A bisection-function technique to characterize heat transport in high-power GaN-based light-emitting-diodes package

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Abstract—**The transient response of the junction temperature of packaged high-power GaN-based light-emitting diodes (LEDs) is numerically simulated. We found the heat transport in LEDs involves two evident processes and can be characterized by a bisection function. One process involves heat transfer from a LED chip to its slug submount, whereas the other involves the heat transfer from the slug submount to the ambient through the heat sink. The thermal time constant of the two processes are identifiable. The time constant of the first process is in millisecond order of magnitude, whereas that of the other process is in hundred-second order of magnitude. The thermal resistance in the two processes can be obtained by analyzing the transient response curve of the junction temperature.**

I. INTRODUCTION

GaN-based light-emitting diodes (LEDs) have wide applications due to their many distinctive advantages, such as low-power consumption, long life span, and high brightness, among others[1]. High-power LEDs have the potential to replace traditional incandescent and fluorescent lamps. However, as the input power increases, additional heat is generated from the chip, resulting in a high junction temperature. As the junction temperature increases, the output power decreases and the wavelength shifts resulting in the degradation of efficiency and reliability. Therefore, an intensive understanding of the heat transport in high-power LED is becoming increasingly important. There were some reports about identity the thermal environment of a semiconductor chip by analyzing the transient response of the temperature. In the present paper, the heat transport of packaged LEDs is studied by simulation on the LED transient response of the junction temperature.

II. DEVICE STRUCTURE

The packaged structure of LEDs under study is shown in Fig. 1. A LED chip mainly consists of a 5 µm GaN active layer and a 75 µm sapphire substrate, and the chip size is 1 mm × 1 mm. The LED chip is connected to a 240 µm silicon submount by a 50 µm thick Pb/Sn solder. The silicon submount is connected to a 2.5 mm thick and 3 mm × 3 mm Cu heat slug. The slug is connected to an Al heat sink. The top of the LED chip is coated by silicone.

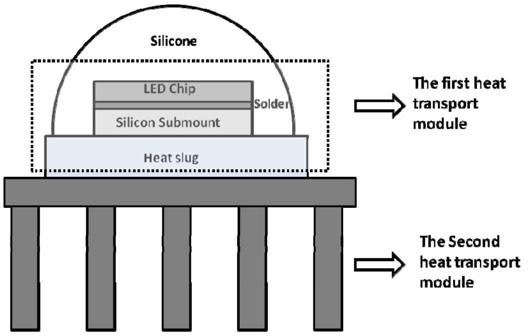

Fig. 1. Typical packaged structure of a high-power GaN LED.

III. RESULTS AND DISCUSSIONS

In order to understand the thermal properties, this packaged structure is simulated to study the transient response of the junction temperature using FEM(Finite Element Method), which is a popular method be used to analyzing the thermal properties of LED chips and packages.

In the simulation, the electro-optical conversion efficiency is assumed to be 20%. The thermal boundary condition is natural convection, and the coefficient of convection is assumed to be 7.5 W/m °C. The ambient temperature is set to 25 °C. The simulation result is shown in Fig. 2.

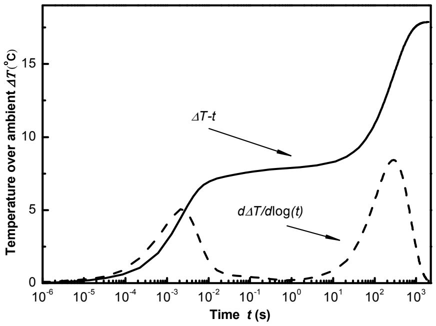

Fig. 2. Simulated curve of junction temperature and corresponding differential curve.

The transient response of the junction temperature involves two evident saturated processes, which can be obtained from the flat regions $[\, d\Delta T / d\log(t) = 0 \,]$ (Fig. 2). In addition, the first heat-saturating time is at millisecond level, whereas the second heat-saturating time is at hundred-second level. Considering the difference in the orders of magnitude for the two values, the slow heat-saturating process can be assumed as the stable heat environment compared with the fast heat-saturating process. Hence, the two heat transport processes can be approximated as two independent processes, and the dynamic equation of

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thermal equilibrium can be described as

$$\frac{d\Delta T}{dt} = G - D\Delta T \tag{1}$$

where ΔT is the junction temperature gradient above the ambient temperature, G is the ratio of heat generated, which includes heat generated inside and heat transferred from outside, and D is the ratio of heat transfer. Equation (1) of thermal equilibrium has a solution in exponential form

$$\Delta T = \Delta T_0[1 - \exp(-\frac{t}{\tau})] \tag{2}$$

Hence, the transient response of the junction temperature can be described as a bisection-exponential function form:

$$\Delta T = \Delta T_1[1 - \exp(-\frac{t}{\tau_1})] + \Delta T_2[1 - \exp(-\frac{t}{\tau_2})] \tag{3}$$

Then, the simulated transient response curve of the junction temperature is fitted using Equation (3) and the fitting result is shown in Fig. 3.The fitting equation is:

$$\Delta T = 4.47 \times [1 - \exp(-t/0.0018)] + 11.07 \times [1 - \exp(-t/307)] \tag{4}$$

According to the fitted curve (Fig. 3), the bisection-exponential function fits well the transient junction temperature response data.

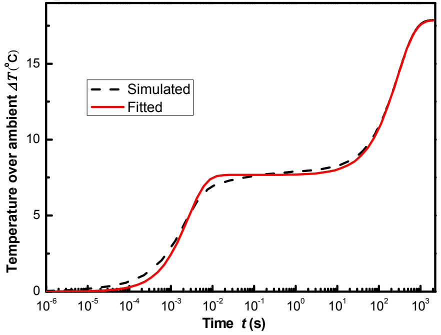

Fig. 3. Simulated data and fitting curve fitted by the bisection-exponential function.

As is known that thermal resistance is one of the important parameters used for evaluating the thermal performance of high-power LED packages. This parameter is defined as the ratio between the temperature difference of two points (or two areas) and the dissipated power. The symbol of thermal resistance is $R\Theta$ or R_{th}, and its unit is K/W or °C/W [2]. The relationship between the thermal resistance of the LED and the junction temperature can be expressed by the following equation:

$$R\theta_{\text{Junction-Ambient}} = \frac{T_{\text{Junction}} - T_{\text{Ambient}}}{P_d} = \frac{\Delta T_{\text{Junction-Ambient}}}{P_d} \tag{1}$$

where T_{Junction} is the junction temperature of LED, and T_{Ambient} is the ambient temperature. P_d is the injected electrical power and given by $P_d = V_f * I_f$, where V_f is the operating voltage and I_f is the operating current.

For the packaged structure of LED (Fig. 1), the thermal transport path can be simplified into two modules of heat transfer: The first heat transport module is heat transferred from the chip to the heat slug, whereas the second heat transport module is heat conducted from the heat slug to the ambient by the packaged heat sink. This heat transport system can be represented by a series circuit model with two equivalent thermal resistances (Fig. 4).

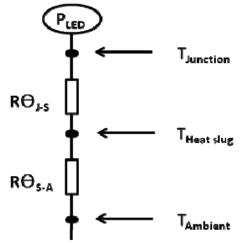

Fig.4. Schematic diagram of the packaged LED series circuit thermal model with two series resistances.

In Fig. 4, the overall thermal resistance of the packaged LED can be given by

$$R\theta_{\text{Junction-Ambient}} = \frac{T_{\text{Junction}} - T_{\text{Ambient}}}{P_d} = \frac{T_{\text{Junction}} - T_{\text{Slug}}}{P_d} + \frac{T_{\text{Slug}} - T_{\text{Ambient}}}{P_d}$$

And

$$R\theta_{\text{Junction-Ambient}} = R\theta_{\text{Junction-Slug}} + R\theta_{\text{Slug-Ambient}}$$

Considering that the fitted curve of the junction temperature has two terms of exponential functions [see Equation (3)], the first term of the exponential function can be attributed to the thermal resistance ($R\Theta_{J\text{-}S}$) contributed by the first heat transport module. The second term of the exponential function is attributed to the thermal resistance ($R\Theta_{S\text{-}A}$) contributed by the second heat transport module. Then, $R\Theta_{J\text{-}S}$ and $R\Theta_{S\text{-}A}$ can be obtained by $R\Theta_{J\text{-}S} = \Delta T_1/P_{LED}$=4.47 °C/W and $R\Theta_{S\text{-}A} = \Delta T2/P_{LED}$=11.07 °C/W.

The overall thermal resistance of the packaged LED is given by $R\Theta_{J\text{-}A} = R\Theta_{J\text{-}S} + R\Theta_{S\text{-}A}$ =15.54 °C/W.

The thermal time constant for the two heat transport processes can be obtained from the fitted curve and the fitting parameters. The first thermal time constant for $R\Theta_{J\text{-}S}$ is 1.8 ms, which is determined by the first transport module. The second thermal time constant for $R\Theta_{S\text{-}A}$ is 307 s, which is determined by the second heat transport module.

IV. CONCLUSIONS

The transient response of the junction temperature of GaN LEDs with a typical packaged structure is examined. The results show that the heat transport in packaged LEDs is mainly influenced not only by heat transport from the chip to the heat slug, but also by heat transport from the heat slug to the ambient through the packaged heat sink. The thermal resistances and the corresponding thermal time constants can be obtained by measuring the transient junction temperature response curves of LEDs. Moreover, the heat transport in LEDs can be characterized by a bisection function. This technique can be useful in the analysis of thermal properties and in obtaining information on the thermal structure of packaged high-power GaN-based LEDs.

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