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Thermal investigation of LED array with multiple packages based on the superposition method

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ABSTRACT

In this paper, the superposition method is used to investigate the complete temperature field of a light-emitting diode (LED) packaging substrate, based on the results of transient temperature rise measurements and the thermal resistance coupling matrix. The feasibility of use of the superposition method in an LED array with multiple packages has been proved first by temperature comparisons with the simultaneous operation of an array (5×5) of 25 high power LEDs mounted on a metal core printed circuit board (MCPCB). Compared with existing approaches, the superposition method will measure the internal temperature of chip directly, accurately and nondestructively. According to the relatively accurate and reliable self-heating and coupling temperature rise data, optimization scheme of LED lamp with multiple packages is proposed. The results show that increasing the heat source separation distance and improving the thermal conductivity of thermal interface materials will reduce the temperature rise and thermal non-uniformity.

1. Introduction

High-power light-emitting diodes (LEDs) are used as light sources in public lighting technology. Because the luminous output of an individual high-power LED is insufficient for replacement of a traditional light source, LED arrays with multiple packages are necessary for general illumination [1], but these arrays also generate significant heat during operation. If the heat cannot be dissipated quickly from the packages, then the LED array illumination intensity and lifetime will be reduced [2]. The ability to thermally manage and control the junction temperature of an LED array has become paramount in the overall development of high-power and high-efficiency LED solid state light sources [3]. The mechanical frame of an LED lamp is a complex structure, while modeling involves simplification. In the conventional use of LED modules, the inhomogeneous temperature may affect the internal quantum efficiencies of the LEDs and the chromatic characteristics of white light LEDs, reduce reliability and cause violent LED module failure. Thus, the average temperature is not suitable for use in the thermal investigation of LED arrays.

Several measurement methods can be used to obtain the junction temperature of the LED module, including thermocouple measurements [4] and infrared measurements [5]. However, while the thermocouples were located next to the chip module and the IR camera obtained the surface temperature of the chip module, the results were always taken at a small distance from the actual heat generation points. Long [6] and Cheng et al. [7] used digital simulation or physical modeling to predict the temperature distributions of LED arrays, but did not obtain the measured data. The transient measurement method is a modern method used to measure the transient forward voltage with temperature rise or fall to evaluate thermal resistance [8,9]. The thermal characteristics of LED arrays are usually calculated based on total power and average junction temperature [10].

In this article, we mainly study the thermal characteristics of 25 (5×5 array) high-power LEDs mounted on an MCPCB using the superposition method. The temperature rise induced in an LED by the adjacent chips will be extracted. A thermal resistance coupling matrix will be established for accurate calculation of the junction temperatures of the LEDs located at the surface. It will be shown that the superposition method can be used for accurate prediction of the junction temperature of the LED lamps with multiple packages.

2. Experimental

Commercial GaN-based single-chip LEDs with electrically neutral thermal paths were used to fabricate the array used in this experiment. A square array (5×5) of 25 high-power LEDs was mounted on

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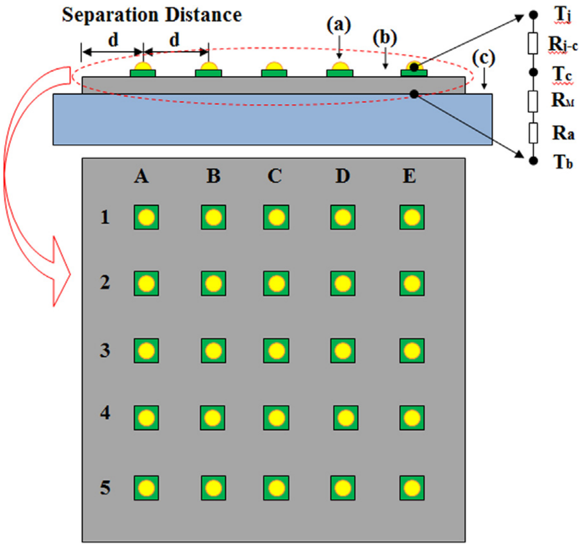

Fig. 1. Schematic diagram of the LED array structure, where $d = 10$ mm ((a) denotes LED, (b) denotes the MCPCB, and (c) is the constant temperature platform).

a 6 cm × 6 cm MCPCB. The distance between the adjacent LEDs is 10 mm. Fig. 1 shows a schematic diagram of the LED array structure mounted on the MCPCB and the array system on a nickel-plated copper constant temperature platform. The bases of the LEDs were soldered to the MCPCB, which was assumed to be at the same temperature.

As shown in Fig. 1, the total thermal path from the junction to the constant temperature platform is divided into several sections that are mainly determined by each distinct material in the thermal path, i.e. from the junction to the case (R_{j-c}), the MCPCB (R_M), and from the MCPCB to the heat sink (R_a). Junction temperature measurements were carried out using the thermal transient measurement system in accordance with the JEDEC JESD15-1 standard [11]. The theoretical framework for thermal analysis using this system is based on a representation of distributed RC networks [12,13]. The system includes real time cooling curve (which has a complementary relationship with the heating curve) data acquisition and evaluates the temperature rise to derive the thermal characteristics. The first step was to obtain the K factor, which defined the junction temperature change with respect to voltage change as a temperature sensitive parameter (TSP). In the calibration process, one of the LEDs was operated over a temperature range from 30 °C to 80 °C using a heat sink with a sensor current of 1 mA. Because of the low sensor current, the self-heating of the LED can be ignored. The 25 LEDs belonged to the same production batch and were all considered to have the same TSP of 1.5 mV/°C. After calibration, coupling cooling curves for each of the 25 LEDs were obtained with a driving current of 1.5 A on each LED. For example, to get the cooling curve of the LED at position A1 (the A1 LED) when affected by the other LEDs, only the A1 LED was kept at a sensing current of 1 mA, whereas the all LEDs were heated with a driving current of 1.5 A for 2 min one by one. After each heating procedure, the cooling curve of the A1 LED was obtained for 2 min. Table 1 shows the measured temperature rise of the A1 LED when the other LEDs were driven with the current of 1.5 A, respectively. Thus, the measurements were repeated 25 times for each LED. The constant temperature platform temperature was set at 30 °C during the thermal transient measurements.

The thermal model of the LED array was built using a three-dimensional finite element simulation with ANSYS12.1 software [7]. The LED array model has the same dimensions as the real modules. The objective of the simulation is to explore the thermal distribution and the coupling temperature rise for the LED array under ideal conditions.

Table 1
Temperature rise (°C) of the A1 LED when each individual LED was driven at 1.5 A. The ranges of A–E and 1–5 denote the active LED position as shown in Fig. 1.

	A	B	C	D	E
1	77.1	2.2	0.9	0.5	0.3
2	2.2	1.2	0.5	0.4	0.3
3	0.9	0.5	0.3	0.3	0.2
4	0.5	0.4	0.3	0.2	0.1
5	0.3	0.3	0.2	0.1	0.1

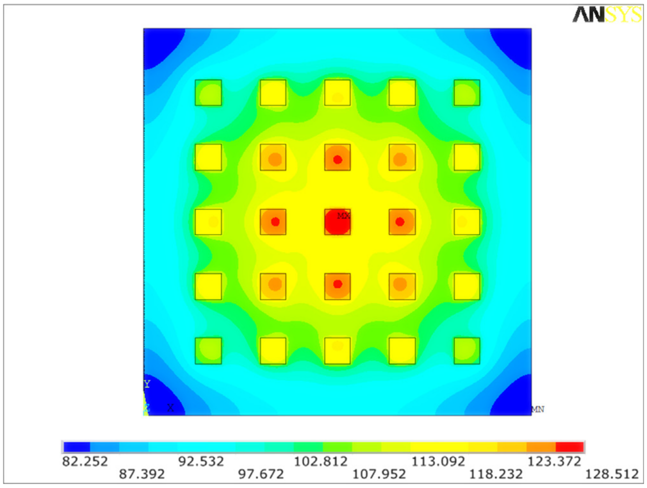

Fig. 2. Simulated temperature distribution (°C) of LED array with input current of 1.5 A.

3. Results and discussion

3.1. Matrix thermal measurements

The simulated temperature distribution of the LED array with input current of 1.5 A is shown in Fig. 2.It is obvious that there is a temperature difference between the chip locations and the substrate edge. The results suggest that the LED array temperature distribution is not uniform. Therefore, the spreading thermal resistance cannot be ignored in the analysis of this LED array.

The thermal resistance of an LED array with multiple packages can be derived from the thermal resistance model of an LED package with multiple chips that was discussed in the literature [14–16], where multiple chips are mounted on a thermal substrate in a single package. In this case, the 25 LED packages are mounted in a MCPCB and an analogy based on the thermal behavior between the two cases (a package with multiple chips and a module with multiple packages) is effective for estimation of the thermal resistance.

When the input power levels changed, the simulation results showed that the temperature difference for each LED remained constant with the variation of the input power. For this reason, the relationship between the LED input powers and the junction temperature differences of different LEDs can also be described using the following linear system. For each LED, following equation can be applied to calculate the thermal coupling resistances:

$$\Delta T_{ki} = (T_{ki} - T_b) = R_{ki} \cdot P_i \qquad (1)$$

where R_{ki} is the thermal-coupling resistance of the kth LED when driving the ith LED, T_{ki} is the junction temperature of the kth chip