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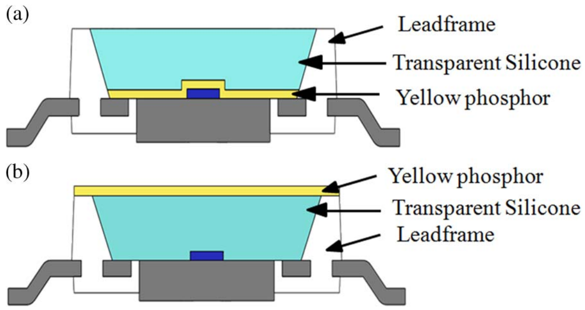

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Effect of the Thermal Characteristics of Phosphor for the Conformal and Remote Structures in White Light-Emitting Diodes

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Abstract: The influence of the thermal effect of phosphor for conformal and remote structures in white light-emitting diodes was investigated using the junction and phosphor temperatures. Comparing the measured temperatures with IR thermometer, the remote structure has a higher phosphor temperature than the conformal structure. This result indicates that the phosphor in the conformal structure has demonstrated superior conduction because of the high thermal conductivity in surrounding. Furthermore, thermal distribution in the simulation results has shown to have favorable agreement with the experimental results. Consequently, the lifetime measurement is shown to verify the results of the simulation and experiment for both structural types.

Index Terms: Light-emitting diodes, electro-optical devices, phosphor, package.

1. Introduction

Recently, white light-emitting diodes (LEDs) have attracted considerable attention because of the small size, high luminous efficiency, and longer lifetime of solid-state lighting (SSL) [1]–[4]. In particular, the advantage of being mercury-free is more environmentally friendly than conventional incandescent [5]. To apply SSL, developing a high-luminous and high-quality steady light source is necessary, especially in white LEDs. Currently, several methods are used to fabricate white light, of which the combination of a blue LED chip and yellow-emitting phosphor has been determined to be of higher luminous efficiency than others [6], [7]. The progress in GaN-based LEDs has enabled the further implementation of phosphor-based conversion material in white LEDs. Thus, it will be of relevance for the authors to provide a brief discussion on the recent progress in the GaN-based LEDs, which has enabled the use of this technology as the practical pump excitation sources in white LEDs. The advances include the progress in high IQE devices via charge separation suppression [8]–[11], improved IQE LEDs via defect reduction [12], [13], and novel LEDs with efficiency-droop suppression [14]–[17]. The conformal and remote phosphor structures of white

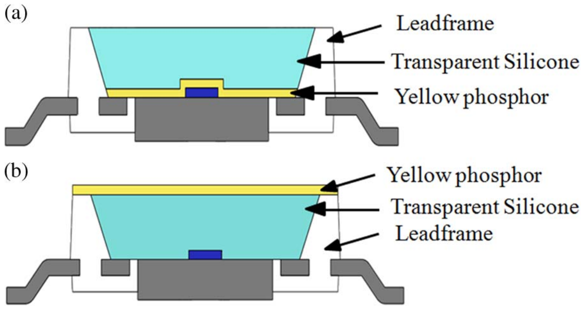

Fig. 1. Schematic diagrams of (a) conformal and (b) remote phosphor structure.

LEDs are fabricated by the combination of the blue and yellow light. The greatest difference between these structures is the position of the phosphor layer. In a conformal phosphor structure, the phosphor film is near the blue chip and most of the light transfers backward to the blue chip. This light would be reabsorbed by the chip and package and lead to a reduction in luminous efficiency. To decrease this backscattering phenomenon, the remote phosphor separates the phosphor layer from the blue chip and further improves luminous efficiency [18], [19]. The phosphor layer effect not only determines the performance of light extraction but influences luminous efficiency as well. Therefore, analyzing the phosphor layer influence on white LEDs is critical.

Numerous previous studies have discussed the influence of the phosphor layer on white LEDs. To increase luminous efficiency, the phosphor particle could be optimized to improve the back reflection light [20], [21]. Accordingly, Narendran *et al.* estimated that a significant portion of the down-converted light backscatters and reduces efficacy [22]. In addition, the backscattering light also converts into heat, thereby damaging the chip and the leadframe. Furthermore, the intensity of the phosphor decreases as the temperature increases, which is attributed to the nonradioactive transition from the excited states to the ground state [23]. Therefore, the influence of the thermal effect on phosphor is critical for the performance of white LEDs, and improving thermal management can increase the reliability of SSL devices [24]. More importantly, the junction temperature becomes the standard for determining the performance of white LEDs because the heat is also generated using the LED die [25], [26]. For phosphor, Hwang *et al.* [27] indicated that the phosphor layer temperature can influence the lifetime of white LEDs. In [28], the influence of phosphor in white LEDs have been studied, but there is no experimental study on the thermal effects of this LED structure. Therefore, to understand the influence of the thermal effect on white LEDs completely, the junction temperature as well as the phosphor temperature should be considered separately.

This study analyzed the thermal characteristics of conformal and remote phosphor structures in white LEDs by investigating specifically both the junction temperature and phosphor temperature. The IR thermometer was used to measure the actual temperatures of the phosphor layers in the conformal and remote structures. In particular, the phosphor temperature in different positions is determined using finite element method (FEM) simulations. Furthermore, the simulation results clearly correspond favorably with the experiment results. Finally, the lifetime measurement verifies the thermal effects of the phosphor layers in the white LEDs.

2. Experimental

In our experiment, the conformal and remote phosphor structures were fabricated using the pulse spray coating (PSC) method [29], [30], which can spray phosphor film uniformly to generate high-quality white LEDs. The blue LED studied here is a conventional face-up LED chip with the emission wavelength around 450 nm. The chip size of the blue LED chip is 1125 μm $\times$ 1125 μm, and the radiant fluxes of the chip are 400 mW at 350 mA. The phosphor slurry was prepared by combining a solvent, a silicone binder, and phosphor powders. For the conformal and remote structures, the phosphor slurry was sprayed onto the blue chip and silicone, as shown in Fig. 1. The

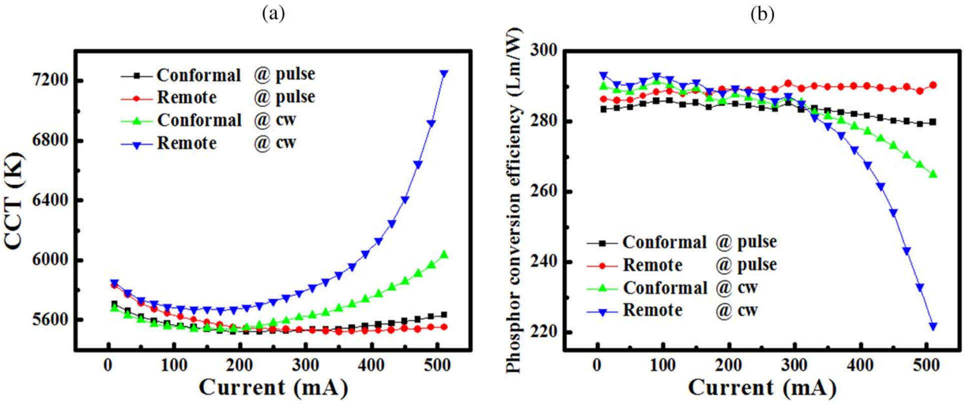

Fig. 2. (a) Correlated color temperature (b) phosphor efficiency with different currents using continuous wave and pulsed current sources.

phosphor layer coating step is the only fabrication difference of the two structures. The phosphor powder used in this experiment was silicate-based, with a particle size of 15 μm and has broadband wavelength distribution (490 $\sim$ 680 nm).To compare both structures, the color temperature was maintained at an injection current of 350 mA.

3. Results and Discussion

To examine the thermal effect on the conformal and remote phosphor structures, continuous wave (CW) and pulsed current sources were employed to compare the different operation currents. The correlated color temperature (CCT) of the conformal and remote phosphor structures is shown in Fig. 2(a). Both types of LEDs were driven by the current between 10 mA and 500 mA. Under pulsed current sources, the CCT of both types of LEDs remains nearly the same with the increased current. However, under the CW current sources, the CCT difference of the conformal phosphor structure is better than that of the remote phosphor structure, especially under higher current driving. With the increase in current from 10 mA to 500 mA, the CCT difference of the remote phosphor structure becomes larger. This indicates that the remote phosphor structure cannot efficiently maintain the stable ratio of the blue and yellow light since the yellow phosphor cannot efficiently transfer the blue light to yellow light. Therefore, the phosphor conversion efficiency (PCE) in white LEDs is calculated and defined as

$$\eta_{pce} = \frac{I \times V}{W} \times WPE \tag{1}$$

where I is the operation current, V is the operation voltage, and W and WPE are the optical power and luminous efficiency, respectively. By the equation, the PCE is calculated by the phosphor efficiency converted by the blue optical power. The conversion efficiency of phosphor at different driven currents under the CW and pulsed conditions are shown in Fig. 2(b). The PCE decreases more rapidly in the remote phosphor structure than that in the conformal phosphor structure, especially under CW conditions. The results are attributed to the heat accumulation in the remote phosphor structure. Therefore, the PCE of the remote structure is strongly dependent on the thermal effect of the phosphor layer.

For the thermal characteristics of white LEDs, the junction temperature becomes a critical standard using the forward voltage method [31], [32]. The LED is placed in a temperature controlled machine, and the voltage drop is measured when achieving the thermal equilibrium with the different temperature. After that, the linear curve for voltage with different temperature could be depicted and obtain the junction temperature. The junction temperatures of the conformal and remote phosphor structures, from 50 mA to 550 mA, are shown in Fig. 3(a). In both structures, the junction temperature increases in conjunction with the current source. In [22], it is reported the

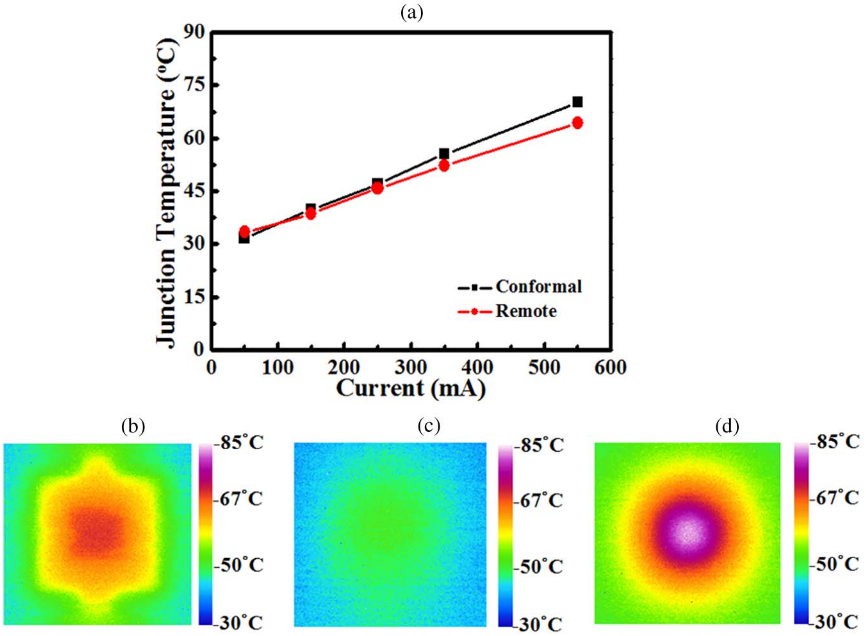

Fig. 3. (a) Junction temperature of conformal and remote phosphor structures at driving currents from 50 mA to 550 mA. The IR images in (b) conformal without silicone (c) conformal with silicone and (d) remote phosphor structure.

phosphor could reflect a significant portion of the down-converted light back to the chip. Therefore, the conformal phosphor structure has higher junction temperatures than the remote phosphor structure, meaning that more backscattering light is absorbed by the blue chip and transfers heat to the conformal phosphor structure, leading to a higher junction temperature, particularly with the higher current. In the remote phosphor structure, the silicone which separates the phosphor layer away from the chip could effectively reduce the backscattering light, resulting in the lower junction temperature.

The actual temperatures of the phosphor layers in the conformal and remote phosphor structures were then measured by the IR thermometer. The samples were prepared for conformal phosphor structure without silicone, conformal phosphor structure with silicone, and the remote phosphor structure, as shown in Fig. 3(b)–(d). The surface temperature of the conformal structure without silicone is higher than that of the conformal structure with silicone.

This is because the silicone layer blocks the heat transfer from the phosphor layer. The phosphor temperature of the remote structure is much higher than the temperature of the conformal structure. This is attributed to the lower thermal conductivity of the silicone, which hardly dissipated the heat into the substrate. Although the conformal structure has higher junction temperature, the heat could dissipate from the chip. However, the heat accumulates in the phosphor, leading to a higher phosphor temperature in the remote phosphor structure. Furthermore, this indicates a serious thermal problem in the remote phosphor structure, which was verified by measuring the phosphor efficiency.

The FEM simulation is employed to simulate the temperature of blue chip and the phosphor layer [33]. First, the three simulated device structures are fabricated as shown in the top of Fig. 4. Second, the thermal conductivity parameters were used for the conformal and remote phosphor structures. The value of the thermal conductivity for the silicone encapsulant, lead-frame, and the air are about 0.18, 400, and 0.025 W/m.K. The power is generated from the LED chip, and the temperature distribution in blue chips and the phosphor layer is calculated by the FEM simulation. Generally, the remote phosphor structure has a higher temperature than that of the conformal phosphor structure with and without silicone, which is obviously in the phosphor layer. For the

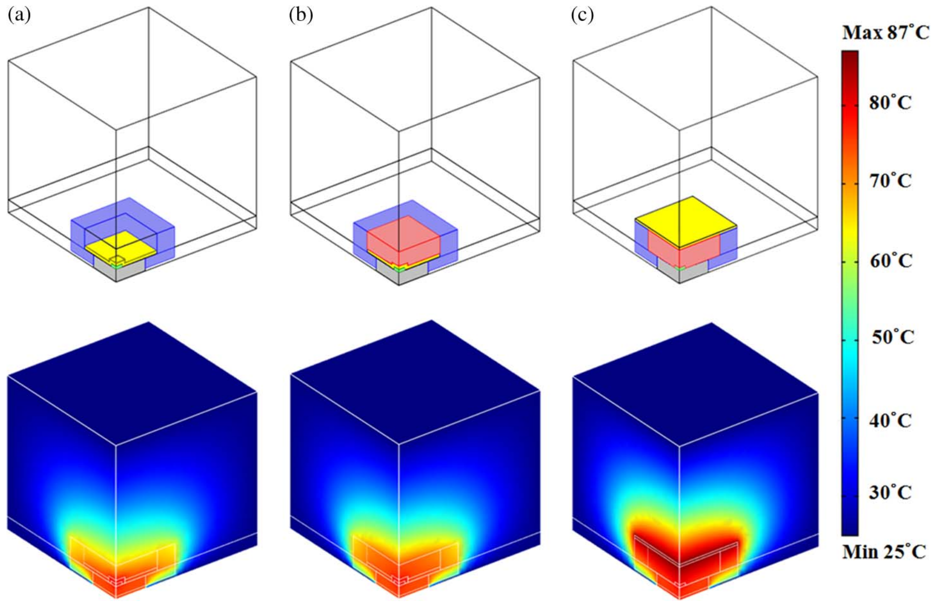

Fig. 4. Schematic diagrams and of thermal distribution (a) conformal without silicone (b) conformal with silicone (c) remote phosphor structure.

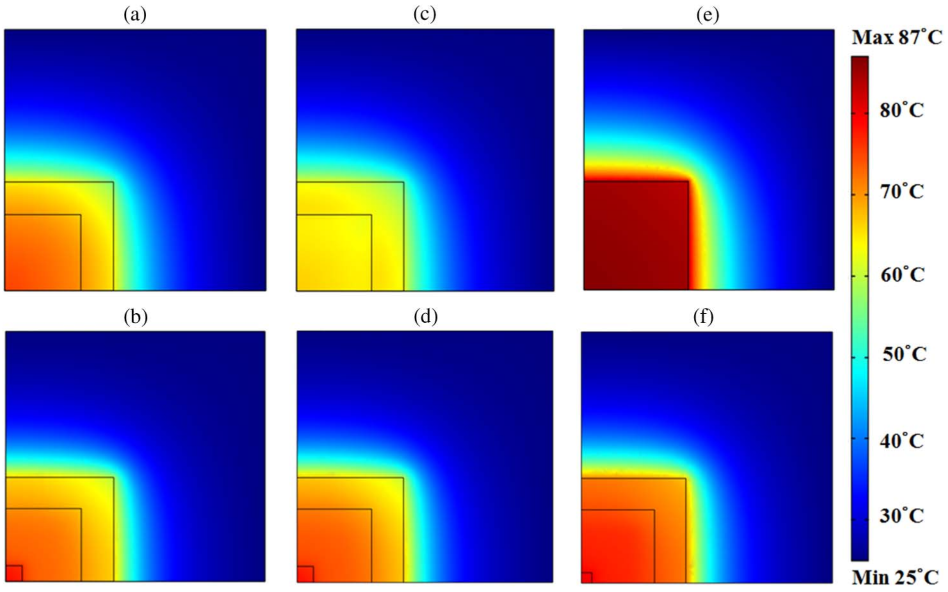

Fig. 5. First and second layer for the top view of (a) and (b) conformal without silicone (c) and (d) conformal with silicone (e) and (f) remote phosphor structure.

conformal phosphor structure, the higher temperature is centralized on the chip because of the backscattering light of the phosphor. The heat can transmit from the chip and leadframe to the outside because of the higher thermal conductivity.

To analyze the different layers of the conformal and the remote phosphor structures, the first and second layers from the top view are also demonstrated as shown in Fig. 5. For the remote phosphor structure, the phosphor achieved a maximal temperature, which is almost the same as the actual temperature in the IR picture. In the second layer form the top view, the maximal temperature exists at the center of the structure and gradually decreases to the outside because of the high thermal

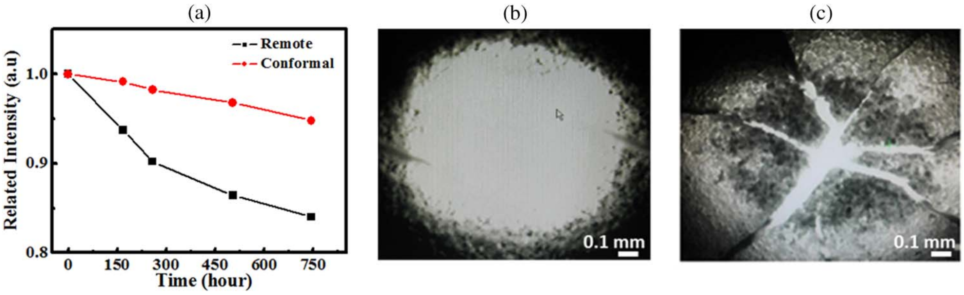

Fig. 6. (a) Lifetime measurement of the conformal and the remote phosphor structure; picture of the phosphor in the (b) conformal and (c) remote phosphor structure after 750 h.

conductivity in the leadframe. This simulation demonstrates that such a conformal phosphor structure can effectively increase the capability of the heat conduction path from the package, thus reducing the effect of thermal problem in the phosphor.

The lifetime measurement of the conformal and remote phosphor structures at 350 mA are shown in Fig. 6(a). The experimental results show that the intensity decay rate in the conformal phosphor structure is slower than the rate in remote phosphor structure. The degradation of intensity is approximately 5% for the conformal phosphor structure and 16% for the remote phosphor structure after 750 hours of operation. The rapid degradation of the conformal and remote structure was caused by the phosphor damage, as shown in Fig. 6(b) and (c). For the remote structure, heat accumulates in the phosphor layer and becomes difficult to dissipate from the silicone layer. The lifetime characterization results agreed to the simulation results in Fig. 5 for the conformal and remote phosphor structures.

The thermal characteristics of the LED device, including the junction temperature and phosphor temperature, are extremely crucial during high-power operations. As the current increases, additional heat generates from the electrical power and phosphor. To replace traditional lighting, efficient thermal conduction for white LEDs should be developed in SSL.

4. Conclusion

In conclusion, the effect of thermal influence on the conformal and remote phosphor structures is demonstrated using the junction temperature and phosphor temperature. The CCT and PCE vary dramatically with the increased current in the remote phosphor structure. Then, the junction temperature in the conformal structure is higher than that in the remote phosphor structure. Furthermore, the phosphor temperature is verified using the IR thermometer, revealing a higher temperature in the remote phosphor structure, which reduces phosphor efficiency. The thermal distribution in the simulation also demonstrated the same phenomenon in the phosphor temperature between both structural types. Therefore, the simulation results correspond favorably to those of the experiment of the phosphor temperature experiment. In addition, the influence of the phosphor temperatures in both structures is characterized by the lifetime measurement. The results show that the thermal characteristic of the phosphor layer in the conformal structure is better than in the remote structure.

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