Conformal Phosphor Distribution for White Lighting Emitting Diode Packaging by Conventional Dispensing Coating Method With Structure Control

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***Abstract*— Conformal phosphor distribution is a well known way to improve optical performance for white light emitting diode (LED) packaging. However, it is difficult to be realized by mature and cheap dispensing coating methods. In this paper, with consideration given to the effect of boundary constraint on liquid wetting morphology, a method to achieve phosphor conformal distribution is presented by conventional dispensing coating with controlling the slanting angle of reflector cups. The numerical simulations and experiments on phosphor dispensed into reflector cups with different slanting angles are conducted. The results show that uniform phosphor distribution can be obtained when the slanting angle is the same as the contact angle between the phosphor slurry and the reflector cup side wall. The rule can be used to guide the design of the reflector cup and a simple change of reflector cup can realize phosphor conformal coating for white LEDs by the low cost traditional dispensing coating process.**

***Index Terms*— Conformal coating, light emitting diodes (LEDs), phosphor.**

I. Introduction

WHITE light emitting diodes (LEDs) have been regarded as the most important and promising solid-state light source for next generation lighting due to many advantages over incandescent and fluorescent in efficiency, life time, chromatic performance, reliability, and environmental protection [1], [2]. Most white LED sources are generated by mixing blue light emitted by the LED chip and re-emission yellow light from the yellow phosphor converting blue light. The phosphor arrangement on LED chip is one of the most important factors which affect LED optical performance, such as light extraction efficiency, correlated color temperature (CCT), and angular color uniformity (ACU) [3], [4].

So far, dispensing method is widely adopted to form phosphor layers in LED packaging industry due to its simplicity and low cost. Nevertheless, because the geometry of phosphor layer is a spherical cap by such a dispensing method, the packaged white LEDs will often generate a big color gradient in the radiation pattern, such as a yellow ring, which discomforts the eyes and leads to poor ACU [5]–[7]. In order to enhance ACU, conformal phosphor coating by which phosphor layer is uniformly distributed around the chip was proposed. Many methods, such as settling, spin coating, self-exposure, electrophoretic deposition, and pulsed spray have been applied for conformal coating [8]–[10]. However, these methods have some limits. The settling approach is a chemical reaction method and can only be applied for flip-chip LED with a flat surface for phosphor coating. Spin coating requires a lot of phosphor slurry, which sometimes leaves dozens of times of phosphor slurry around the LED chip. Therefore, it significantly increases the cost of LED packaging. Self-exposure or electrophoretic deposition can produce a uniform phosphor coating, but these chemical processes cause Cr ion pollution. Pulsed spray demands complex auxiliary equipments and also wastes phosphor slurry. Therefore, a simple and cost-effective conformal coating method is urgently needed in industry.

In this paper, a simple method based on conventional dispensing coating is proposed to get a conformal phosphor coating effect through controlling the slanting angle of the reflector cup side wall. The numerical simulations and experiments were conducted to show final phosphor geometries in reflector cups with different slanting angles. The experimental results agreed well with the simulation results. Both results show that the phosphor layer is flat only when the contact angle equals the slanting angle. Therefore, through designing a reflector cup whose slanting angle is the same as the phosphor contact angle, uniform phosphor distribution can be obtained by using conventional dispensing process, which will make LED packaging module own good optical performance through a mature and cheap process.

II. Phosphor Geometry Control Theory

For liquid feature in the micro range, the surface to volume ratio is exceedingly large. Thus, the energy associated with the boundary constraints and interfaces determines the overall shape. For a liquid droplet on substrate, because the total energy of liquid structure is toward the minimum [11], [12], the equilibrium shape varies from different boundary constraints in terms of the contact angle on substrate and the

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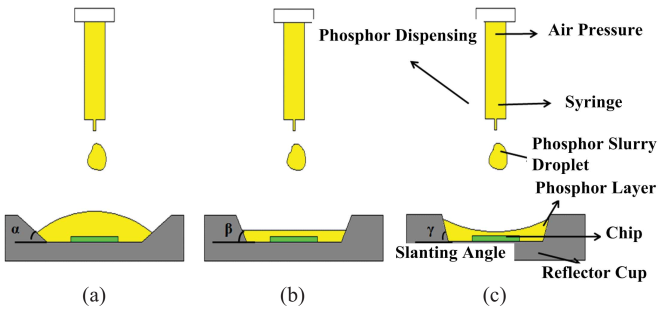

Fig. 1. Different phosphor geometries in reflector cups with different slanting angles in dispensing process. (a) Convex phosphor shape. (b) Flat phosphor shape. (c) Concave phosphor shape.

geometry of solid surface at three-phases (air, liquid, and solid) boundary line. Therefore, through designing the boundary conditions or constraints, the uniform phosphor distribution can be realized even using the conventional dispensing coating. Fig. 1 shows the different geometries of phosphor layers in reflector cups by controlling slanting angles. As shown in Fig. 1(b), the desired uniform phosphor distribution is obtained. From Fig. 1, it clearly reveals that the slanting angle of side wall reflector cup is a key parameter to affect the geometry of phosphor layer. When the slanting angle is small, the upper interface of phosphor layer is convex. In the extreme case that the slanting angle is 0°, the reflector cup is the flat sheet, and the phosphor spherical cap would form, which is the common packaging style in LED packaging industry. While the slanting angle is large enough, the concave upper interface of phosphor layer would form in the reflector cup. So there exists a proper slanting angle through which uniform phosphor distribution could be obtained. Following this part, numerical simulations and experiments were conducted in order to find this slanting angle for uniform phosphor distribution on LED chip.

III. Numerical Simulation

A. Simulation Theory

The spreading of phosphor slurry in reflector cup involves in gas and liquid flow, and is a typical wetting phenomenon. The volume of fluid model is employed to capture the interfaces of liquid and gas during the wetting; the continuum surface force (CSF) model is used to model surface tension [13], [14]. Considering the liquid and gas as incompressible flows with constant properties, the continuity and momentum equations are given by

$$\nabla \bullet \vec{V} = 0 \tag{1}$$

$$\frac{\partial(\rho\vec{V})}{\partial t} + \nabla \bullet (\rho\vec{V}\vec{V}) = -\nabla P + \nabla(\mu\nabla\vec{V}) + F_g + F_{st} \tag{2}$$

where $\vec{V}$ is the velocity, ρ is the density, P is the pressure, μ is the viscosity, F_g is the body force, and F_{st} is the surface tension force. The liquid volume of fraction is denoted by ϕ and is defined by

$$\phi = \begin{cases} 1, & \text{inside the liquid phase} \\ 0 \sim 1, & \text{at the free surface} \\ 0, & \text{inside the gas phase.} \end{cases}$$

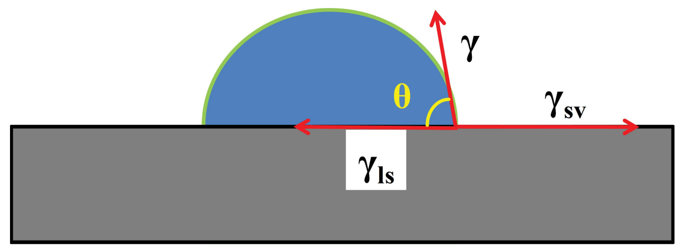

Fig. 2. Schematic illustration of contact angle of a droplet on flat sheet.

The transport equation for ϕ is

$$\frac{\partial\phi}{\partial t} + \vec{\mathrm{V}} \bullet \nabla\phi = 0. \tag{3}$$

The density and viscosity of fluid in the cells located at the interface are physical properties, which are computed based on the volume fractions of liquid and gas in the cells

$$\rho = \phi \times \rho_{\text{liquid}} + (1-\phi) \times \rho_{\text{gas}} \tag{4}$$

$$\mu = \phi \times \mu_{\text{liquid}} + (1-\phi) \times \mu_{\text{gas}}. \tag{5}$$

In the CSF model, surface tension force is given by

$$F_{st} = \sigma K \vec{n} \tag{6}$$

where σ is the coefficient of surface tension, K is the interface curvature, and $\vec{n}$ is the unit vector normal to the interface at each interface point. K and $\vec{n}$ are calculated as

$$\vec{n} = \frac{\nabla\phi}{|\phi|} \tag{7}$$

$$K = -\nabla \bullet \vec{n}. \tag{8}$$

B. Contact Angle and Viscosity Measurement

The two key parameters in determining the phosphor slurry spreading behavior and the equilibrium geometry are its contact angle and viscosity. The contact angle is the one at which a liquid/vapor interface meets the solid surface. Fig. 2 reveals the section of liquid droplet on flat horizontal solid surface. Here, γ_{sv} denotes the solid–vapor interfacial energy, γ_{ls} is the solid–liquid interfacial energy, and γ_{lv} is the liquid–vapor interfacial energy. The contact angle θ depends on the three phase interface energies and the relationship is determined by the Young's equation

$$\gamma_{sv} - \gamma_{ls} - \gamma_{lv}\cos\theta = 0. \tag{9}$$

The γ_{sv}, γ_{ls}, and γ_{lv} is only decided by the material of liquid and solid.

The droplet geometry on flat horizontal solid surface trends to be the spherical cap in order to minimize the free energy. In [15], a method to obtain contact angle was used through measuring the contacting area between droplet and solid surface and the volume of droplet. The relationship can be expressed as

$$\mathrm{A} = \left(\frac{3\sqrt{\pi}V\sin^3\theta}{2 - 3\cos\theta + \cos^3\theta}\right) \tag{10}$$

where A is the area of droplet in contact with solid surface, V is the volume of droplet, and θ is the contact angle.

TABLE I
PROPERTIES OF AIR AND PHOSPHOR SLURRY

ρ_{liquid} (Kg/m^3)	ρ_{gas} (Kg/m^3)	μ_{liquid} (Pa·s)	μ_{gas} (Pa·s)	σ (mN/m)	Contact Angle θ (Degree)
1020	1.156	4.2	1.86×10^{-5}	24.3	31

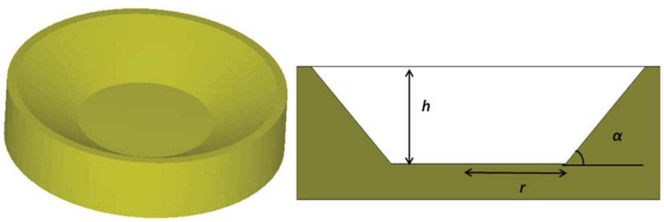

Fig. 3. Schematic representation of reflector cup in simulations.

Based on (10), we can find that different phosphor droplet volumes can lead to different droplet contact area with solid surface. However, it should be noted that the contact angle keeps constant even though the liquid volume changes. From (10), through measuring the volume and area of the phosphor droplet in contact with solid surface, we can gain the contact angle between the phosphor slurry and the reflector cup wall. The viscosity of phosphor slurry was measured by viscometer. The contact angle and viscosities of air and phosphor slurry were measured and shown in Table I.

IV. SIMULATIONS

The shape of the reflector cup in the simulation is conical and the depth of the circular truncated cone h is 800 μm and its small end radius r is 1.5 mm, as shown in Fig. 3. The slanting angles α of the reflector cups side wall are 10°, 25°, 31°, 38°, 45°, and 60°, respectively. The properties of air and phosphor are listed in Table I. For each case, the phosphor slurry was dispensed into the reflector cup along the axis with the same volume. The flow of phosphor slurry reached the equilibrium state finally. The contours of the volume fraction of phosphor slurry in different slanting angle reflector cups are shown in Fig. 4. The blue part presents air and the red part means the phosphor slurry. It can be found that the phosphor layer with the flat upper interface is obtained in the reflector cup when the slanting angle is 31°, in which the slanting angle is equal to the contact angle of phosphor slurry on reflector cup side wall. While the slanting angle is larger than the contact angle, the phosphor layer upper interface is concave. When the slanting angle is smaller than the contact angle, the phosphor layer upper interface presents convex. As the difference between the contact angle and the slanting angle is bigger, the unflatness of the phosphor layer is more obvious.

V. EXPERIMENTS

The copper conical reflector cups were fabricated. The depth h, the small end radius r, and the slanting angles α were the same as those in the simulations and the slanting angles had the $\pm1°$ fabrication bias. In order to precisely control the volume of phosphor slurry dispensing into reflector cup, the

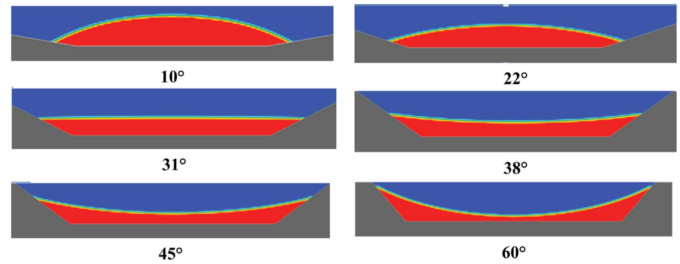

Fig. 4. Distribution of phosphor slurry in reflector cups with different slanting angles in simulations.

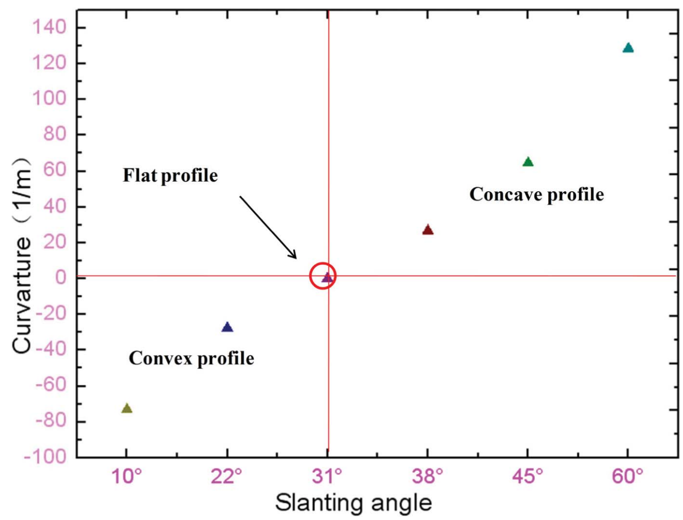

Fig. 5. Phosphor layer curvatures versus different slanting angles.

micro syringe was used. The phosphor slurry was dispensed into reflector cup along the axis. The volume of phosphor slurry dispensed into reflector cups with different slanting angles maintained 3 ± 0.1 μl. Actually, we also conducted the experiments in other volumes. Since 3 μl is commonly used in this kind of LED packaging, we choose its results to describe. The phosphor slurry in reflector cup reached equilibrium state finally. Then, the reflector cup with phosphor slurry had been transferred into baking oven to accomplish the cure process at 120 °C for 30 min. In order to measure the profile of cured phosphor layer upper interface, the optical profiling system was employed. This measurement setup can be used to obtain the profile of the interface between the phosphor layer and the air in the reflector cup. Based on the profile, the curvatures of the profiles can be calculated. After finishing measurement, phosphor layers were separated from reflector cup and the sections of phosphor layers in different reflector cup were fabricated in order to compare with simulation results.

VI. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 5 shows the curvatures of phosphor layer upper interfaces in reflector cups with different slanting angles. Here, the curvatures were defined as positive for concave and negative for convex. It can be seen that the curvature increases with increasing slanting angle. If the slanting angle is smaller than contact angle, the curvature is negative and the curvature of smaller slanting angle has smaller value. While the slanting

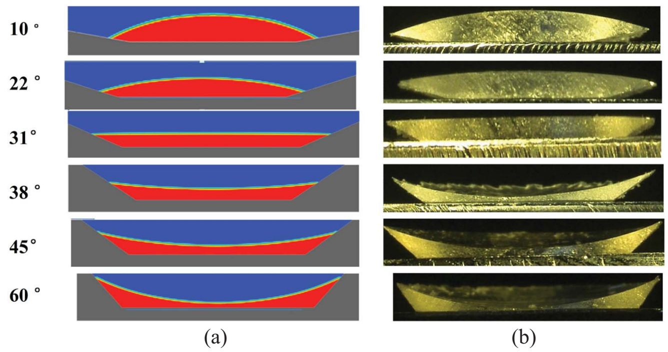

Fig. 6. Distribution of phosphor slurry in reflector cups with different slant angles by (a) simulations and (b) experiments.

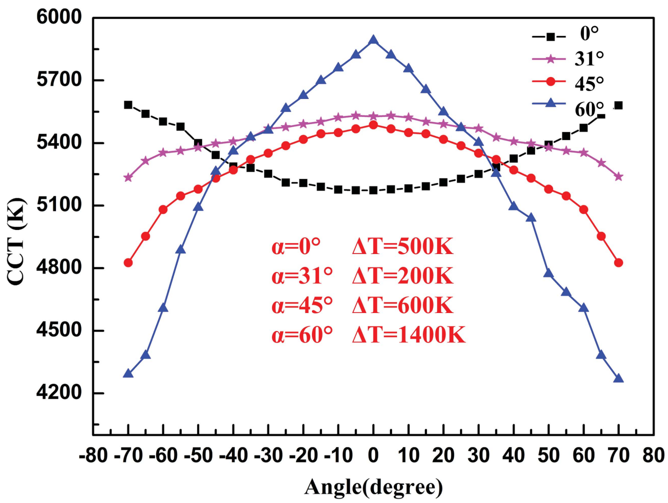

Fig. 7. Angular CCT distribution of white LED modules with different reflector cup slanting angles α.

angle is larger than contact angle, the curvature is positive and the curvature of larger slanting angle has larger value. The curvature of zero value happened in the reflector cup with 31° slanting angle and the flatness of phosphor slurry upper interface is about 2 μm. This trend agrees well with the simulation result. Fig. 6 reveals that the sections of phosphor layers in simulations and experiments. Fig. 6(a) shows the simulation results. Fig. 6(b) shows the experimental results. It can be found that the simulation results agree well with the experimental results. Both the numerical and experimental results reveal the same rule that the flat phosphor layer can be gained when the slanting angle is equal to the contact angle of phosphor slurry on side wall. The rule can be used to design reflector cup for phosphor conformal coating by dispensing method.

The optical parameter ACU of LED modules with different reflector cup slanting angles were measured. The experimental results are shown in Fig. 7. From the Fig. 7, it can be seen that the ACU is the best when the slanting angle equals 31° and the phosphor geometry is flat. Therefore, the uniform phosphor distribution can improve the ACU in this kind of reflector cup packaging structure. However, it must be mentioned that besides the phosphor geometry, the LED chip type and size, and the lens size all affect the optical performance. The optimal phosphor geometries depend on the detailed packaging structures and there are other appropriate phosphor geometries for different LED packaging structure [4]. Due to the flexiblility of the present method to control the phosphor geomtry, the present idea of phosphor geometry control by structure design can also be applied in other LED packaging structure.

VII. Conclusion

The simulations and experiments on phosphor slurry dispensing in reflector cups with different slanting angles were conducted. The comparison revealed that they were in agreement. Different phosphor geometries were obtained in reflector cups with different slanting angles. The results showed that when the slanting angle is equal to the contact angle, the phosphor layer is flat. The flatness of phosphor layer is high enough in the experiment and it could meet the requirement of the LED conformal coating. Thereby, through controlling the slanting angle of the small reflector cup with consideration of the phosphor contact angle at substrate, a uniform phosphor distribution is able to be gained by conventional dispensing. Due to the flexibility of realizing different phosphor geometries, the present method would inspire better means to realize other appropriate phosphor geometries for different LED packaging styles.

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