Enhanced Luminous Efficiency of WLEDs Using a Dual-Layer Structure of the Remote Phosphor Package

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***Abstract*—This study demonstrates how the insertion of a thin silicone layer into a dual-layer remote phosphor structure enhances light extraction in white light-emitting diodes (WLEDs). In the experiment, a dual-layer phosphor structure yielded a higher intensity of blue and yellow components than a conventional structure. Moreover, the lumen flux was 5% higher than a conventional remote phosphor package at the same correlated color temperature (CCT). Using a TFCalc32 simulation, the electric field intensity was calculated for different thicknesses of the dual-layer remote phosphor structures, and the enhanced use of blue rays was verified. Additionally, the dual-layer structure reduces chromaticity deviations as the driving current increases.**

***Index Terms*—Coatings, GaN, light-emitting diodes, optoelectronic devices, packaging, phosphor.**

I. INTRODUCTION

PHOSPHOR-CONVERTED white light-emitting diodes (WLEDs) are a promising light source because of their small size, high energy efficiency, low cost, and color stability [1]–[4]. WLEDs apply the principle of complementary colors: Blue light from a blue chip is combined with yellow light from phosphor [5]. WLEDs have the potential to be used in solid-state lighting, but their luminous efficiency must be enhanced [6]. Generally, freely dispersed coating is the most common method used to fabricate white light. In this process, transparent encapsulated resin is combined with phosphor powder and is dispersed on the phosphor package. Although this approach allows the thickness of the phosphor layer to be controlled easily and reduces much of the cost, it does not produce high-quality WLEDs [7]. Therefore, the conformal coating method can be used as an alternative. This method distributes colors uniformly, resulting in angular homogeneity of correlated color temperature (CCT) [8]. However, the disadvantage of a conformal phosphor structure is the backscattering effect, which reduces luminous efficiency.

Previous studies have demonstrated the concept of separating the chip and the phosphor layer of remote phosphor structures [9], [10]. The enhanced light extraction internal reflection (ELiXIR) structure, which uses a polymer hemispherical shell lens with interior phosphor coating, is known to increase extraction efficiency [11]. Furthermore, an air-gap embedded structure can enhance luminous efficiency by reflecting downward light [12].

In addition to the structure of the package, the concentration of phosphor plays an important role on luminous efficiency. The re-absorption loss in the phosphor layer raises when the phosphor concentration increases. Therefore device luminous efficiency would be degraded, especially at lower CCTs [13]. Similarly, Narendran *et al.* demonstrated that high occurrence of scattering and reflecting also reduces luminous efficiency [14]. Therefore, it is essential to enhance the emission of blue and yellow rays and reduce the amount of light lost from backscattering and reflection.

In this study, a dual-layer phosphor structure was employed in a remote phosphor package to increase light output compared to a conventional remote phosphor structure at the same CCT. The experimental results indicate that a dual-layer phosphor structure yielded higher light transmission than a conventional phosphor structure. Furthermore, a TFCalc32 simulation demonstrated that the power intensity between the silicone layer and the phosphor layers was enhanced. The chromaticity coordinate deviations were also improved by increasing the driving current of the LED.

II. EXPERIMENT

In this experiment, a dual-layer structure was fabricated using the pulse spray coating method, which creates a uniform phosphor layer [15]–[17]. The phosphor powder was YAG:Ce^{3+} with the particle size of 13 $\mu\mathrm{m}$. An InGaN-based blue LED with a peak emission wavelength of approximately 450 nm was bonded on silver glue with gold wire in a lead-frame package. The schematic cross-sectional view of a dual-layer remote phosphor structure is shown in Fig. 1. The samples were fabricated

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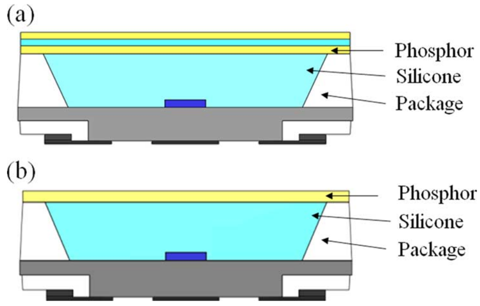

Fig. 1. Schematic cross-sectional view of (a) dual-layer and (b) conventional remote phosphor structures.

by the following steps: First, the silicone encapsulant was filled in a commercial plastic lead-frame package.

The pulse spray coating method was then employed to spray phosphor and silicone binder on the surface of each layer of the remote phosphor structure. Finally, phosphor was sprayed on top of the remote phosphor structure to obtain the same CCT as the conventional remote phosphor structure. In the experiment, the total density of the phosphor in the experiment is set up as $6\ \mathrm{mg/cm}^2$ for all the samples and the density of phosphor is approximately 1.0 mg/cm2 from one spray coating step. To obtain the better luminous efficiency of the devices, the thickness of the top and bottom phosphor layers was adjusted. Thus, the ratio of the sample A, B, and C represent the different density of phosphor layer in the dual-layer structure.

III. RESULTS AND DISCUSSION

The effect of changing the ratios of the first and the second layers of the phosphor structure is shown in Fig. 2(a), which represents the transmission of the different samples in relation to the wavelength. The remote phosphor package composed of a dual-layer structure yielded the highest transmission at wavelengths ranging from 400 to 800 nm. The sample containing the optimized ratio, Sample C, produced greater transmission than the other samples in the experiment. Enhanced transmission means that the LED device emits more photons, reducing light reflection and increasing light output.

The drop in intensity at a wavelength of 460 nm can be attributed to the absorption of phosphor. Fig. 2(b) shows a comparison of the lumen enhancement of the different samples. Sample C exhibits a 5% lumen enhancement over the conventional remote phosphor structure. The transmission measurement verified that this was the result of increased extraction of rays in the yellow band. Therefore, increasing light extraction is critical to improving the luminous efficiency of LED structures.

The emission spectra of Sample C and the conventional remote phosphor structure are shown in Fig. 3(a). These structures had the same CCT at approximately 5400 K, and both operated at a current of 120 mA. The dual-layer structure produced a higher intensity in blue and yellow components and yielded a higher light output than the conventional structure. Fig. 3(b) shows the luminous flux and the luminous efficiency of both Sample C and the conventional remote phosphor structure, each driven at currents from 20 to 420 mA. Since the optical trapping in the phosphor layer degrades device luminous efficiency due to the self-absorption of phosphor [18]. Comparing to the reference structure (the single-layer structure), the dual-layer structure can reduce the optical trapping of the phosphor layer, and increase luminous flux.

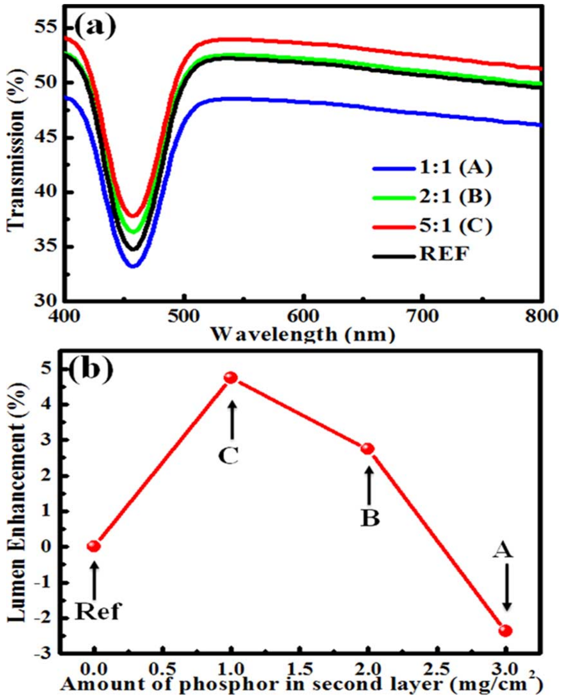

Fig. 2. (a) The transmission of the different ratios of phosphor layers as wavelength increases (b) The lumen enhancement of the amount of phosphor in the second layer under the regular operation current.

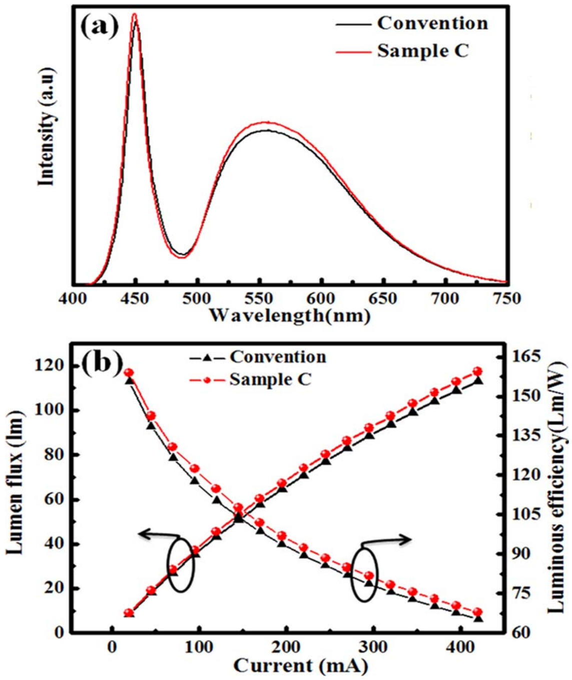

Fig. 3. (a) The emission spectra (b) Luminous flux and luminous efficiency of the dual-layer and the conventional remote phosphor structures driven at currents from 20 to 420 mA.

In general, yellow rays scatter in all directions when pumped by a blue ray. Consequently, most of the downward rays are lost

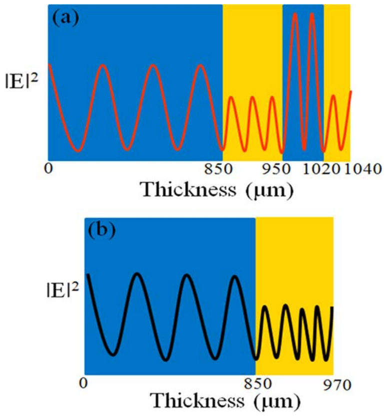

Fig. 4. Thickness-dependent $|\mathrm{E}|^2$ of (a) the dual-layer and (b) the conventional LEDs by TFCalc32 simulation.

in the package and light output is reduced. Conversely, in the dual-layer phosphor structure, a thin silicone layer with a low refractive index is inserted into the phosphor layer. The refractive indices of the phosphor and silicone encapsulants used in this study were 1.8 and 1.4, respectively.

According to Snell's law, the total reflection angle needed to be increased because of the phosphor/encapsulant layer. Reflecting the blue ray could improve its use because it increases the probability of phosphor excitation [12]. Therefore, a TFCalc32 simulation was employed to observe the actual effect of blue photons coupling to the phosphor layer.

In the simulation, the lengths of the first and second silicone layers were approximately 850 $\mu\mathrm{m}$ and 70 $\mu\mathrm{m}$, respectively. The lengths of the first and second phosphor layers were approximately 100 $\mu\mathrm{m}$ and 20 $\mu\mathrm{m}$, respectively. Regarding the conventional phosphor structure, the silicone layer was approximately 850 $\mu\mathrm{m}$, and the phosphor layer was roughly 120 $\mu\mathrm{m}$. These layers were simultaneously subjected to 450 nm light by a GaN LED. The results of this simulation are displayed in Fig. 4, which shows the electric field intensity for the different thicknesses of dual-layer and conventional phosphor structures. The electric field intensity in the second silicone layer was higher than in the conventional phosphor structure. Therefore, the advantage of the former structure is that the incident blue ray can be trapped in the lower refractive index medium, increasing the absorption ability of the phosphor layer and transferring more yellow rays than the conventional structure.

The power intensity of dual-layer and conventional remote phosphor structures in WLEDs can be calculated as shown in (1)–(2) at the bottom of the page, where n_s and n_p are the refractive indices silicone and phosphor, and $|\mathrm{E}|^2$ is the electric field intensity.

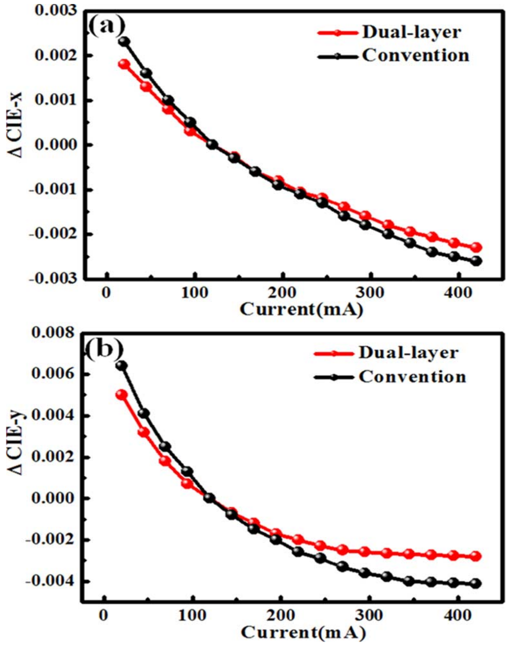

Fig. 5. The chromaticity deviations of (a) CIE X coordinate and (b) CIE Y coordinate with dual-layer and conventional remote phosphor structures at different LED injection currents.

According to (1) and (2), the power intensities of the dual-layer and conventional remote phosphor structures were 20.2% and 13.8%, respectively, at a wavelength of 450 nm. Furthermore, the power intensity reached a maximum of 46.4%, an enhancement that mainly occurred between the thin silicone layer and the phosphor layers. The enhanced electric field intensity allows more blue rays to be trapped and raises the probability of phosphor excitation. In turn, this recycling of photons allows for the production of more yellow rays.

Fig. 5 shows the chromaticity deviations of (a) CIE X coordinate and (b) CIE Y coordinate with dual-layer and conventional remote phosphor structures from 20 to 420 mA, the light quality of the dual-layer and conventional remote phosphor structures can be compared. As the current increased, incident blue rays were generated from the blue chip and converted the phosphor layer to yellow photons. Therefore, the manner in which the phosphor layer is used determines the quality of color mixing in WLEDs, especially at different currents. The lowest-

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$$W=\frac{\int_{850\ \mu\mathrm{m}}^{970\ \mu\mathrm{m}} n_p^2\times|E|^2dT}{\left[\int_{0}^{850\ \mu\mathrm{m}} n_s^2\times|E|^2dT+\int_{850\ \mu\mathrm{m}}^{970\ \mu\mathrm{m}} n_p^2\times|E|^2dT\right]} \tag{1}$$

$$W=\frac{\int_{850\ \mu\mathrm{m}}^{950\ \mu\mathrm{m}} n_p^2\times|E|^2dT+\int_{950\ \mu\mathrm{m}}^{1020\ \mu\mathrm{m}} n_s^2\times|E|^2dT+\int_{1020\ \mu\mathrm{m}}^{1040\ \mu\mathrm{m}} n_p^2\times|E|^{2}dT}{\left[\int_{0}^{850\ \mu\mathrm{m}} n_s^2\times|E|^2dT+\int_{850\ \mu\mathrm{m}}^{950\ \mu\mathrm{m}} n_p^2\times|E|^2dT+\int_{950\ \mu\mathrm{m}}^{1020\ \mu\mathrm{m}} n_s^2\times|E|^2dT+\int_{1020\ \mu\mathrm{m}}^{1040\ \mu\mathrm{m}} n_p^2\times|E|^2dT\right]} \tag{2}$$

quality color-mixing structure occurred in the conventional remote phosphor structure. Conversely, the dual-layer structure exhibited less color deviations because it better uses the phosphor layer to maintain almost the same CCT at different currents. Therefore, the dual-layer remote phosphor structure not only enhanced the luminous flux of the WLED, but also provided greater stability of CIE coordinates as the driving current increased.

IV. Conclusion

This study demonstrates that a dual-layer remote phosphor structure enhances the luminous efficiency of WLEDs. Inserting a thin silicone layer into the phosphor layer and optimizing the ratio of the different layers increased transmission, thereby increasing light output. Moreover, TFCalc32 simulation results verified that more incident blue rays were reflected in the thin silicone layer of the dual-layer structure, increasing the probability of phosphor excitation and producing higher yellow components in the emission spectra. Accordingly, the luminous flux of the dual-layer structure was 5% higher than that of the conventional remote phosphor package at a driving current of 120 mA. Finally, the dual-layer structure reduces chromaticity deviations as the driving current increases. These results establish WLEDs as a capable source of solid-state lighting.

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