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Thermal spreading resistance characteristics of a high power light emitting diode module

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HIGHLIGHTS

- We performed an experimental and numerical study for heat transfer in a LED.
- The thermal spreading resistance effect is significant in the LED module.
- Lateral thermal conductivity of the substrate is critical to the spreading resistance.
- The thermal spreading resistance effect increases with increasing of LED power.

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ABSTRACT

In this study, effects of the dimensions and the thermal conductivity of the substrate on the heat transfer characteristics of a LED module are investigated. The total thermal resistance corresponding to a LED module operating at different power levels is measured using a method following JESD51-1 and JESD51-14 standards. In addition, a finite element method (FEM) numerical simulation is carried out to analyze the heat transfer phenomena in the LED module. It is found that, for the current experimental conditions, the importance of the thermal spreading resistance effect increases with decreasing substrate thickness and/or increasing input power of the LED module, which corresponds to an increase in the total thermal resistance and correspondingly a higher chip temperature. Experimental and numerical results show that the thermal spreading resistance and thus the chip temperature can be reduced by increasing the substrate thickness or by utilizing materials with high lateral thermal conductivities (directionally-dependent) for the substrate. In consequence, for LED modules with the same substrate thickness, using graphite composite to replace aluminum as the substrate material reduces the spreading resistance by nearly 14% in the current study.

1. Introduction

The development of light emitting diodes (LEDs) systems has received a lot of attention due to requirements for energy efficient lighting sources in a variety of applications worldwide. In addition to high energy efficiency, LEDs also are preferred for their fast response and low environmental impact [1,2]. The performance of LEDs in terms of light output quality has improved significantly and efforts have been made to replace traditional lighting sources with LEDs in many countries [3]. However, the light emitted from LEDs degrades over time [4–8]. Possible reasons contributing to the light degradation of LEDs include thermal-induced deterioration of the encapsulation, die-attach [9], reflector and lead wires, as well as impurities and crystalline defects [5,10,11]. The chip temperature has a significant impact on these factors. In addition, nearly 80% of the energy input to a LED can be dissipated as heat [12]. Thus, thermal management is critical to attain high efficient, high power and long lasting LEDs [13–15].

Thermal management of a LED system includes two major factors: packaging and system performance [16]. In addition to the design and optimization of heat sinks such as fin arrays [17–19] and single phase liquid cooling device [20], advanced

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Nomenclature

A	in-plane surface area [m^{-2}]
h_{fc}	convective heat transfer coefficient [$\mathrm{W\ m^{-1}\ K^{-1}}$]
K_{f}	K factor [$\mathrm{K\ V^{-1}}$]
k	thermal conductivity [$\mathrm{W\ m^{-1}\ K^{-1}}$]
P_{i}	input electrical power [W]
$\dot{q}'''$	volumetric heat source [$\mathrm{W\ m^{-3}}$]
Q	input power as heat [W]
R	thermal resistance [$^{\circ}\mathrm{C\ W^{-1}}$]
R_{t}	total thermal resistance of the LED module [$^{\circ}\mathrm{C\ W^{-1}}$]
T_{a}	ambient temperature [°C]
T_{j}	junction (chip) temperature [°C]
$\overline{T}$	average temperature [°C]
t	thickness [m]
Greek symbols	
ε	aspect ratio
ΔT_{j}	change in the LED's junction (chip) temperature [°C]
ΔV_{f}	change in the LED's forward voltage [V]
Subscripts	
p	substrate
s	source

thermal management techniques have been studied for the system and/or the heat sink section for LEDs. For example, Wang et al. [21,22] utilized a vapor chamber based plate to successfully cool a high power LED module. Oscillating heat pipes have also been applied to improve the thermal performance of two-phase flow chamber based heat sinks [23]. Chen et al. [24] applied ionic wind to induce convection and thus promote the rate of heat transfer for a LED module. The package aspect of thermal management involves design of the structure, selection of materials for chip, die-attach and substrate [25]. Heat generated in the chip is transferred through these layered structures. In practice, the thickness of these layers is much thinner than the thickness of the heat sink. However, the package does contribute to a significant fraction of the overall thermal resistance due to low thermal conductivities and small surface areas that result from the fabrication and electrical insulation limitations. In addition, studies of the thermal spreading resistance have emphasized varying the ratio of the chip (heat source) area to the substrate area (heat sink), i.e. the aspect ratio [26–31]. It was found that the thermal spreading resistance effect can be significant for electronic packaging should be included in LED package design. However, there is lack of study for the spreading resistance effects with respect to the power of the heat source (chip), which is one of the issues to be addressed in the present work.

In this study, experiments and numerical analysis were carried out to investigate the thermal performance of LED modules, especially for high power LEDs. The effects of substrate materials and thicknesses on the thermal spreading resistances are discussed based on the results. In particular, a new approach to study the thermal spreading resistance effects was designed and conducted on a LED module with an anisotropic medium (directionally-dependent thermal conductivities) as the substrate material and adjustable input power; this contrasts with the usual approach where isotropic materials (same thermal conductivity in all directions) are used, and the aspect ratio is the controlling parameter. Recommendations for the design of the LED thermal spreader are provided.

2. Experimental apparatus and measurements

A schematic of the experiment is shown in Fig. 1(a). A thermal resistance testing system (T3Ster®) was utilized in conjunction with a data acquisition system, booster extension box (for boosting high power LEDs) and power supply. A thermoelectric cooler (TEC model: Arroyo instruments 5310-TEC Source and 286-TEC Mount, accuracy: ±0.004 °C) was used to maintain the temperature of the LED substrate (bottom surface) at 25 °C. The detailed measurement procedure is provided in a previously published work [32]. A chip-on-board structured LED module with adjustable input power from 10 to 50 W was used as the testing module. A photograph of the testing LED is shown in Fig. 1(b). Geometrical configurations and materials of different layers of the LED module are presented in Table 1 and in Fig. 3. Four substrates were tested: aluminum plates with 0.9 mm, 1.1 mm, 1.6 mm thicknesses and a graphite composite plate with a 1.6 mm thickness. The graphite composite plate was fabricated at the Industrial Technology Research Institute in Taiwan. The graphite composite plate is an anisotropic medium, where the thermal conductivities in the x, y and z directions are 503.1, 531.4 and 178.3 $\mathrm{W\ m^{-1}\ K^{-1}}$, respectively (Fig. 3 shows the corresponding directions). Thermal conductivity measurements were carried out using an LFA 447 NanoFlash™ system (range: 0.1 $\mathrm{W\ m^{-1}\ K^{-1}}$ to 2000 $\mathrm{W\ m^{-1}\ K^{-1}}$, accuracy: ±5%, repeatability: ±3%) in the Material & Chemical Research Laboratories of Industrial Technology Research Institute in Taiwan. Measurements of the thermal performance of the LED module were carried out for power inputs from 10 to 50 W, with 5 W intervals, for all four substrates. A thermal pad with a thermal conductivity $k = 2.8\ \mathrm{W\ m^{-1}\ K^{-1}}$ is used between the LED and substrate to reduce the thermal contact resistance.

The principle of the measurements is that of the Joint Electron Device Engineering Council (JEDEC) standard. The electrical test method (ETM) is based on the JESD51-1 standard [33], and the transient dual interface measurement (TDIM) for the thermal resistance is based on the JESD51-14 standard [34]. First, the temperature sensitivity parameter (TSP) noted as the K-factor was calibrated for every LED module to be tested. The K-factor is defined as:

$$K_{\mathrm{f}} = \frac{\Delta T_{\mathrm{j}}}{\Delta V_{\mathrm{f}}} \tag{1}$$

where ΔT_{j} is the change in the junction (chip) temperature and ΔV_{f} is the change in the forward voltage of the LED, respectively. In the present study, K-factors were calibrated with 1 mA bias current from 25 to 115 °C, and the results are shown in Fig. 2. Note that in the temperature range of the current study junction temperature varies linearly with the forward voltage. K-factors for those four tested LED-substrate modules are listed in Fig. 2. All four cases have comparable K-factors since the same LED was utilized on all the substrates. This result confirms the repeatability of the K-factor measurement. Based on the calibrated K-factor, the junction temperature variation with respect to time (i.e., the cooling curve) during the thermal resistance measurement can be obtained from the recorded transient forward voltage data. The thermal resistance of each layer of the LED module from the chip to the environment can then be identified and determined from the structure function that is derived from the cooling curve. Uncertainty analysis for the thermal resistance measurements was performed according to the specifications of instrument and the experimental conditions [35]. The uncertainty in the thermal resistance measurement results is estimated to be less than 5.1%. Detailed information for the test method of the thermal resistance of semiconductor devices with heat flow through a single path utilized with the T3Ster® system is