

# Improvement of emission uniformity by using micro-cone patterned PDMS film

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**Abstract:** Micro-patterned PDMS film was fabricated and combined with LED chip on board (COB) package to improve the emission uniformity of LED chip. The micro scale patterned sapphire substrate (PSS) was used as a mold to fabricate micro-cone patterned PDMS (MC-PDMS) film. A strong scattering effect from this MC-PDMS film can be verified by the high haze ratio and the Bi-directional Transmission effect. The angle dependent color temperature measurement system was used to measure the  $\Delta$ CCT of COB with and without MC-PDMS. The measurement results indicate that the  $\Delta$ CCT was reduced from 1025K to 428K. This improvement can effectively eliminate the yellow ring effect of LED chip. This technology can be thus considered as a cost-effective way for the next generation of light source packages.

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## 1. Introduction

As the global warming is looming the future of human beings, eco-friendly technology is becoming an important issue. Therefore, highly efficient light emitting diode (LED) has been one of the key green-technology to replace the inefficient incandescent light bulbs [1–3]. For various lighting applications, high performance white LEDs (WLEDs) have proven their values in terms of long lifetime and high flux of illumination. However, there are still some issues which make the WLEDs imperfect in the solid state lighting application, such as the yellow ring effect [3]. The reason leading to yellow ring effect could be attributed to the lambertian emission pattern of blue LED chip and the omni-directional emission of yellow phosphor. These features result in higher blue light output power at the normal direction than that at the oblique angle. Therefore, the color temperature will be anisotropic, which could cause the yellow ring effect in the far field emission pattern. To solve this problem, previous studies have proposed several methods to deal with the yellow ring effect for different package form, such as, using material with strong scattering capability or different lens design [4–6].

The COB package has some advantages in solid state lighting application, such as high intensity, good thermal performance, better lifetime, high stability, and high reliability [7]. Previous research mostly focused on external packaging solution, while the COB is left unexplored. Besides, it is expensive to design different types of lens by using different molds and the outcome is still not good enough to eliminate the yellow ring effect [8].

In this study, we combined MC-PDMS film with COB package to fabricate WLEDs with highly uniform color temperature. This approach provides excellent scattering capability and improves the blue light emission of COB at large angle. The COB with uniform CCT could be

achieved so the yellow ring effect was reduced. Furthermore, the cost of this method is not expensive as compared with general mold fabrication and can be used in mass production.

## 2. Experiments

Today, the patterned sapphire substrate (PSS) is widely used in LED industry to enhance the light extraction efficiency (LEE) by high scattering ability [9,10] and improved internal quantum efficiency (IQE) due to the epitaxial lateral overgrowth [11–14]. In general, the PSS can be fabricated by dry etching [14], wet etching [9–11], or solid state conversion process [12,13]. From previous studies, the micro-cones structure could be fabricated by nano-scale [15–18]. In this work, patterned sapphire substrate is used as an imprinting mold to fabricate the micro-cone patterned polydimethylsiloxane (MC-PDMS) film in a simple way to be competitive for commercialization. The diameter and interval of the cone shaped patterns on PSS used in this research are both about  $2.5\mu\text{m}$ , and the height of the cone shaped patterned is about  $1.3\mu\text{m}$  as shown in Fig. 1(a). To produce such MC-PDMS film, the following steps need to be completed. Firstly, the PSS is attached on the 3.5 inches Petri dish. Then the PDMS is spread and spun at 700 rounds per minute for 60 seconds and then it was baked at  $70^\circ\text{C}$  to solidify the film. The thickness of PDMS film measured by scanning electron microscope (SEM) was approximately  $80\mu\text{m}$ . After pulling up the PDMS film, the PDMS was cut to fit the shape of COB packages. Figure 1(a) and 1(b) shows the SEM image of PSS mold and MC-PDMS, respectively. The patterns have been reversely transferred from PSS to PDMS and formed the cone shape structure.

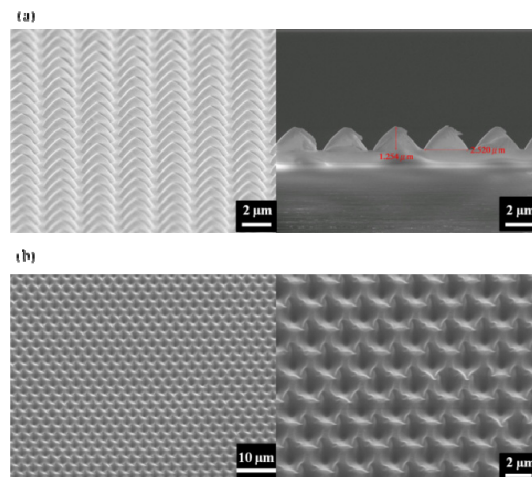


Fig.1. SEM image of (a) PSS mold and (b)MC-PDMS film.

Figure 2(a) illustrates the fabrication flow of MC-PDMS chip on board sample. A blue LED chip (450nm emission peak wavelength) with the size of 45 mils square was bonded on the top of the chip on board package. The radiant flux of COB with four bare blue LEDs was 1.735 W at 350 mA. The  $\text{Y}_3\text{Al}_5\text{O}_{12}$  (YAG) phosphor used in this experiment has an emission peak at 560 nm and the particle size is about  $12\mu\text{m}$ . To form a phosphor-suspension, the phosphor powders was mixed in to the transparent silicone. The phosphor-suspension was then dispensed to fill up the package and then followed by baking at  $150^\circ\text{C}$  for 2 hours to solidify the phosphor glue. Finally, the prepared MC-PDMS film was covered on the top of the COB package, and the MC-PDMS chip on board sample is ready for testing. The patterned up MC-PDMS, patterned down MC-PDMS COB samples and the COB sample without PDMS have been prepared for comparison as shown in Fig. 2(b).

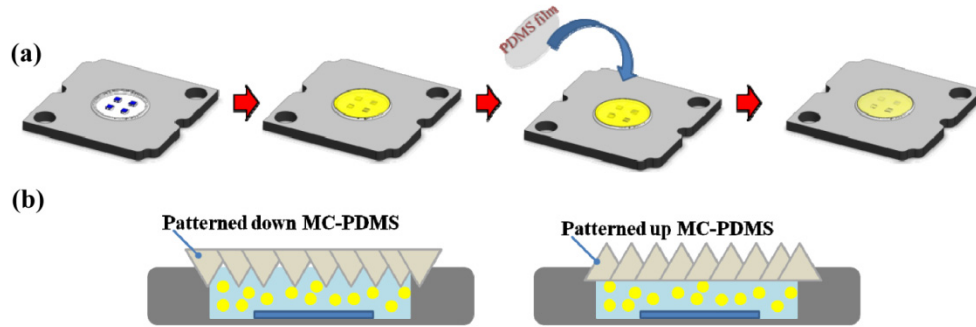


Fig. 2. (a) Fabrication flow of MC-PDMS chip on board sample and (b) Illustrations of patterned up and patterned down MC-PDMS samples.

### 3. Results and discussion

In general, the angular correlated color temperature (CCT) uniformity could be evaluated by  $\Delta\text{CCT}$  which is defined by the maximum CCT minus minimum CCT in the range of  $-70^\circ\sim 70^\circ$ . Figure 3 shows the angular-dependent CCT for the three cases mentioned previously, COB without PDMS film, COB with patterned up MC-PDMS and patterned down MC-PDMS. It can be seen that the color temperature of COB sample with patterned down MC-PDMS film was more uniform than others samples. As shown in Fig. 3(b), the  $\Delta\text{CCT}$  of patterned down MC-PDMS samples improve from the 1025 K to 428 K as compared with reference sample. The reason for COB package suffering from the large  $\Delta\text{CCT}$  issue could be attributed to the different emission light patterns of LED chips and yellow phosphor, resulting in the lower blue light intensity at the large angles. This phenomenon leads to the color temperature of LED near normal direction is higher than the oblique direction. For the case of MC-PDMS covering on the top of COB, the better  $\Delta\text{CCT}$  was achieved due to the stronger scattering at large angle brought by patterned PDMS and a better mixed blue/yellow light can be produced.

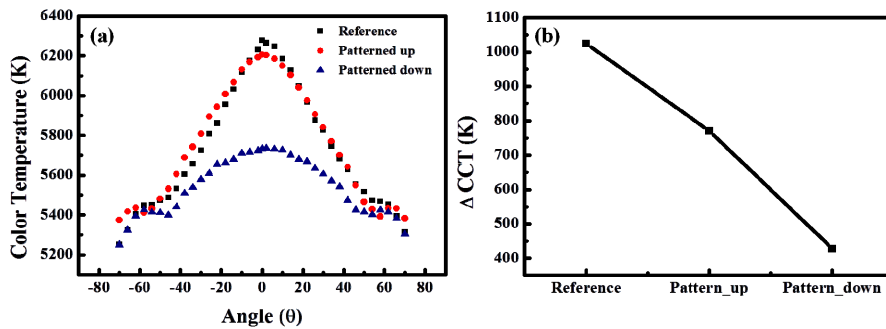


Fig. 3. (a) The angular-dependent CCT and (b)  $\Delta\text{CCT}$  of COB without PDMS (reference), with patterned up MC-PDMS and the patterned down MC-PDMS covering on the top of COB package.

To further discuss the emission light color temperature of these three samples in different angles, the angular-dependent intensity ratio of yellow to blue rays ( $I_{\text{yellow}}/I_{\text{blue}}$ ) was measured, as shown in Fig. 4. The blue light of COB with patterned down MC-PDMS film is more uniform than the reference sample. This indicates that the patterned down MC-PDMS film can scatter the blue light from normal direction to large angle. Besides, the MC-PDMS can increase the light path of blue light. Thus, the yellow light was also enhanced slightly.

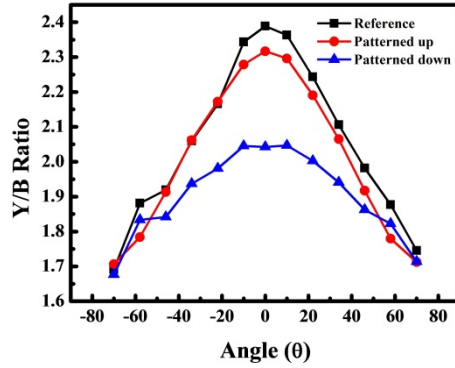


Fig. 4. The yellow/blue light ratio of COB with and without MC-PDMS films on the top of the COB package.

For the LED package, the reason for the CCT non-uniformity usually comes from the anisotropic (or wavelength-dependent) diffraction of the various optical layers in the structure. When there are two or more types of photons (for example, blue and yellow photons), this dispersion in light emission can cause the spatial non-uniformity of the photon distribution and eventually lead to the uneven color rendering in the detected LED emission. This phenomenon is most known the major cause of yellow ring in LED, and such condition is not favorable for high quality solid state lighting. To overcome this, it is conceivable to place an extra layer which can diffuse the photons omni-directionally. To evaluate this capability numerically, a haze value is frequently used. It is defined by the ratio of non-specular photons over the all diffracted photons. The higher the value is, the better light scatter it becomes, and the haze percentage was calculated by using the following equation [5,19]:

$$\text{Haze (\%)} = T_{\text{diffraction}} / T_{\text{total}} \times 100\% \quad (1)$$

where  $T_{\text{diffraction}}$  is the diffractive transmittance (total transmittance – specular diffraction) and  $T_{\text{total}}$  is the total transmittance. By the definition of Eq. (1), the wavelength-dependent haze of these three samples are presented, as shown in Fig. 5(a). Figure 5(b) shows the sketches of patterned up and patterned down samples in haze measurement. It can be clearly seen that the MC-PDMS film scatters more 50% of the lights from 300 to 800nm while the flat PDMS film is almost zero. This indicates that the MC-PDMS film has higher scattering ability of normal incident light and thus can be a very efficient diffuser.

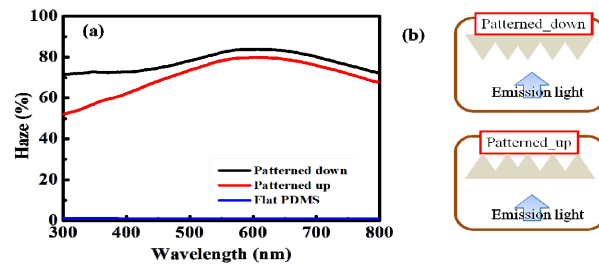


Fig. 5. (a) The measured wavelength-dependent haze intensity of patterned up MC-PDMS, patterned down MC-PDMS and the flat PDMS. (b) the sketches of patterned up and patterned down.

However, the Haze measurement only measures the integrated intensity at non-zero order angles. To further discuss the angle-dependent scattering effect of different incident angle of blue light, the Bi-directional Transmission Distribution Functions (BTDF) measurement was used. The BTDF measurement could figure out the diffraction distribution with different

incident angle [20,21], in this work, the BTDF measurement have been used to imitate the LED light source incident to the MC-PDMS film. Generally, the intensity of GaN based LED in different angles shows as a lambertian light distribution [22], and it would follow the below equation [8].

$$I(\theta) = I_0 \times \cos\theta \quad (2)$$

where  $I_0$  is the intensity of the emission light emitting in the normal vector ( $0^\circ$ ) related to the sample,  $\theta$  is the angle between the emission light and normal direction, and  $I(\theta)$  is the intensity of the emission light in different angles  $\theta$ . Considering the actual LED chips emission light performs as a lambertian pattern, the BTDF measurement can simulate the actual condition in the COB package. Figure 6(a) shows the angular dependent back scattering intensity under a 460nm incident light source. The remarkable interference effect reflects the patterned PDMS film is similar to the multi-slit diffraction [23]. Moreover, this diffraction phenomenon could also been observed under 550nm incident light, but the peak interval changes from  $10^\circ$  to  $12^\circ$ . The following equation shows the relationship between angles and wavelength of far-field diffraction.

$$\tan\theta \approx \frac{\lambda}{b} \quad (3)$$

Where  $\theta$  is the angle interval between two peaks,  $\lambda$  is the wavelength of the incident light and  $b$  is the spacing of two slits. From the above equation,  $b$  was calculated as  $2.6 \mu\text{m}$ . This value is close to the spacing between two reverse cone shapes which is about  $2.5 \mu\text{m}$  as shown by SEM, and this result also indicates the good transfer of the original patterned sapphire. Figure 6(b) shows the sum of the intensity and the fitting of the BTDF measurement in polar coordinates (from  $0^\circ$  to  $50^\circ$ ) and the scattering effect of MC-PDMS under lambertian light source could be observed. The fitting procedure was carried out by the built-in fast Fourier Transform algorithm of Origin®. Because our BTDF data did not populate densely enough to smooth the sum of intensity curve, the final summation still bears the aforementioned multi-slit diffraction pattern, and the fitting is not optimal. Nevertheless, this result shows that the normal incident light could be scatter to larger angle. And also explained why COB package with patterned down MC-PDMS has such outstanding  $\Delta\text{CCT}$  performance.

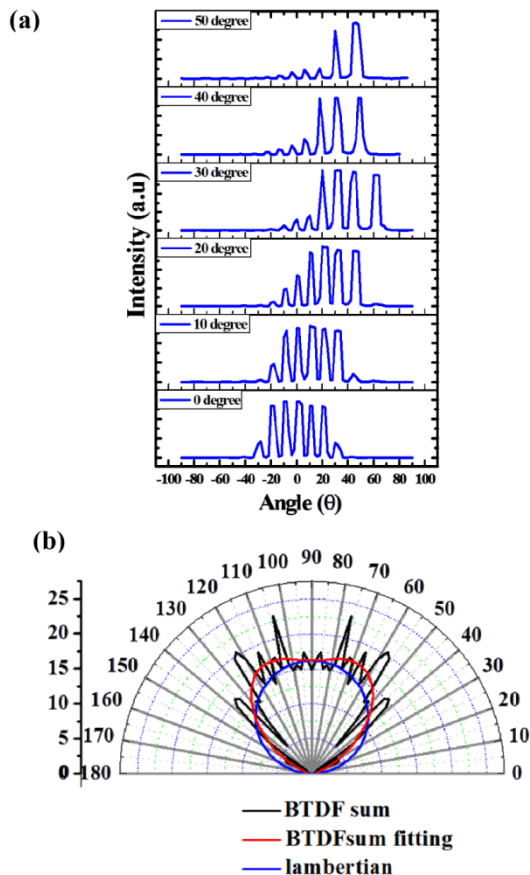


Fig. 6. (a) BTDF measurement from 0 to 50°. (b) Sum of the BTDF measurement in polar coordinate.

#### 4. Conclusion

In conclusion, the micro-patterned PDMS film was applied on the top of chip on board package by using a simple, low cost, hand-made process. From the angular correlated color temperature uniformity measurement, the  $\Delta$ CCT of COB covered by patterned down MC-PDMS film is improved from 1025K to 428K, as compared to standard COB package. The haze measurement shows the great scattering ability of patterned down MC-PDMS film. The BTDF measurement of different incident angles of 460 nm Lambertian light source further proved why PDMS film can improve the  $\Delta$ CCT. Finally, this work provides a simple and cost-effective method to greatly improve the  $\Delta$ CCT, whose magnitude is crucial to determine the light quality of a LED chip on board package. Based on this study, we believe this technology is promising for the future LED packaging development.

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