Color Consistency Enhancement of White Light-Emitting Diodes Through Substrate Design

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***Abstract*— We demonstrate a new kind of substrate structure to enhance the correlated color temperature (CCT) consistency of white light-emitting diodes through controlling the liquid morphology by the wetting theory. Based on this method, the effect of the coating phosphor volume variation on CCT can be effectively reduced. Numerical simulations and experiments on the dispensing process with different phosphor gel volumes are conducted. The results show that the height fluctuation of the phosphor layer on the new substrate is 54.5% of that on the conventional substrate when the dispensed phosphor gel volume changes from 3.38 to 4.98 μl. The optical simulation results show that compared with the conventional structure, the CCT consistency of the new substrate is improved by 42.3%.**

***Index Terms*— Correlated color temperature consistency, LEDs, optical simulation, phosphor coating.**

I. Introduction

WHITE light-emitting diodes (LEDs) have significantly developed in luminous efficiency and white light quality in recent years [1]–[3]. They have been widely applied into many illumination areas such as large size flat panel backlighting, street lighting, vehicle forward lamp, museum illumination and residential illumination [1]. In order to further spread the application of white LEDs into the general lighting market, it is critical to cut down the cost of white LED products [4].

The correlated color temperature (CCT) consistency is believed to be very important for the cost reduction in LED packaging. Bad CCT consistency means that many LED products are not in the desirable CCT range. It reduces the yield. The variation of the phosphor layer parameters in terms of phosphor type, volume and phosphor concentration is the main reason for bad CCT consistency in the LED packaging [5]–[7].

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In general, phosphor powder is firstly mixed into transparent epoxy. Then, the mixture is directly dispensed around the LED chip. The volume of dispensed phosphor gel is affected by the viscosity and the equipment parameters. However, the viscosity of the phosphor gel changes with temperature and time, and the parameters of the dispensing phosphor gel equipment may also fluctuate. These result in phosphor gel volume variation from packaging to packaging in mass production [8]. Larger phosphor gel volume leads to the thicker phosphor layer. Because the thickness of the phosphor layer is one of the most important factors to affect the CCT [9], phosphor gel volume variation leads to the bad CCT consistency in LED packaging.

For improving the CCT consistency, it is critical to minimize the variation of the phosphor gel volume coated around the LED chip. An apparent method to reduce the dispensed phosphor gel volume variation is through highly accurate control of the phosphor dispensing process, such as improving the equipment precision or reducing the phosphor gel viscosity fluctuation. However, due to the high viscosity and complicated fluid properties of the phosphor and epoxy mixture, a highly accurate control is very difficult or associated with the high cost.

In this letter, a method is proposed to enhance the CCT consistency through substrate structure design even when the dispensed phosphor gel volume has relatively big fluctuation. Numerical simulations and experiments were carried out. The results show that the height variation of the phosphor layer was significantly reduced using the new substrate. Optical simulation results show that the CCT consistency of white LEDs with the new substrate is dramatically enhanced.

II. Theory

A kind of typical LED packaging structure is shown as Fig. 1(a). Due to the pinning effect of the step edge on the liquid and the effect of the surface tension, phosphor gel is limited on the top surface of the heat slug and forms a spherical cap shape during the phosphor dispensing process [10]. Therefore, as shown in Fig. 1(b), the height h of the phosphor spherical cap increases with higher dispensed phosphor gel volume. This variation would worsen the CCT consistency of white LEDs. In general, more phosphor gel volume generates lower CCT of white LEDs, which deviates from desirable range in manufacturing.

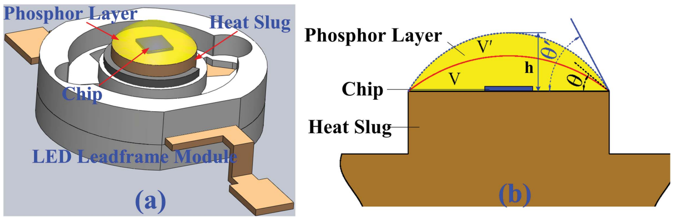

Fig. 1. (a) Typical structure of white LED packaging. (b) Schematic diagram of phosphor gel pinned at step edge.

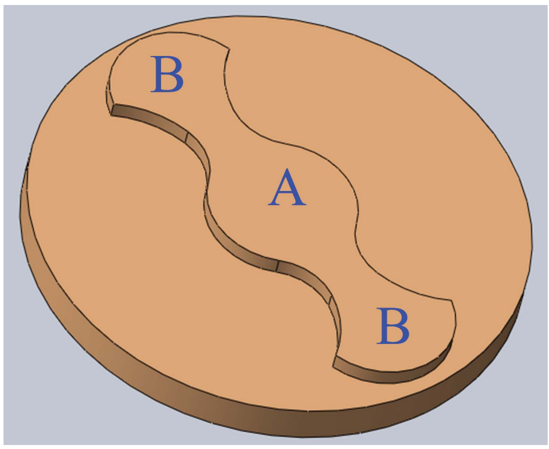

Fig. 2. Schematic illustration of new substrate structure.

The new substrate structure is presented in Fig. 2. Here, it only shows the heat slug, because other parts are not relevant for the phosphor coating. Other structures are the same as that shown in Fig. 1(a). The new substrate is a two-layer structure. The top surface of the heat slug includes two zones, zone A and zone B. Zone A is circular, and zone B is sectorial in both sides of the zone A. The zone A is used to bond the LED chip. The phosphor dispensing process is a wetting phenomenon. In the wetting theory, the final liquid geometry meets the rule of the interfacial free energy minimization [11]. The total interfacial free energy is given by

$$E = \gamma_{LV} A_{LV} + \sum (\gamma_{SV} - \gamma_{SL}) A_{SL} \quad (1)$$

where γ is the interface tension, A is the interface area, the subscript LV, SV and SL present the "liquid and vapor", "solid and vapor" and "solid and liquid", respectively. In the phosphor dispensing process, the phosphor gel is dispensed at the center of zone A. With increasing dispensed phosphor gel volume, phosphor gel starts to spread along the top surface of the heat slug to keep the interfacial free energy minimal. When it meets the step edge, the phosphor gel is pinned at the step edge. When the dispensed phosphor gel volume reaches some value, it would spread into the zone B. A higher dispensed phosphor gel volume would spread farther into zone B. Therefore, the new substrate structure could reduce the phosphor gel volume variation in zone A when even more phosphor gel is dispensed onto the substrate. The additional phosphor gel volume entering into zone B with increasing the dispensed phosphor gel volume is far away from the LED chip and has very little effect on the CCT of white LEDs. Therefore, the new substrate structure could be used to improve the CCT consistency in LED packaging to compensate even big variations of the dispensed phosphor gel volume.

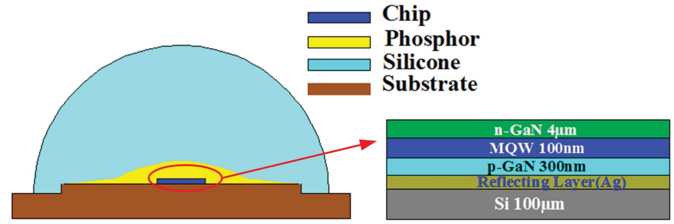

Fig. 3. Optical model for simulations. (a) Structure of white LEDs. (b) Schematic diagram of chip model.

III. Phosphor Layer Morphology and Optics Simulations

The free open software, Surface Evolver was applied to simulate the phosphor layer equilibrium morphology [12], [13]. In the software, the minimization of the interfacial free energies presented as the Eq. 1, is carried out by a gradient descent method under the volume constraint and other boundary constrains. The surface tension and the density of the phosphor mixture which is used into the experiments are 27 dyn/cm and 1020 kg/m^3, respectively. The contact angle between the mixture and the heat slug surface is 20.1°. Because the height of the phosphor layers is far less than the capillary length of 1.64 mm, gravity has a little effect on layer equilibrium morphologies [12]. The contact line of the mixture and the heat slug surface is limited within the area of the top surface. The phosphor layer equilibrium morphologies with the dispensed phosphor gel volumes, 3.38 μl, 3.78 μl, 4.18 μl, 4.58 μl and 4.98 μl on the new substrate were simulated, respectively.

The Monte Carlo ray tracing method was applied to analyze the optical performance of the white LEDs with the new substrate and the conventional substrate. The optical models were built as shown in Fig. 3. The size of the chip is 1 mm $\times$ 1 mm. The thicknesses of the layers are n-GaN 4 μm, MQW 100 nm, p-GaN 300 nm, and Si 100 μm. The absorption coefficients and refractive indices for n-GaN, MQW, and p-GaN are 5, 8, and 5 mm^{-1} and 2.42, 2.54, and 2.45, respectively [14].

The phosphor layer geometries of white LEDs with the new substrate structure were built as the above simulation results by Surface Evolver. The phosphor layer geometries of the conventional white LEDs were built as described in Ref. 15. The phosphor concentration was chosen as 0.25 g/cm^3. Based on the Mie theory, the absorption and scattering coefficients of phosphor are 2.27 and 3.82 mm^{-1} for blue light and 0.043 and 5.31 mm^{-1} for yellow light [16]. The lenses are hemispheres with a radius of 5 mm and the refractive index 1.5. In order to simplify the calculation, specific wavelengths of 465 and 555 nm were used in the calculation to represent blue and yellow light, respectively. The conventional white LEDs and modified white LEDs with the new substrate structure

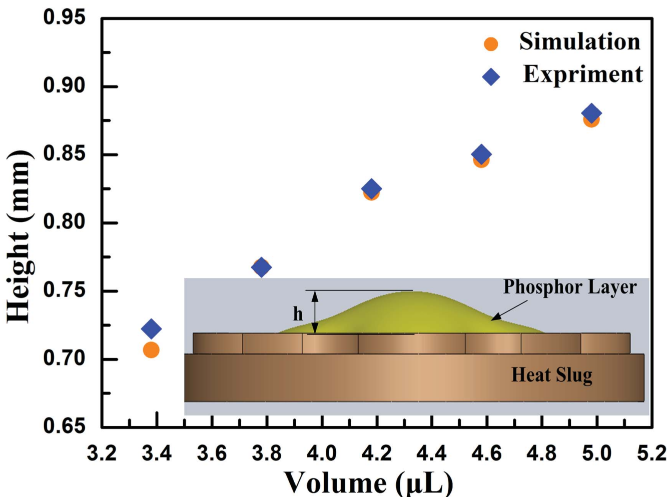

Fig. 4. Phosphor layer height on new substrates by simulations and experiments.

were simulated with the phosphor layer volume varying from 3.38 μl to 4.98 μl.

IV. Experiments

The experiments on the phosphor coating process were carried out on the new substrate. These substrates whose structures were the same as shown in Fig. 2, were fabricated. The mixture of the phosphor power and the silicone was dispensed at the center of the zone *A*. The dispensed phosphor gel volume is difficult to measure directly. Here, we firstly measured the phosphor layer weight by an analytical balance whose accuracy is 0.01 mg. Then, the volume of the phosphor layers was calculated through the phosphor layer weight divided by phosphor gel density. The height of the phosphor layers was measured by an advanced digital microscope (VHX-600, KEYENCE, Japan) whose accuracy reaches 1 μm. In the experiments, the phosphor layer volumes had the deviation $\pm$ 0.02μl, compared with that in simulations.

V. Results and Discussion

Fig. 4 presents the phosphor layer height by numerical simulations and experiments. It can be seen that numerical simulations and the experiments agree well with each other. They both show that the height of the phosphor layer enlarges with increasing phosphor volume. The height comparison of the phosphor layers coated on the new substrate and the conventional substrate is shown in Fig. 5. It can be found that the simulation height difference between the maximal and the minimal thickness of the phosphor layers on the new substrate is 0.1689 mm and is 54.5% of that on the conventional substrate when the phosphor layer volume varies from 3.38 μl to 4.98 μl.

The ratio of the yellow light power to the blue light power (YBR) was introduced to illustrate the CCT of white LEDs in optical simulations [12]. The YBRs of the white LEDs packaged with the new structure and the conventional substrate are shown in Fig. 6. Both modules were subjected

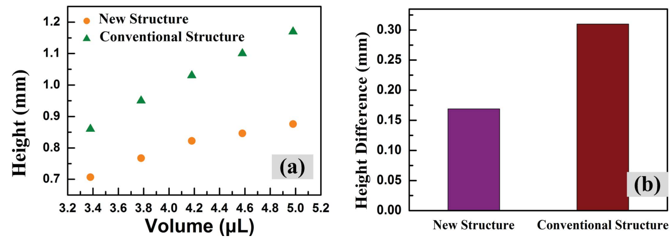

Fig. 5. (a) Comparison of simulation phosphor layer height under same phosphor gel volume variation. (b) Height difference of phosphor layers between new substrate and conventional substrate.

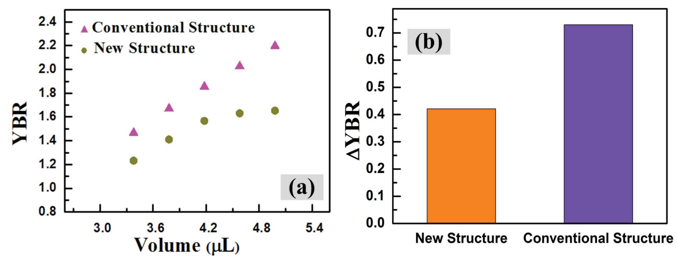

Fig. 6. (a) Comparison of YBR of white LEDs by using new substrate and conventional substrate under the same volume of phosphor layers. (b) YBR difference of LED modules.

to the same variation of the phosphor layer volume during the packaging processes. It can be seen both YBR get larger with increasing the dispensing phosphor gel volume. However, the YBR difference of the present white LEDs is only 0.42 and 57.7% of that of the white LEDs with the conventional structure.

VI. Conclusion

In summary, a new substrate structure was proposed for enhancing the CCT consistency of the white LEDs. The phosphor coating process of the white LEDs with the new substrate structure was studied by numerical simulations and experiments. Both results reveal that compared with the conventional structure, the new substrate can effectively cut down the phosphor layer height variation induced by the dispensed phosphor volume fluctuation. The optical simulation results show that the YBR variation of the LEDs module with the new structure is almost half of that of the white LEDs with the conventional structure when they have the same volume variation of the phosphor layers.

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