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Phosphor distribution optimization to decrease the junction temperature in white pc-LEDs by genetic algorithm

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ABSTRACT

In this study, genetic algorithm (GA) was utilized to optimize the phosphor distribution to decrease the junction temperature of white phosphor-converted light-emitting diodes (pc-LEDs). The key steps of the GA were introduced, including selection, crossover, and mutation. Both the junction temperature and the entransy dissipation of each evolution were calculated. It was found that with evolutions, the phosphor particles tend to build a "thermal bridge" between the chip and the convective boundary and spread along the convective boundary. The junction temperature decreases from ~157.5 °C to ~150 °C and the entransy dissipation decreases from ~18 W K to ~6 W K. The least entransy dissipation principle was demonstrated to be the rule that governs the optimization processes.

1. Introduction

In recent decades, light-emitting diode (LED) technology has created more turmoil in the lighting industry than anything occurring over the previous century. The conventional incandescent and fluorescent light sources are increasingly being replaced by more energy-efficient, longer-lived, and environmentally friendlier white LEDs [1–5]. However, white LEDs still suffer from challenges related to brightness, efficiency, reliability, and performance. Due to the limited optoelectronic conversion efficiency of LED chip, more than 70% of the input power converts into heat. Heat, however, plays a negative role that heat will increase the junction temperature, which is the most important thermal parameter in LEDs. High junction temperature will decrease the internal quantum efficiency, reduce the luminous output, degrade the packaging materials, lower the reliability, and shorten the lifetime, etc. [1,2]. Thermal management, hence, is important for high power white LEDs and its primary goal is to decrease the junction temperature.

According to the current state-of-the-art white LEDs, the phosphor-converted LEDs (pc-LEDs) are the most frequently-used method to generate white light [1,2,6]. In pc-LEDs, since the phosphor silicone matrix is coated on the chip, it badly influences the chip heat dissipation. Moreover, in the pc-LEDs, besides the heat generated in the active layer of the chip, it has been reported that phosphors also generate heat [7–11]. Based on the Kubelka–Munk theory, we also proposed a method to calculate the heat generation in phosphors [12,13]. Although the heat generated in phosphors is much less than that in chip, there is no good heat dissipation medium for the phosphor particles since they are embedded in silicone with low thermal conductivity (~0.2 W/(m K)). The phosphor self-heating, not only affects the phosphor characteristics, but also increases the LED junction temperature.

So far, most thermal management methods for LED packages focus on enhancing the heat dissipation outside of the package, like air cooling, liquid cooling, etc. [14–17]. According to the Bar-Cohen star-shaped thermal resistance model, part of heat will be dissipated through phosphor layer, lens, to the ambient air [18,19]. However, few reports focus on the internal thermal management that aims at improving the heat dissipation inside the LED package, more specifically dealing with the phosphors. It is affirmative that the internal thermal management will benefit the external heat dissipation.

In this study, we focused on the internal thermal management of pc-LED package. The phosphor distribution in pc-LEDs was optimized to decrease the junction temperature by genetic algorithm (GA). The details about the GA procedure dealing with this problem were introduced. The evolutions about the phosphor distributions were presented and the corresponding junction temperature and

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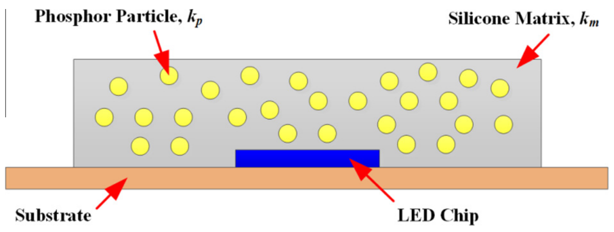

Fig. 1. Schematic of pc-LED package.

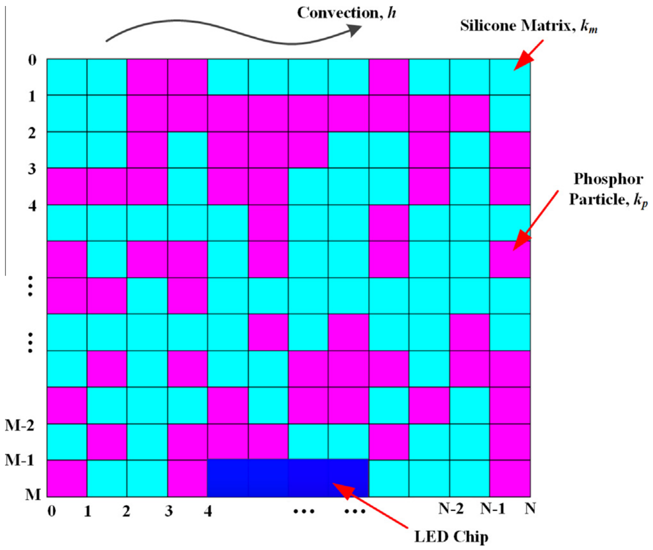

Fig. 2. Calculation model for phosphor distribution optimization.

entransy values were evaluated. At last, the optimized phosphor distribution was given.

2. Problem statement

In pc-LEDs, the mixture of phosphor particles and silicone matrix is dispersed onto the LED chip that is mounted onto the substrate previously. The schematic of the pc-LEDs is pictured in Fig. 1. The thermal conductivities of the phosphor particle and the silicone matrix are k_p and k_m, respectively. In the phosphor layer, it is reported that the phosphor distribution, due to relatively high thermal conductivity of phosphors (~13 W/(m K)), influences the heat conduction processes in silicone [8–10]. But what's the best phosphor distribution that makes the LED junction temperature lowest? This is the exact motivation behind this study and the following part clarifies the detailed solving procedure.

To optimize the phosphor distribution to obtain the lowest junction temperature, we established a model, as shown in Fig. 2. The width and height of the phosphor layer is L and H, respectively. The chip dimension is one third of the width and it is placed in the middle of the x axis. The phosphor layer is divided into $M \times N$ grids along the y and x axes respectively, and each grid corresponds to a unit cell, i.e. either one phosphor particle or silicone matrix. The magenta grids in Fig. 2 denote the phosphor particle with thermal conductivity k_p. The cyan grids in Fig. 2 denote the silicone matrix with thermal conductivity k_m. As the original intention of this study, we put aside the external thermal management and mainly focus on the internal thermal management of the pc-LED packages. So, in the model, we neglected the substrate and only the top surface is cooled with a convective heat-transfer coefficient, h, and other surfaces are insulated. The heat sources in this model contain two parts: LED chip and phosphor particles. The LED chip is assumed as a homogenous heat source with power of q_c. Each phosphor particle is also assumed as a homogenous heat source with the power of q_p. It is predicted that the total phosphor heat generation may be not homogenous because it is dependent on the distribution of phosphor particles. The phosphor volume fraction, ϕ, is defined as $N_p/(M \times N)$, where N_p is the number of phosphor particles. The mathematical description of this problem is

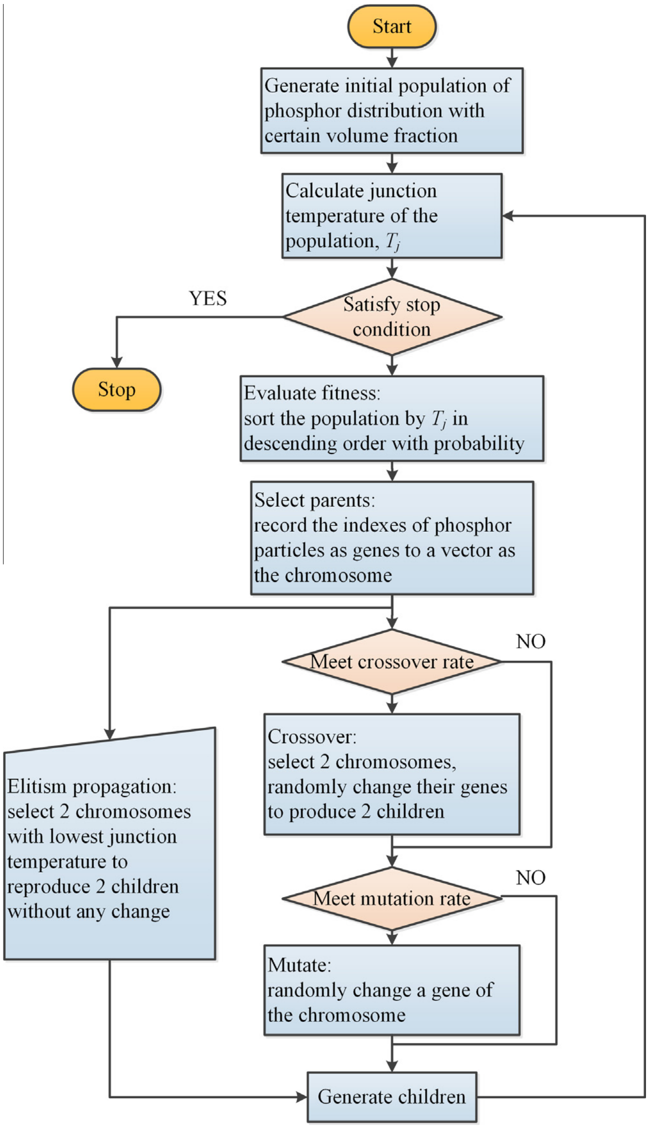

Fig. 3. Flowchart of GA procedure.

$$\begin{cases} \min(\max T) \\ s.t.\ \nabla(k_i \nabla T_i) + q_i = 0,\ i = p, m \end{cases} \tag{1}$$

with boundary conditions

$$\begin{cases} \partial T/\partial y = q_c/k_i, & \text{at } y = 0; 1/3L \le x \le 2/3L \\ \partial T/\partial y = 0, & \text{at } y = 0; x < 1/3L, x > 2/3L \\ \partial T/\partial y = h/k_i(T - T_a), & \text{at } y = H \\ \partial T/\partial x = 0, & \text{at } x = 0, L \end{cases} \tag{2}$$

where q_m equals zero because silicone will not generate heat. Another constraint condition is the phosphor volume fraction ϕ. The precise solution to such a nonlinear problem is not easy and