Improving the Angular Color Uniformity of Hybrid Phosphor Structures in White Light-Emitting Diodes

Kuo-Ju Chen, Hau-Vei Han, Bing-Cheng Lin, Hsin-Chu Chen, Min-Hsiung Shih, *Member, IEEE*, Shih-Hsuan Chien, Kuan Yu Wang, Hsin-Han Tsai, Peichen Yu, Po-Tsung Lee, Chien-Chung Lin, *Member, IEEE*, and Hao-Chung Kuo, *Senior Member, IEEE*

***Abstract*— This letter examines a hybrid phosphor structure for white light-emitting diodes. The hybrid phosphor structure produces more efficient luminosity and more uniform angular correlated color temperature (CCT) than the conventional dispensing method. The experimental results show that the CCT deviation improved from 453 to 280 K between −70° and 70°. This was likely caused by the large blue light divergent angle. The lumen output produced was higher than that produced by dispense and conformal phosphor structures. Therefore, the results show that the hybrid phosphor structure can be used in solid-state lighting.**

***Index Terms*— Color distribution, light-emitting diodes (LEDs), packaging, phosphor.**

I. Introduction

White light-emitting diodes (LEDs) have been developed and improved to the extent that they may replace traditional light sources, such as mercury lights and halogen lamps, in solid-state lighting (SSL) [1]. Usually, blue chip and yellow phosphor are combined to produce white-light LEDs for SSL [2]. To increase the adoption of LEDs, high-power white LEDs have been developed to enhance quantum or lumen efficiency [3]. Researches have shown that large electron-hole wavefunction overlap quantum wells and the surface plasmon approach increase internal quantum efficiency [4], [5]. Enhanced light extraction by internal reflection (ELiXIR) has been proposed to increase extraction efficiency. ELiXIR uses internal reflection to extract light from reflectors and enhance light extraction [6]. Luo *et al.* [7] used a hemisphere-shaped encapsulation to increase luminous efficiency and reduce the total internal reflection losses.

The phosphor-dispensing method is used to fabricate white LEDs because it is low cost and easy to control. This method, however, focuses on a convex surface, resulting in a heterogeneous angular correlated color temperature (CCT) [8]. A nonuniform angular CCT causes the yellow ring phenomenon and generates harmful effects when using white LEDs for general lighting applications. This phenomenon may be attributed to different blue and yellow light extracted from the package and causes ineffective color mixing in white LEDs [9]. To solve this problem, a patterned remote phosphor structure is used to maintain a phosphor coating-free perimeter, extracting more blue light, especially at a larger angle [10]. A conformal phosphor structure was fabricated by stacking phosphor layers to obtain a uniform CCT [11]. Backscattering light from the phosphor layer, however, contributes to 60% of the luminous flux [12]. This backscattering light is reabsorbed by the blue chip and reduces the luminous efficiency. Although researches have reduced backscattering light, this did not produce a uniform angular CCT. Therefore, maintaining a balance between luminous efficiency and uniform angular CCT is crucial for LED packages.

This letter develops a hybrid phosphor structure to maintain luminous efficiency and a uniform angular CCT by combining dispensing and conformal phosphor structures. The CCT deviation of the hybrid phosphor structure was more uniform than that of dispensing phosphor structures, indicating that the structure can be used in high-quality white LEDs.

II. Experimental Process

The pulse spray coating (PSC) and dispensing methods were used to fabricate the hybrid phosphor structure. For the experiment, the phosphor slurry was sprayed onto a lead frame using the PSC method. This slurry formed a uniform phosphor layer for easily controlling the CCT. Phosphor powders were then blended with silicone and dispensed onto the lead frame. A schematic diagram of the three packaging methods is shown in Fig. 1(a)–(c). The chip size of the blue chip was 600 μm × 600 μm and its emission wavelength was ~450 nm. Fig. 1(d) shows a scanning electron microscope (SEM) image of

Manuscript received July 19, 2013; revised July 31, 2013; accepted August 3, 2013. Date of publication September 9, 2013; date of current version September 23, 2013. This work was supported by the National Science Council in Taiwan under Grant NSC102-3113-P-009-007-CC2, and Grant NSC-102-2221-E-009-131-MY3. The review of this letter was arranged by Editor O. Manasreh.

K.-J. Chen, H.-V. Han, B.-C. Lin, S.-H. Chien, H.-H. Tsai, P. Yu, P.-T. Lee, and H.-C. Kuo are with the Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan (e-mail: hckuo@faculty.nctu.edu.tw).

H.-C. Chen is with the Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan, and also with the Electronics and Optoelectronics Research Laboratories, Industrial Technology Research Institute, Hsinchu 30010, Taiwan.

M.-H. Shih is with the Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan, and also with the Research Center for Applied Sciences, Taipei 115, Taiwan (e-mail: mhshih@gate.sinica.edu.tw).

K. Y. Wang and C.-C. Lin are with the Institute of Photonic System, National Chiao Tung University, Tainan 711, Taiwan.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LED.2013.2278336

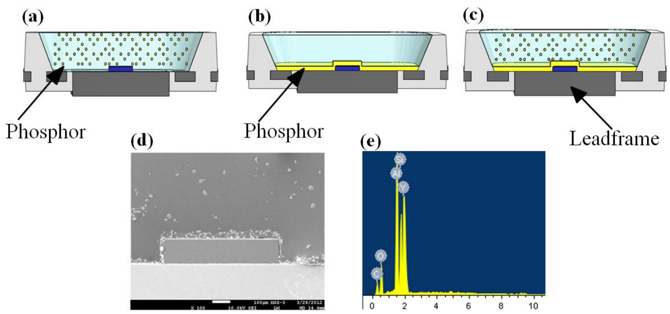

Fig. 1. Schematic diagram of three type packaging methods. (a) Dispense. (b) Conformal. (c) Hybrid phosphor structure. (d) SEM images of cross section of hybrid phosphor structure. (e) EDS of the silicone and YAG compound.

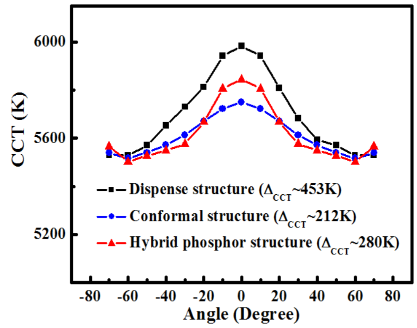

Fig. 2. Angular-dependent CCL of three type packages.

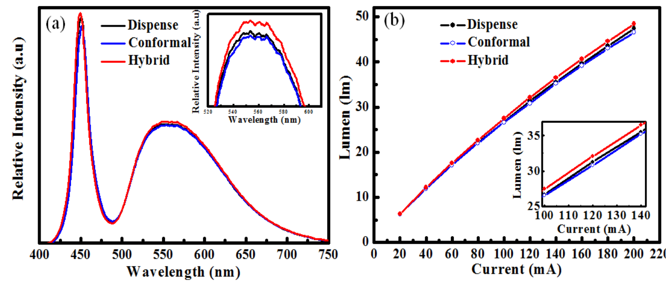

Fig. 3. (a) Emission spectra. (b) Lumen output of dispense, conformal, and hybrid phosphor structure from 20 to 200 mA.

the cross section of the hybrid phosphor structure, which could distinguish the interface layer clearly by the PSC and dispensing method. The PSC method phosphor layer was ~25-μm thick and the dispensing method phosphor layer was randomly distributed. $Y_3Al_5O_{12}$ (YAG) was used in the experiment and was analyzed with an energy dispersive spectrometer (EDS), as shown in Fig. 1(e). The CCTs of the hybrid, dispense, and conformal phosphor structures were maintained at 120 mA.

III. Results and Discussion

To understand the LED CCT characteristics, the CCT deviation must be calculated as follows:

$$\Delta\text{CCT} = \text{CCT(Max)} - \text{CCT(Min)} \tag{1}$$

where CCT(Max) and CCT(Min) represent the maximal CCT at the 0° of viewing angle and minimal CCT at the 70° of viewing angle, respectively. The angular-dependent CCTs of the three package types are shown in Fig. 2. The CCT deviations from −70° to 70° for the dispense, conformal, and hybrid phosphor structures were 453, 212, and 280 K, respectively. The yellow ring phenomenon was generated in the dispense phosphor structure because of the differing large and central degree blue and yellow light ratios [13]. The hybrid phosphor structure produced higher uniformity than the dispense phosphor structure did. Although the delta CCT in the hybrid structure was slightly higher than in the conformal structure, white LEDs produced more uniform angular CCTs. The emission spectra and lumen output of the three structures are shown in Fig. 3. The differently structured LEDs produced the same CCT of ~5500 K. The blue and yellow emissions from the hybrid structure produced the most radiation flux. The phosphor enhanced the yellow band, producing higher luminous efficiency. At a driving current of 120 mA, the lumen output of the hybrid structure was 4.25% and 2.57% more than that produced by the dispense and conformal phosphor structures, respectively. Fig. 3(b) shows the lumen output of the three types of structures as a function of a driving current between 20 and 200 mA. As the driving current increased, the lumen output differences between the three structures increased.

Some backscattering light is lost inside the package of the conformal phosphor structure, decreasing the lumen flux [14], [15]. The hybrid structure has a thinner phosphor layer than the conformal structure. This reduces the reflection of the backscattering light, enhancing the lumen output. The refractive indexes (RI) of silicone and phosphor are 1.4 and 1.8, which are obtained from [16]. Thus, the RI of the phosphor layer with silicone is calculated as follows [15]:

$$\text{RI} = V_1\text{RI}_1 + V_2\text{RI}_2 \tag{2}$$

where V_1 and V_2 are the concentrations of the materials, which is calculated in the weight ratio of the materials. For the hybrid structure, the mixing ratio of the phosphor to silicone layer in the conformal and dispensing methods were 50 and 2.5 wt. %, respectively. Therefore, the RIs of the phosphor layer in each layer were 1.6 and 1.41. The RI of the dispensing method phosphor layer was 1.42. This indicates that the hybrid structure performed better than the dispensing method because of the RI variation between the chip and phosphor layers. The hybrid structure has the gradual refractive index from the PSC structure to the dispense structure, resulting in decreasing the reflection loss in the interface. This indicates that the hybrid structure is suitable for light output and provides better optical characteristics.

To discuss the improvement of the uniform CCT for dispense and hybrid phosphor structures, the relative blue intensities of two structures are shown in Fig. 4. The hybrid structure produced a larger blue light divergent angle than the dispense structure. As the large blue light angle increased, the difference between the central and large angle decreased. Therefore, the hybrid structure enhanced the blue light intensity in the large angle, improving the light quality of white LEDs.

The chromaticity coordinate shift of the hybrid structure at a current regulation from 20 to 200 mA is shown in Fig. 5. With the increase in current from 20 to 200 mA, the chromaticity

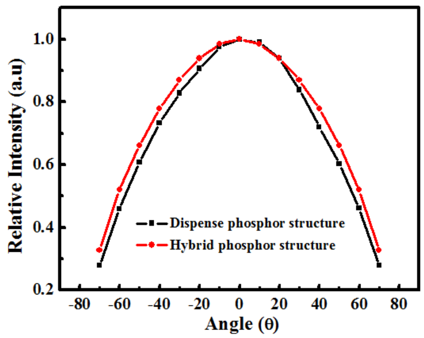

Fig. 4. Relative blue intensity of dispense and hybrid phosphor structure.

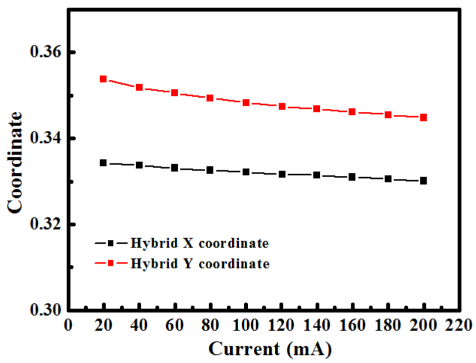

Fig. 5. Chromaticity coordinate of dispense and hybrid phosphor structure at the current from 20 to 200 mA.

coordinate shift varied steadily and the illumination characteristics of the hybrid structure were nearly the same. Therefore, the hybrid structure provides an appropriate solution for the white LEDs.

IV. Conclusion

This letter develops a hybrid phosphor structure to produce highly uniform white LEDs using the pulse spray and dispensing methods. The CCT deviation from $-70°$ to $70°$ produced by the hybrid phosphor structure was 280 K that is better than the 453 K produced by the conventional dispensing method at 120 mA. This improvement occurred because the blue light divergent angle in the hybrid structure was larger than in the dispense structure. The lumen output of the hybrid structure at a driving current of 120 mA was 4.25% and 2.57% more than that produced by dispense and conformal phosphor structures, respectively. The hybrid phosphor structure produced a high luminous efficiency and a uniform angular CCT, providing a suitable SSL solution.

References

[1] E. F. Schubert and J. K. Kim, "Solid-state light sources getting smart," *Science*, vol. 308, no. 5726, pp. 1274–1278, May 2005.

[2] C. C. Lin and R. S. Liu, "Advances in phosphors for light-emitting diodes," *J. Phys. Chem. Lett.*, vol. 2, no. 11, pp. 1268–1277, May 2011.

[3] C. H. Wang, D. W. Lin, C. Y. Lee, *et al.*, "Efficiency and droop improvement in GaN-based high-voltage light-emitting diodes," *IEEE Electron Device Lett.*, vol. 32, no. 8, pp. 1098–1100, Aug. 2011.

[4] C. H. Lu, C. C. Lan, Y. L. Lai, *et al.*, "Enhancement of green emission from InGaN/GaN multiple quantum wells via coupling to surface plasmons in a two-dimensional silver array," *Adv. Funct. Mater.*, vol. 21, no. 24, pp. 4719–4723, Dec. 2011.

[5] M. Funato, T. Kondou, K. Hayashi, *et al.*, "Monolithic polychromatic light-emitting diodes based on InGaN microfacet quantum wells toward tailor-made solid-state lighting," *Appl. Phys. Lett.*, vol. 1, pp. 011106-1–011106-3, Jan. 2008.

[6] S. C. Allen and A. J. Steckl, "ELiXIR-solid-state luminaire with enhanced light extraction by internal reflection," *J. Display Technol.*, vol. 3, no. 2, pp. 155–159, Jun. 2007.

[7] H. Luo, J. K. Kim, E. F. Schubert, *et al.*, "Analysis of high-power packages for phosphor-based white-light-emitting diodes," *Appl. Phys. Lett.*, vol. 86, no. 24, pp. 243505-1–243505-3, Jun. 2005.

[8] M. R. Krames, O. B. Shchekin, R. Mueller-Mach, *et al.*, "Status and future of high-power light-emitting diodes for solid-state lighting," *J. Display Technol.*, vol. 3, no. 2, pp. 160–175, Jun. 2007.

[9] H. C. Chen, K. J. Chen, C. C. Lin, *et al.*, "Improvement in uniformity of emission by ZrO_2 nano-particles for white LEDs," *Nanotechnology*, vol. 23, no. 26, p. 265201, Jul. 2012.

[10] H. C. Kuo, C. W. Hung, H. C. Chen, *et al.*, "Patterned structure of REMOTE PHOSPHOR for phosphor-converted white LEDs," *Opt. Exp.*, vol. 19, no. S4, pp. A930–A936, Jul. 2011.

[11] H. T. Huang, C. C. Tsai, and Y. P. Huang, "Conformal phosphor coating using pulsed spray to reduce color deviation of white LEDs," *Opt. Exp.*, vol. 18, no. S2, pp. A201–A206, Jun. 2010.

[12] N. Narendran, Y. Gu, J. P. Freyssinier-Nova, *et al.*, "Extracting phosphor-scattered photons to improve white LED efficiency," *Phys. Status Solidi A*, vol. 202, no. 6, pp. 60–62, May 2005.

[13] Z. Liu, S. Liu, K. Wang, *et al.*, "Optical analysis of color distribution in white LEDs with various packaging methods," *IEEE Photon. Technol. Lett.*, vol. 20, no. 24, pp. 2027–2029, Dec. 15, 2008.

[14] Y. Shuai, N. T. Tran, and F. G. Shi, "Nonmonotonic phosphor size dependence of luminous efficacy for typical white LED emitters," *IEEE Photon. Technol. Lett.*, vol. 23, no. 9, pp. 552–554, May 2011.

[15] Y. H. Won, H. S. Jang, K. W. Cho, *et al.*, "Effect of phosphor geometry on the luminous efficiency of high-power white light-emitting diodes with excellent color rendering property," *Opt. Lett.*, vol. 34, no. 1, pp. 1–3, Jan. 2009.

[16] S. Yun, Y. He, N. T. Tran, *et al.*, "Angular CCT uniformity of phosphor converted white LEDs: Effects of phosphor materials and packaging structures," *IEEE Photon. Technol. Lett.*, vol. 23, no. 3, pp. 137–139, Feb. 2011.