AN2008-03

Thermal equivalent circuit models

replaces AN2001-05

Industrial Power

Never stop thinking

Edition 2008-06-16

Published by
Infineon Technologies AG
59568 Warstein, Germany

AN2008-03		
Revision History:	2008-06-16	V1.0
Previous Version:	none	

Page	Subjects (major changes since last revision)

Author: Dr. Thomas Schütze IFAG AIM PMD ID TM

We Listen to Your Comments

Any information within this document that you feel is wrong, unclear or missing at all?
Your feedback will help us to continuously improve the quality of this document.
Please send your proposal (including a reference to this document) to:

Info.power@infineon.com

Introduction

The thermal behavior of semiconductor components can be described using various equivalent circuit models:

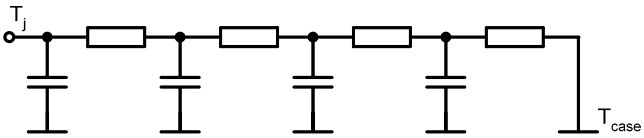


Fig. 1: Continued fraction circuit (also known as Cauer model, T model or ladder network)

The continued fraction circuit reflects the real, physical setup of the semiconductor – thermal capacities 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, base plate). The network nodes therefore allow access to internal temperatures of the layer sequence.

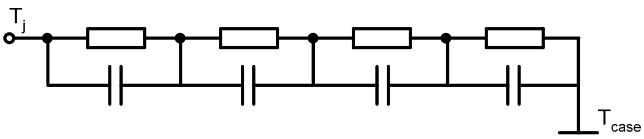


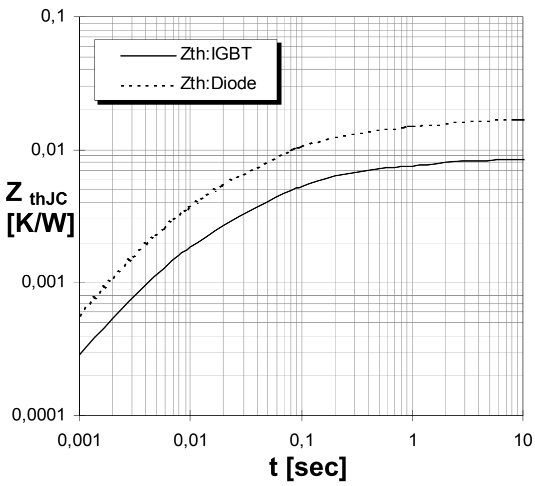
Fig. 2: Partial fraction circuit (also known as Foster model or pi model)

In contrast to the continued fraction circuit, the individual RC elements of the partial fraction circuit no longer represent the layer sequence.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 coefficient can be easily extracted from a measured cooling curve of the module and it can also be used to make analytical calculations.

The partial fraction coefficients are provided in the datasheet in tabular form as r and τ pairs. Here is an example:

i	1	2	3	4
r_i [K/kW] : IGBT	1,56	4,25	1,26	1,44
τ_i [sec] : IGBT	0,0068	0,0642	0,3209	2,0212
r_i [K/kW] : Diode	3,11	8,49	2,52	2,88
τ_i [sec] : Diode	0,0068	0,0642	0,3209	2,0212

With $\tau_i = r_i * c_i$ the thermal impedance curve can be written as a closed equation:



$$Z_{thjc}(t) = \sum_{i=1}^{n} r_i \times (1 - e^{-\frac{t}{\tau_i}})$$

If the switching and forward losses are known and assuming a known base plate temperature T_{case}, the junction temperature T_j can be determined as follows:

$$T_j(t) = P(t) * Z_{thjc}(t) + T_{case}(t)$$

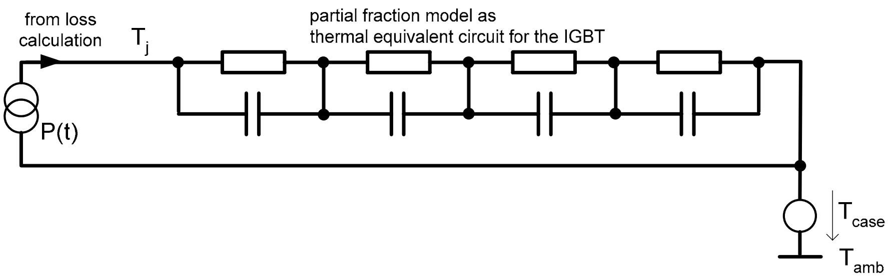


Fig. 3: Simulation model with fed-in power P(t), case temperature T_{case} and IGBT in partial fraction model

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

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. In the partial fraction model, however, a step input of power fed into the IGBT causes an immediate temperature rise via the grease and therefore a junction temperature rise that is not actually present in the real device. There are two ways to bypass the problem:

1) If the Z_{th} of the heat sink shall be determined by measurement, the base plate temperature T_{case} should be used instead of the heat sink temperature T_{hs}. In this case the thermal grease is included into the heat sink measurement, and must no longer be considered separately.

2) If an IGBT setup is available, where the fed-in power loss P(t) is known, the base plate temperature $T_{case}(t)$ can be measured directly and included into the calculation in accordance with fig. 3.

IGBT plus heat sink as partial fraction or continued fraction model?

The user will often avoid the expense for measurements and want to draw on existing model data for IGBT and heat sink. Both a continued fraction and a partial fraction model can represent the respective transfer functions junction to case of the IGBT and heat sink to ambient of the heat sink. If IGBT and heat sink models are to be combined, the question arises which of the two models should be used, especially if IGBT and heat sink have been characterized separately from each other.

IGBT and heat sink in continued fraction model

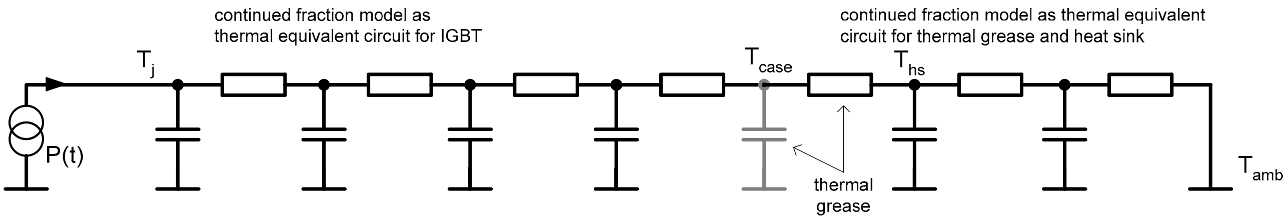


Fig. 4: Merging continued fraction models

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 above model – is reaching and heating the heat sink with a certain delay. A continued fraction model can be achieved by simulation or transformation from a measured partial fraction 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 heat sink, as the heat sink has a reverse effect on the thermal spreading within the IGBT, and therefore on the time response and the resulting R_{thjc} of the IGBT. If the heat sink in the application deviates from the simulated heat sink, 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_{thjc} can be provided advantageously as a closed solution. A mathematical transformation of a partial fraction model to a continued fraction model is possible. This transformation is not unambiguous – there are various solutions for possible R_{th} / C value pairs – nor do the individual RC elements and the node points of the new continued fraction model have 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.

IGBT and heat sink in partial fraction model

The IGBT partial fraction model, as it appears in the data sheet, is based on a measurement in combination with a specific heat sink. While an air cooled heat sink results in a wide spread of the heat flow in the module and therefore leads to better, i.e. lower R_{thjc}, in the measurement, the limited heat spreading in a water cooled heat sink results in a comparably higher R_{thjc} 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.

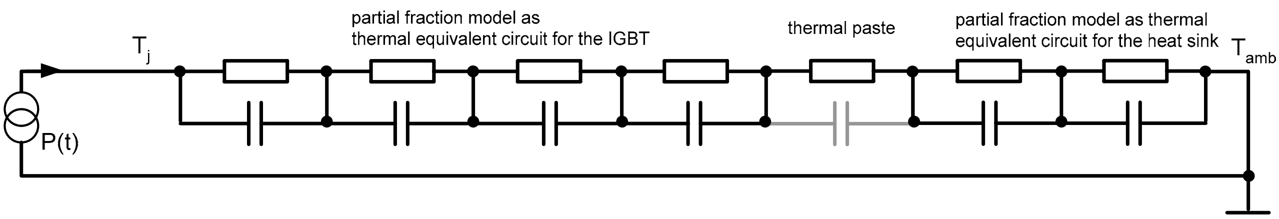


Fig. 5: Merging partial fraction models

Due to the series connection of the two networks, the power fed into the junction – in the equivalent curcuit the current – reaches the heat sink without delay. Therefore the rise of the junction temperature depends already in the early phase, in which actually only the thermal capacities of the module are active, on the type of heat sink.

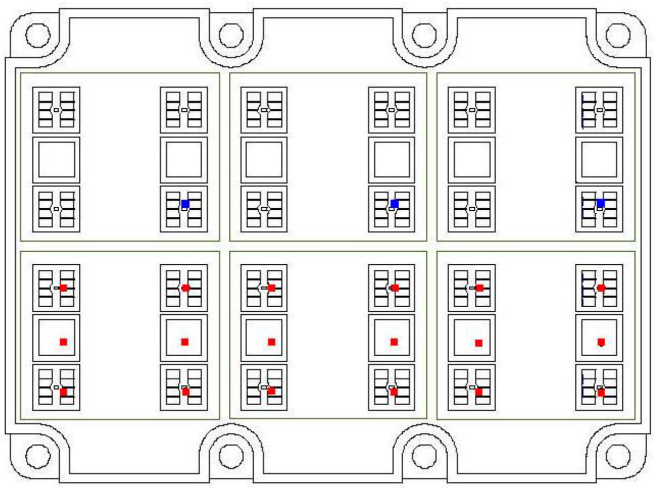
However with air-cooled systems the time constants of the heat sinks are ranging from some 10 to several 100 s, which is far above of the values for the IGBT itself with just approximately 1 s. In this case the calculated heat sink temperature rise falsifies the IGBT temperature only to a very small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

Because of the reverse effect on the thermal spreading in the module, the linking of IGBT and heat sink is not possible fault-free, either in the continued fraction or in the partial fraction model, as long as modeling or Z_{th} measurement of IGBT and heat sink are performed independently from each other.

A completely fault-free model for the system of IGBT plus heat sink can only be achieved by a measurement of the thermal resistance Z_{thja}, i.e. with simultaneous measurement of the complete thermal path from the junction via IGBT, thermal grease and heat sink to ambient. This delivers a partial fraction model of the entire system, with which the junction temperature can be calculated fault-free. The principle of the junction temperature measurement will be described in the following.

Determination of impedance curves

Example: 3.3kV module with140x190 m base plate



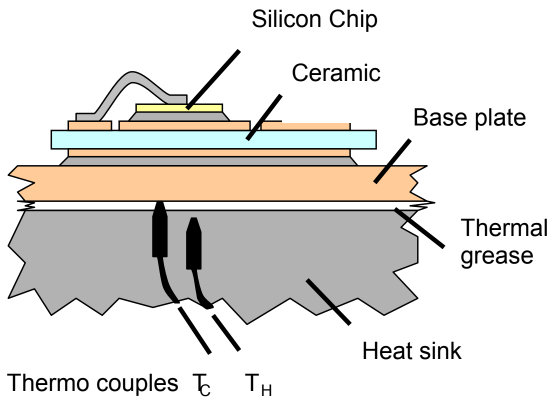


Fig. 6: Position of measurement points for the determination of the base plate temperature

A constant power P is fed to the module by a current flow, so that a stationary junction temperature is reached after a transient period. After turning off the power the cooling down of the module is recorded. 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 $T_j = f(V_{CE}\ @\ I_{ref})$. Its reverse curve $V_{CE} = f(T_j\ @\ I_{ref})$ was recorded earlier by means of external, homogenous heating of the tested module.

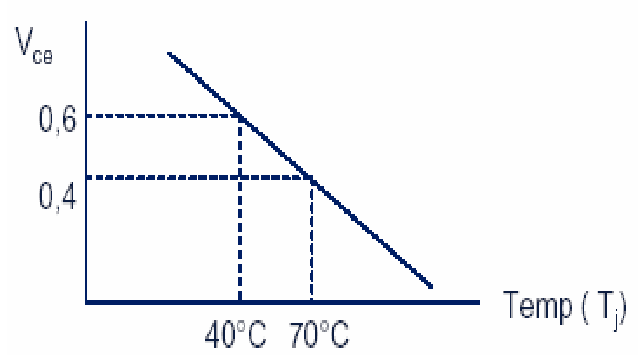


Fig. 7: Calibration curve, used to determine the junction temperature by measuring the saturation voltage at a defined measuring current

The base plate temperatures below the IGBT and diode positions (see red markings) are measured by pressure contacted sensors. The average base plate temperature T_{case} determined by the measurements is then used for calculating a $Z_{thjc} = (T_j - T_{case}) / P$, separately for diodes and IGBT chips. Inhomogenities and scatterings in the temperature measurements must be covered by appropriate safety margins.

The thermal resistance of the interface to the heat sink can be calculated accordingly using the three blue marked measurement points in the heat sink. However, it is beneficial to determine the Z_{thja}, i.e. the thermal resistance from junction to ambient, which is the entire chain made up of IGBT, transfer and heat sink.

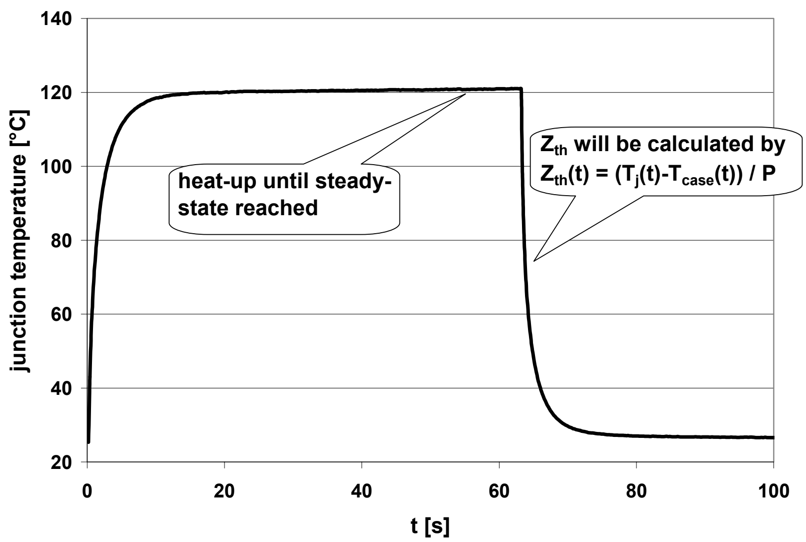


Fig. 8: Measured heating and cooling curve

If the expense of determining the junction temperature is off-putting, then at least the thermal grease should be included into the characterization of the heat sink. To do this the Z_{thca}, the thermal resistance of the thermal grease plus the heat sink, must be determined by measuring the base plate temperature T_c against the ambient temperature T_{amb}.