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

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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

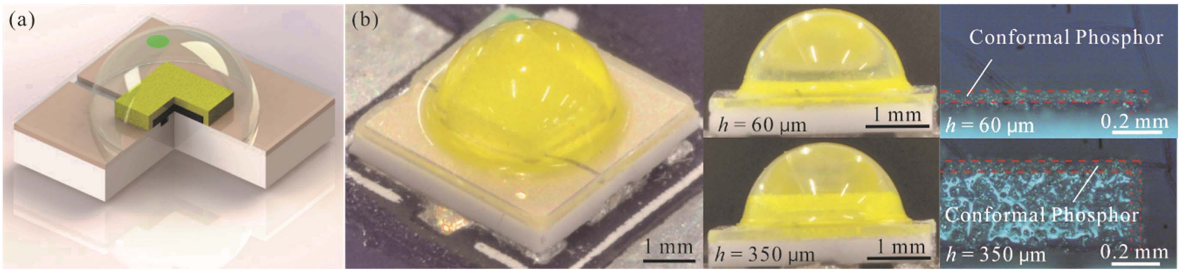

Fig. 1. (a) Cross-sectional diagram of a white LED with the conformal phosphor structure and (b) samples of conformal white LEDs with different chip heights *h*.

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

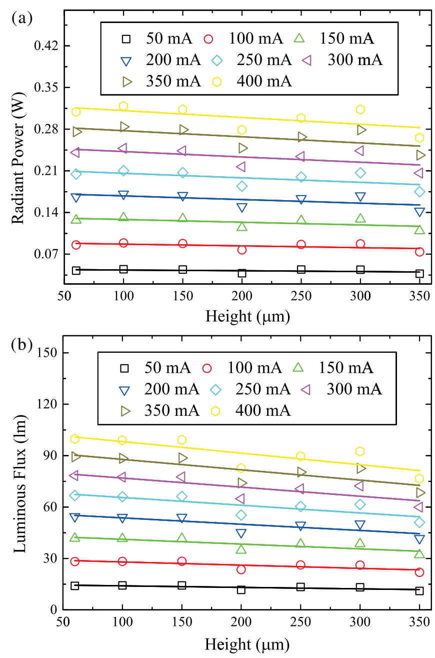

Fig. 2. (a) Radiant power and (b) luminous flux of white LEDs with different chip heights measured from 50 to 400 mA.