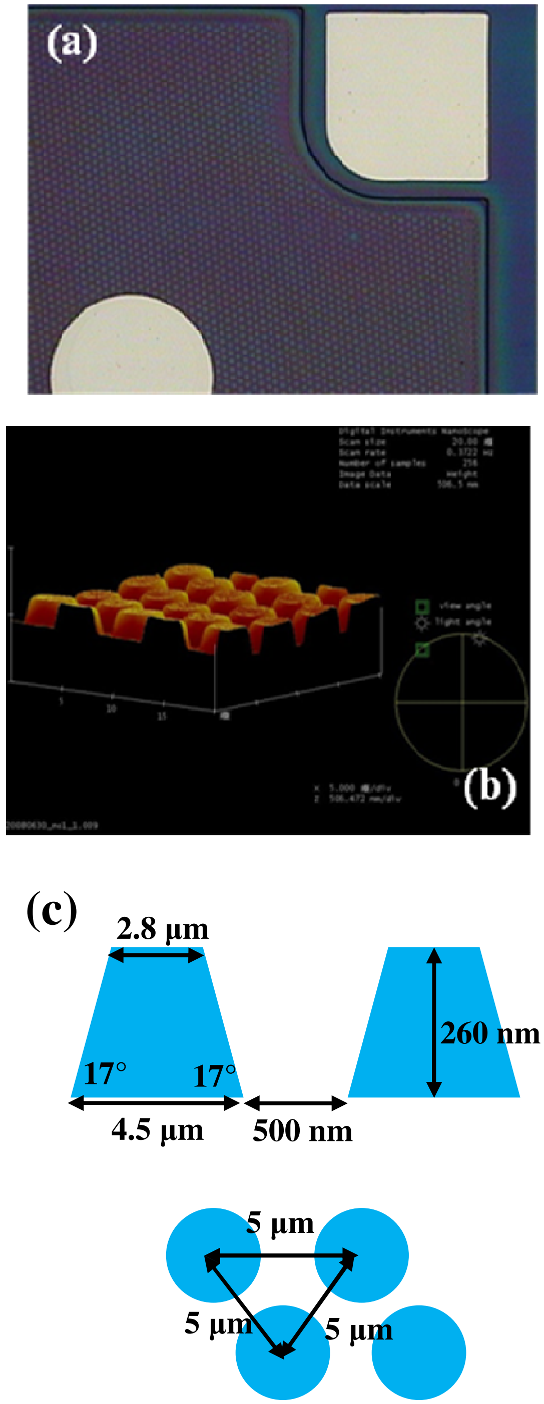

Fig. 2. The pictures and dimension scheme of imprinting structure (a) the OM top view of imprinting structure (b) the AFM tilt view of imprinting structure (c) the imprinting structure geometric parameters (not to scale)

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3. Measurements

The electric performances of imprinting and planar LED chip are shown in Figs. 3. The Fig. 3(a) shows the applied voltage versus current (I-V) curve measured by the probe stage. The forward voltage of imprinting LED was 3.4V at 20mA current similar to that of planar LED. This result explained that the electric property of LED chip was not affected by the imprinting process. Even an additional press and anneal processes were experienced, the forward voltage can still keep at 3.4V. Figure 3(b) shows the injection current versus output power (L-I) curve measured by an integral sphere. Figure 3(b) indicates that the output power enhancement was 40% for the imprinting LED, compared to that of planar LED at an input current of 20mA. The enhancement of output power was resulted from the refractive index difference reduction and surface roughness. The index difference was reduced by the insertion of an SOG surface texture layer because the refractive index of SOG was 1.5. Thus, the light trapping resulted from Fresnel loss was reduced. The other reason for the light output enhancement was due to the TIR was suppressed by the imprinted surface texture. Figure 3(c) shows the intensity distribution results of both planar and imprinting LED chips. The planar LED had an intensity distribution of a Lambertian-like pattern due to the surface light source [12]. The half angle of far-field pattern of the planar LED was ± 60°. The standard deviation (STD) of intensity distribution inside the half angle of planar LED was about 0.1. Compared to the result of planar LED, the intensity distribution of imprinting LED showed a large full width at half-maximum radiation angle of 150°. A uniform intensity distribution across 110° is shown in Fig. 3(c). Inside this uniform distribution angle the intensity was larger than 90% to the peak intensity and the STD of intensity distribution was only 0.018. In other words, the imprinting LED produced a non-Lambertian light source by insertion the imprinting layer. The random scattering inside this imprinting layer provided a uniform intensity distribution across a wide angle range. This expanded light source was adopted for the further secondary optics design.

3. Optical design and simulation

The imprinting LED far-field pattern was used as the light source file and then imported into ASAP optical software for the design of street lamp secondary optical element. The characteristics of an ideal street lamp included the elimination of glare effect, a sufficient illumination and a uniform intensity distribution on the target area [11]. The quantified specifications of street lamp are listed in Table 1.

Table 1. The street lamp design specifications

Secondary optics design for Street lamp item	Condition
Center intensity ratio	25~45% of peak intensity
Peak intensity angle	60°~70°
Glare effect control	below 20% of peak intensity at 80°
50% intensity across angle	65°~75°

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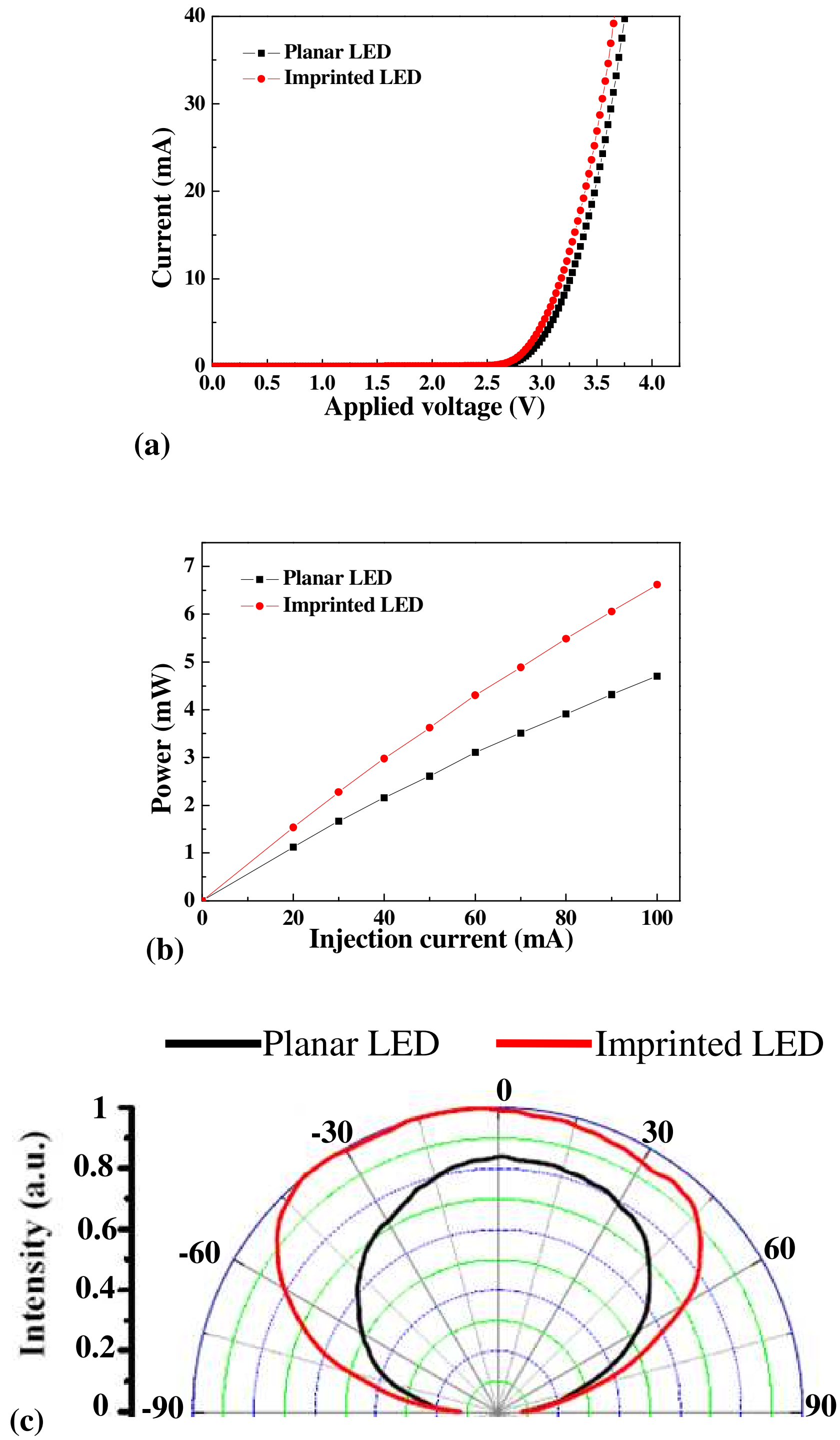

Fig. 3. The electric performance of imprinting and planar LED (a) The applied voltage versus current curve (b) The injection current versus luminous curve (c) The intensity distributions of planar and imprinting LED

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The radiation pattern of an ideal street lamp included several characteristics such as center intensity, peak intensity and glare effect control. The peak intensity at best located at the angle of 60° to 70° while the center intensity is half value of peak intensity. The center intensity crosses an angle range of 65° to 75° symmetric to the normal axis of street lamp. The difference between center and peak intensity provided uniform illumination intensity onto the target area. The glare effect can be eliminated by the cut-off emitting light with emitting angle larger than 80°.

We attempted to obtain those specifications listed at Table 1 by the imprinted LED far-field pattern and a designed secondary optics element. Because, the flat far-flied pattern produced by imprinted structure constructed a superior circumstance for the center intensity ratio, and constant intensity at the distributive angles from 0 to 40°. Finally, the glare effect elimination, the peak intensity and the 50% intensity angle were achieved by the designed secondary optics element. In order to prevent the flux loss during interface transmission, a reflective surface for once reflection was considered in this paper.

For the design of reflector, the Bezier curve was used to shape the reflector side wall profile. We used the star point, control point, end point and weight factor to control the Bezier curve and construct the Bezier curve to be a simple reflector. Consequently, the all specification of street lamp were taken as the merit functions that can be the optimization conditions of Bezier curve while constructing the structure of reflector [9,13].

Figures 4 demonstrate the structure of designed optical element and the far-field pattern with imprinted LED light source inside this secondary optics element. Figure 4(a) shows the geometric structure side view of the reflector with diameter 1.05 mm and height 0.3 mm. The LED chip was assembled in the center of this reflector. Figure 4(b) shows the oblique view of the reflector. The LED chip was mounted at the center of reflector. Compared to the OSRAM commercial products [14], the reflective surface designed in this paper have a compact size and lower cost because this reflective surface can be fabricated by simple metal manufacture. In OSRAM's design an epoxy lens without anti-reflection coating was used so that the flux loss during light penetrated the interface must take into considering. Figure 4(c) shows the far-field patterns of the designed street lamp and the OSRAM commercial product. Both the designed street lamp and OSRAM commercial product possessed the intensity peaks at ± 75°. Those emitting peaks of both street lamp ensured a gradual decay of illumination from central to the edge was prevented. The designed street lamp also had a flatter intensity distribution between ± 70° than OSRAM commercial product. This flat intensity distribution provided a uniform illumination effect. Moreover, the designed street lamp integrated an imprinted LED, thus more photons can be extracted for lighting. The designed street lamp performed a rapidly decay of light with emission angle larger than 80°. This phenomenon prevented the designed street lamp from the glare effect. However, OSRAM commercial product cannot filter the light with high emitting angle completely so that there was still somewhat glare effect. Figure 5(a) presents the LED lighting unit array; the lighting modules were assembled in 6 × 8 array to simulate a real street lamp illumination. The intensity distribution on the illumination area is presented on Fig. 5(b). The simulation condition was that the street lamp was located at 5m above the illuminate area and the illuminate area was 10 × 10m^2. The intensity was concentrate at the center area about 2.5 × 2.5m^2, and then the intensity distribution kept constant in an outer area. In substance the intensity distribution on the illuminated area was uniform.

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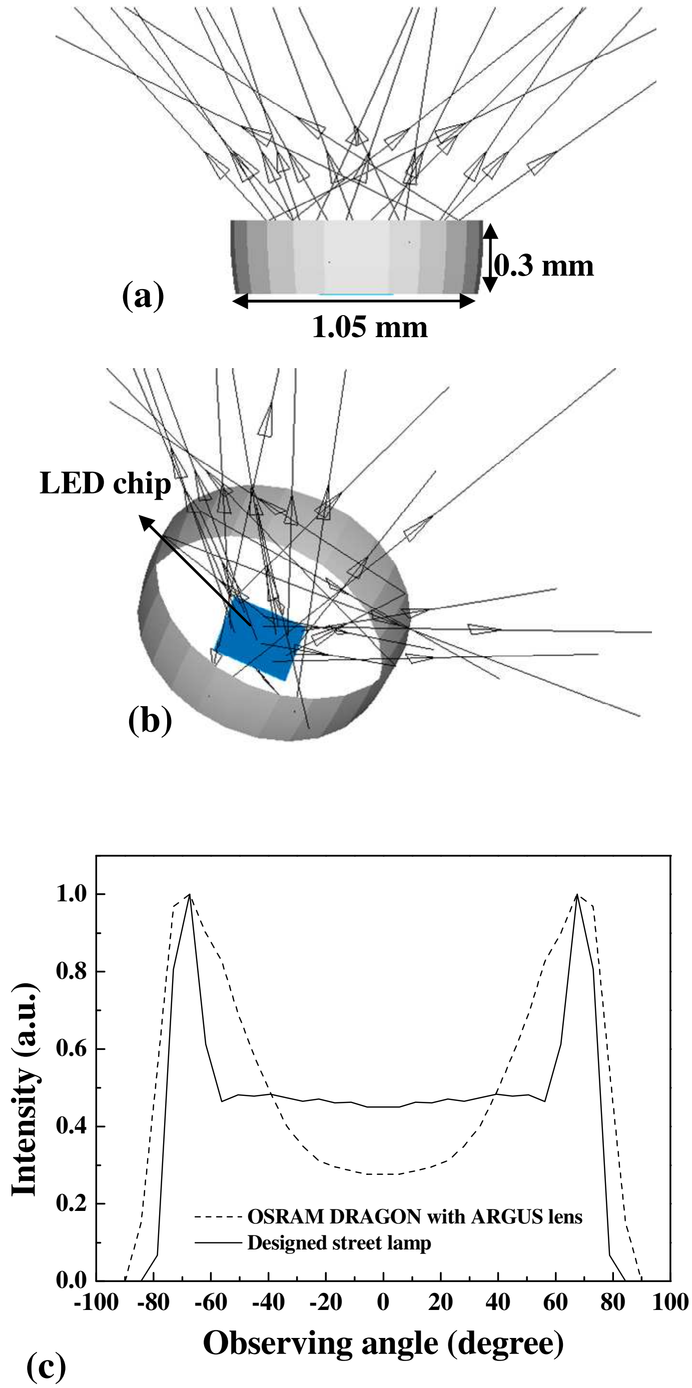
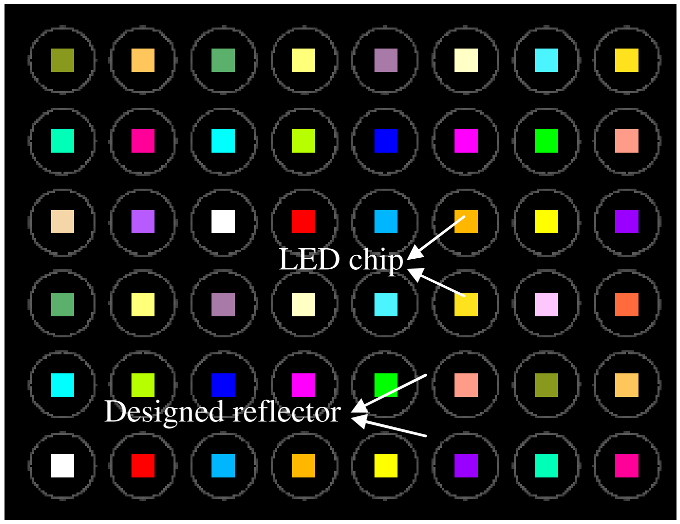
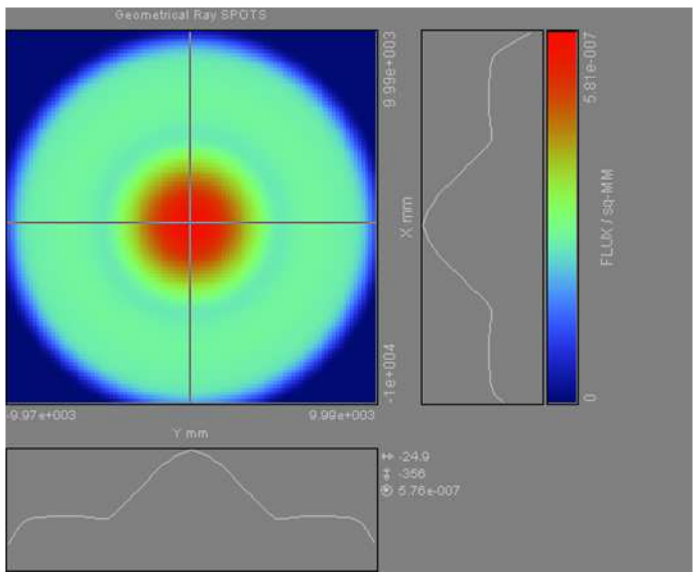


Fig. 4. The practical application of the imprinting LED chip (a) the side view of designed reflector for street lamp (b) The tilt view of designed reflector for street lamp (c) The far-field pattern of designed street lamp and OSRAM commercial product



(a)



(b)

Fig. 5. The structure and intensity distribution of imprinting LED street lamp(a) The street lamp composed of 6 × 8 LED light source array (b) The intensity distribution on the illuminated surface

Finally, we summary the detail comparisons for our design to Osram Dragon with ARGUS lens as shown in Table 2. Compared to conditions listed in Table. 1, the emitting light with emitting angle larger than 80° was almost cut-off in the designed reflector. The OSRAM street lamp left somewhat light that existed beyond the 80° cut-off angle. The glare effect was suppressed in the designed street lamp. Moreover, the designed street lamp possessed a more uniform intensity and a higher intensity in the center area than the commercial products. After the price query to the lamp manufacturer [15] in Taiwan, the reflector designed by our group was cost effective, and impact volume than the commercial street lamp. For the sake of real fabrication, the tolerance was also introduced by simulation. The tolerance analyses was divided into two parts the assembling and the tilt tolerance. The

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assembling tolerance analysis was completed with a constant tilt condition while the tilt tolerance completed with a constant assembling condition. The assembling tolerance was 0.7 for both designed lamp and the commercial product. This assembling tolerance value was accepted by manufacture factory. The tilt tolerance of the designed street lamp was 2.5 fold of the commercial product.

Table 2. Specification comparisons between with designed street lamp and Golden Dragon with ARGUS lens

Specification	Designed street lamp	Golden Dragon
Intensity at 80° for glare effect	6% relative to maximum intensity (little glare effect)	46% relative to maximum intensity (unavoidable glare effect)
Intensity at 0°~20° for directional illumination	45% relative to maximum intensity owing to micro structure	28% relative to maximum intensity
Optical structure	Simple reflector (reflective type)	Complex lens (refractive type)
Cost of element under 10000 units/month [15]	$0.2	$0.7
Tooling cost [15]	$1200	$2400
Total high of second optics element	0.3 mm	1.5 mm
Assembling tolerance (X,Y direction)	0.07 mm	0.07mm
Title tolerance (X. Y axis rotation)	0.5 degree	0.2 degree

5. Conclusion

We applied the cost effective, high throughput, and high yield imprinting technique onto the LED chip. The imprinting layer not only increased the light extraction efficiency of LED chip, 40%, but also modulated the intensity distribution in the chip level. A flat intensity distribution was achieved by this imprinting layer. Furthermore, a corresponding reflective optical element was designed for the street lamp application. The characteristics of this reflective optical element include impact size, inexpensive, acceptable manufacture tolerance and low optical loss. After integration of the imprinting LED and the designed optical element, a street lamp module with higher illumination intensity, uniform intensity distribution and glare effect elimination was obtained.

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