Transient Thermal Measurements and thermal equivalent circuit models

Replaces AN2008-03

About this document

Scope and purpose

The base of a power electronic design is the interaction of power losses of an IGBT module with the thermal impedance of the power electronic system.
With a precise model the system can be designed for high output current without exceeding the maximum junction temperature limit and being reliable in terms of power cycling, respectively.
To meet the requirement Infineon has optimized the measurement method.
The following sections describe how to thermally characterize a power electronic system and how to model it for application oriented investigations.

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1 Determination of thermal impedance curves

1.1 Principle of Measurement – R_{th}/Z_{th}-Basics

The principle of measurement is described in IEC 60747-9 Ed. 2.0 (6.3.13.1) [1].
The approach of thermal impedance determination is shown in figure 1. A constant power P_L is fed into the IGBT module by a current flow, so that a stationary junction temperature T_j is reached after a transient period. After turning off the power, the cooling down of the module is recorded.

The thermal resistance $R_{th(x-y)}$ is the difference of two temperatures T_{x0} and T_{y0} at t=0, divided by P_L. For calculating the time dependent thermal impedance $Z_{th(x-y)}(t)$, the recorded temperature curves need to be horizontally mirrored and shifted into the origin of the coordinate system. Then $Z_{th(x-y)}(t)$ is calculated dividing the difference of $T_x(t)$ and $T_y(t)$ by P_L.

$$R_{th(x-y)} = \frac{\Delta T_{xy0}}{P_L}$$

$$Z_{th(x-y)}(t) = \frac{\Delta T_{xy}(t)}{P_L}$$
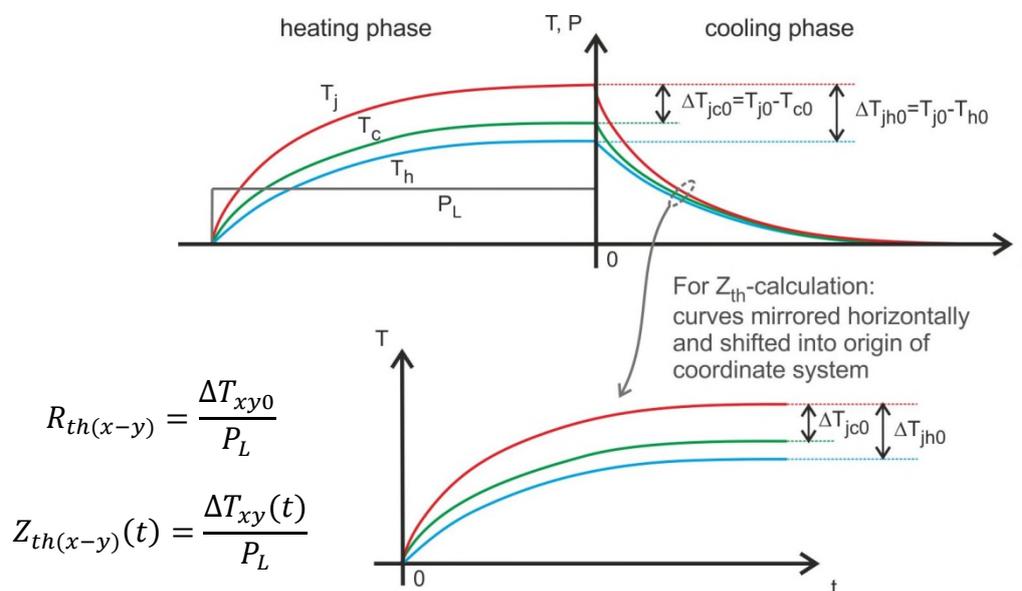
Figure 1   Principle approach of thermal impedance measurement

For determining the junction temperature in the cooling phase, a defined measurement current (I_{ref} approx. 1/1000 I_{nom}) is fed to the module and the resulting saturation or forward voltage is recorded. The junction temperature $T_j(t)$ can be determined from the measured forward voltage with the aid of a calibration curve $T_j = f(V_{CE}/V_F @ I_{ref})$. Its reverse curve $V_{CE}/V_F = f(T_j @ I_{ref})$ (see figure 2) was recorded earlier by means of external, homogenous heating of the tested module.
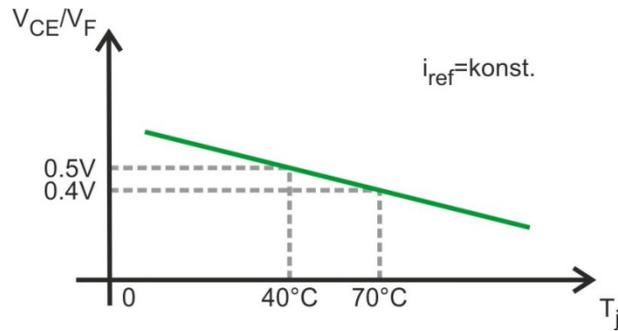
Figure 2   **Example for a calibration curve, used to determine the junction temperature by measuring the saturation voltage at a defined measuring current.**

The case temperatures T_c and the heatsink temperatures T_h are determined by means of thermocouples. The thermocouples are thermally isolated with exception of their top. With this, they contact the modules baseplate and the heatsink, respectively (figure 3, left). In both cases, the projected thermocouple axis is located in the center of each chip (figure 3, right).
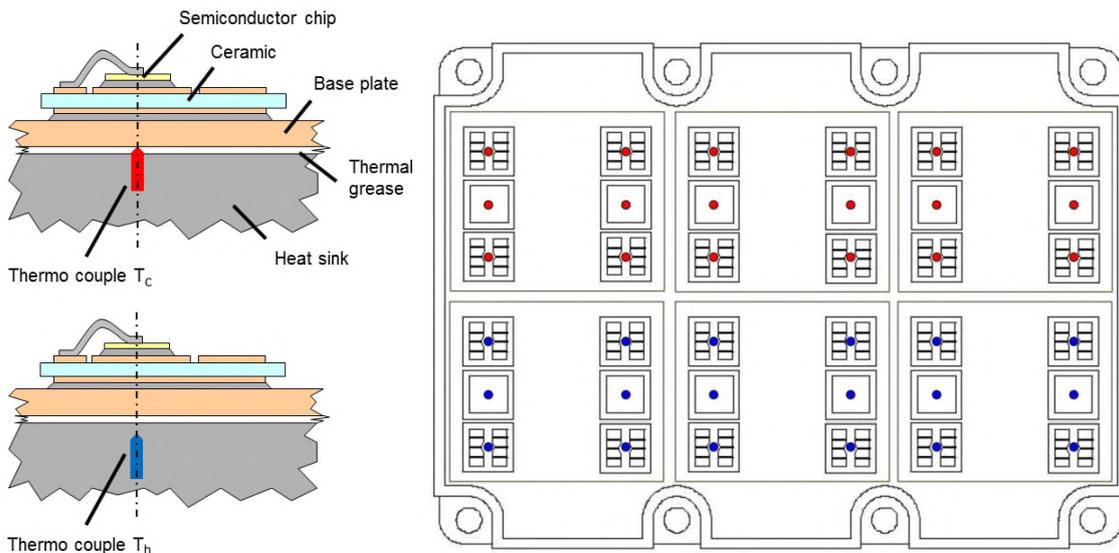
Figure 3   **Determination of case temperature T_c and heatsink temperature T_h and example for the projected sensor positions based on a 3.3kV 140x190mm² module.**

1.2   Challenges and optimization of R_{th}/Z_{th}-measurement

Precise measurements are required for determination of T_j and T_c right at the time the cooling phase begins. On the one hand, directly after turn-off the smallest thermal time constants effecting T_j. On the other hand, parasitic effects lead to transient disturbances in the measured signals.

In order to overcome the hurdles from above, a modified measurement system (see figure 4) is being used.

Determination of thermal impedance curves
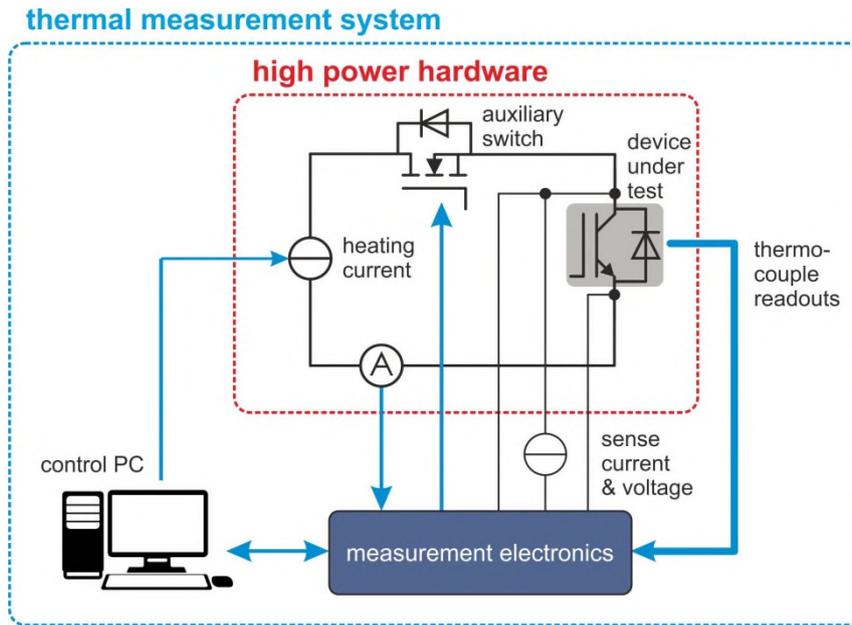
Figure 4   Optimized analog/digital measurement equipment

Due to advancements in technologies and products Infineon has reviewed the R_{th}/Z_{th} measurement method and simulation approach. R_{th}/Z_{th} measurements were modified accordingly. By using a new measurement equipment it is now possible to determine more precise R_{th}/Z_{th} values of IGBT modules. In a simplified manner, this is depicted in figure 5. The difference between T_j and T_c at t=0 is larger for the modified measurement system "B" in comparison to the former measurement system "A". As given in figure 1, this temperature difference is proportional to the thermal resistance R_{th} and also affects the thermal impedance Z_{th}.

The modified measurement system is able to determine precise data also in the early time.
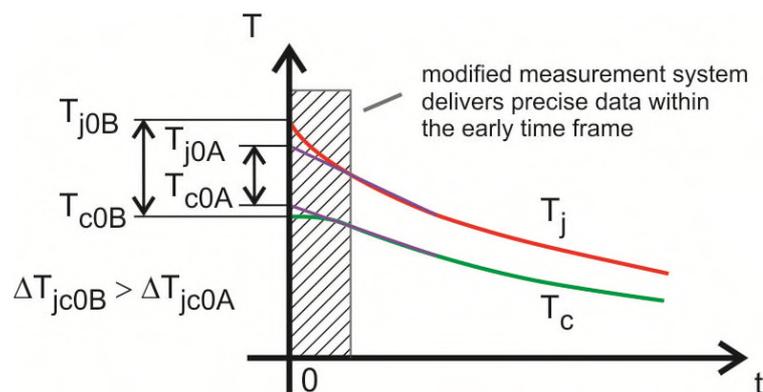
Figure 5   Comparison of formerly measurement system (A) and the modified one (B)

2 Thermal equivalent circuit models

2.1 Introduction

The thermal behavior of semiconductor components can be described using various equivalent circuit models:
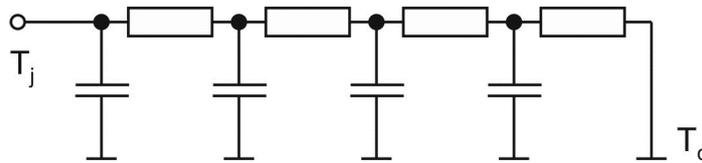
Figure 6 **Continued fraction circuit, also known as Cauer-model, T-model or ladder-network**

The continued fraction circuit (figure 6) reflects the real, physical setup of the semiconductor based on thermal capacitances with intermediary thermal resistances. The model can be set up where the material characteristics of the individual layers are known, whereby, however, the correct mapping of the thermal spreading on the individual layers is problematic. The individual RC-elements can then be assigned to the individual layers of the module (chip, chip solder, substrate, substrate solder, baseplate). The network nodes therefore allow access to internal temperatures of the layer sequence.
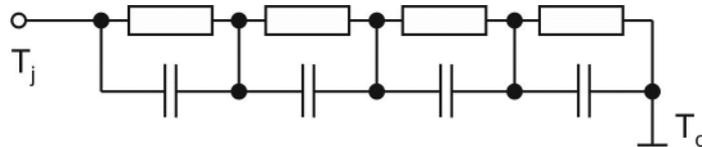
Figure 7 **Partial fraction circuit, also known as Foster-model or pi-model**

In contrast to the continued fraction circuit, the individual RC-elements of the partial fraction circuit no longer represent the layer sequence. The network nodes do not have any physical significance. This illustration is used in datasheets, as the coefficients can be easily extracted from a measured cooling curve of the module. Furthermore, they can be used to make analytical calculations.

The thermal impedance of a partial fraction model from can be expressed as:

$$Z_{th}(t) = \sum_{i=1}^{n} r_i \left(1 - e^{-\frac{t}{\tau_i}} \right) \tag{1}$$

whereas

$$\tau_i = r_i \, c_i \tag{2}$$

As an example, in figure 8 the module datasheet Z_{th}(j-c) of an IGBT is given based on a partial fraction model. The corresponding coefficients are provided in tabular form as resistance (r) and time constant (τ) pairs.
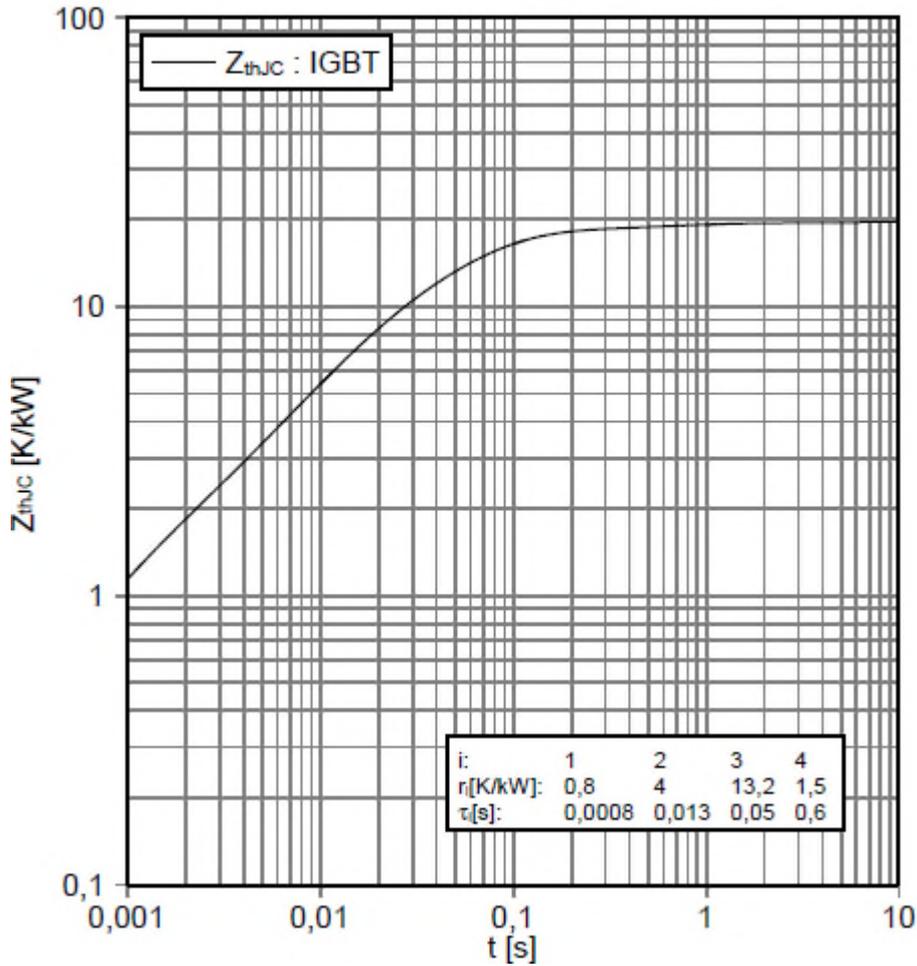
Figure 8   Example of how the thermal impedance is given in a datasheet based on a partial fraction model

With given switching and forward losses $P_L(t)$ and under the assumption of a known case temperature $T_c(t)$, the junction temperature $T_j(t)$ can be determined as follows:

$$T_j(t) = P_L(t) * Z_{th(j-c)}(t) + T_c(t) \tag{3}$$
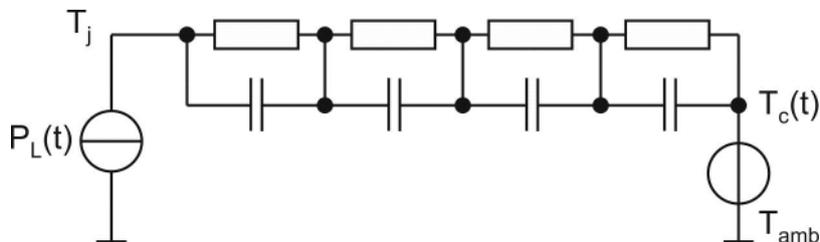
Figure 9   Partial fraction model for determining $T_j(t)$ for given semiconductor losses $P_L(t)$ under the assumption of a known case temperature $T_c(t)$

The simplifying assumption of a constant case and heatsink temperature is not always given in practice, as the period of the load is not negligibly short compared to the time constants of the heatsink. For considering non-stationary operating conditions either $T_c(t)$ must be measured or the IGBT model must be linked to a heatsink model.

2.2 Considering the thermal paste

In both models, the use of R_{th} instead of the usually unknown Z_{th} for the thermal grease is conceivable for a worst case assessment. Neglecting the capacitances in the partial fraction model, a fed in power step causes an immediate temperature drop across the whole resistor chain. The junction and also the thermal grease temperature rise immediately to a constant value, which is not representing the physical behavior of the system. There are two ways to bypass the problem:

- If the Z_{th} of the heatsink shall be determined by measurement, the case temperature T_c should be used instead of the heatsink temperature T_h. In this case, the thermal grease is included into the heatsink measurement and must no longer be considered separately.
- If an IGBT setup is available, where the fed-in power loss $P_L(t)$ is known, the case temperature $T_c(t)$ can be measured directly and included into the calculation in accordance with figure 9.

2.3 Merging the semiconductor module and the heatsink into a system model

The user often will avoid the expense for measurements and will create a thermal system model out of the existing IGBT/diode model and the desired heatsink data. Both, a continued fraction and a partial fraction model, can represent the respective transfer functions "junction to case" of the IGBT and "heatsink to ambient" of the heatsink. If IGBT and heatsink models are to be combined, the question arises, which of the two models should be used, especially if IGBT and heatsink have been characterized separately from each other.

2.3.1 Thermal system model based on continued fraction model

The continued fraction model and the linking of individual models of this type visualize the physical concept of individual layers which are sequentially heating one another. The heat flow – the current in the model from figure 10 – is reaching and therefore heating the heatsink with a certain delay. A continued fraction model can be achieved by simulation or transformation from a measured partial fraction model.
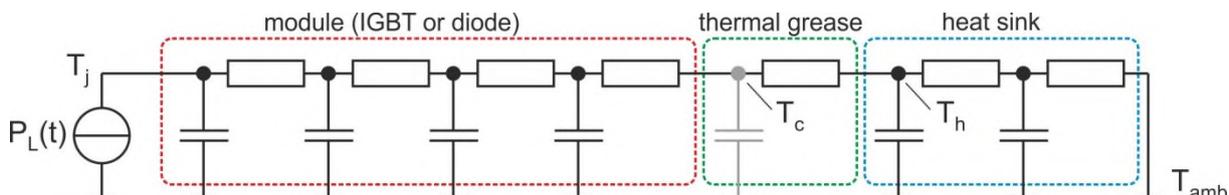
Figure 10   Merging continued fraction models to a system model

It is self-evident to set up a model by material analysis and FEM simulation of the individual layers of the entire setup. But this is only possible by including a specific heatsink, as the heatsink has a reverse effect on the thermal spreading within the semiconductor module, and therefore on the time response and the resulting $R_{th}(j\text{-}c)$ of the module. If the heatsink in the application deviates from the simulated heatsink, the model will not take this into consideration.

In data sheets commonly the partial fraction model is given, as this is the result of a measurement-related analysis and the Z_{th}(j-c) can be provided advantageously as a closed solution. A mathematical transformation of a partial fraction model into a continued fraction model is possible. This transformation is not unambiguous. Various thermal resistance (R_{th}) and thermal capacitance (C_{th}) value pairs are possible. Also the individual R_{th} and C_{th} elements as well as the node points of the new continued fraction model have not any physical significance after the transformation. A merging of continued fraction models that are not coordinated with one another can therefore result in all kinds of errors.

2.3.2 Thermal system model based on partial fraction model

The semiconductor module partial fraction model, as it appears in the data sheet, is based on a measurement in combination with a specific heatsink. While an air cooled heatsink results in a wide spread of the heat flow in the module and therefore leads to better, i.e. lower R_{th}(j-c), in the measurement, the limited heat spreading in a water cooled heatsink results in a comparably higher R_{th}(j-c) value in the measurement. By the use of a water-cooling bar for the characterization, the partial fraction model provided in the Infineon datasheets represents a comparably disadvantageous operation mode – and therefore an appraisal on the safe side in favor of the module.

Due to the series connection of networks (figure 11), the power fed into the junction – in the equivalent circuit represented by the current – reaches the heatsink without delay. Therefore the rise of the junction temperature depends on the type of heat sink already in the early phase, in which actually only the thermal capacities of the module are active.
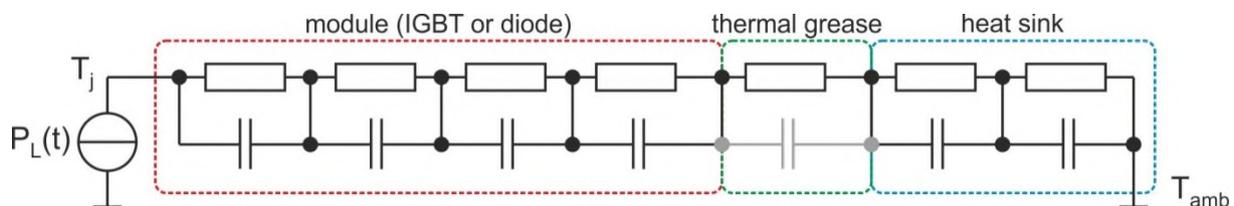
Figure 11   Merging partial fraction models to a system model

However with air-cooled systems the time constants of the heatsinks are ranging from some 10 to several 100s, which is far above of the values for the IGBT itself with just approximately 1s. In this case the calculated heatsink temperature rise falsifies the IGBT temperature only to a very small degree. On the other hand water-cooled systems are critical, since they have comparably low thermal capacitances, i.e. correspondingly low time constants. For "very fast" water cooled heatsinks, i.e. systems with direct water cooling of the IGBT baseplate, a Z_{th} measurement of the complete system of IGBT plus heatsink should be performed.

Because of the reverse effect on the thermal spreading in the module, the linking of IGBT and heatsink is not possible fault-free, either in the continued fraction or in the partial fraction model. A way to overcome this issue is to model or measure the Z_{th} of the semiconductor module and the heatsink not independently from each other. A complete fault-free thermal system model can only be obtained by a measurement of the thermal impedance Z_{th}(j-a), i.e. with simultaneous measurement of the complete thermal path from junction via module, thermal grease, heatsink to ambient. This delivers a partial fraction model of the entire system, with which the junction temperature can be calculated fault-free.

3 References

[1]   IEC 60747-9 Ed. 2.0 (6.3.13.1) 'Semiconductor devices - Discrete devices - Part 9: Insulated-gate bipolar transistors (IGBTs) [3]

Revision History

Major changes since the last revision

Page or Reference	Description of change