Estimation of Non-Reciprocal Behavior and Junction Temperature of an IC LED Driver by Thermal Impedance Matrix Measurement

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Abstract — *The thermal path behaviour of the electronic device is often characterized by considering the single heat source and single junction to ambient thermal resistance. In case of IC drivers, the heat source within the device is multiple due to many integrated components such as transistor, internal resistor, and etc on the single die. Hence the evaluation of IC drivers with multiple heat sources is absolutely necessary for imparting suitable thermal management design within the devices. This study aims at evaluating the factor affecting the thermal performance of the IC driver. In this study, thermal transient measurement method and linear superposition technique have been used to measure the junction temperature of the Device under Test (DUT). Also, the thermal impedance of the DUT has been characterized using structure function extracted from the cooling curve. The obtained result of the thermal impedance showed the non-reciprocal behaviour of the thermal transfer impedance (off-diagonal). In terms of structure function, the total* $R_{th\text{-}JA}$ *of region A is higher than region B and C. From the linear superposition technique, the junction temperature was calculated which showed that the region A (148.07 °C) showed the higher value compared to region B (132.72 °C) and C (139.46 °C). Therefore, it can be concluded that a single die has multiple heat source which increase exponentially in multiple directions resulting in invariable driver performance and failure. Thus, the presence of multiple heat source in the driver was identified as potential performance affecting factor as it caused non-uniform thermal heat distribution within the driver. The outcome of this study benefits in selection of suitable thermal management technique in IC packages.*

Keywords — *Thermal transient measurement, non-reciprocal, multiple heat source, LED IC driver*

I. INTRODUCTION

LED driver is an electrical device which has capability to regulate the power to LED system. The functionality of LED driver depends on power electronic system which either acts as voltage regulator or power switching mode. Most of the LED system uses power switching mode because it is relevant compared to voltage regulator due to high efficiency in terms of thermal management [1, 2].

Good thermal management techniques are required to achieve everlasting device without exceeding the recommended maximum junction temperature [3, 4]. The miniaturization of the device causes the difficulty in thermal management which emerges as a major problem to maintain the operation of device in difference of environment and in rugged system [5, 6, and 7]. Hence, special attention was given by researchers around the world to study and manage thermal problem since the devices are becoming smaller and smaller over the time [5, 6].

The junction temperature (T_J) is the critical temperature of any component in an electronics device at the optimum operating conditions. During operation of any electronic system, T_J is always higher than the temperatures of the case and the exterior part. The difference of temperatures is directly proportional to the product of heat transfer from junction to cases and junction-to-case thermal resistance. Maintaining the T_J value of semiconductor devices below their limit is the key performance in most of the electronics package [8, 9]. Generally, T_J value depends on three main factors (i) power dissipation that determines how much heat is generated, (ii) thermal resistance of substrate and assembly and (iii) ambient condition which dictates how efficiently heat can be removed.

Most of the researchers are giving more attention on thermal impedance measurement to measure multi-die package which can be used to determine the T_J. According to Zahn et al, thermal matrix is more complex for the device manufacture to measure rather than single thermal resistance measurement [10]. As reported by Kim et al, it was demonstrated that the dependence of the thermal resistance and T_J value on the number of the chip is stronger for the LED package with higher ratio of partial thermal resistance between chip and the slug with respect to partial thermal resistance between slug and ambient [12]. Previous studies by Andras Poppe et al proposed the non-reciprocal behaviour of off-diagonal matrix due to the different size of the dies for multi-die package [11]. Therefore, this technique provides a more accurate thermal prediction of the multiple heat output device.

In this study, thermal transient behaviour of IC package (multiple heat source) has been captured using Thermal Transient Tester (T3Ster). Further, multiple heat source has been determined in one package of IC driver on single die by Thermal Transient measurement. Thus, three driving regions (*A*, *B* and *C*) have been tested at different place in single die IC package. Besides that, thermal transfer impedance is characterized with respect to Z_{th} curve by mathematical transformation from cooling curve captured by Thermal Transient Tester (T3Ster). The results are analysed by T3ster master software.

II. Methodology and Thermal Impedance

The aim of the experimental measurements is to determine the effect of multiple heat source in IC LED driver on the thermal impedance of single die at different region of heat sources.

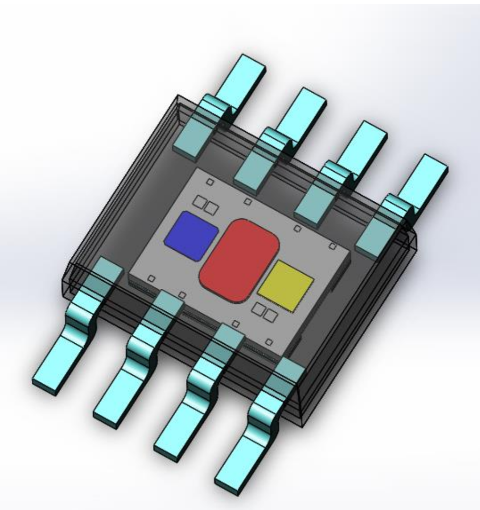

Fig. 1. Multiple heat source LED driver was used to investigate the thermal performance of IC driver.

In this study, three different driving points have been carried out on the single die of IC driver as shown in Fig. 1. The assumption has been made for location of every heat source according to the restricted information given by the company. Basically, the IC driver consists of different integrated component on single die in order to accomplish its functions. The measurement and heating currents are 1 mA and 150 mA respectively and constantly maintained throughout the experiments. The blue, red and yellow colour are denoted as region *A*, region *B* and region *C* respectively. At first, a power step has been applied on the region *A* and later on *B* and *C* accordingly to capture its cooling curve in each case on all the regions. As a result, three driving point of thermal impedance were obtained which is heating as well as measuring at the same location while six thermal transfer impedance were produced. By definition, thermal transfer impedance is a change in temperature at one location when power change is applied at a junction. At every point, thermal transfer impedance is explained with respect to impedance curve Z_{th}.

Multiple junction temperatures are obtained by using linear superposition equation which can be described by thermal impedance matrix in terms of time-domain function (impedance curve) or frequency domain (complex loci) [13]. The impedance curve is used to calculate the temperature feedback to any applied power in die at different point of heating as described in Fig.1. Thus, linear superposition equation is given by: [14]

$$\begin{bmatrix} \Delta T_A \\ \Delta T_B \\ \Delta T_C \end{bmatrix} = \begin{bmatrix} Z_{AA} & Z_{AB} & Z_{AC} \\ Z_{BA} & Z_{BB} & Z_{BC} \\ Z_{CA} & Z_{CB} & Z_{CC} \end{bmatrix} \begin{bmatrix} P_A \\ P_B \\ P_C \end{bmatrix} \quad (1)$$

Where ΔT is total temperature difference between ambient and junction temperature, Z is thermal impedance, and P is power step. Z_{AA} is the rise in temperature per Watt at region *A* due to heat dissipated at junction (region A). Off-diagonal Z_{AB} & Z_{BA} are the temperature rise per Watt at region *B* due to heat dissipated at junction region A and vice versa. Similarly, Z_{BC} & Z_{CB}, are the temperature rise per Watt at region *C* due to heat dissipated at junction region *B* and vice versa.

A. *Thermal transient analysis*

Thermal characterization of any semiconductor device can be performed by using thermal transient testing. T3ster (by Mentor Graphics Corporation) is an equipment to measure the thermal transient characterization of any electronic component. The thermal transient data provides a step function response of the IC package. This unit-step response is vital as it serves as the base of generating dynamic thermal network model of the package. The thermal transient curve of IC package consists of several layers of material with different thermal properties which produces a time-function of the chip temperature rise.

Temperature rise begin a few microseconds after excitation, but steady state will be reached only after some hundreds or thousands of second. This is the reason plotting thermal transient response on a logarithmic time axis. Plateaus in the heating curve indicate the existence of different layers inside the IC package. This is due to the fact that different materials have different time constant and thermal resistances. Evaluation of step-function response provides comprehensive heat flow path of the IC package, known as structure function. The structure is more precisely known as cumulative structure function.

In prior to obtain the thermal characterization of any devices understanding the operation of thermal transient measurement is compulsory. This equipment is compliant to JEDEC thermal testing standard for electrical test method. According to JEDEC 51 current jump measurement is suitable to use for device based diode. Current jump can be understood by changing of power level due to fast switching ON to switching OFF. Fig. 2 shows the proper way of system work for the electrical test method where the total of I_{drive} and I_{sense} ($I_{measurement}$) is consider heating current while $I_{measurement}$ is consider as sensing current.

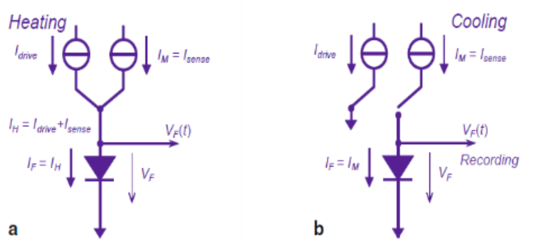

Fig. 2. Practical measurement a) heating and b) cooling configuration of T3Ster.

III. RESULT AND DISCUSSION

A. Structure function

The thermal performance of LED IC driver mounted on FR-4 PCB are captured at 25°C on cold plate using T3Ster and the obtained results are presented as shown in Fig. 3. In Fig. 3 (a), blue curve indicates the heating at region *A* while red curve and black curve indicates sensing at region *B* and region *C* respectively. In Fig. 3 (b), region *B* is used as a heating which is denoted by blue curve and others two regions are sensing at region *A* and *C* which are shown in red and black respectively. Beside that, Fig. 3(c) shows a heating region (blue curve color) at *C* and and sensing at region *A* (red) and *B* (black) respectively.

Based on Fig. 3, the cumulative structure function has been plotted to describe thermal path of the IC LED driver from p-n junction to cold plate. Fig. 3 also indicates a complete thermal profile of the sample recorded between the point at heat generation and point at heat dissipation. Every layer in package can be described by this structure function. From the Fig. 3, the red circle clearly indicates that there is difference in heat dissipation from the junction. This is due to location of heat sources at different spatial co-ordinates as affirmed by the different thermal capacitance value. From this transient measurement, the region *A* has generated power 0.358W whereas region *B* and *C* generated power step 0.453W and 0.473W respectively. Thus, as observed in Fig. 3, the total $R_{th\text{-}JA}$ of region *A* is higher than region *B* and *C*. It is related by

$$R_{th} = \frac{\Delta T}{Q} \tag{2}$$

where R_{th} is the thermal resistance of a material, ΔT is temperature difference, and Q is the rate of heat flow [15]. From the above equation, it is evident that heat generation (Q) is inversely proportional to thermal resistance (R_{th}). Thus, when Q is low, R_{th} becomes higher provided the temperature rise is constant.

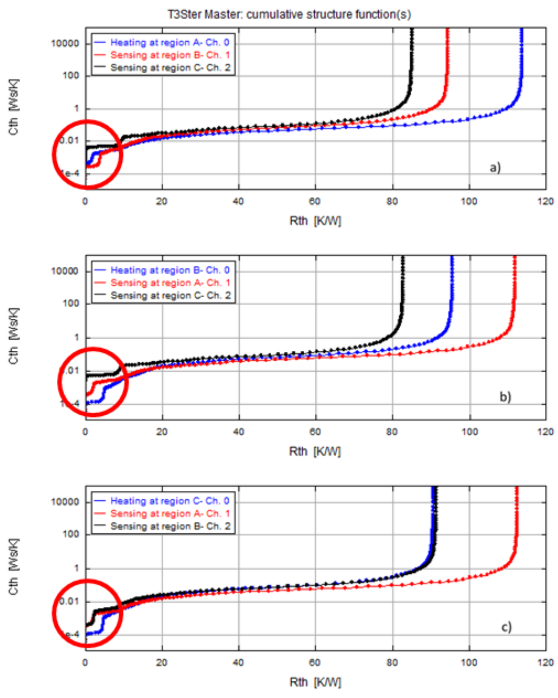

Fig. 3. All Cumulative structure function of different driving point a) Heating at region A, b) Heating at region B, and c) Heating at region C in open air environment.

B. Thermal impedance analysis

Thermal impedance is derived from thermal transient measurement and it can be defined as the difference in temperature between two isothermal surface divided by the rate of heat flowing from the hotter isothermal boundary. In the other words, thermal impedance can be assumed as dynamic test while the thermal resistance is static test.

Fig. 4 illustrates a plot of thermal impedance versus heating time after a step change in power dissipation at open air boundary condition. This Z_{th} curve is used to explain the thermal impedance matrix of three different regions of heating on single die that is *a(t)* unit-step response curves normalized to 1W dissipation. The *X*-axis of this graph shows the heating time in second while normalized temperature rise in Degree Celsius appear on *Y*-axis.

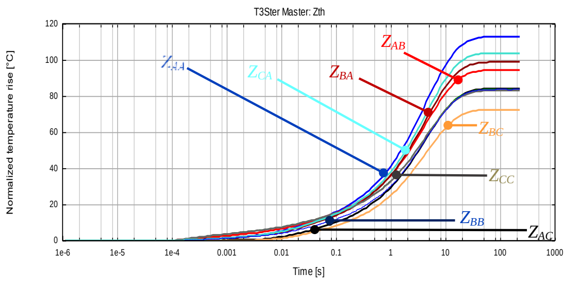

Fig. 4. Thermal impedance curve at open air environment.

As observed in fig. 4, driving points (diagonal matrix) of region *A*, *B*, and *C* are 112.99°C, 84.03°C, and 83.08°C respectively. There is a significant change in value between regions *A*, *B* and *C* which is due to difference in power steps. However, Z_{BB} and Z_{CC} depicted slight difference in thermal impedance. Apart from that, the thermal transfer impedance can be described in off-diagonal matrix element. The thermal transfer impedance can be explained as Z_{AB} which is thermal impedance due to heating at region *B* and the rise in temperature is detected at region *A*. Supposedly Z_{AB} and Z_{BA}, Z_{AC} and Z_{CA}, Z_{BC} and Z_{CB} shows the reciprocal behavior for multi die package if the size of die and material are same for each die inside the package [11]. However, in this study the time constant range of Z_{AB} is lower than Z_{BA}. This may be due to integration of different component on die of IC LED driver. As can be seen from Fig. 4, Z_{th} thermal impedance matrix of the IC driver die depicts non-reciprocal behavior as $Z_{AB} \neq Z_{BA}$, $Z_{AC} \neq Z_{CA}$, and $Z_{BC} \neq Z_{CB}$ are not symmetrical.

It can be clearly seen from Fig. 4, Z_{BB} and Z_{CC} depicted overlapping to each other. Similar observations were recorded for line Z_{AC} and Z_{CB}. It indicates that the thermal transfer impedance of these regions achieved the equilibrium temperature. Z_{AA}, Z_{CA}, Z_{AB}, and Z_{BA} are raise dramatically. This might be due to thermal crowding and component distribution on single die [13].

The non-reciprocal behavior also can be explained by frequency-domain (complex loci) which transformed from $a_{lk(t)}$ time-domain response of the l_{-th} die when unit power step is applied at die *k* [16].

$$Z_{lk}(\omega) = \frac{1}{P}\int_0^\infty a_{lk}(t)e^{-j\omega t}dt \qquad (3)$$

The complex loci in Fig. 5 represents frequency domain of impedance matrix of IC LED driver. Also, the horizontal axis in Fig. 5 indicates the real value of thermal impedance while vertical axis show imaginary value for this Nyquist diagram. This Nyquist diagram shows frequency responses of linear system. To support the earlier discussion, it again shows the graph are not symmetrical which affirms the non-reciprocal behavior.

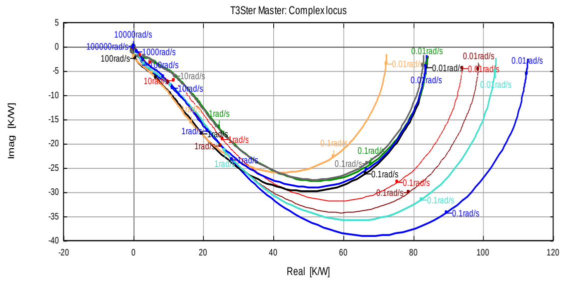

Fig. 5. Complex locus of the frequency domain thermal impedance of IC driver for single die

C. Junction temperature

As explained earlier, junction temperature is an important parameter in determining lifetime of electronic devices. Increasing the junction temperature results in degradation of device and even failure for few critical parameters in thermo-mechanical and functional testing. In this study, thermal transient measurement and linear superposition technique has been used to measure junction temperature.

TABLE I. CALCULATED JUNCTION TEMPERATURE OF MULTIPLE HEAT SOURCE ON SINGLE DIE IC DRIVER

Heating point	**Calculated T_J (°C)**	**Power step (W)**
A	148.07	0.358
B	132.72	0.453
C	139.46	0.473

The linear superposition for junction temperature matrix can be calculated as follows:

$$\begin{bmatrix}\Delta T_A\\ \Delta T_B\\ \Delta T_C\end{bmatrix} = \begin{bmatrix}112.99 & 94.42 & 84.24\\ 98.87 & 84.03 & 72.42\\ 103.82 & 83.88 & 83.08\end{bmatrix}\begin{bmatrix}0.358\\ 0.453\\ 0.473\end{bmatrix}$$

$\Delta T = T_J - T_a$ where T_J is junction temperature and T_a is ambient temperature.

From the Table 1 the junction temperature of IC LED driver was calculated using linear superposition technique to gain its value. The junction temperature was obtained by superposition technique and tabulated in Table 1 according to region that have been measured. It is obvious that the T_J value for the region *A* is the higher value which is 148.07°C. From the Fig.1 observation, region *A* consists of main components of the device. Thus, the higher value for this region proves to be valid.

IV. CONCLUSIONS

In this study, thermal transient measurement has been explained in terms of thermal impedance, cumulative structure function and junction temperature that is recorded from cooling curve by mathematical extrapolation. The obtained results of the thermal impedance show a non-reciprocal behavior of the thermal transfer impedance (off-diagonal). In terms of structure function, the total $R_{th\text{-}JA}$ of region *A* is higher than region *B* and *C*. And finally, the junction temperature calculated by linear superposition technique for the region *A*, *B* and *C* are 148.07°C, 132.72°C and 139.06°C respectively These results confirmed the presence of multiple heat source on the single die of IC driver. Further, non-reciprocal behaviour can be obtained by thermal transient measurements. However, more investigation are needed die architecture for accurate predictions.

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