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Impact of nonlinearities on electronic device transient thermal responses

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ABSTRACT

This paper investigates the influence of nonlinearities on electronic device thermal transient responses. The discussions in the paper are based on practical examples where thermal responses of a power device are recorded in various boundary conditions for different values of dissipated power. Then, the measurement results are analysed using the Network Identification by a Deconvolution method and the differences between particular cases are discussed in detail. The presented experimental results demonstrate that the nonlinearities due to the temperature dependence of thermal model parameters might have important influence on the results, especially when still air cooling is applied. In addition, in selected cases the simulations results obtained with compact thermal models were compared with measurements.

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1. Introduction

The Network Identification by the Deconvolution (NID) method is currently one of the most frequently used approaches for thermal characterisation and analysis of electronic systems. This method, developed by the research group of Szekely, is based on the concept commonly known from the signal theory that transient responses of linear systems to arbitrary excitations can be found as the convolution of an excitation and characteristic functions which are system time responses to the unit-step function. When the temperature response for a given excitation is known, it is possible to determine these characteristic functions performing a deconvolution. This basic property of linear systems is used for the identification of thermal models from system transient thermal responses in the NID method.

The above-mentioned characteristic functions in the case of the heat equation represent the spectral density of thermal resistance, expressed in (K/J), and they are known as the time constant spectra of thermal responses. Thus, according to the NID method, any thermal system can be identified by the recording of its transient temperature response which after the substitution of the logarithmic time variable has to be differentiated. Then, the time constant spectrum of the thermal response can be computed performing numerical deconvolution.

The time constant spectra constitute in turn the base for the determination of other useful thermal analysis tools such as the Nyquist plots of thermal impedance or the cumulative structure functions, which are a kind of a thermal resistance and capacitance map of the entire heat-flow path since the origins of these curves correspond to the location where power is dissipated and the singularities at their ends could be associated with the ambient [1].

Furthermore, electronic system Compact Thermal Models (CTMs) in the form of RC ladders can be found by dividing time constant spectra [2] or cumulative structure functions [3] into a limited numbers of RC segments corresponding supposedly to individual stages in a heat flow path such as semiconductor chip, package or heat sink. However, this task is not trivial and might be subject to important errors due to measurement noise or nonlinearities. For example, in [4,5] the authors observed that all values of CTM elements depended on ambient temperature due to changes in cooling, hence demonstrating the influence of nonlinearities. Here, in the following section we provide more evidence on the impact of nonlinearities where several cases are investigated based on the analyses of time constant spectra.

2. Experimental results

The experiments presented in this paper were carried out on a commercial dual SiC power diode CSD20030 placed in the TO-247 package. The transient thermal responses of the device were recorded by the T3Ster® manufactured by Mentor Graphics and

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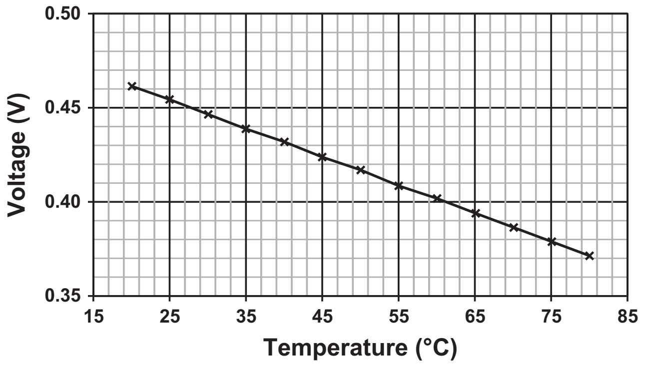

Fig. 1. Calibration curve of measurement diode.

processed with the software implementing the NID method provided together with the equipment. The device was measured with and without a heat sink in still air and with forced liquid cooling at different water temperatures.

Before each measurement the device was heated until the thermal steady state was reached and then the power was switched off. The cooling curve was recorded forcing through the diode the constant current of 10 mA and reading the voltage drop across the junction. Then, the voltage was converted into corresponding temperature values using the calibration curve presented in Fig. 1.

2.1. Still air cooling

The first experiment was aimed at the investigation of the influence of power dissipation on obtained results in the case of still air cooling. Initially, the measurements were taken without a heat sink and for different values of heating current. The results shown in Fig. 2 represent the cooling curves, the time constant spectra and the cumulative structure functions. Note that throughout this paper the units on the vertical exes in the figures representing the time constant spectra are K/W because the original values of the spectra in each time interval, i.e. 20 samples per time decade, were multiplied by the difference of the logarithmic time values at interval limits what corresponds to the numerical integration with the rectangle method. Owing to this, the peaks corresponding in the spectra to high frequencies were emphasised. These values are normally added up to calculate the accumulated thermal resistance in the structure functions.

An additional advantage of this representation is that the individual values on the vertical axis are just the partial thermal resistances in the heat flow path and they can be simply added up to produce the cumulative thermal resistance which in the thermal structure functions is plotted on the horizontal axis. Similarly, the minima in the time constant spectra correspond to the locations where heat penetrates to another material. Therefore, the division of the spectra at these points allows the generation of compact RC ladder thermal models, whose elements, after the conversion to the Cauer canonical form could have physical significance [2].

The device cooling times, as can be seen in the figure, were equal to almost 10 min and the junction-to-ambient thermal resistance was around 30 K/W. The exchange of heat with ambient is reflected in the last peak of the time constant spectra located at the time constant of 100 s and the remaining parts of the spectra describe to heat flow from the junction to the outer package surfaces.

Analysing the partial thermal resistances it can be concluded that the thermal resistance inside the package, i.e. the accumulated resistance including all the peaks in the time constant spectra but the last one, increases with dissipated power from 2.5 K/W at 0.5 A to 4.2 K/W at 2.5 A. Quite the opposite, the thermal resistance from the package to the ambient decreases respectively from 28.5 K/W to 25.7 K/W.

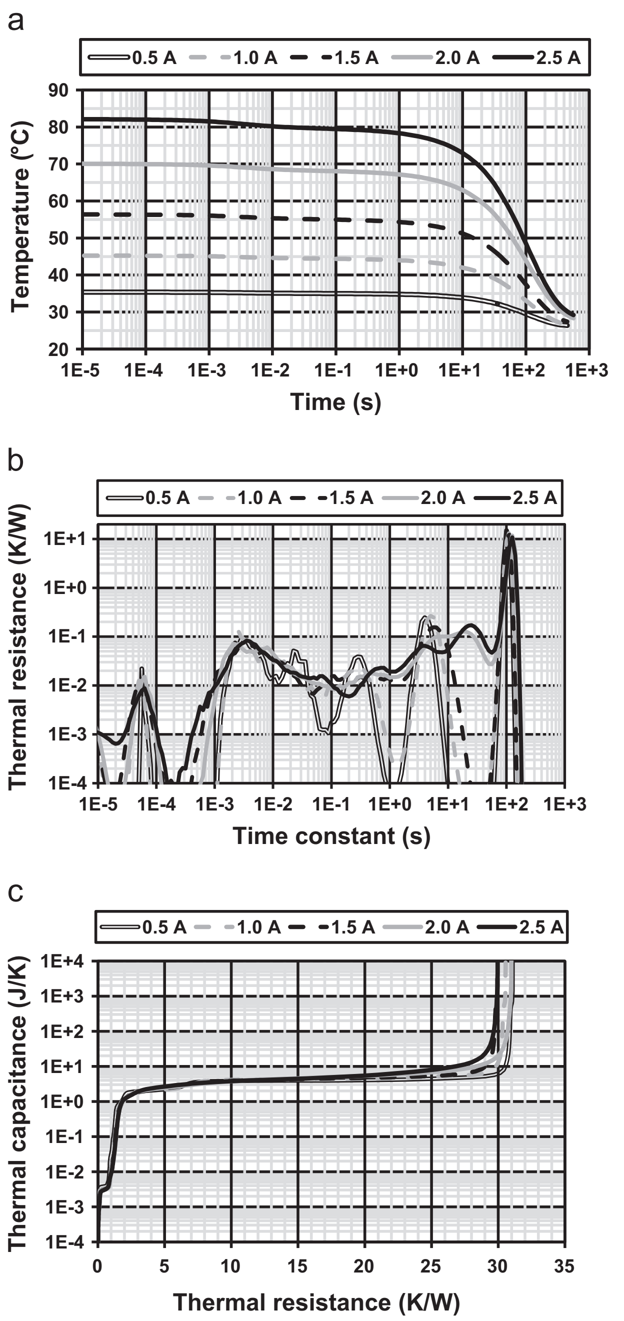

Fig. 2. Results for free convection cooling without heat sink: (a) cooling curves, (b) time constant spectrum, and (c) cumulative structure function.

This can be explained by the fact that inside the package thermal conductivity of semiconductor and other materials decreases with temperature whereas at the package surfaces the heat transfer is enhanced with increasing package temperature what is also visible in the cumulative structure functions. Moreover, in the structure functions there are also visible 2 plateaus at some 3 mJ/K and at 3 J/K, which should correspond to the thermal capacitance of the semiconductor and the package respectively.

Then, the measurements were repeated for the device attached to a heat sink. This time each measurement lasted for 40 min. The results presented in Fig. 3 show that owing to the presence of the

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