Phosphor Temperature Overestimation in High-Power Light-Emitting Diode by Thermocouple

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***Abstract*— Phosphor temperature in high-power white light-emitting diodes can greatly affect the optical properties, reliability, and lifetime. Accurate estimation of phosphor temperature is the first step for enhancing thermal management inside the package. In this paper, the phosphor temperature was measured by a plug-in method with thermocouple. The thermocouple's bead was inserted into the phosphor layer, and then the silicone matrix got cured. The phosphor temperature was measured under various input currents. Under 350 mA, the temperature difference between the measured value and the junction temperature was about 17 °C higher than those in the references. The reason for this overestimation was attributed to light energy absorption and conversion of the bead, which was confirmed by thermal simulations.**

***Index Terms*— Light-emitting diode (LED), overestimation, phosphor temperature, thermocouple.**

I. Introduction

As THE power of phosphor-converted light-emitting diode (pc-LED) package increases, more heat is generated in the package due to the imperfect combination of electrons and holes in the quantum well [1]–[3]. Correspondingly, the increasing temperature would weaken the optical performance and reliability of LED packages. Since the phosphor conversion efficiency decreases exponentially with the increase in phosphor temperature, high phosphor temperature can be a critical problem for pc-LEDs [4], [5]. In addition, it is reported by Yan *et al.* [6] that the junction temperature cannot characterize the thermal behavior of LED packages alone and phosphor temperature must be taken into account. Therefore, research on phosphor configuration is essential for LED's thermal management.

So far, most of the researches involved with phosphor temperature use simulations to get the phosphor temperatures. Hu *et al.* [7] studied the hotspot location shift in pc-LED by an optical-thermal simulation method. They found that the hotspot location in remote phosphor coating packages shifted with the changes in phosphor concentration. Hwang *et al.* [8] investigated the effect of relative position of the phosphor layer on the lifetime of LED, and found that the phosphor temperature in die-contact case was lower than the remote case through thermal simulation. Luo *et al.* [9] studied the silicone carbonization of high-power LED, which resulted from local high temperature caused by the phosphor self-heating. Extremely high phosphor temperature was obtained by simulation to verify the explanation. Besides, some researchers tried to measure phosphor temperature via experimental methods. Fan *et al.* [10] used an infrared (IR) camera to detect the surface temperature of the LED's phosphor layer. However, what they really measured was the temperature of the outer surface of the optical lens. In order to directly detect the phosphor temperature, Shih *et al.* [11] cut the entire package along the plane of symmetry in half and got the temperature distribution of the whole package by IR camera. But they considered the experimental results as inaccurate due to the light leak out from the cut surfaces. Recently, Kim and Shin [12] reported that they made a hole through the top side encapsulant by using a heated iron wire and measured the phosphor temperature by thermocouple. Their results were higher than the junction temperature and the simulated phosphor temperatures regardless of phosphor-substrate distance.

In this paper, we plugged the thermocouple's bead into the phosphor layer of LED package after the phosphor gel dispensing process and cured it inside. Then the phosphor temperatures were measured under various driving currents. The test mechanism was clearly explained. The light energy absorbed by the bead was calculated and inputted into the simulations as a function of the driving currents.

II. Experimental Setups and Results

A. Experimental Setup

The structural schematic of the LED package and experimental setup are shown in Fig. 1. The size of the chip is 1 mm × 1 mm × 0.1 mm. A heat sink was used for sufficient heat dissipation. A manual fixture was made for structural support. The vertical plane of the fixture and the top surface of the heat sink are perpendicular to each other. The utilized thermocouple is K-type and the materials of each

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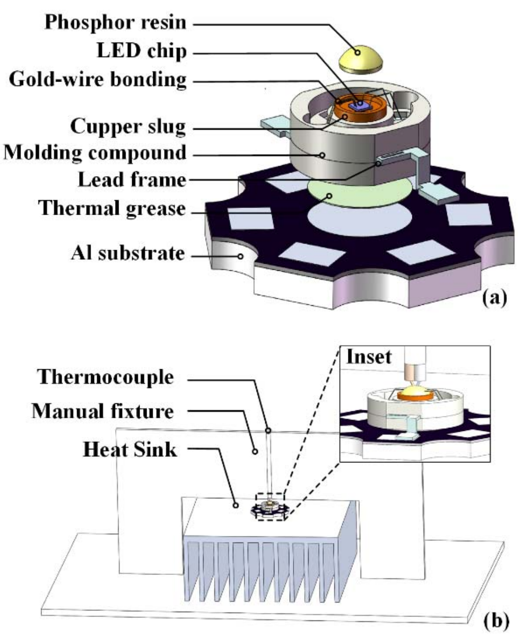

Fig. 1. Schematic of (a) LED package and (b) setup for the experiments.

thermocouple wires are alumel and chromel, respectively. The diameters of the thermocouple wire and bead are 0.3 and 0.6 mm, respectively.

The plug-in operating sequence is as follows. First, the phosphor resin with a concentration of 0.3 g/cm^3 was prepared and dispensed onto the LED chip via the volume-control method to ensure good consistency [13]. Second, the LED package was fixed in proper position and the thermocouple bead was inserted into the phosphor resin. Due to the limited volume of the phosphor resin, it is hard to place more than one thermocouple's bead inside at the same time. Instead, we adopted repetitive testing in which the thermocouple's beads were fixed at different locations in the phosphor resin to explore the location effect. The optical properties of the specimen were measured before and after the plug-in operation by an integrating sphere (ATA-1000, Everfine Inc.). Third, the phosphor resin was cured with the bead inside. After that, the packages were operated under various driving currents in room temperature, while the thermocouples measured the phosphor temperatures. Also, the junction temperatures of the packages were measured by forward voltage method using a thermal transient tester (T3Ster, Mentor Graphics Inc.).

B. Experimental Results

The results of measured phosphor temperature under various driving currents are shown in Fig. 2. The temperatures increase with the driving current and gradually stabilize after about 600 s. The phosphor temperature under 350 mA is 58.5 °C. The results for different locations of thermocouple's bead did not show much difference. Fig. 3 shows the phosphor temperature and junction temperature as a function of current. It is remarkable that under 350 mA, the phosphor temperature is 26.5 °C higher than the junction temperature and this value increased with input current. In [6], [7], and [12], the temperature differences between phosphor and junction are within

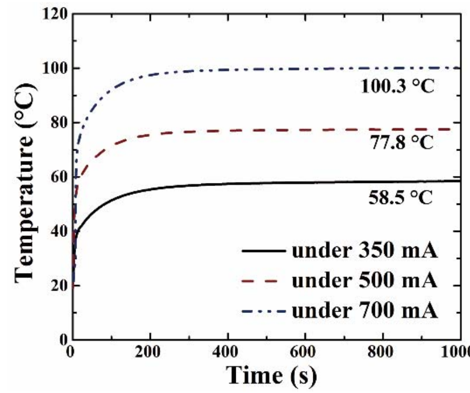

Fig. 2. Phosphor temperatures under various currents as a function of time.

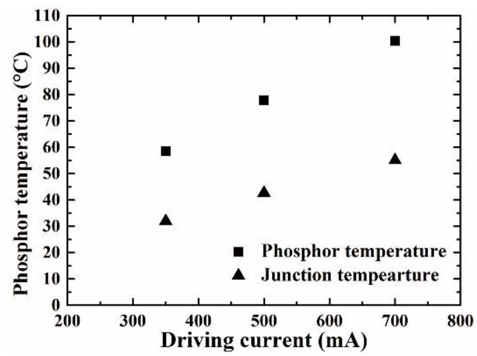

Fig. 3. Phosphor temperatures and junction temperatures as a function of input current.

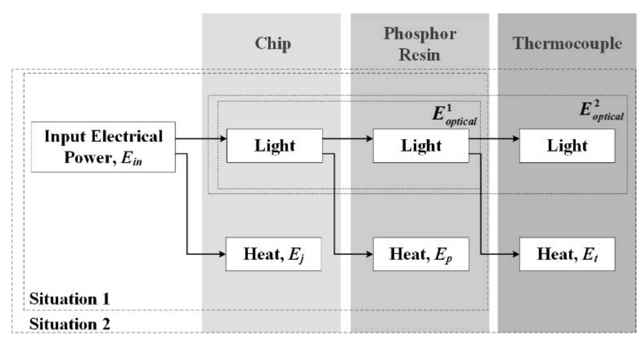

Fig. 4. Energy flow of the temperature measuring process.

10 °C even with local heat generation considered under the same input current of 350 mA. By comparison, it is obvious that the measured phosphor temperature is much larger than the junction temperature in our experiment. The deviation is beyond the scope of measurement error and some factors that can cause the overestimation must be missing. Note that the thermocouple's bead is buried inside the phosphor resin; the only factor that can affect the temperature besides the heat flux is light absorption and conversion by the bead. Therefore, the course of transition and transformation of input electrical energy was analyzed in detail.

The energy flow of the whole temperature measuring process was first analyzed. Fig. 4 exhibits the energy flow. In situation 1, the thermocouple's bead was not inserted into the phosphor resin. The input electrical energy splits into two parts (light and heat) at the chip, where the generated

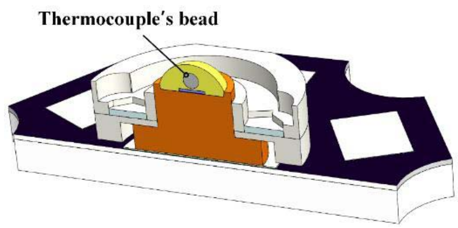

Fig. 5. Cross-sectional view of the LED package for thermal simulation.

heat was defined as E_j. The light keeps going before exiting the LED module. It should be noticed that at the phosphor resin area, part of the light was converted into heat, which was defined as E_p. In situation 2, the thermocouple was plugged in to measure the phosphor temperature. Compared with situation 1, part of the light from phosphor resin reaches the outer surface of the thermocouple's bead before going out of the LED package. There, considering the absorptivity of the thermocouple's bead, part of the light was absorbed and converted into heat. The other was scattered and went out of the package finally.

According to the energy conservation principle, the energy transformations in situations 1 and 2 could be expressed, respectively, as follows:

$$E_{\text{in}}^1 = E_{\text{optical}}^1 + E_j^1 + E_p^1 \tag{1}$$

$$E_{\text{in}}^2 = E_{\text{optical}}^2 + E_j^2 + E_p^2 + E_t \tag{2}$$

where $E_{\text{in}}^{1,2}$ is the total input electrical energy, $E_{\text{optical}}^{1,2}$ is the output optical energy, and $E_j^{1,2}$ and $E_p^{1,2}$ are the heat energy generated at the LED chip and phosphor resin, respectively. E_t is the heat energy absorbed by the thermocouple's bead. Here, a reasonable assumption was made that the heat energy generated at the LED chip and phosphor resin was the same with each other in both situations. That is to say

$$E_j^1 = E_j^2, \quad E_p^1 = E_p^2. \tag{3}$$

In the experiments, both $E_{\text{in}}^{1,2}$ and $E_{\text{optical}}^{1,2}$ were measured by the integrated sphere. According to the test results, E_t under 350 mA is 55mW, which accounts for 20.1% of the E_{optical}^1. So much light energy was absorbed by the thermocouple's bead and converted into heat. It would increase the measured phosphor temperature. To better illustrate the effect of light energy absorption and conversion, thermal simulations were carried out in Section III.

III. Simulation Setup and Results

A. Simulation Setup

To estimate the effect of light energy absorption on the measurement accuracy, a simplified thermal model was established based on the actual package and the thermal simulation was conducted by using the finite-element method. Two assumptions were made that the heat energy generated at the LED chip and phosphor resin were unchanged before and after the thermocouple's bead was inserted, i.e., $E_j^1 = E_j^2$, $E_p^1 = E_p^2$. Fig. 5 shows the cross-sectional view of the simulation model. A metal ball representing the thermocouple's bead was added into the phosphor resin. For modeling simplification, the wires that were linked with the bead were neglected. Thermal mass effect of the thermocouple was taken into account in the result discussion part. The boundary conditions were summarized in Table I. The ambient temperature is the same with the temperature on the spot, which is 20 °C. The boundary conditions of package's surfaces except the bottom surface are typical natural convections with a heat transfer coefficient of $h = 3$ W/m$^2 \cdot$K. For the bottom surface of the package, the equivalent convection heat transfer coefficient was calculated based on the dimensions of the heat sink and the value is $h_{\text{eq}} = 228$ W/m$^2 \cdot$ K [14].

TABLE I

Boundary Conditions for the Thermal Simulation

Boundary	Conditions	Values
Ambient	Constant temperature	20 °C
PCB bottom surface	Equivalent convection heat transfer coefficient	228 W/(m^2·K)
PCB top surface	Constant convection heat transfer coefficient	3 W/(m^2·K)
LED outer surfaces	Constant convection heat transfer coefficient	3 W/(m^2·K)

TABLE II

Input Variables for the Thermal Simulation

Variables		Values (mW)		
Input power of LED, $E^1_{in}=E^2_{in}$		1120	1685	2506
Output optical power,	$E^1_{optical}$	274	361	471
	$E^2_{optical}$	219	286	374
Heat generation at the LED junction, E_j		790	1240	1910
Heat generation by LED phosphor layer, E_p		56	84	125
Heat generation at the thermocouple, E_t		55	75	97

With this model, the temperature distribution could be calculated. The implemented parameters, including input power and heat generations at each component, were collected according to calculation results based on (1)–(3). $E_{\text{in}}^{1,2}$ and $E_{\text{optical}}^{1,2}$ were experimental values measured by the integrated sphere. The heat generated at the phosphor resin E_p was assumed to be 5% of the input power [8], [15]. The corresponding variables and their values used in the calculations are listed in Table II.

B. Simulation Results

Fig. 6 shows the calculated temperature fields of the package under various currents from 350 to 700 mA. With the increase of input current, the temperatures of the LED packages increased and the highest temperature point was in the metal ball due to the light energy absorption regardless of the increase in current. The simulated junction and phosphor temperatures can be obtained from the temperature distribution and they were compared with those obtained by experiments. Fig. 7 shows the simulated and experimental results of T_j and T_p as a function of driving current for the LED package. The simulation results are higher than the experimental results. This is because in the experiments, the thermocouple's wires would act as heat sink and take away part of the heat. This effect can decrease the temperature a little bit. In the simulation, the thermocouple's wires were neglected for modeling simplification, thus leading to the fact that simulation values are higher than the experimental ones. Besides, the simulated values of T_j and T_p are both in good agreement with the experimental data, which confirms the existence of the light

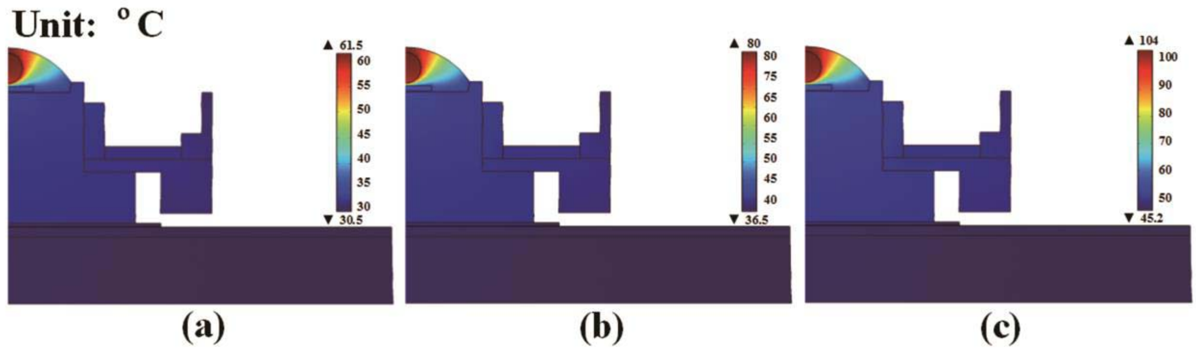

Fig. 6. Calculated temperature fields of the LED package under different currents (a) 350 mA (b) 500 mA (c) 700 mA.

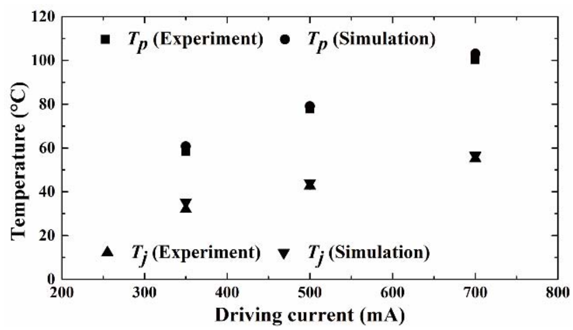

Fig. 7. Phosphor temperature (T_p) and junction temperature (T_j) from the experimental data and thermal simulation of the LED package as a function of current.

energy absorption. Besides, as the driving current increases, more light emits from the LED chip and gets absorbed by the thermocouple's bead. Thus, the effect of light energy absorption on the temperature overestimation is enhanced. This is also verified by the results in Fig. 7.

From the above analysis, it can be concluded that the overestimation by thermocouple measurement results from the light energy absorption. And this influence must be considered when using thermocouple to measure phosphor temperature of the LED package. One possible approach to weaken the deviation is to reduce the area for light absorption by decreasing the diameter of the thermocouple's bead.

IV. Conclusion

In this paper, phosphor temperature of the LED package was measured by a plug-in testing method with thermocouple. The thermocouple's bead was cured inside the phosphor resin during the phosphor dispensing process. The tested values were considered to be overestimated compared with the results from previous researches. A thermal simulation considering light absorption was conducted and the simulated results exhibited good coherence with the experimental data. The factor accounting for the overestimation of phosphor temperature was concluded to be the light energy absorption. It needs to be considered when using thermocouple to measure phosphor temperature of the LED package.

References

[1] X. Luo, R. Hu, S. Liu, and K. Wang, "Heat and fluid flow in high-power LED packaging and applications," *Prog. Energy Combustion Sci.*, vol. 56, pp. 1–32, Sep. 2016, doi: 10.1016/j.pecs.2016.05.003.

[2] C. Yuan, L. Li, B. Duan, B. Xie, Y. Zhu, and X. Luo, "Locally reinforced polymer-based composites for efficient heat dissipation of local heat source," *Int. J. Thermal Sci.*, vol. 102, pp. 202–209, Apr. 2016, doi: 10.1016/j.ijthermalsci.2015.11.015.

[3] C. Yuan, B. Xie, M. Huang, R. Wu, and X. Luo, "Thermal conductivity enhancement of platelets aligned composites with volume fraction from 10% to 20%," *Int. J. Heat Mass Transf.*, vol. 94, pp. 20–28, Mar. 2016, doi: 10.1016/j.ijheatmasstransfer.2015.11.045.

[4] M. Zachau, D. Becker, D. Berben, T. Fiedler, F. Jermann, and F. Zwaschka, "Phosphors for solid state lighting," *Proc. SPIE*, vol. 6910, p. 691010, Feb. 2008, doi: 10.1117/12.760066.

[5] P. F. Smet, A. B. Parmentier, and D. Poelman, "Selecting conversion phosphors for white light-emitting diodes," *J. Electrochem. Soc.*, vol. 158, no. 6, pp. R37–R54, 2011, doi: 10.1149/1.3568524.

[6] B. Yan, N. T. Tran, J.-P. You, and F. G. Shi, "Can junction temperature alone characterize thermal performance of white LED emitters?" *IEEE Photon. Technol. Lett.*, vol. 23, no. 9, pp. 555–557, May 1, 2011, doi: 10.1109/lpt.2011.2115997.

[7] R. Hu, X. Luo, and H. Zheng, "Hotspot location shift in the high-power phosphor-converted white light-emitting diode packages," *Jpn. J. Appl. Phys.*, vol. 51, no. 9S2, p. 09MK05, 2012, doi: 10.7567/jjap.51.09mk05.

[8] J.-H. Hwang, Y.-D. Kim, J.-W. Kim, S.-J. Jung, H.-K. Kwon, and T.-H. Oh, "Study on the effect of the relative position of the phosphor layer in the LED package on the high power LED lifetime," *Phys. Status Solidi C*, vol. 7, nos. 7–8, pp. 2157–2161, 2010, doi: 10.1002/pssc.200983493.

[9] X. Luo, X. Fu, F. Chen, and H. Zheng, "Phosphor self-heating in phosphor converted light emitting diode packaging," *Int. J. Heat Mass Transf.*, vol. 58, nos. 1–2, pp. 276–281, Mar. 2013, doi: 10.1016/j.ijheatmasstransfer.2012.11.056.

[10] B. Fan, H. Wu, Y. Zhao, Y. Xian, and G. Wang, "Study of phosphor thermal-isolated packaging technologies for high-power white light-emitting diodes," *IEEE Photon. Technol. Lett.*, vol. 19, no. 15, pp. 1121–1123, Aug. 1, 2007, doi: 10.1109/lpt.2007.901098.

[11] B.-J. Shih *et al.*, "Study of temperature distributions in pc-WLEDs with different phosphor packages," *Opt. Exp.*, vol. 23, no. 26, pp. 33861–33869, Dec. 2015, doi: 10.1364/oe.23.033861.

[12] J. H. Kim and M. W. Shin, "Thermal behavior of remote phosphor in light-emitting diode packages," *IEEE Electron Device Lett.*, vol. 36, no. 8, pp. 832–834, Aug. 2015, doi: 10.1109/led.2015.2441139.

[13] Q. Chen, R. Hu, B. Xie, and X. Luo, "Effect study of chip offset on the optical performance of light-emitting diode packaging," *IEEE Photon. Technol. Lett.*, vol. 27, no. 12, pp. 1337–1340, Jun. 15, 2015, doi: 10.1109/lpt.2015.2421345.

[14] F. Harahap and H. N. McManus, "Natural convection heat transfer from horizontal rectangular fin arrays," *J. Heat Transf.*, vol. 89, no. 1, pp. 32–38, 1967, doi: 10.1115/1.3614318.

[15] X. Luo and R. Hu, "Calculation of the phosphor heat generation in phosphor-converted light-emitting diodes," *Int. J. Heat Mass Transf.*, vol. 75, pp. 213–217, Aug. 2014, doi: 10.1016/j.ijheatmasstransfer.2014.03.067.

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