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Effect of flip-chip height on the optical performance of conformal white-light-emitting diodes

Zongtao Li,[1,3] Yong Tang,[1] Jiasheng Li,[1,3,*] Xinrui Ding,[2] Caiman Yan,[1] and Binhai Yu[1]

[1]Engineering Research Center of Green Manufacturing for Energy-Saving and New-Energy Technology, South China University of Technology, Guangdong 510640, China
[2]Department of Mechanical Engineering, University of California, Berkeley, California 94720-5800, USA
[3]Foshan Nationstar Optoelectronics Company Ltd., Foshan 528000, China
*Corresponding author: jiasli@foxmail.com

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To improve the optical performance of the conformal white light-emitting diodes (LEDs), previous studies mainly focus on the phosphor structures design by simulations and experiments methods. However, one of the most critical parameters, i.e., the height of chips, is barely studied. In this study, we have experimentally investigated the effect of the flip-chip height on the optical performance of conformal white LEDs. The results show that larger chip height can cause lower radiant power and luminous flux, while wider viewing angles can be achieved. By selecting a suitable chip height of 200 μm, superior color uniformity for white LEDs can be obtained with only 168 K correlated color temperature (ΔCCT). This study can provide a new perspective to improve the color uniformity without changing the phosphor structures or using special scattering elements; moreover, it can facilitate the selection of a proper chip height, considering different illumination requirements. Further investigations on the chip height considering packaging structures are still necessary to improve the luminous flux and the color uniformity simultaneously.

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Light-emitting diodes (LEDs) are regarded as one of the most promising solid-state light sources, owing to their long life and high efficiency [1]. It is a universal strategy to obtain white LEDs by using blue chips to excite phosphor-converted elements (PCEs), which generally consist of a phosphor and silicone matrix. The package structures are essential for the optical performance of white LEDs [2], especially the conformal structures (PCE directly attached to the chip surface) with advantages of better heat dispersion and color consistency [3]. Significant efforts have been paid to design the conformal PCEs in order to further improve the light extraction and color uniformity for white LEDs. Sommer *et al.* observed that the optimization of particle size [4] and height–width relations [5] of conformal PCEs result in high color uniformity. Alongside these studies, Liu *et al.* further indicated that the phosphor concentration should also be considered for conformal white LEDs when optimizing the particle size to improve the luminous flux and color uniformity [6]. In addition to the particle sizes, the gradient concentration [7,8] and gradient thickness [9] structures of conformal PCEs have been studied. However, owing to the difficulties in the manufacture of PCEs, these studies are only conducted by optical simulations.

The pulse-sprayed method was introduced by Huang *et al.* to fabricate white LEDs with uniform PCEs and had successfully decreased the color deviation [10]; it has proven to be an effective method for the fabrication of high-performance white LEDs. Using this method, we have proposed cost-effective multi-layered conformal structures to further improve the color uniformity and phosphor utilization [11]. Most of the studies only focused on PCE structure design and fabrication, while the optical influence of the LED chip is barely studied in packages, especially for conformal structures. Sommer *et al.* have mentioned that the chip size has a significant impact on the optimized results of height–width relation for conformal PCEs to achieve high color uniformity [5]. Our previous works have indicated that the surface morphology of the chips plays an important role in the optical performance of conformal white LEDs, including their intensity and correlated color temperature (CCT) [12]. However, the height of the chips, which is also a critical parameter of LED chips, has not been studied yet, suppressing its significant potential to further improve the optical performance of conformal white LEDs. In this study, we experimentally investigate the effect of chip height on the optical performance of conformal white LEDs, providing a more comprehensive design guide for white LEDs.

The conformal white LEDs are fabricated using the pulse-sprayed method, as shown in Fig. 1, and the detailed processes can be found in our previous studies [11,13]. The blue source is a flip-chip (3.5 μm AuSn/0.5 μm Ag/0.5 μm p-GaN/0.02 μm

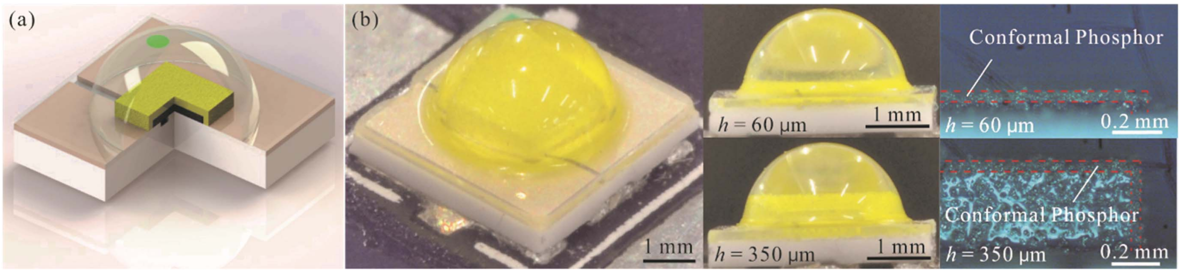

Fig. 1. (a) Cross-sectional diagram of a white LED with the conformal phosphor structure and (b) samples of conformal white LEDs with different chip heights *h*.

InGaN multiple quantum well (MQW)/5 μm n-GaN/sapphire substrate) with 1.14 mm size, and its *h* is controlled to be 60 μm, 100 μm, 150 μm, 200 μm, 250 μm, 300 μm, and 350 μm by merely grinding the sapphire substrate. It should be noticed that all the flip-chips have the same emission spectra centered at 450 nm, and their full width at half-maximum (FWHM) are 18 nm. The conformal PCE consists of yttrium aluminum garnet (YAG) phosphor, silicone, and diluent, and their overall ratios are 30.9%, 20.6%, and 48.5%, respectively. The pulse-sprayed process is repeated three times to achieve a targeted CCT of approximately 6000 K, and the phosphor mass for each white LED remains the same. The thickness of phosphor layers is measured by the LEICA DM 2500M microscope. A semispherical lens with a radius of 1.3 mm, fabricated using the compression modeling method [14] with silicone material, is used to protect the PCE and improve the light extraction. The radiant flux, luminous flux, and spectra are measured using the integrated sphere system from Instrument Systems; the intensity and CCT distributions are measured using our homemade T930 systems. The injection current is provided by a Keithley adjustable DC source.

The radiant power and luminous flux of white LEDs with different heights of chips from 60 to 350 μm are shown in Figs. 2(a) and 2(b), respectively. Figure 2(a) shows that the radiant power decreases as the height of the chips increases; compared with white LEDs with the chip height of 60 μm, the radiant power of LEDs with the chip height of 350 μm shows a decrease of approximately 13%. This indicates that a larger height of chips can lead to a more serious energy loss for white LEDs, which will be discussed in detail later. Moreover, the luminous flux also shows a decrease with the increase in the height of chips; the luminous flux of white LEDs with the chip height of 350 μm decreases by approximately 22% compared with that of LEDs with a smaller chip height of 60 μm. As the reduction of luminous flux is apparently larger than that of radiant power, it can be inferred that a more significant loss may occur for the phosphor light, as it is more sensitive to the luminous efficiency function.

To further illustrate this issue, the radiant power of chip light without phosphor coating, chip light with phosphor coating (called chip light for short), and phosphor light is provided by integrating the spectrum (measured at a typical injection current of 350 mA) from 360 to 830 nm, from 360 to 480 nm, and from 480 to 830 nm, respectively, as shown in Fig. 3(a). It is evident that the radiant power of both the chip light with and without phosphor coating increases, whereas it is opposite for phosphor light with the increase in chip height. This indicates that a larger chip height benefits the chip light extraction, whereas it simultaneously decreases the radiant power of phosphor light. Further, the reduction in phosphor light is responsible for the decrease of radiant power and luminous flux. Some reasonable reasons behind these results are provided. Typical tracing light paths are shown in Fig. 4. From Fig. 4(a), there is a high probability that the chip light generated from the MQW layer (inside the epitaxy layers) undergoes total internal reflection (TIR) at the interface between sapphire and phosphor. This reflected light can be absorbed by chips or bases. A larger chip height can provide a larger lateral light extraction window (LEW), which is extremely helpful for TIR light with larger emission angles escaping from chips and avoiding absorption loss by chips or bases. Moreover, a larger chip height can also provide a larger sprayed area, resulting in a thinner lateral conformal phosphor layer under the same sprayed mass [11,13]. It is evident that the thicknesses of the lateral conformal phosphor layer are 51.2 and 42.3 μm for chip height with 60 and 350 μm, respectively, while both their upper thicknesses are approximately 50 μm, as shown in Fig. 1(b). Therefore, the chip light emitting from the lateral chip surface has higher probability to escape from this thinner conformal phosphor layer [5], contributing to

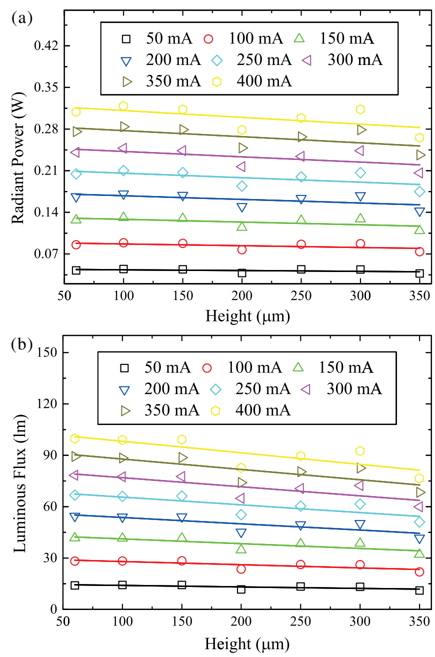

Fig. 2. (a) Radiant power and (b) luminous flux of white LEDs with different chip heights measured from 50 to 400 mA.

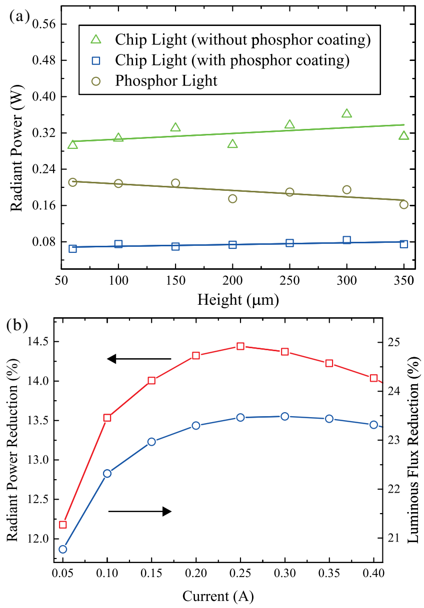

Fig. 3. (a) Radiant power of chip light without phosphor coating, chip light with phosphor coating, and phosphor light for LEDs with different chip heights measured at 350 mA; (b) Reduction in the radiant power and luminous flux of white LEDs with a large chip height of 350 μm compared with that of LEDs with the chip height of 60 μm.

an increase in the radiant power of chip light observed in Fig. 3(a). However, when the chip height is sufficiently small, the reflected chip light from the upper TIR interface could be backward scattered by the micro-patterned structures at the interface between sapphire and epitaxy layers, and some of this backscattered chip light can propagate into the upper phosphor layer again and extract successfully, as shown in Fig. 4(b). However, as for large chip height, chip light should have been propagated to the upper phosphor layer, owing to the comprehensive effect of TIR and scattering that can directly propagate to the lateral phosphor layer, which is due to the larger lateral LEW, as discussed above. This indicates that a larger chip height results in much more phosphor light emission at the lateral phosphor layer instead of the upper phosphor layer; in other words, some of the phosphor light emitting from the upper phosphor layer is transformed to emit from the lateral phosphor layer. Owing to the isotropic emission characteristic of phosphor, this phosphor light from the lateral layer can lead to serious backward emission, which has been demonstrated to be a major factor that decreases the optical performance of LED devices by introducing additional absorption loss by bases [15]. Therefore, a decrease in the radiant power of phosphor light with the increase in chip height can be observed in Fig. 3(a).

To further support this explanation, the reductions in radiant power and luminous flux at different injection currents are shown in Fig. 3(b), and white LEDs with the chip height of 350 μm compared with that of 60 μm are used as an example. It is evident that the reduction in radiant power increases with the increase in injection current, indicating that a larger amount of chip light can lead to serious energy loss for white LEDs with large chip height. According to the same reason given in Fig. 3(a), it is because more amounts of chip light can propagate into the lateral phosphor layer through the larger chip height, causing much more phosphor light emission from the lateral phosphor layers to be absorbed by bases. When the injection current continues to increase, the reduction in radiant power starts to decrease. This is because the radiant power of chip light is so large that the absorption of phosphor at the lateral layers becomes saturated, and the increase in the down-conversion amount of phosphor light emission from the lateral layers can be neglected while the radiant power of chip light still continues to increase. Hence, it suppresses further reduction of radiant power when the injection current is sufficiently large. Similar changes in the luminous flux reduction can be observed, whereas its decrease at a large injection current is less obvious compared with that of the reduction in radiant power. This is because the decrease is mainly caused by the increase of chip light, as discussed above, which is less sensitive to the luminous flux. Consequently, the backward emission loss of phosphor light should be a major concern when increasing the chip height.

CCT distributions of white LEDs with different chip heights measured at the injection current of 350 mA are shown in Fig. 5(a). The CCT at the center angles does not change

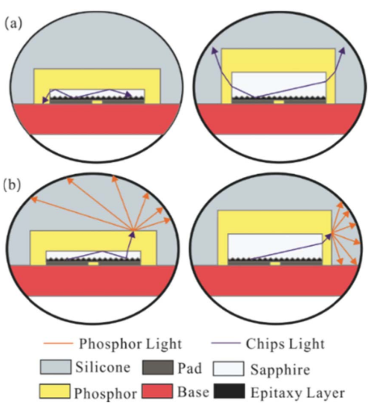

Fig. 4. Typical light dynamic analysis for white LEDs with different height of chips: (a) reduction in chips/base absorption loss of chips light and (b) increment in base absorption loss of phosphor light by increasing the height of chips.

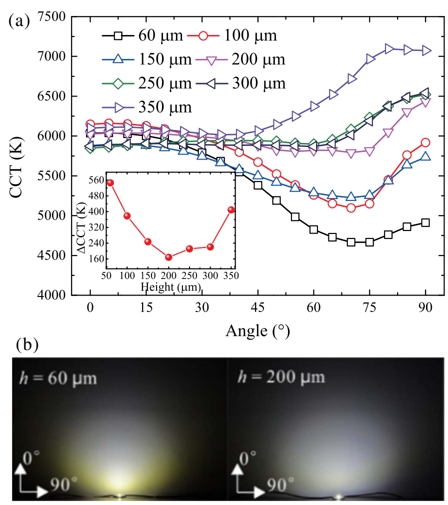

Fig. 5. Color uniformity of white LEDs with different chip heights measured at 350 mA: (a) CCT distributions and their standard deviation shown in the insert, (b) light spots of white LEDs with chip heights $h = 60$ μm and $h = 200$ μm.

obviously, whereas it is opposite at the edge angles. It is evident that the CCT increases at the edge angles with the increase in chip height. Two mechanisms discussed in Fig. 4 may be responsible for these results. A larger chip height leads to an increase in the amount of chip light emission from both the lateral chip surface and the lateral conformal phosphor layer, which tends to propagate to the edge angles; moreover, more phosphor light emission from the upper layers is re-emitted to the lateral layers, and the phosphor light with a large emission angle tends to be absorbed by bases instead of propagating to the edge angles. Notably, the CCT standard deviation ΔCCT decreases with the increase in chip height, as shown in the insert of Fig. 5. However, as the chip height increases, the increase of CCT at the edge angles is too large to balance the CCT at the center angles, and the ΔCCT increases. Therefore, 200 μm is the optimized chip height considering the superior color uniformity, which is only 168 K for the ΔCCT, a decrease of 69.1% compared with that of the chip height of 60 μm. A light spot for the chip height of 200 μm with very uniform color distribution can be also observed in Fig. 5(b). Therefore, it is evident that it must be acknowledged that high color uniformity white LEDs can be obtained by only selecting a flip-chip with proper height parameters; more importantly, it is unnecessary to further optimize the phosphor structures [4,14] or introduce scattering structures [16,17] in contrast to most of the previous studies. This is a convenient and effective alternative for high color uniformity white LEDs, which can provide a new perspective to improve the light quality by using a matched chip source. The intensity distributions measured at the injection current of 350 mA are shown in Fig. 6. A more dispersed intensity distribution with larger FWHM can be achieved by increasing the chip height; the FWHM for the chip height of 350 μm is 147°, which shows an increase of 22.5% compared with the 60 μm chip height sample. This indicates that a larger chip height results in wider viewing angles for illumination, which is also evidently shown in Fig. 5(b). With the increase in chip height, the amount of phosphor light decreases at the edge angles, whereas the trend of chip light is the opposite, as discussed in Fig. 5. Therefore, the increase in intensity at the edge angles can further reveal that the increasing amount of chip light increases the CCT at the edge angles. It is possible to simultaneously achieve high color uniformity and luminous flux by decreasing the loss of phosphor

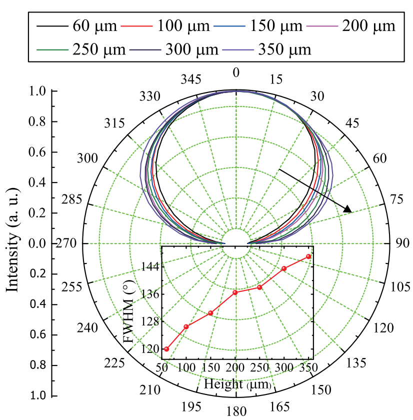

Fig. 6. Intensity distributions of white LEDs with different chip heights measured at 350 mA. The insert is their full width at half-maximum (FWHM).

light at the edge angles, and further studies on chip height considering different packaging structures are still required.

The effect of the flip-chip height on the optical performance of conformal white LEDs is experimentally investigated. A larger chip height leads to a reduction in radiant power and luminous flux, owing to the increasing backward emission loss of phosphor light from the lateral phosphor layers. However, it can promote much more chip light emission from the lateral chip surface, which increases the CCT values at the edge angles and results in wider viewing angles. It has been demonstrated that high color uniformity can be obtained by selecting suitable chip heights; white LEDs with the chip height of 200 μm can achieve a ΔCCT of only 168 K, which shows a decrease of 69.1% compared with the 60 μm chip height sample. We believe that these results can provide a new perspective to improve the color uniformity without changing the phosphor structures or using special scattering elements; moreover, they facilitate the selection of a proper chip height considering different illumination requirements. In the future, further studies on chip height combining different packaging structures is expected to simultaneously achieve large luminous flux, high color uniformity, and wide viewing angles for white LEDs.

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