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Dynamic compact thermal model of high power light emitting diode

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ABSTRACT

Dynamic compact thermal model plays important roles in predicting the junction temperature and characterizing the transient thermal behavior of an electronic device. In this paper, analytical dynamic compact thermal model for high power LEDs is established based on the three-directional heat flow paths under junction-to-ambient definition. Comparative results with finite element method model indicate that the presented model is accurate and efficient. It is further reduced by analyzing the influence of different components of the LED package. Good agreement with experimental results confirms that the reduced analytical model can predict the junction temperature and characterize the thermal behavior effectively.

1. Introduction

Effective thermal management is crucial to the reliability and efficiency for high power light emitting diodes (LEDs) [1,2]. In order to characterize the thermal performance of the LED package, the junction-to-case and junction-to-ambient static thermal resistances are the most commonly used parameters in manufacturer data for LED productions [3]. However, these parameters can only reflect the thermal characteristics of the entire package, but not the internal structure or assembly defects of components in the heat dissipation path. Dynamic thermal model extracted from thermal transient measurement data is used to characterize the thermal properties of different materials along the heat flow path starting at the heat source till the ambient [4,5]. It can be applied to analyze the thermal behavior of individual components, such as chip, die attach and heat sink.

A high power LED package consists of six basic elements: junction, die attach, heat slug, molding compound, lead frame, and capsule [6]. If a source of electrical power is suddenly applied on a LED chip for thermal transient measurement, the generated heat has three heat flow paths from junction to environment. The first path is via die attach and heat slug to the air, the second is via capsule, the third is via die attach, molding compound and lead frame [7]. For thermal transient measurements under the definition of junction-to-case thermal resistance specified in JESD51-1 [8], the LEDs adhere to a cold plate for accurate reference temperature of body case. Thus almost all heat generated by the junction is dissipated out to the ambient along the heat flow path via the first path where heat successively flows through the junction, die attach layer, heat slug, thermal grease and cold plate. One-directional thermal resistor and thermal capacitor (RC) network is considered accurate enough to describe the transient thermal property in the heat flow path, which has been studied in other researches [4,9–11]. However, as to the definition of junction-to-ambient was specified in JESD51-2 [12], the second and third paths also play an important role in heat dissipation of the LED package. Thus, it is not a simple one-directional but three-directional heat flow paths. The accuracy of the one-directional heat flow model is very limited. It is not suitable for simulation and prediction of thermal transient behavior LED package. Dynamic compact thermal models should be performed to characterize the thermal behaviors of multi-directional heat flow paths of high power LED package.

There are some reports on the dynamic compact thermal model of electronic devices for thermal analysis. The boundary condition independent compact thermal models are firstly developed with DELPHI and PROFIT projects [13,14]. Unfortunately, the results of model elements do not have any physical meaning, hence it is impossible to run parametric analyses. Once one of the geometrical or material parameter is changed, the entire compact model should be regenerated. This problem can be settled by analyzing the time constant spectra or structure functions of system transient thermal responses. Each stage in the heat flow path corresponds to an individual component, which provides the solution for model parameters with physical meanings [15,16]. However, time constant spectra are difficult to analyze in the case of multi-directional heat flow paths. Then, Fourier series, Green's function and Eigenvalue methods are applied to solve the heat expressions [17,18]. It seems a little complicated with these approaches for solving the heat equations semi-analytically for the time-domain step response of the dynamic compact model. So far, there still has no report about the application of dynamic compact thermal model on LED package.

In this paper, combining the analytical method and time constant spectra theory, we set up heat transfer equations in turn based on the

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heat flow paths of the LED package to produce the analytical dynamic compact thermal model. Laplace solution is presented to get the junction temperature response in frequency domain of the analytical model. The detail numerical model is also constructed to verify the analytical model. The time constant spectra calculated from junction temperature response are used as a verification criterion to build a connection between both models. Further, the dynamic compact thermal model is reduced through the effect analysis of different components on time constant spectra and verified by experimental results.

2. Analytical dynamic compact thermal model

The overall heat transfer characteristics of the LED package without attachment on a cold plate can be described using the thermal network model in Fig. 1. It is worth noting that the lead frame is embed in the molding compound, only a minority of area expose to the air and its influence on the thermal property of the LED package can be ignored.

In Fig. 1, dQ is the heat transfer rate from one layer to an adjacent layer. T is the temperature of each layer. P_d is the input electrical power. The temperatures of each thermal layer are defined as a single value (thermally lumped). The dynamic compact thermal model from Fig. 1 for the heat transfer of thermally-lumped components can be derived by using the energy conservation principle as [6]:

$$(\mathit{Junction})\quad C_j dT_j = k_h P_d - dQ_{jc} - dQ_{ja} = k_h P_d - \frac{T_j - T_{cap}}{R_{cap}} - \frac{T_j - T_{att}}{R_j}, \tag{1}$$

$$(\mathit{Capsule})\quad C_{cap} dT_{cap} = dQ_{jc} - dQ_{cap} = \frac{T_j - T_{cap}}{R_{cap}} - \frac{T_{cap} - T_a}{R_{cap.conv}}, \tag{2}$$

$$(\mathit{Die\ attach})\quad C_{att} dT_{att} = dQ_{ja} - dQ_{ah} = \frac{T_j - T_{att}}{R_j} - \frac{T_{att} - T_{hs}}{R_{att}}, \tag{3}$$

$$(\mathit{Heat\,slug})\quad C_{hs} dT_{hs} = dQ_{ah} - dQ_{hs} = \frac{T_{att} - T_{hs}}{R_{att}} - \frac{T_{hs} - T_{hs.surf}}{R_{hs}}, \tag{4}$$

$$\frac{T_{hs} - T_{hs.surf}}{R_{hs}} = dQ_{sc} + dQ_{hk} = \frac{T_{hs.surf} - T_a}{R_{hs.conv}} + \frac{T_{hs.surf} - T_{mold}}{R_{mold}}, \tag{5}$$

$$(\mathit{Molding})\quad C_{mold} dT_{mold} = dQ_{hk} - dQ_{kc} = \frac{T_{hs.surf} - T_{mold}}{R_{mold}} - \frac{T_{mold} - T_a}{R_{mold.conv}}, \tag{6}$$

where k_h is the heat dissipation coefficient representing the portion of input power dissipated as heat. R_{cap}, C_{cap}, R_j, C_j, R_{att}, C_{att}, R_{hs}, C_{hs}, R_{mold} and C_{mold} are the thermal resistance and thermal capacitance of capsule, junction, die attach, heat slug and molding compound. $R_{cap.conv}$, $R_{hs.conv}$, and $R_{mold.conv}$ are the equivalent thermal convection resistances of capsule, heat slug and molding compound. It's worth noting that the temperatures of the bottom and side surface of heat slug are equal to $T_{hs.surf}$ for simplification. Each equation can be described by an individual dynamic thermal equivalent circuit. Such as in Eq. (1), the overall heat of equivalent heat source of LED is $k_h P_d$. Heat dQ_{ja} and dQ_{jc} from the source flow through the equivalent thermal resistors R_{cap}, R_j, and the equivalent thermal capacitor C_j, as shown in the dashed box in Fig. 2. All the equations form the overall dynamic thermal network can be demonstrated in Fig. 2.

Transient junction temperature response T_j plays an important role in analyzing the thermal behavior of LED package which is calculated from the analytical dynamic compact thermal model. It is very difficult to calculate the junction temperature response T_j directly in time domain, whereas it is easy to obtain the response function in Laplace (complex frequency) domain. Firstly, the thermal impedance Z_{th} of the thermal equivalent model should be calculated. By applying a power function $\prod(t) = \prod_0 H(t)$, where $H(t)$ is the unit-step function, the temperature variation across the LED package is given by the product of the thermal impedance and the power function in the frequency domain [19].

$$T_j(s) = Z_{th}(s)\prod(s) = \frac{Z_{th}(s)\prod_0}{s}. \tag{7}$$

From Fig. 2, we can calculate the thermal impedance Z_{th} as:

$$Z_{capsule} = R_{cap} + \frac{R_{cap.conv}}{1 + R_{cap.conv} \cdot C_{cap} \cdot s}, \tag{8}$$

$$Z_{mold} = R_{mold} + \frac{R_{mold.conv}}{1 + R_{mold.conv} \cdot C_{mold} \cdot s}, \tag{9}$$

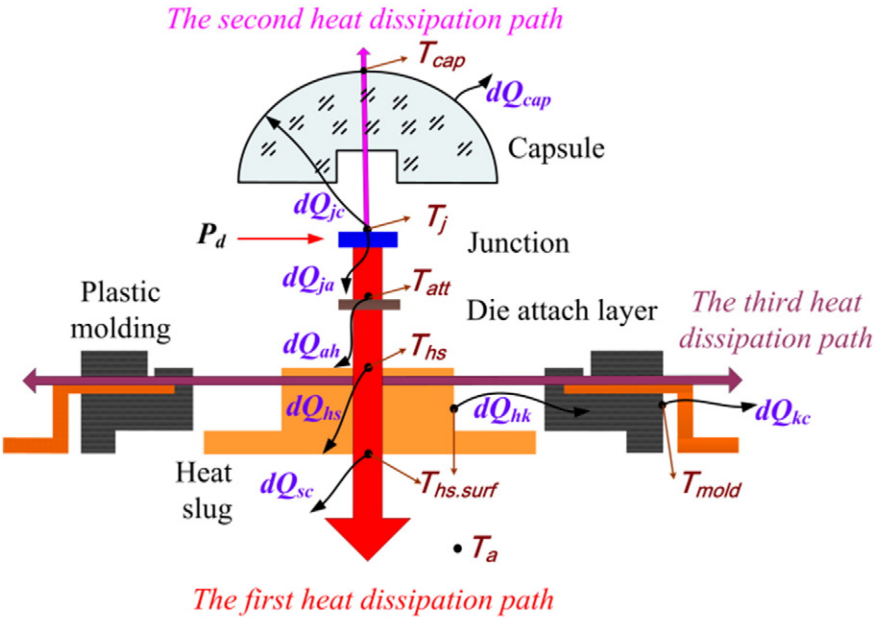

Fig. 1. Thermal network model of high power LED package at junction-to-ambient condition.