Study on the Optical Properties of Conformal Coating Light-Emitting Diode by Monte Carlo Simulation

Run Hu, Xiaobing Luo, and Sheng Liu

***Abstract*—The light extraction efficiency (LEE), correlated color temperature (CCT), and angular color uniformity (ACU) of the conformal coating phosphor silicone gel were investigated by Monte Carlo ray-tracing simulations. Relative to the conventional dispensing method, the conformal coating method can make the light-emitting diode (LED) module obtain better optical properties. It was found that the thickness of the phosphor layer in conformal coating was a key factor determining the optical performance. The thickness could be optimized for good optical properties. The optimal thickness is around 50–70 μm when taking LEE, CCT, and ACU into consideration.**

***Index Terms*—Angular color uniformity (ACU), correlated color temperature (CCT), light-emitting diodes (LEDs), Monte Carlo simulation, phosphor-conversion.**

DUE to the numerous advantages over traditional lighting sources, LEDs have been widely used in many areas, such as backlighting for liquid crystal display (LCD), headlamps for automobiles, road lamps and even general indoor lighting fixtures [1]–[4]. In these applications, the superior optical properties of white LEDs, such as LEE, CCT and ACU, are highly demanded [5]–[7]. For the phosphor-converted white LEDs, since the geometry of the phosphor layer plays an important role in determining the optical performances, the phosphor coating is a key process in LED packaging [8], [9]. To overcome the drawbacks of the conventional dispensing method, conformal coating method was developed to improve the optical quality of white LEDs. Conformal coating can be realized by electrophoresis [10], slurry, pulsed spray [11], settling [12], evaporating solvent [13], and wafer level coating [14]. As far as we are concerned, people usually think the conformal coating method is good for high performance and the thickness of the phosphor layer in conformal coating process is an important factor, but there are few literatures involved the mechanism to explain why conformal coating method is better. In this letter, we first simulated the phosphor layer coated by both conventional dispensing method and conformal coating method. It was found conformal coating method led to better optical performance. The conformal coating phosphor layers under different thickness were then examined, and the simulation results about LEE, CCT and ACU of LED modules were obtained and discussed.

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R. Hu is with the School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China.

X. Luo is with the School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China, and also with the Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: luoxb@mail.hust.edu.cn).

S. Liu is with the Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China.

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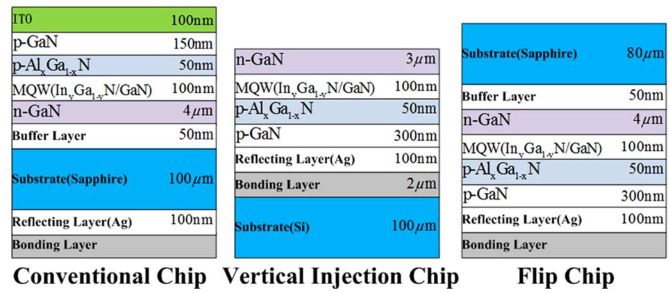

Fig. 1. Typical structures of three types of blue chips.

In order to study the adjustability of conformal coating method on various chip structures, three blue chips including conventional chip, vertical injection chip and flip chip were simulated. Fig. 1 shows typical structures of three GaN based blue LED chips [15]. Thickness and compositions of LED materials in each structure were given and the chip sizes were all 1×1 mm to refer to high power LEDs. The top and bottom surfaces of the Multiquantum Well (MQW) were set as luminescent surfaces with Lambertian light distribution. The electrode pattern was neglected for simplicity. The absorption coefficients and refractive indices for p-GaN, MQW, and n-GaN were 5 mm^{-1}, 8 mm^{-1} and 5 mm^{-1} and 2.45, 2.54, and 2.42, respectively [7], [16]. The scattering coefficient of the reflecting layer (Ag) was set as 0.95. By setting the absorption coefficients and refractive indices of the materials, the precise model of GaN based conventional LED chip was successfully achieved. As shown in Fig. 2, the simulation models included precise LED chips, phosphor silicone gel layer, a submount and a semispherical detector. The phosphor layer in Fig. 2 was coated by conformal coating method, therefore the thickness on all the surfaces was uniform. As for conventional dispensing method, the phosphor layer could be modelled as a spherical cap with the same amount of phosphor silicone gel as that in conformal coating method [17]. The refractive index and scattering index of the phosphor silicone gel are very important as they determine the optical properties. The two indices vary with the concentration of the phosphor in the silicone gel. In our simulations, the concentration of the phosphor was 0.35 g/cm^3. The absorption and scattering coefficients of phosphor were

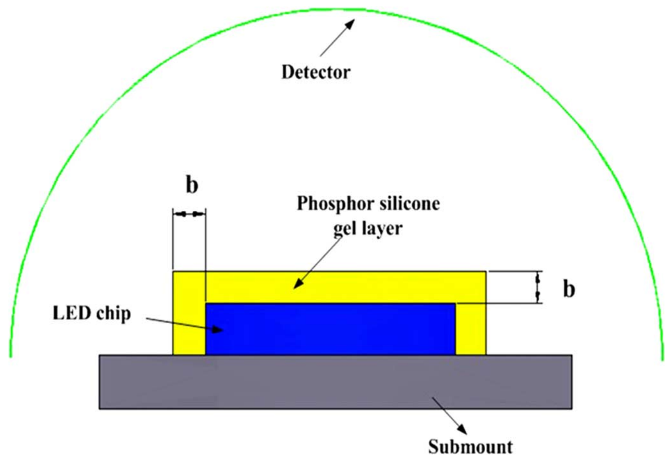

Fig. 2. Sketch of the simulation model with conformal coating phosphor layer.

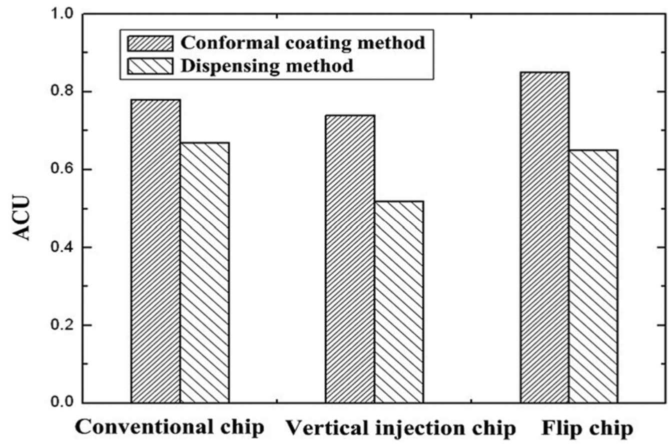

Fig. 4. ACU comparison under different coating methods with three types of blue LED chips.

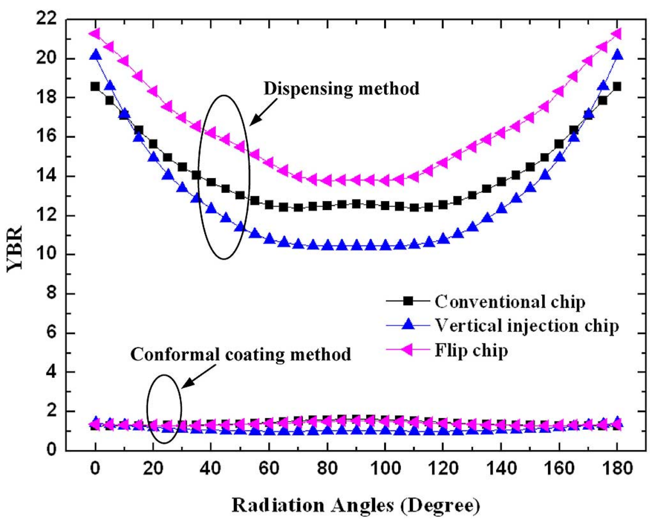

Fig. 3. YBR comparison at the whole radiation angles.

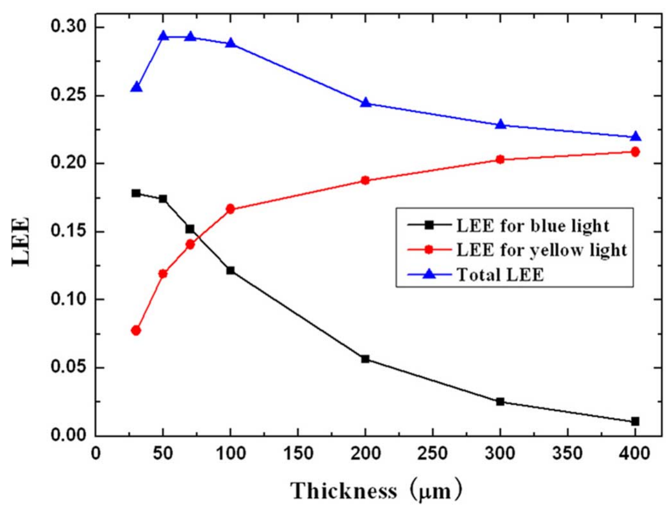

Fig. 5. LEE variations under different thicknesses of phosphor layer.

3.18 and 5.35 mm^{-1} for blue light and 0.03 and 7.74 mm^{-1} for yellow light [18]. Silicon was selected as the material of the submount.

For modelling the light conversion process, the rays of blue and yellow light were simulated separately by Monte Carlo ray-tracing method. For simplicity, specific wavelengths of 465 nm and 555 nm were used in the calculation to represent blue and yellow light respectively [18]. As for the blue light, the top and bottom surfaces of the MQW layer were the luminescent surfaces; as for yellow light, the phosphor layer firstly absorbed the blue light and then re-emitted yellow light. The optical models have been validated and were used to simulate the LEDs chips accurately in our previous studies [3], [4], [15]–[18].

We introduce a yellow-blue ratio (YBR) to illustrate the variation of CCT [18]. The higher YBR is, the lower CCT is. The ACU could be calculated as the ratio of minimum YBR to maximum YBR in the whole radiation angles ranging from 0 to 180 degrees [7].

The comparisons of the optical properties of LED modules produced by conventional dispensing method and conformal coating method were conducted at first. In Fig. 3, it is obvious that the YBR of dispensing method is much larger than that of conformal coating method. The YBR curvatures of the dispensing method rise at the sides, so there exists yellow rings at the edges of the radiation pattern. As shown in Fig. 4, the ACUs of conformal coating method are larger than those of dispensing method for all three types of chips, which validates the uniformity of YBR shown in Fig. 3. The above phenomena can be explained as follows. For the conventional dispensing coating method, the thickness variations of phosphor silicone gel cause nonuniform spatial distribution of the blue light and the re-emitted yellow light. On the other hand, the uniform thickness by conformal coating method overcomes these drawbacks and improves the performance. This is probably one reason why most famous LED manufacturers spend great efforts on developing conformal coating technology.

In Figs. 5 to 7, we simulated the optical performance of phosphor layer made by conformal coating method under different thicknesses, i.e., 30 μm, 50 μm, 70 μm, 100 μm, 200 μm, 300 μm and 400 μm. Fig. 5 shows the LEE variations under different thicknesses. It is noticed that with the increase of the thickness, the LEE for blue light decreases and the LEE for yellow light increases. This is because when the phosphor layer grows thicker, more blue light will be absorbed and more yellow

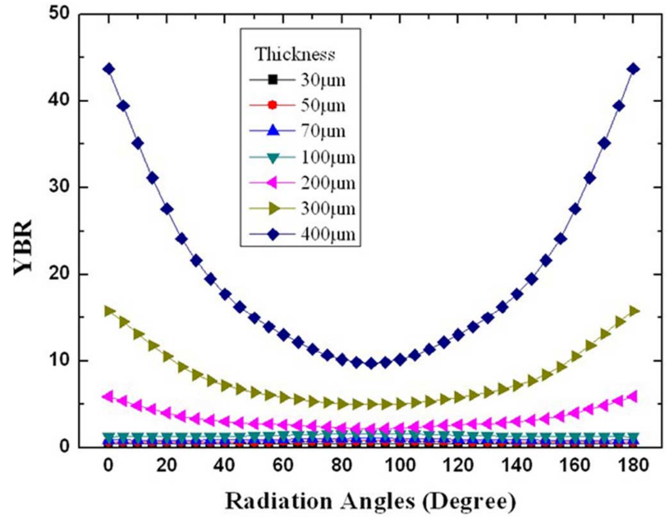

Fig. 6. YBR variations under different thicknesses of phosphor layer at whole radiation angles.

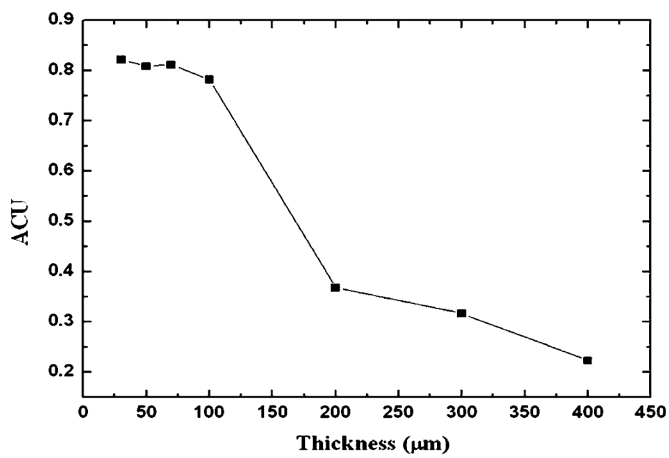

Fig. 7. ACU variations under different thicknesses of phosphor layers.

light will be re-emitted. But the total LEE increases at first and then decreases in the end, which means the increase of LEE for yellow light can not compensate the decrease of LEE for blue light. Figs. 6 and 7 show the variations of YBR and ACU respectively. It is observed that with the increase of thickness, the YBR increases (i.e., CCT decreases) and ACU decreases greatly. This will produce the yellow rings at the edges of the radiation patterns as a result. It is therefore confirmed that optical performance varies when the thickness of conformal coating phosphor layer changes. ACU and LEE of the LED are optimized when the thickness is around 50 to 70 μm.

In conclusion, based on the optical simulations, the adoption of conformal coating method could improve the optical performance compared with the conventional dispensing method but the thickness of conformal coating phosphor layer plays an important role in determining the optical properties of phosphor-converted white LEDs. In our simulations, the optimal thickness is around 50–70 μm when taking LEE, CCT and ACU into consideration.

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