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# Phosphor self-heating in phosphor converted light emitting diode packaging

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ABSTRACT

Silicone carbonizations were observed in the multiple high power LEDs modules. This phenomenon was explained to be caused by the effect of phosphor self-heating. Comparative experiments were conducted, and the results validated the existence of phosphor self-heating, which caused the local high temperature. A thermal model of LED packaging based on phosphor particles under stair-like thermal load was built, and simulations were carried out to analyze the thermal performance of the phosphor layer. It is found that the highest temperature of the phosphor particles can reach 315.9 °C, which would result in the phosphor quenching. As the phosphor quenching happens, the temperature can gradually increase to 540.16 °C, which is highly enough to cause the silicone carbonization. One method to decrease temperature of the phosphor layer was proposed in the final part of this paper.

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## 1. Introduction

Light emitting diode (LED), with a series of advantages, is considered as the next generational light source [1–5]. To realize the white light emission, blue light from a blue LED are needed to emit through a yellow phosphor layer [6–12]. Such a blue LED covered with a phosphor layer is called as phosphor converted LED (pcLED). For the pcLED, part of the blue light is captured by the phosphor particles, which are filled in the encapsulant, and then converted to yellow light. Since only a part of the captured blue light is transferred into yellow light, there exists an optical energy loss during the color conversion process, and the lost optical energy is transformed into heat. Because of the low thermal conductivity of the encapsulant, local high temperature may appear in the phosphor layer, which would bring many disadvantages, such as peak shift of emitting spectrum, decrement of quantum efficiency, phosphor degradation and so on [13,14].

Some researchers paid attentions to the phenomenon of phosphor self-heating. Hwang et al. [15] studied the effect of the relative position of the phosphor layer in the LED packaging on the lifetime of high power LED, and found that the phosphor in the die – contact case had a lower temperature than the remote phosphor case. Yan et al. [16] investigated thermal performance of phosphor-based white LEDs by simulation with considering the thermal and optical interaction. They found that the temperature of the phosphor is higher than the junction temperature of LED regardless the phosphor placement. Hu et al. [17] studied the hot-spot location shift in the high power phosphor-converted white light-emitting diode packages by combining the Monte Carlo optical simulation and finite element simulation together. Both of them treated the phosphor layer, which is the mixture of phosphor particles and silicone, as a whole with uniform thermal conductivity obtained by the percolation theory [18], and gave the phosphor layer a volume thermal load. Arik et al. [19] studied the effects of localized heat generation caused by the color conversion in phosphor particles and different layers of high brightness LEDs. They found that there was significant light output reduction because of the localized heating of the phosphor particles in the experiments and excessive temperatures appeared when a 3 mW heat was loaded on a 20 um diameter spherical phosphor particle in the simulation.

In this work, based on the comparison experiments, we validated that the silicone carbonizations observed in our experiments are caused by local high temperature, which results from the phosphor self-heating. A thermal model of the LED packaging based on the phosphor particles under stair-like thermal load was built. Simulations were carried out to investigate the temperature field of the phosphor layer, as well as to explore methods to decrease the temperature of the phosphor particles.

## 2. Experiments and phenomenon description

The LED modules used in our experiment are shown in Fig. 1(a). Twelve LED chips are mounted on a substrate as an array of 2 × 6, in which six LED chips are electronically connected in series and two rows of six chips parallelly connected. The drive current of the module is 1.4 A and the total voltage is about 22 V. Therefore, the drive current for each LED chip is 700 mA, and the electric power for one chip is about 2.57 W. The phosphor layer, which is

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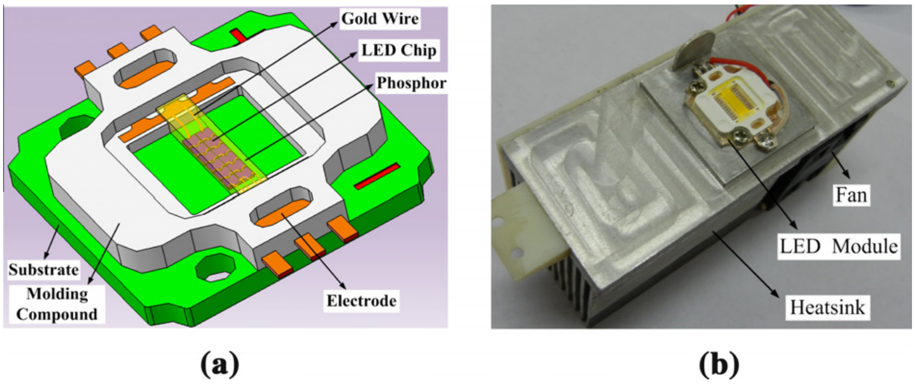

**Fig. 1.** (a) Schematic of multiple LEDs module. (b) Cooling system of the LEDs module.

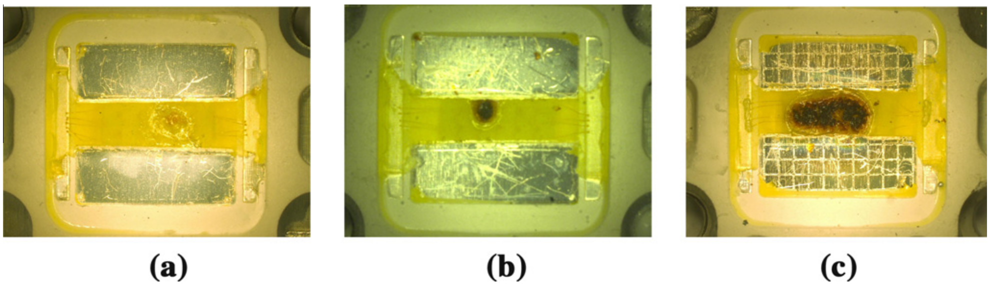

**Fig. 2.** Silicone carbonized modules.

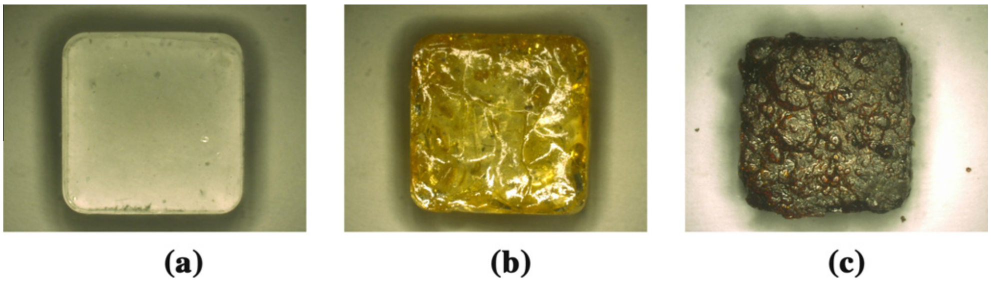

**Fig. 3.** Images of cured pure silicone cuboid in different temperature (a) Ambient temperature, (b) 450 °C and (c) 500 °C.

a mixture of silicone and YAG:Ce$^{3+}$ phosphor particles, is conformally coated on the chip. The height of the phosphor layer is 0.8 mm and the concentration of the phosphor layer is 0.087 g/g.

The cooling system of the multiple LEDs module is indicated in Fig. 2(b). The module is mounted on a heatsink, which is cooled by a fan. The ambient temperature is 19.0 °C, and the average temperature of the four corners of the top surface of the substrate is 29.2 °C when the module is light up. Based on tested temperature of the substrate, the dimensions and the materials of the substrate and solder, it can be inferred that the maximum junction temperature of the LEDs is less than 80 °C based on the basic thermal resistance model [20–22]. However, it was found that a black spot appeared in the phosphor layer after the module lighting up for a while, and then the silicone around the black spot was carbonized. Fig. 2 shows three phosphor carbonized modules, whose carbonization degrees are different because of different lighting time. For module (a) shown in Fig. 2(a), the phosphor layer is just beginning to soften and make transformation, but a small black point appears in module (b). In module (c), most of the silicone is carbonized. In addition, it is noted that the carbonization point usually firstly appears in the middle part of the phosphor layer.

The phosphor used in our experiment is extremely thermally stable, it keeps stable even when it is sintered in the oven with a temperature of 1000 °C. As to the silicone, the thermal performance is totally different. Experiments were carried out to measure the carbonization temperature. Small cured pure silicone cuboid, as shown in Fig. 3(a), was put in the oven with a temperature range from 300 to 550 °C, and the temperature was maintained for a quarter of an hour with each increment of 50 °C. It was observed the transparent silicone cuboid turned to yellow and cracks appeared at the temperature of 450 °C, as indicated in Fig. 3(b).[1] The silicone cuboid was totally carbonized at the temperature of 500 °C, as shown in Fig. 3(c). It was found the silicone cuboid started to carbonize at the temperature of 480 °C, so we can know the carbonization temperature of the present silicone is around 480 °C.

To sum up the above experiments, the carbonization temperature of the silicone used is about 480 °C, the junction temperatures of the LEDs are inferred to be less than 80 °C. So the carbonization

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[1] For interpretation of color in Figs. 3, 5 and 6, the reader is referred to the web version of this article.

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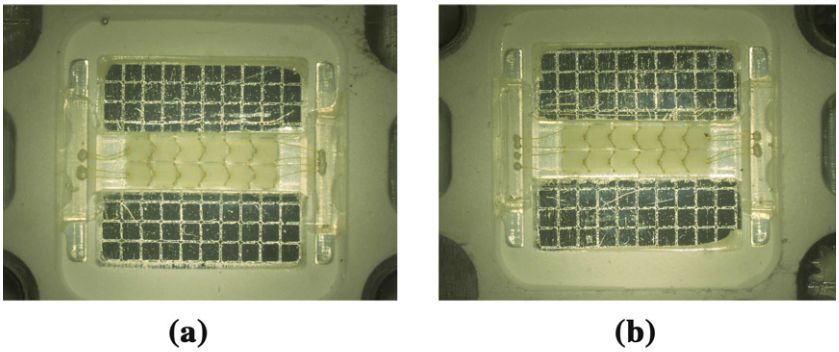

**Fig. 4.** Comparative modules at the same input conditions.

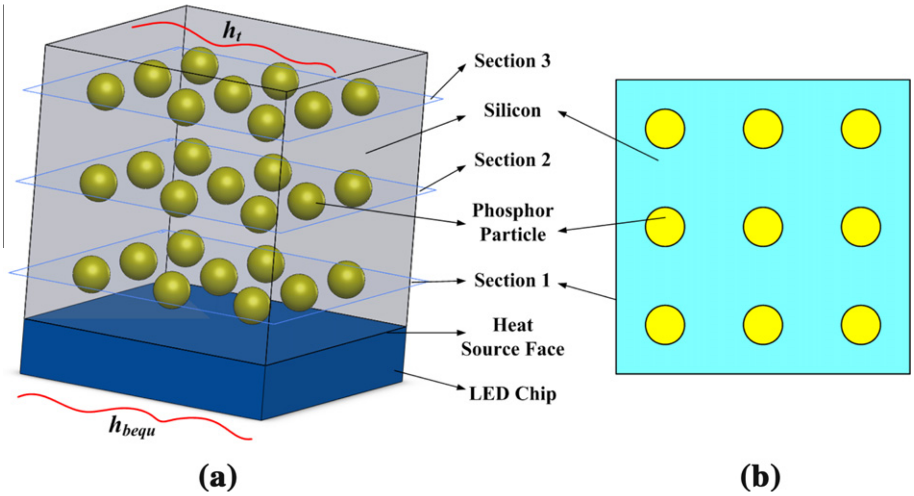

**Fig. 5.** (a) Thermal model of LED packaging based on phosphor particles. (b) Phosphor section.

phenomenon could not be caused by the high temperature of the LED chip. The other heat source in the LED packaging is the phosphor particles, we may think that phosphor self heating results in the silicone carbonization. To validate the supposition, comparative experiment was conducted. In the experiment, a pure silicone layer replaced the phosphor layer while all of the other parameters remained the same with the modules shown in Fig. 2. The results are shown in Fig. 4, it was found that no black spot appeared and no silicone was carbonized in the module with pure silicone layer, which proves that the phosphor carbonization is caused by the local high temperature due to the phosphor self-heating.

## 3. Thermal modeling and discussion

To study the phenomenon of phosphor self-heating further, a thermal model of LED packaging based on the phosphor particles instead of a uniform phosphor layer was built. As shown in Fig. 5(a), phosphor layer which consists of phosphor particles and silicone is mounted on the LED chip. The chip is bonded on a substrate, which is cooled by a heatsink. To simplify the thermal model, the substrate and the heatsink are leaved out and an equivalent convective coefficient $h_{bequ}$ is given at the bottom surface of the LED chip. The equivalent convective coefficient $h_{bequ}$ is approximately calculated based on the temperature of the heatsink, the ambient air, and the dimensions of heatsink, substrate and LED chips. The top surface of the phosphor layer is convective cooled by giving a convective coefficient $h_t$. The phosphor particles are evenly distributed in the silicone with a stack way as shown in Fig. 5(a), and the space is decided by the phosphor concentration. The phosphor particles are assumed to be spheres with a uniform size. The blue light emitting from the top surface of the LED chip is absorbed by the phosphor particles in a stair-like way, which will be interpreted later.

We define the phosphor section as the transaction across the equatorial circle of the phosphor particles on the same height, as shown in Fig. 5(b). Considering the angle between the light and the spherical surface, the light absorption can be treated as only happening on the phosphor section. When the blue light reaches the $i$th phosphor section, part of blue light is absorbed by the phosphor particles. The absorbed optical power of the $i$th phosphor section $Q_{ai}$ can be calculated by the equation as following,

$$Q_{ai} = Q_{ini} \times \frac{A_{pi}}{A_{ti}} \tag{1}$$

where $Q_{ini}$ is the optical power of blue light before it passes $i$th phosphor section. For the first phosphor section, $Q_{in1}$ is equal to the optical power emitting form the LED chip. $A_{pi}$ is the total area of the phosphor particles in the $i$th section, and $A_{ti}$ is the area of the $i$th section. Because of the uniform distribution of the phosphor particles, $A_{pi}$ and $A_{ti}$ are constants in all the sections.

$Q_{ini}$ can be obtained by the equation as following,

$$Q_{ini} = Q_{in(i-1)} - Q_{a(i-1)} \tag{2}$$

where $Q_{in(i-1)}$ is the optical power of blue light before it passes $(i-1)$th phosphor section, and the $Q_{a(i-1)}$ is the optical power absorbed by the $(i-1)$th phosphor section.

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**Table 1**
Material parameters of phosphor and silicone.

| | Density (kg/m$^3$) | Specific heat (J/(kg K)) | Thermal conductivity (W/(m K)) |
|---|---|---|---|
| Phosphor | 4300 | 620 | 13 |
| Silicone | 1140 | 1300 | 0.16 |

**Table 2**
Other constant parameters used in simulations.

| | | | |
|---|---|---|---|
| Height of LED chip (um) | 150 | Thermal conductivity of LED chip (W/(m K)) | 48.12 |
| Electrical power of LED cuboid (mW) | 46.72 | LED wall-plug efficiency | 20% |
| Phosphor color conversion efficiency | 70% | Radius of phosphor sphere (um) | 7 |
| $h_{bequ}$ (W/(m$^2$ K)) | 90000 | $h_t$ (W/(m$^2$ K)) | 10 |

The blue light absorbed by the phosphor particles is partly converted to yellow light and the other is transformed to heat. The generated heat of the phosphor particles across the $i$th phosphor section $Q_{hi}$ can be obtained by the equation below,

$$Q_{hi} = Q_{ai} \times (1 - \eta_c) \tag{3}$$

where $\eta_c$ is the color conversion efficiency of the phosphor.

Assuming the absorbed optical power of each phosphor particle across the same phosphor section is the same, the heat generated by each phosphor particle across the $i$th phosphor layer $Q_{his}$ can be obtained as following,

$$Q_{his} = \frac{Q_{hi}}{N_i} \tag{4}$$

where $N_i$ is the number of phosphor particles across the $i$th phosphor section.

In order to obtain $N_i$, the total amount of the phosphor particles in the phosphor layer $N$ should be gotten firstly, which can be calculated by the equation below,

$$N = V_{pg} \times \frac{x \times \rho_s}{x \times \rho_s + \rho_p} \bigg/ \left(\frac{4}{3} \times \pi \times r^3\right) \tag{5}$$

where $V_{pg}$ is the volume of the phosphor layer, $x$ is the phosphor concentration which is usually the mass ratio of phosphor and silicone, $\rho_s$ and $\rho_p$ are the density of the phosphor and silicone, respectively, $r$ is the radius of the phosphor sphere.

$N_i$ can be obtained by the equation as following,

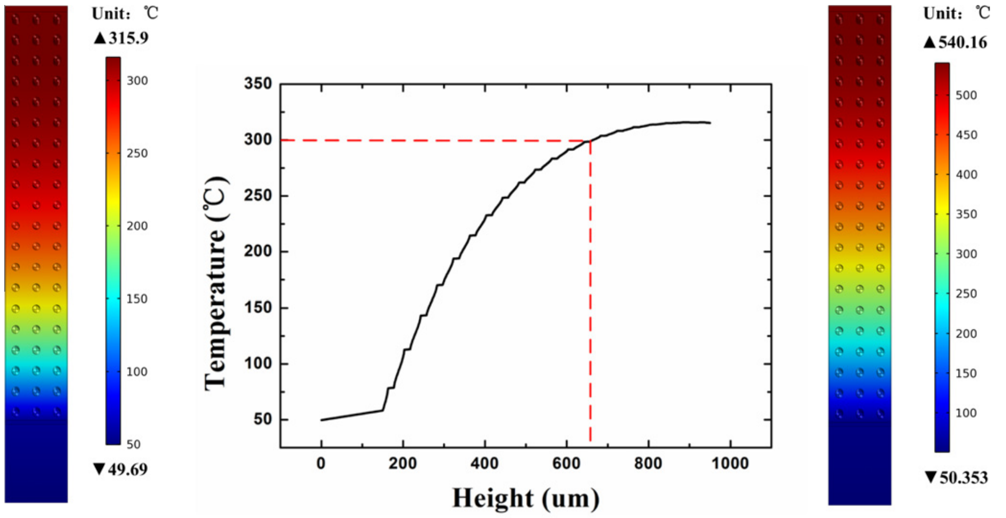
$$N_i = \left[ N \times \sqrt[3]{\frac{V_{pg}}{N}} \bigg/ H \right] \tag{6}$$

where $H$ is the height of the phosphor layer.

The model is based on the phosphor particles, whose amount is about hundreds of thousands in the phosphor layer. Restricted by the computer hardware, it is hard to conduct full simulations for the whole LED packaging. Also, we concern much more about the temperature variety in the height direction, here we conducted thermal simulations on a small cuboid, whose length and width were 120 um and the height was the same as the real LED packaging. The electric power of the small cuboid was in proportion with the whole LED chip. The constant parameters used in our simulations are listed in Tables 1 and 2.

The temperature field of the LED module used in the experiments was firstly simulated. In the module, the height of the phosphor was 800 um and the phosphor concentration was 0.087 g/g. The temperature field of the phosphor layer is indicated in Fig. 6(a). It can be seen that the phosphor temperature increases with the elevation of the height of the phosphor layer, and the highest temperature reaches 315.0 °C, which is much higher than the junction temperature of the LED chip. When the phosphor temperature increases, the color conversion efficiency decreases, and it means that more heat would be generated in the phosphor particles. When the phosphor temperature is high, the thermal quenching of phosphor is very remarkable, and the phosphor color conversion efficiency quickly reduces [23]. When the phosphor temperature reaches a certain value, like 300 °C, the color conversion efficiency decreases to 14%, much less yellow light will emit from the phosphor. This process agrees with what we observed in the experiments, in which a black spot appeared in the phosphor layer before the silicone carbonization.

When the phosphor quenching occurs, almost all the optical power of blue light captured by the phosphor particles in the quenching layers is transformed into heat. Therefore, we need to



(a) (b) (c)

**Fig. 6.** (a) Temperature field of original packaging model. (b) Temperature variation with the height of the middle line of the model. (c) Temperature field of packaging model considering the phosphor quenching.

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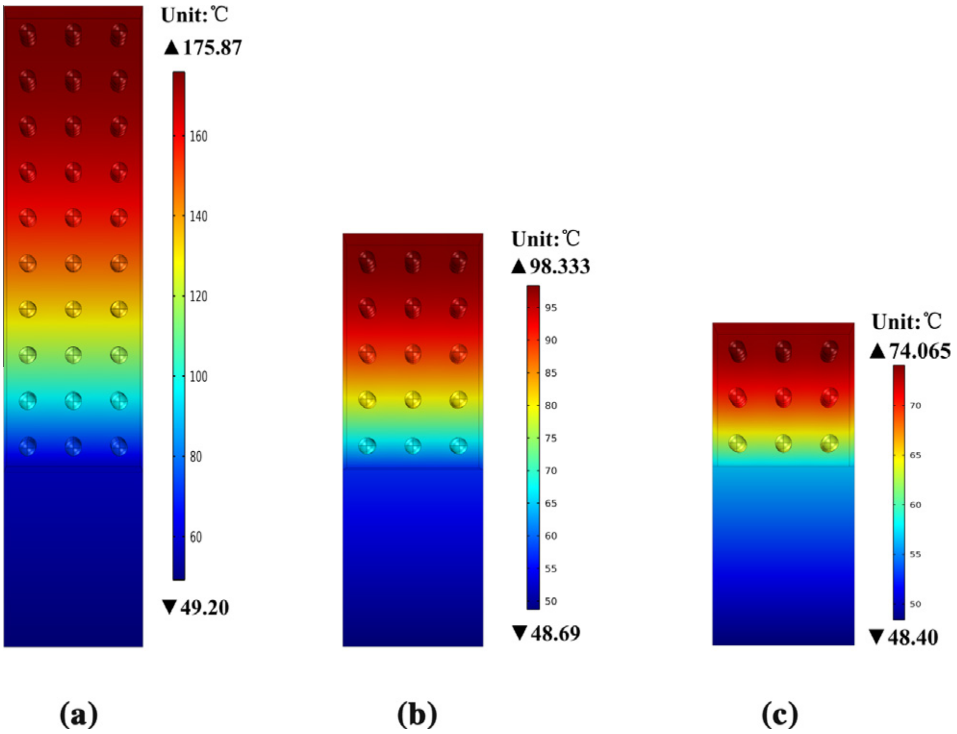

**Fig. 7.** Temperature fields of the models with thinning phosphor layer.

change the thermal loads of the phosphor particles whose temperatures are higher than 300 °C. The new thermal loads were given based on the temperature distribution shown in Fig. 6(b), in which the temperature variation with the height of the middle line of the model is indicated. The new temperature field under the refreshed thermal loads is indicated in Fig. 6(c), which shows that the maximum temperature of the phosphor particles is as high as 540.16 °C. Silicone around this phosphor particle is easily carbonized by such a high temperature. Once the silicone is carbonized, it becomes less transparent for the light and more heat will generate, leading to more silicone being quickly carbonized.

In the aforementioned simulations, we focused on a small part of a single chip and assumed that the optical power and heat transfer condition are uniformly distributed. However, the optical flux at the middle part of the module is actually the biggest and the heat transfer condition at that location is usually the worst. Both these unfavorable factors will lead to the carbonization firstly occurs in the middle, and this accounts for why the carbonization always appears at the middle part of the phosphor layer, as shown in Fig. 2.

As the bottom cooling of the thermal model is stronger than the top cooling, thinning the phosphor layer is able to decrease the maximum temperature of the phosphor particles. To prove this, we conducted simulations. Fig. 7 shows the temperature fields the model after thinning the phosphor layer. For models (a)–(c) shown in Fig. 7, the height of phosphor layer is reduced to 400 um, 200 um and 120 um, respectively, while the phosphor concentration maintains the same as the one in the original simulation. From Fig. 7, it is seen that the highest temperature significantly decreases with the reduction of the height of the phosphor layer. So thinning the phosphor layer will greatly decrease the temperature and enhance the reliability of LED modules.

## 4. Conclusions

It was observed that silicone was carbonized in the experiments, which results from local high temperature caused by the phosphor self-heating. Comparative experiments were conducted and validated the effect existence of phosphor self-heating. A thermal model of the LED packaging based on phosphor particles under stair-like thermal load was built and simulations were carried out. It is found the highest temperature of the phosphor particles can reach 315.9 °C, which would lead to the phosphor quenching and final silicone carbonization. Simulation also proves that thinning the phosphor layer can reduce the phosphor temperature effectively.

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## References

[1] S. Liu, X.B. Luo, LED Packaging for Lighting Applications: Design, Manufacturing, and Testing, John Wiley Press, USA, 2011. pp. 39–68.
[2] E.F. Schubert, J.K. Kim, Solid-state light source getting smart, Science 308 (2005) 1274–1278.
[3] M.S. Shur, A. Zukauskas, Solid-state lighting: toward superior illumination, Proc. IEEE 93 (10) (2005) 1691–1703.
[4] E.F. Schubert, J.K. Kim, H. Luo, J.Q. Xi, Solid state lighting – a benevolent technology, Rep. Prog. Phys. 69 (2006) 3069–3099.
[5] J.Y. Tsao, M.E. Coltrin, M.H. Crawford, J.A. Simmons, Solid-state lighting: an integrated human factors, technology, and economic perspective, Proc. IEEE 98 (7) (2010) 1162–1179.
[6] P. Schlotter, R. Schmidt, J. Schneider, Luminescence conversion of blue light emitting diodes, Appl. Phys. A 64 (1997) 417–418.
[7] J.K. Kim, H. Luo, E.F. Schubert, J. Cho, C. Sone, Y. Park, Strongly enhanced phosphor efficiency in GaInN white light-emitting diodes using remote phosphor configuration and diffuse reflector cup, Jpn. J. Appl. Phys. – Express Lett. 44 (21) (2005) L649–L651.
[8] H. Zheng, X.B. Luo, R. Hu, B. Cao, X. Fu, Y.M. Wang, S. Liu, Conformal phosphor coating using capillary microchannel for controlling color deviation of phosphor-converted white light-emitting diodes, Opt. Express 20 (5) (2012) 5092–5098.
[9] X. Fu, H. Zhen, S. Liu, X.B. Luo, Effects of the packaging structures on the phosphor-converted light-emitting diodes, Front. Optoelectron. 5 (2) (2012) 153–156.

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[10] R. Hu, X.B. Luo, H. Zheng, S. Liu, Study of optical constants of YAG:Ce phosphor layer doped with SiO2 particles by Mie theory for white light-emitting diode package, Front. Optoelectron. 5 (2) (2012) 138–146.

[11] R. Hu, X.B. Luo, H. Feng, S. Liu, Effect of phosphor settling on the optical performance of phosphor converted LED, J. Lumin. 132 (5) (2012) 1252–1256.

[12] R. Hu, X.B. Luo, S. Liu, Study on the optical properties of conformal coating LED by Monte Carlo simulation, IEEE Photon. Technol. Lett. 23 (22) (2011) 1673–1675.

[13] N. Narendran, Y. Gu, J.P. Freyssinier, H. Yu, L. Deng, Solid-state lighting: failure analysis of white LEDs, J. Cryst. Growth 268 (3–4) (2004) 449–456.

[14] B. Fan, H. Wu, Y. Zhao, Y. Xian, G. Wang, Study of phosphor thermal-isolated packaging technologies for high-power white light-emitting diodes, IEEE Photon. Technol. Lett. 19 (15) (2007) 1121–1123.

[15] J. Hwang, Y. Kim, J. Kim, S. Jung, H. Kwon, T. 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 7 (7–8) (2010) 2157–2161.

[16] B. Yan, N.T. Tran, J. You, F.G. Shi, Can junction temperature alone characterize thermal performance of white LED emitters?, IEEE Photon Technol. Lett. 23 (9) (2011) 555–557.

[17] R. Hu, X.B. Luo, H. Zheng, Hotspot location shift in the high power phosphor converted white light-emitting diode package, Jpn. J. Appl. Phys. 51 (2012) 09MK05.

[18] I.A. Furgel, O.V. Molin, V.E. Borshch, E.M. Sigal, M.A. Tyrtsakova, Thermal conductivity of polymer composites with a disperse filler, J. Eng. Phys. Thermophys. 62 (3) (1992) 335–340.

[19] M. Arik, S. Weaver, C. Becker, M. Hsing, A. Srivastava, Effects of localized heat generation due to the color conversion in phosphor particles and layers of high brightness light emitting diodes, in: Proceeding of International Electronic Packaging Technical Conference and Exhibition, Maui, Hawaii, USA, 2003.

[20] X.B. Luo, T. Cheng, W. Xiong, Z.Y. Gan, S. Liu, Thermal analysis of an 80 W light-emitting diode street lamp, IET Optoelectron. 1 (5) (2007) 191–196.

[21] X.B. Luo, W. Xiong, T. Cheng, S. Liu, Temperature estimation of high power LED street lamp by a multi-chip analytical solution, IET Optoelectron. 3 (5) (2009) 225–232.

[22] T. Cheng, X.B. Luo, S.Y. Huang, S. Liu, Thermal analysis and optimization of multiple LED packaging based on a general analytical solution, Int. J. Therm. Sci. 49 (1) (2010) 196–201.

[23] B. Volker, R. Cees, M. Andries, Temperature quenching of yellow $Ce_3$+ luminescence in YAG:Ce, Chem. Mater. 21 (10) (2009) 2077–2084.