Chapter 1
Why Was Written and How to Read This Book

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Thermal transient measurements have become the most important characterization method of the thermal behavior of electronic systems in the last decades. This development is mainly due to the emergence of a new methodology, the *structure function method*, which is based on the network identification by deconvolution, introduced by V. Székely. This methodology in its mature form offers a “look inside the structure” of an electronic component with a single electrical measurement and the subsequent automated evaluation in software. It helps reveal data about the partial thermal resistances and capacitances inside the structure at all levels of an assembly, starting at a chip in a device package or module, through thermal interface and other material layers and various cooling mounts. The method may even provide temperature data on internal surfaces in the heat-conducting path which are otherwise not accessible for temperature measurements.

The users of the method soon understood that it is not pure magic, and to be able to fully exploit the capabilities of the methodology, a large amount of advanced knowledge is needed about the operation and the structure of the devices that are tested. In this book the authors, who are electrical engineers and university professors, tried to collect all information that is needed to fully understand the capabilities and the specialties of the thermal transient measurement technique.

The book is very timely now. The primary challenge in present engineering tasks is coping with the growing *power level* in electronic systems. Power controller units of electric cars and locomotives switch hundreds and thousands of amperes and forward many kilowatts toward the engine in order to bring tons of weight into

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motion. Solid-state lighting luminaires now operate in dozens and may dissipate hundreds of watts. Wind turbines and their power conversion units operate in the kilowatt to megawatt range, some high-voltage direct current electricity grid links are already in operation worldwide, and many new ones in Europe are under construction with a planned capacity of 1400 MW. The *power density* further increases in most of the systems in electronics. Processors run now at aggressive clock frequencies and dissipate hundreds of watts in a small box, video projectors which were formerly of suitcase size now resemble a pocketbook, and mobile phones produce although a few watts only but in a densely packed very thin case with no ventilation at all. These high-power levels represent an increased danger of overheating and damaging the devices.

Many of the power electronic systems work in extremely *harsh environments*. Automotive electronics, for example, must operate in the −30 to +80 °C external temperature range; this is similar for wind turbines, automotive lighting solutions, or street lighting luminaires.

Traditionally, the temperature of the internal semiconductor devices has been the principal factor which limited the system operability and influenced the system's reliability and lifetime. Due to the moderate cost and mature manufacturing technologies semiconductor power devices today are still mostly produced from silicon. Under the above-outlined environmental conditions, they sometimes reach their operation limits around 150 °C or 175 °C. With the advent of revolutionary wide band gap semiconductor materials, this is expected to change soon, and the structural materials of the device package will represent the new bottleneck in the system construction.

With increasingly sophisticated engineering and with the help of new thermal design methods based on *measurements* and *simulation*, the overheating of critical components can be prevented. Failure analysis shows that nowadays systems are correctly designed in this respect; the typical component breakdown is caused by the repeated *thermal transients*. Heating and cooling induce shear stress at the material interfaces in the structure, mostly at the die attach, or the solder joints, resulting in delamination, tear-off, etc. The poorer heat removal through a diminished surface can cause then thermal runaway.

The theory of heat propagation in materials was elaborated as early as the first decades of the nineteenth century. Since then, we know that the heat flows from the heat source toward the ambient, and the actual temperature of any point in between depends on the geometrical structure and the material properties of the parts where the heat flows through. Knowing the structure and the material parameters, the temperature distribution and the heat flow paths can be determined, if the heating sources are known. This calculation is done by *thermal simulati*on. Thermal simulation can also reveal the time dependence of the temperature at any point in the structure.

In the case of thermal transient testing, the opposite is done. The time dependence of the temperature change is measured at a well-selected point in the system, resulting from a sudden change in the amount of the generated heat, and if the structure and the material composition of the system are known, the resulting and captured temperature transient enables determining the value of important structural parameters. This is of course an ill-defined problem with an infinite number of solutions, but if we have preliminary knowledge about the structure and we can control the direction of the heat flow, we can significantly limit the number of potential solutions. In the case of standard components in electronics, this is the case. In the methodology, we start a "heat signal" in an inner point of the system, measure the resulting temperature change in the same point of the system, and with mathematical calculations based on the theory of linear systems calculate the partial thermal resistances and capacitances of the heat flow path. The obtained system description that is called the *structure function* is a unique signature of the system. Any change in the structure results in a different "signature," rendering the method perfectly applicable for testing purposes. A special advantage is that the methodology is nondestructive, in contrast with the usual structure testing methods.

The technique can be used in all stages of design and manufacturing. The spectacular technological development described above has been enabled and achieved by *thermally aware system design*. In the last decades, thermal management has become an integral part of the design procedures, resulting in changing roles of different engineering disciplines in the overall design process.

Thermal managements usually start with simulation in the design phase and are followed by measurement on actual manufactured samples. Thermal transient measurements help in identifying the internal constituents of the system. Some parts in an assembly of an electronic system show high stability (die, ceramics, heat sink, etc.), while others, like die attach or thermal interface material (TIM) layers, may vary among samples, or during the lifetime of the assembly. With detecting the changing values in the structure during production testing, or from time to time in ageing monitoring, transient thermal testing also provides feedback on manufacturing stability.

During quality assurance in production, first, measurements are carried out, typically more of them at different boundary conditions, and then simulation can help in finding the root causes of eventual faults.

Two pillars of thermally aware design have been introduced above, namely, *measurement* and *simulation*. However, both implicitly rely on a third one that is *modeling* the thermal behavior of the system. When the measurement results are expressed in the form of thermal resistances and thermal capacitances or the peak temperature, a quite simple model of the analyzed system is inherently set up. More complex models can provide a better device or system description, can prevent unforeseen device failure, and help in avoiding overengineering. In up-to-date practice, *compact thermal models* and *reduced order thermal models* seem to be the promising direction for electronic datasheets and vendor-independent thermal models for simulation tools.

The precision of thermal testing depends on the *resolution*, *accuracy*, *repeatability*, and *reproducibility* of the measurement. It must be noted that the implicitly introduced models frequently use simplifications, such as "chip temperature" and "package case temperature." These system components are not point-like bodies but always have a certain finite size. This leads to an inhomogeneous temperature distribution on any surface unless the temperature is stabilized with and external force. These factors manifest as inherent *uncertainty* of the measurement that is usually much higher than the values one can enjoy in the case of, e.g., current or voltage measurements.

With our book we planned to fulfill various interests. It can be especially useful for engineering students who wish to understand the deeper physical and mathematical background of this broadly used new measurement technique. They should read the entire book from the beginning. Numerous examples throughout the book help in understanding the practical applicability of the theories.

For improving the readability of the book, the examples are typographically separated from the main text body by gray shades, as here.

Chapter 2 outlines the underlying physical and mathematical notions, and their relationships needed to understand the thermal transient analysis technique. It contains the theory of thermal transient measurement evaluations. This chapter presents also the thermal metrics, used for the characterization of the thermal behavior of systems, and certain fundamentals about the standards that need to be considered when doing thermal measurements on electronics packages.

Chapter 3 presents the standardized and other thermal metrics used for the simplified characterization of packages and evaluates the advantages and disadvantages of the different methods used for determining them.

Chapter 4 summarizes the temperature-dependent electrical characteristics of the major semiconductor devices that may be used as heaters and sensors in the thermal transient measurements. After some introductory fundamentals of solid-state physics that is needed to understand the operation of these devices, the chapter presents the m features of the most frequently used semiconductor devices and their governing equations. From these equations the reader can see how the material properties and the structure of the devices that we wish to characterize or what we use as means to characterize the system influence the thermal transient measurements.

This book can be particularly useful for engineers who use the methodology in their everyday engineering practice and sometimes have difficulties in understanding or explaining the measured results. They can skip the details of the first mostly theoretical chapters, and after refreshing their knowledge on thermal metrics and semiconductor devices, they may jump soon to Chap. 5.

Chapter 5 presents the general scheme of thermal transient measurements and the usual additional tools that can extend the usability of the methodology. This chapter focuses on the current engineering practice of thermal transient characterization from the aspect of the measurement, evaluating also the different measurement methods.

For the practicing engineers, separate sections in Chap. 6 offer detailed information on the specialties of thermal transient testing of different electronic devices, with insight into the various sources of inaccuracies or potential mistakes in the measurements. This chapter is the most important part of the book for the novices of thermal transient measurement, as it presents all the details needed to accomplish the thermal characterization of the different devices.

Chapter 7 discusses the versatile applicability of the method, by highlighting the details of the most important use cases of the methodology from thermal qualification through the calibration of thermal simulation models, and reliability testing. These parts may bring innovative ideas also for the thermal engineers who currently use thermal transient testing for one purpose only.

Chapter 8 deals with the accuracy of the measurements, discussing all the factors that contribute to the uncertainty of the thermal transient measurements.

The chapters are written in such a way that enables reading them without reading the entire book. For this reason, some chapters start with some repetitions that enable the reader to understand the chapter without all the prior details.

At the end of the book, a well-structured Reference section provides links to information needed for a deeper understanding of the topics, as well as to details that expand the reader's knowledge in related curricula. References [1–17] refer to books, book chapters, or data compendiums which cover a wide range of physics background and thermal testing principles. References [18–53] specify standards and guidelines related to thermal or combined thermal and optical measurements. References [54–57] list software handbooks and test equipment manuals for thermal simulation and measurement control. In the last reference section, from [58] on journal and conference papers are listed which highlight related knowledge complementing the content of the book.

The authors hope that with the help of this book, the readers will gain a deeper understanding of the thermal transient measurements, and will find answers to all their questions related to their thermal transient measurement problems.

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