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Cylindrical Tuber Encapsulant Layer Realization by Patterned Surface for Chip-on-Board Light-Emitting Diodes Packaging

In this study, we realized a cylindrical tuber silicone layer for improving the light efficiency of chip-on-board light-emitting diodes (COB-LEDs) by fabricating patterned LED substrate with both silicone-wetting and silicone-repellency surfaces. To realize silicone-repellency surface, low surface energy modified nanosilica particles were prepared and deposited on the LED substrate to form porous hierarchical structure. Light efficiency enhancement for blue light COB-LEDs with pure cylindrical tuber silicone layer and white light COB-LEDs with phosphor–silicone composite layer was studied. The results show that for blue light COB-LEDs with pure cylindrical tuber silicone layer, the light efficiency increases with the contact angle and a highest light efficiency enhancement of 62.6% was achieved at 90 deg when compared to the flat silicone layer. For white light COB-LEDs at correlated color temperature (CCT) of ~5500 K, the cylindrical tuber silicone layer enhances the light efficiency by 13.6% when compared to the conventional flat phosphor layer. [DOI: 10.1115/1.4042982]

Keywords: cylindrical tuber encapsulant layer, COB-LEDs, light efficiency

1 Introduction

Nowadays, white light-emitting diodes (wLEDs) have been widely applied in our daily life [1,2]. Since bare LED chips cannot generate white light directly currently, to produce white light, it usually integrate multicolor LED chips or combine LED chip with phosphors, and the latter method is more widely used due to its simplicity, low cost, high light efficiency, and high reliability [1–5].

Phosphor coating is the key process for combining the LED chip with phosphors. In the phosphor coating process, the phosphors are mixed with the silicone and then coated onto the LED chip to form a stable phosphor layer. The phosphor layer geometry decides the optical performance of wLEDs such as light efficiency and angular color uniformity [6–8]. However, subject to the low surface tension (about 30 mN/m) of phosphor gel, the phosphor gel tends to wet all the substrate surface with a very small contact angle less than 30 deg [9,10], resulting in significant light efficiency droop due to total internal reflection (TIR) [11]. Such situation becomes more serious for chip-on-board LEDs (COB-LEDs) whose size ranging from several centimeters to dozens of centimeters. As shown in Fig. 1, the phosphor layer of COB-LEDs presents flat geometry due to the large coating area. The flat phosphor layer geometry suffers from serious TIR with a critical angle θ_c of 38–45 deg due to the refractive index difference between the phosphor gel (1.4–1.7) and ail [12].

To diminish the TIR effect of the COB-wLEDs, several methods were proposed including patterned leadframe substrate [12], scattering layer [13], roughened LED chip [14], and roughened encapsulant layer [15,16]. The principle of these methods is to redirect the light that reflected from the encapsulant–air interface to the angle within the critical TIR angle. Another feasible method is to guide the light emit out directly through dome-shape encapsulant (silicone) layer [17,18]. However, dome-shape silicone layer realization is a great challenge in LED packaging due to the low surface tension of the silicone [9,10]. In our previous study, we realized a hemispherical encapsulant layer by fabricating patterned LED substrate with both silicone-wetting and silicone-repellency surfaces [18]. The wetting principle of the patterned LED substrate is shown as Fig. 2. Silicone on the patterned surface is restrained within the silicone-wetting surface, and its contact angle can be adapted to any value between θ_1 and θ_2. θ_1 is the contact angle between the silicone and the silicone-wetting surface, and θ_2 is the contact angle between the silicone and silicone-repellency surface. Since the silicone presents wetting property the LED substrate, so the main challenge is to realize silicone-repellency surface. To solve this issue, we modified the LED substrate by depositing a thin layer of 1H,1H,2H,2H-perfluorooctyltrichlorosilane modified nanosilica (FOTS-NS) particles with an average diameter of 70 nm. The self-assembly of FOTS-NS forms hierarchical surface with nanoscale and microscale structures. Combining with the low surface energy

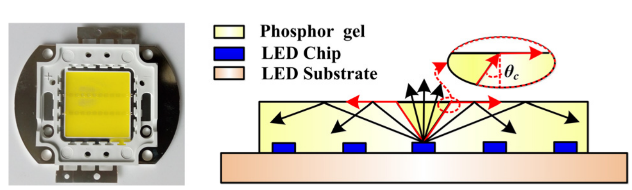

Fig. 1 COB-LED module with conventional flat phosphor layer

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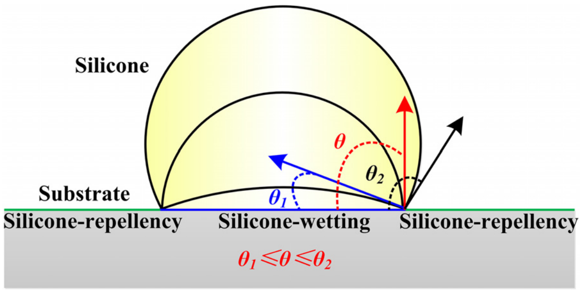


Fig. 2 Wetting principle of patterned substrate

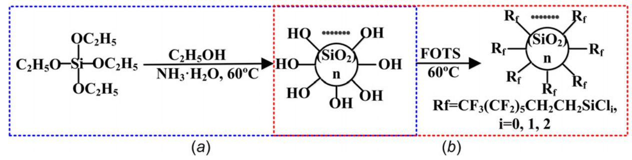


Fig. 4 Synthesis process of FOTS-NS particles: (*a*) pristine NS particles preparation and (*b*) NS particles modification

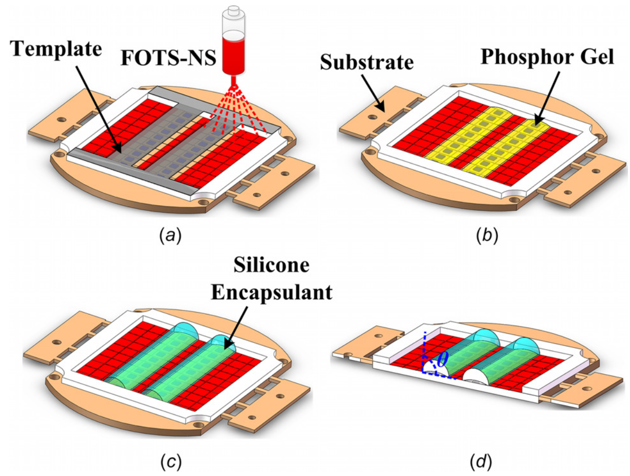


Fig. 5 Fabrication process of the patterned surfaces and realization of the cylindrical tuber encapsulant layer

functional groups (−CF2, and −CF3) of the FOTS-NS, the silicone-repellency surface can be realized and the contact angle between the silicone and the surface can be large than 150 deg depending on the particle deposition density of the FOTS-NS.

The previous study is applied to COB-LEDs with sparse distribution LED chip array. In this study, we further applied the patterned LED substrate to realize cylindrical tuber encapsulant layer for COB-LEDs with LED chip in series. The preparation of FOTS-NS particles and the fabrication of the patterned substrate were introduced. The cylindrical tuber encapsulant layer fabrication and its light efficiency enhancement for blue light and white light COB-LEDs were studied.

2 Methodology

When a droplet contacts with a flat solid surface as shown in Fig. 3(*a*), its intrinsic contact angle θ can be calculated by the Young's equation [19]

$$\cos\theta = \frac{\gamma_{SG} - \gamma_{SL}}{\gamma_{LG}} \tag{1}$$

where γ_{SG}, γ_{SL}, and γ_{LG} represent the solid surface energy, the solid–liquid interfacial tension, and the liquid surface tension, respectively.

From the Young's equation, it can be seen that the contact angle decreases with the liquid surface tension. Therefore, the low surface tension liquid such as silicone always presents extremely small θ on solid surface. A feasible method to enlarge θ is to modify the surface with low surface energy materials. However, the enhancement of this method is limited since the minimum surface energy of available materials is about 10 mN/m. Hierarchically structured surfaces possessing more than one scale roughness is proposed to be an effective way to further enlarge the apparent contact angle θ^* between liquid droplet and solid substrate by supporting the droplet in Cassie–Baxter state [20] as shown in Fig. 3(*a*). The θ^* can be calculated as

$$\cos\theta^* = f_{SL}\cos\theta - f_{LV} \tag{2}$$

where $f_{SL} + f_{LV} = 1$, f_{SL} and f_{LV} represent the area fraction of the solid–liquid interface and the liquid–vapor interface.

3 Experiments

Figure 4 shows the synthesis process of FOTS-NS particles. First, the pristine NS particles were prepared according to the Stöber method [21]. Second, the pristine NS particles were modified with the FOTS. The resultant FOTS-NS particles were cleaned through four cycles of centrifugation/redispersion in acetone to remove the residual FOTS. Finally, the FOTS-NS particles were dispersed in ethanol for surface coating.

Figure 5 shows the fabrication process of the patterned surfaces and realization of the cylindrical tuber silicone layer. It contains three steps: (a) covering the LED module with a tailored template and spraying FOTS-NS on the uncovered surface using spray gun (VL-SET; Paasche Airbrush Company, Kenosha, WI) at 300 kPa air pressure; (b) coating the phosphor gel and curing it. The phosphor gel wets the uncoated surface naturally and reaches to a thin layer with a contact angle of ∼20 deg; and (c) coating the silicone on the phosphor gel layer. The silicone stops spreading at the boundary between the uncoated and coated surface and cylindrical tuber silicone layer with a contact angle of ∼90 deg can be achieved by controlling the coating volume. As shown in Fig. 5(*d*), the contact angle of the cylindrical tuber is defined as the contact angle of its short axis cutaway view.

In the experiments, silicone produced by Dow Corning (OE-6550 A/B) and phosphor particles produced by Intematix (YAG-04) were mixed with a mass ratio of 1:0.2 to form the phosphor gel. The silicone (OE-6550 A/B) was also used as the encapsulant

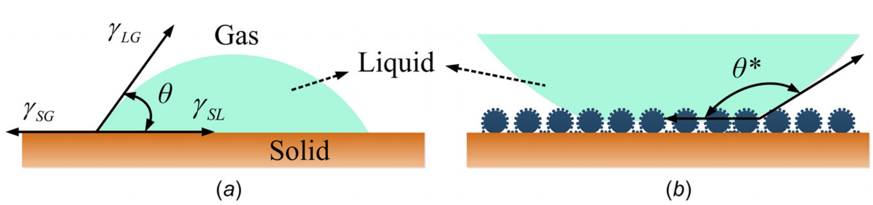
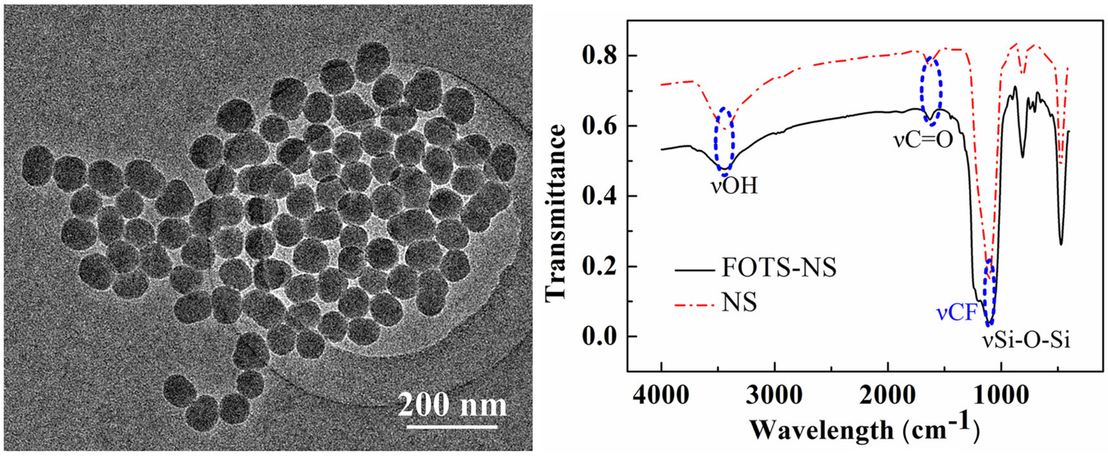


Fig. 3 (*a*) Droplet on flat surface and (*b*) droplet on hierarchically structured surface with Cassie–Baxter wetting state



(*a*) (*b*)

Fig. 6 (*a*) Transmission electron microscope (TEM) image of the FOTS-NS particles and (*b*) FR-IR spectra of the pristine NS particles and the FOTS-NS particles

material. The light efficiency of COB-LEDs were measured with an integrating sphere (ATA-1000; Everfine, Hangzhou, China).

The morphology of the FOTS-NS particles was characterized with transmission electron microscope (TEM, Tecnai-G20, FEI, Hillsboro, OR). The chemical composition of FOTS-NS particles were analyzed by FR-IR spectrometer (VERTEX 70, Bruker, Hamberg, Germany). The morphologies of the FOTS-NS-coated surfaces were observed by scanning electron microscope (JSM-7600F; JEOL, Akishima, Japan).

4 Results and Discussion

Figure 6(*a*) shows the TEM image of the FOTS-NS particles. It shows that the FOTS-NS particles are closed to be a sphere with an average diameter of 70 nm. Figure 6(*b*) shows the FR-IR spectra of the pristine NS particles and the FOTS-NS particles. Compared to the spectra of pristine NS particles, a characteristic absorption bands of C–F (1240 cm^{-1}) is found for the spectra of FOTS-NS particles which illustrated that the pristine NS has reacted with the FOTS.

To further characterize the property of pristine NS and FOTS-NS, they were deposited on clean glass substrates with deposition density of 0.5 g/m^2 by spraying coating and the wetting property of coated glass substrates was characterized. Figure 7 shows the wetting state comparison of water droplets with a volume of 5 μl on the FOTS-NS-coated (left) and pristine NS-coated (right) glass substrates. It shows that FOTS-NS-coated substrate exhibits hydrophobic property, while the pristine NS-coated substrate displays hydrophilic property, which proves that the pristine NS was successfully low surface energy modified.

After then, patterned surfaces were fabricated by depositing the prepared FOTS-NS particles and applied in COB-LEDs packaging. Figure 8 shows the COB-LED module with patterned surface. Twenty LED chips with the size of 1 mm × 1 mm were bonded on the aluminum substrate in two serious at a distance of 6 mm. The size of the two uncoated regions (shown as red-dashed box) is 4 mm × 20 mm and the contact angle of silicone on the aluminum was measured as 20 deg. For the silicone-repellency surface, the FOTS-NS particles deposition density was set as 3 g/m^2 and the scanning electron microscope image shows porous hierarchical structure was generated due to the self-assembly of the particles. Combining with low surface energy of FOTS-NS, a high contact angle of silicone of 135 deg was realized on the coated surface.

We applied the prepared patterned COB-LED module to verify the light efficiency enhancement for blue light COB-LEDs with pure cylindrical tuber silicone layer. In the experiments, cylindrical tuber silicone layers with various contact angles were fabricated. Considering the contact angle of silicone on the silicone-wetting and silicone-repellency surface, the contact angle of the cylindrical tuber silicone layer was set as 30–120 deg. To make comparison, blue COB-LEDs with 1.5 mm thickness flat silicone layer were used. Figure 9(*a*) shows the light efficiency of COB-LEDs with flat and various cylindrical tuber silicone layer under driven current of 100–700 mA. Figure 9(*b*) shows the light efficiency enhancement of cylindrical tuber silicone layer with various contact angle when compared with the flat silicone layer. The results show that the light efficiency increases with the contact angle when the contact angle is smaller than 90 deg while decreases when the contact angle is larger than 90 deg, and a highest light efficiency enhancement of 62.6% was achieved under a contact angle of 90 deg.

Light efficiency enhancement for white light COB-LEDs with both phosphor gel layer and cylindrical tuber silicone layer was also studied. For the white light COB-LEDs packaging, a thin phosphor layer with a contact angle of 20 deg was coated on the uncoated surface first, then the cylindrical tuber silicone layer with a contact angle of 90 deg was coated on the phosphor layer.

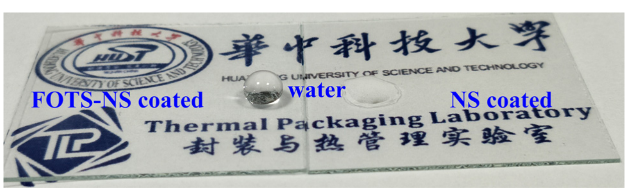


Fig. 7 Water droplets on the FOTS-NS-coated (left) and pristine NS-coated (right) glass substrates

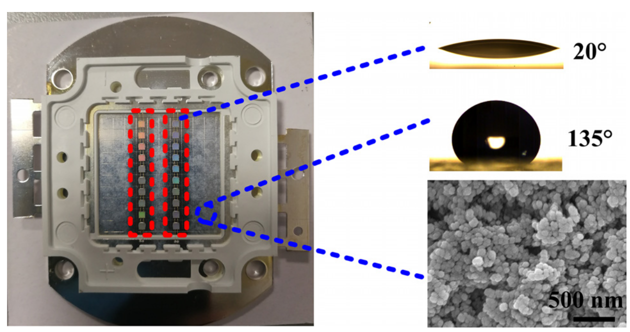


Fig. 8 COB-LED module with patterned surface

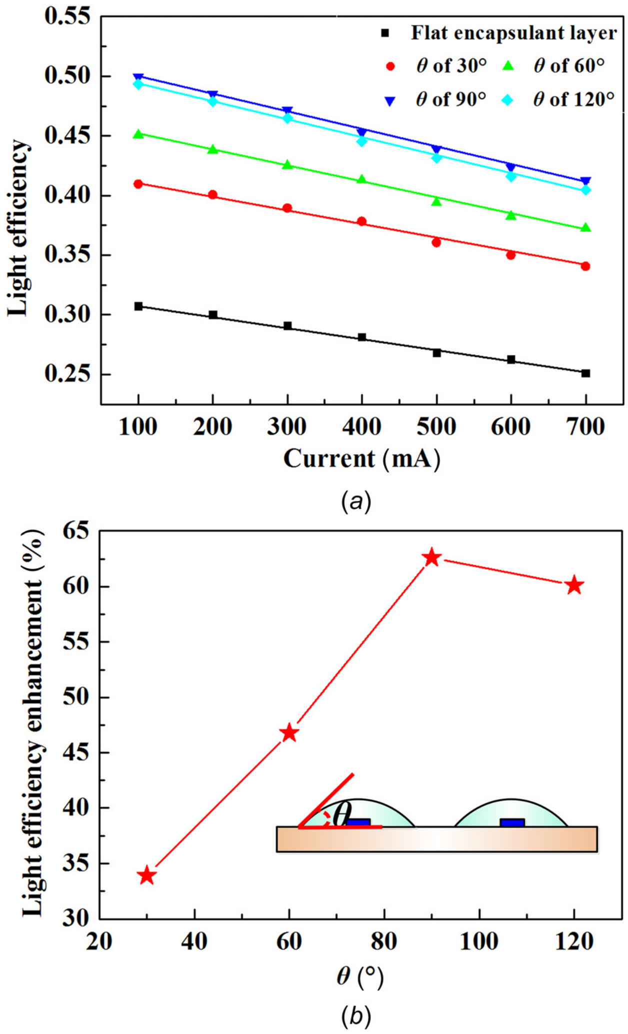


Fig. 9 (*a*) Light efficiency of COB-LEDs with flat and various cylindrical tuber silicone layer and (*b*) light efficiency enhancement of cylindrical tuber silicone layer with various contact angle

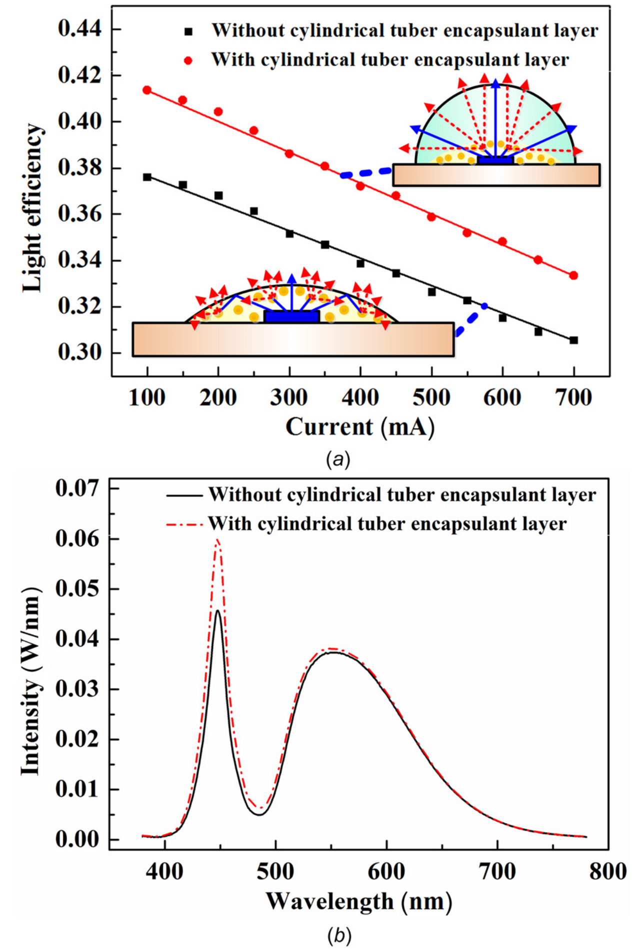


Fig. 10 (*a*) Light efficiency and (*b*) light spectra of the COB-LEDs with and without the cylindrical tuber silicone layer

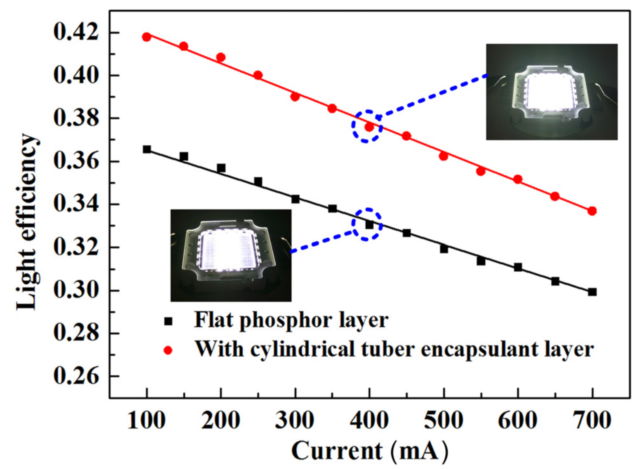


Fig. 11 Light efficiency of COB-LEDs with cylindrical tuber silicone layer and flat phosphor layer

Figure 10 shows the light efficiency and light spectra of the COB-LEDs with and without the cylindrical tuber silicone layer. Figure 10(*a*) indicates that the light efficiency was enhanced by 9.8% after coating the cylindrical tuber silicone layer. Figure 10(*b*) shows that both the blue light intensity and yellow light intensity were enhanced after coating the cylindrical tuber silicone layer. Moreover, the blue light intensity increases more than the yellow light intensity after coating the cylindrical tuber silicone layer. As the insert figures in Fig. 10(*a*) show, for the COB-LEDs without the cylindrical tuber silicone layer, part of the blue light was reflected from the phosphor layer–air interface and converted into yellow light. However, after coating the cylindrical tuber silicone layer, more blue light emit out from the dome-shape silicone–air interface directly which indicates less yellow light was generated. As a result, the blue light intensity increases more than the yellow light. Due to the unequal increasement of the blue and yellow light intensity, a correlated color temperature (CCT) shift from ~5000 K to ~5500 K was observed.

To make comparison, COB-LEDs with conventional flat phosphor layer at CCT of ~5500 K were used. Figure 11 shows the light efficiency comparison of COB-LEDs with conventional flat phosphor layer and cylindrical tuber silicone layer. Compared to the conventional flat phosphor layer, the cylindrical tuber silicone layer enhances the light efficiency by 13.6%.

5 Conclusions

In summary, we proposed a flexible method to realize a cylindrical tuber silicone layer. First, patterned LED substrate with silicone-wetting and silicone-repellency surfaces was prepared by depositing low surface energy modified nanosilica particles; second, coating phosphor gel onto the LED chip; thirdly, coating the encapsulant (silicone OE6550A/B) onto the phosphor gel layer.

The silicone stops spreading at the border of silicone-wetting and silicone-repellency surfaces and its final contact angle can be adjusted to any value between the contact angle of silicone-wetting and silicone-repellency surface, so it is very easy to realize dome-shape silicone layer with a contact angle of ∼90 deg. For COB-LEDs with LED array in series, the final silicone layer geometry is similar to the cylindrical tuber. The results show that compared to the conventional flat encapsulant layer, the proposed encapsulant layer can improve the light efficiency by >60% for pure blue light and 13.6% for white light at CCT of ∼5500 K.

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