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Evaluation of thermal transient characterization methodologies for high-power LED applications

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ABSTRACT

In the past, thermal characterization methodologies for LED packages have mainly been derived from already existing solutions of the microelectronics industry. Within this paper, several issues regarding the determination of the junction-to-case thermal resistance R_{thJC} for LED packages are addressed. The new JESD51-14 standard is taken into consideration and especially the so called "point of separation" of the underlying dual-interface method is investigated. Experiments and finite element simulations were carried out in order to investigate the environmental influences on this crucial point. The investigations reveal that the point of separation changes depending on the thermal boundary condition at the case of the LED module, viz the quality of the package attach.

1. Introduction

For LED packages, the measurement of the thermal impedance and resistance follows a widely accepted determination of the thermal transient which is specified in the JESD51 standard [1]. Furthermore, the transient dual-interface (TDI) method, proposed by Schweitzer [2], has currently been standardized [3]. This method is used in order to extract the junction-to-case thermal resistance R_{thJC} of a single device from two thermal impedance measurements. In the first of these two measurements, a thermal interface material (TIM) is placed between the device and the heat sink, and in the second measurement this interface material is removed. The new JESD51-14 standard [3] suggests to use the point at which the thermal impedance graphs of both measuring setups separate as an approximation for R_{thJC}.

2. Issues in determining R_{thJC} for LED applications

Since LEDs convert a significant amount of electrical power into optical power, ambiguities already arise when the thermal impedance is to be defined.

$$Z_{th}^{eff} = \frac{\Delta T}{P_{el}} \tag{1}$$

$$Z_{th}^{real} = \frac{\Delta T}{P_{el} - P_{opt}} = Z_{th}^{eff} (1-\eta)^{-1} \tag{2}$$

Eq. (1) represents the original definition of the thermal impedance as specified by the JESD51 standard. Here, Z_{th} is termed as effective thermal impedance because in reality, LED modules convert a significant amount of electrical power into optical power as well. Thus, the value of Z_{th} has to be corrected accordingly, which can be expressed in terms of the LED efficiency η (see Eq. (2)). Hence, using Eq. (1) instead of Eq. (2) would result in a reduced amplitude of the thermal impedance and therefore in a reduced value for R_{thJC}. Unfortunately, this is not standardized.

Moreover, as it had already been mentioned by Schweitzer et al. [4], one significant problem with respect to thermal characterization is the notion of the thermal resistance itself. The thermal resistance is defined as the change in temperature between two equipotential surfaces of the same cross-section, divided by the amount of heat which flows through those surfaces per unit time. However, in reality the situation is quite different (see Fig. 1).

Both junction and case level, show non-homogenous temperature profiles and first investigations taking this situation into account had already been performed by Schweitzer [5]. For this study, various thermal resistances were defined according to the temperature profiles introduced in Fig. 1.

$$R_{MM} \equiv \frac{T_{J,MAX} - T_{C,MAX}}{P_{th}} \tag{3}$$

$$R_{AA} \equiv \frac{T_{J,AVG} - T_{C,AVG}}{P_{th}} \tag{4}$$

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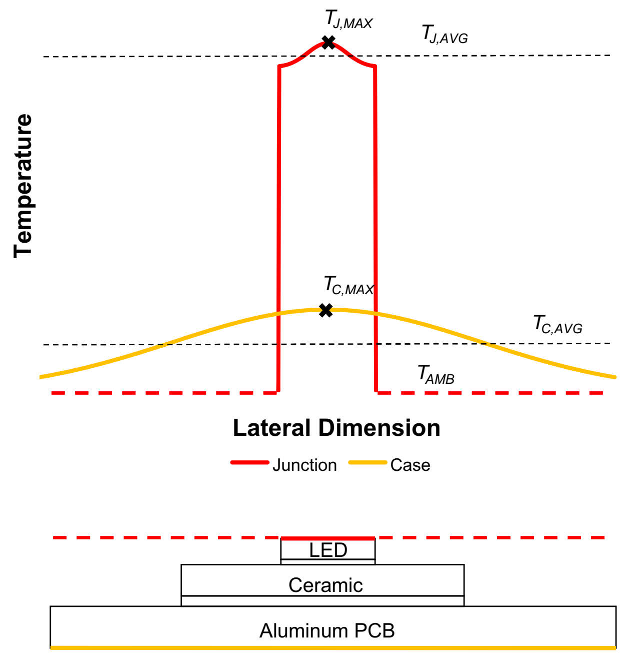

Fig. 1. Illustration: Junction and case temperature profiles for a one-chip LED package. Characteristic temperatures are indicated by crosses and dashed lines. The inhomogeneity of the profiles is clearly observable.

$$R_{MA} \equiv \frac{T_{J,MAX} - T_{C,AVG}}{P_{th}} \tag{5}$$

$$R_{AM} \equiv \frac{T_{J,AVG} - T_{C,MAX}}{P_{th}} \tag{6}$$

$$R_{MAMB} \equiv \frac{T_{J,MAX} - T_{AMB}}{P_{th}} \tag{7}$$

$$R_{AAMB} \equiv \frac{T_{J,AVG} - T_{AMB}}{P_{th}} \tag{8}$$

These thermal resistances are investigated in more detail in Section 4 in order to see if they depend on the thermal boundary conditions (die attach, package, cooling) and, thus, on the changing temperature profile inside the case.

Moreover, this directly leads to another problem in R_{thJC} determination. For multi-chip LED packages like headlamp modules, the LEDs are connected in series in order to improve the homogeneity of the light output. According to the JESD51 standard, the temperature is measured with respect to the change in forward voltage of the device. When the thermal performance of headlamp modules is determined in this way, it is important to be aware that an average temperature is measured and not the hot-spot temperature which is, however, the crucial value for device failure. The notion of an average temperature originates from the fact that the forward voltages of the individual LEDs do not change simultaneously but are instead affected by the temperature profile along the series connection.

The thermal impedance graphs of Fig. 2 had been derived from finite element analysis. The thermal response of the headlamp modules to an overall thermal power of 1 W was calculated and, both, the normalized hot-spot and the normalized averaged thermal transient are depicted in the graph. For stationary operation, the difference can be quite significant, e.g., for our simulation it was approximately 10%.

Furthermore, when the same simulation model as shown in Fig. 2 is used and compared to results obtained from transient

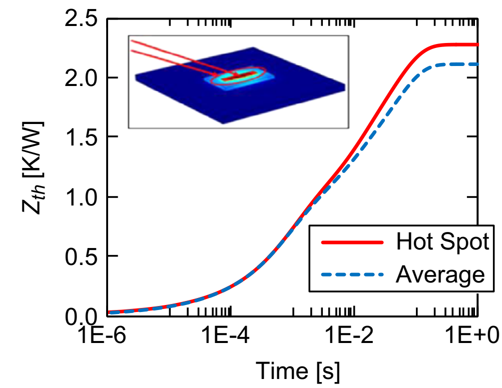

Fig. 2. Simulated thermal impedance graphs extracted at junction hot-spot (solid line) and averaged over all five LED chips (dashed line).

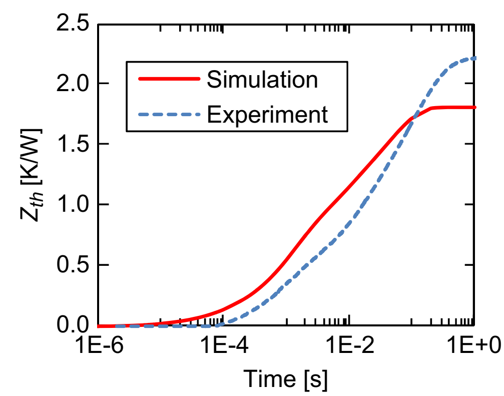

Fig. 3. Comparison of thermal transient data obtained from experiment and simulation.

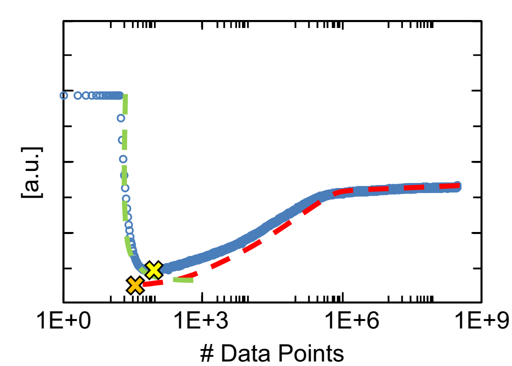

Fig. 4. Illustration: Parasitic electrical transient (green line) superimposed on the actual thermal signal (red line) results in the real measurement signal (blue line) and artifacts in the R_{th} extraction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

measurements, the thermal impedance graphs differ as shown below (Fig. 3).

The discrepancy between experiment and simulation is either caused by wrong assumptions for the simulation model (e.g., a heat capacity which is assumed too low) or it occurs due to measurement parasitics as indicated in Fig. 4.

Simulations revealed that the heat capacity of the pn-junction would have to be increased tenfold in order to compensate for the shift. Since this is far from physical reality, the mentioned discrepancy is expected to be caused by parasitic capacitances in the measurement setup (Fig. 4). Hence, the difference between