TEN GOOD REASONS WHY THERMAL MEASUREMENTS ARE IMPORTANT TO YOUR DESIGN

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INTRODUCTION

Amid all the promotion of solid-state superlatives ranging from data rate to feature size to LED light output, one characteristic is never touted: junction temperature. That's because junction temperature (T_J) is an undesired but unavoidable side-effect of high currents and/or switching speeds. A p-n junction, whether it is one of millions on a CPU chip or the only one within a power LED, generates heat. In the past two decades the industry has seen heat dissipation increase by orders of magnitude. Faster is better, but faster is also hotter.

This trend is not without consequences. A 10° increase in T_J can cause a 50% reduction in a semiconductor device's life expectancy. Differing thermal expansion responses where dissimilar packaging materials meet can degrade and ultimately destroy devices. In LEDs, both brightness and color can suffer as T_J increases. And of course the twin issues of safety and cooling can impact the design of an entire system, not just the semiconductor device producing the heat.

All these facts point toward the need for a thorough grasp of thermal behaviors at the chip level, and beyond that to thermal interface materials (TIM) and even heat sinks. True understanding comes with physical measurements performed on actual devices. The Mentor Graphics MicReD T3Ster, a best-in-class thermal measurement system, is fully equipped to deliver the efficiency, repeatability, flexibility, and ease of use needed for this application.

There are at least ten good reasons to include thermal measurements as a routine step in any electronic component or system design process:

1. TAKING OUT "INSURANCE" AGAINST PREMATURE PRODUCT FAILURES

Junction temperature measurements made with tools designed for the purpose deliver accurate readings of T_J values. Quantifying T_J is part of a "due diligence" regime that ensures a product design will not fail prematurely. It helps designers detect unforeseen high T_J levels and either decrease the current driving the device or select a different component. This forestalls failures that might occur later in the design process or worse yet, in the marketplace. Long experience has taught manufacturers that the cost of re-thinking a poorly-chosen component in the design phase is orders of magnitude lower than the cost of recalling a product that has reached consumers.

2. NAVIGATING THE COMPLETE HEAT FLOW PATH

A single junction temperature reading under operating conditions is a reasonable predictor of design success. But measuring the junction temperature transient that occurs when switching a device on or off produces even more useful information. Measurements that produce $\Delta T_J(t)$ readings[1] can observe the heat flow path far beyond the heat-producing junction. Of course, that assumes that the *temperature transient* measurement is done with sufficient accuracy and resolution and rigorous post-processing of the data.

Figure 1 depicts the heat path leading away from a power LED. The path is made up of a series of interfaces, each with its own reaction to the flow. For example, the heat slug conducts heat very efficiently, as it is meant to do. In contrast the glue bonding the LED to the metal-core printed circuit board is a less efficient conductor of heat. And of course, imperfections in any element along the path can affect its response to heat.

All this is important because it is almost always necessary to remove heat from the junction and guide it to a dispersing medium - usually the ambient environment but in Figure 1, a cold plate. Using thermal transient measurements, an engineer can determine the best and most cost-effective materials to serve this purpose. Is the cold plate really necessary, or could a cheaper heat sink do the job? What type of interface material can be used to

[1] *The parenthetical "t" denotes time-dependent change in the junction temperature; in other words, the thermal transient. If (t) is taken from t=zero to infinity and divided by the applied power, the result is the thermal impedance.*

couple the MCPCB to the cold plate most cost-effctively? Thermal measurements can help the designer select from a vast range materials, components, and interface compounds, and fine-tune each element to best fulfill system design goals.

Connectors and housings, too, are part of many heat flow path designs, and these also are observable with thermal

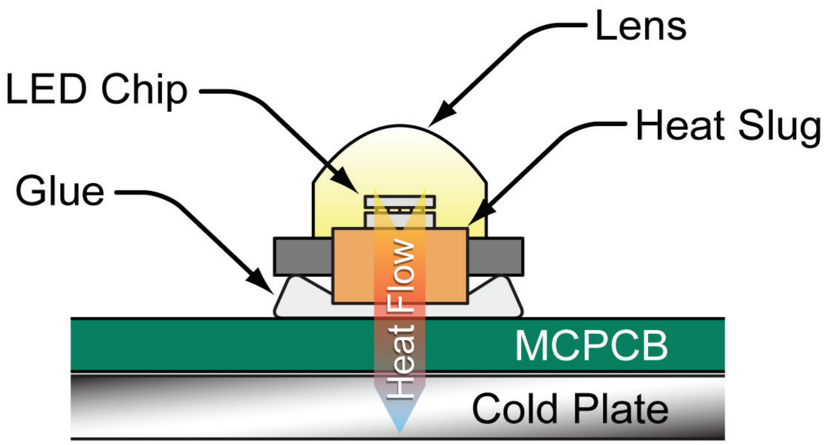

Figure 1: The heat flow path from a power LED. Thermal measurements can help designers determine which types of interface materials will best transport heat and meet system design goals.

transient measurements. A connector with its pins and receptacles is nothing more than another element in the heat-conduction path if the measurement system is sensitive enough to “see” it. Reason #3 offers some background on this concept and explains the benefits.

3. DEVELOPING COMPACT MODELS FOR SIMULATION

Compact models are a cornerstone of the simulation processes used in all forms of electronic design today, and thermal design is no exception. In the thermal realm, compact models do more than just express the thermal resistances and capacitances along the heat flow path. They also provide a medium that preserves proprietary component information while delivering performance characteristics the recipient - perhaps a system designer in another enterprise - can use to model the device in his/her application. A tool such as Mentor Graphics FloTHERM is designed to accept measured values and/or a compact model of a device such as a power transistor or LED and produce reliable predictions of the component’s heat behavior in the end application, as shown in Figure 2.

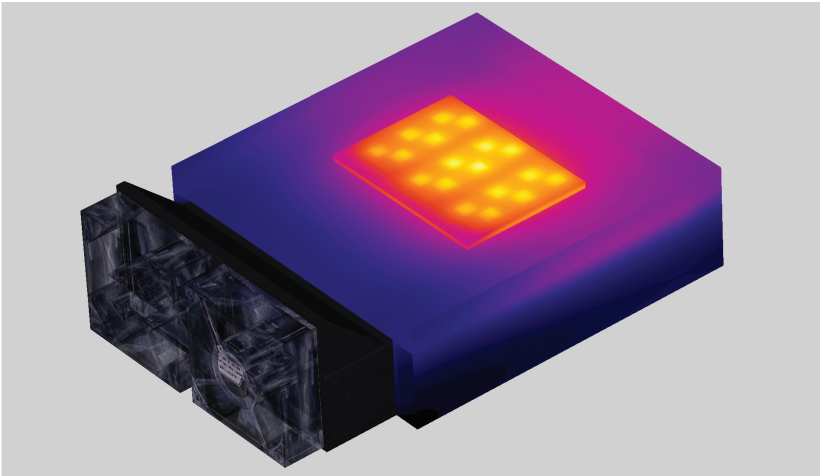

Figure 2: Surface temperature distribution of an IGBT device mounted on air cooled fins. For this simulation, the Mentor Graphics FloTHERM CFD tool used a compact model derived from thermal measurements and cumulative structure functions.

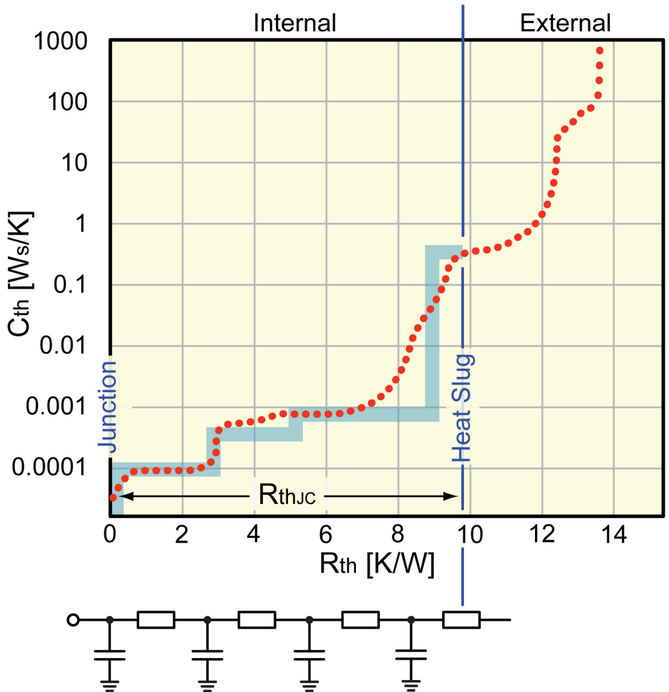

Figure 3: A cumulative structure function graph showing the RC equivalents that can be inferred from transitions in the heat flow path.

It all begins with a cumulative structure function graph derived from thermal transient measurements taken with a T3Ster system. As heat travels away from its source (a junction), it encounters thermal resistances (RTH) and capacitive attributes. Figure 3 depicts the journey. In this type of plot the origin of the heat is literally the origin of the graph. Each step upward denotes the heat's progress, going from one resistance, through a capacitance to another resistance. With the graph as a "road map" of the heat path, it is easy to evaluate the performance of individual materials along the way. For example, the chip itself has a low RTH/CTH ratio, while a layer of thermal grease or plastic might have a much higher ratio.

A T3Ster system can easily perform measurements to support steady-state modeling. A single thermal resistance value known as RthJC, where the "JC" subscript denotes "junction-to-case," suffices. If a dynamic compact model of the LED package is needed, the simple RthJC resistance value must be replaced by a proper model of the thermal impedance of the entire junction-to-case heat-flow path. These values too can be derived from T3Ster measurements.

A step-wise approximation of the cumulative structure function can be used to derive a set of lumped thermal resistance and thermal capacitance values for a Cauer-type ladder model spanning several stages. The RC model of the junction-to-case path is shown beneath the graph. Again, each resistor or capacitor symbolizes a real physical feature with a now-quantified value. This is all the information that a customer needs in order to model the device in an application under development.

4. REFINING AND OPTIMIZING LIBRARY MODELS

Most modeling environments include a library of "canned" models implemented with the RC network methods already described. These models spare designers the effort of starting from scratch with every new type of component they touch. A model is chosen - a Ball Grid Array, for instance - and any custom parameters are keyed in. The result is presumed to mirror a genuine BGA performing in the end-user application.

But library models rarely reflect the many imperfections that can arise in real-world components. Mating surfaces may not be flat, glue or grease applications may be uneven, or materials may suffer from the effects of "tolerance stacking." It is also conceivable that library models may be outdated or derived from measurements made with tools far less accurate than those available today.

In any case, these unforeseeable issues can affect actual thermal characteristics. The solution to this is to make rigorous thermal measurements on sample devices to ensure that library models are as accurate as they claim to be, and to provide data to support any necessary refinements to the models. Some modern tools, notably the MicReD T3Ster, offer temperature resolution at least 10X better than legacy measurement systems.

5. COMPLYING WITH EMERGING INDUSTRY STANDARDS

While data rates and other "banner" characteristics are specified to the picosecond and device packaging is subject to stringent compliance requirements, the science of thermal specification is not nearly as advanced. The interpretation of what's important, heat-wise, is largely left to the component end-user. For example, a device specification might summarize the component's behavior within a narrow ambient temperature range that is nowhere near that which it will encounter in routine real-world conditions. As other industries have learned, vague or inconsistent specification practices can hamper acceptance of new technologies and retard industry growth.

Thermal standards for measuring individual so-called "steady-state thermal metrics" have existed for decades; the JEDEC JESD51 Series is just one example. But standards defining the dynamic thermal properties that represent transient behavior have been conspicuous in their absence. Both vendors and users recognize this, and the situation is changing.

Practical proposals for measuring and expressing thermal transient characteristics are emerging under the aegis of JEDEC and other entities, and will soon come into effect as full-fledged standards. Among recent developments, the JEDEC JC15 committee has addressed transient methods for junction-to-case thermal resistance measurements in power semiconductors. The new method is based on structure functions, which deliver much higher repeatability for RthJC measurements than do the classical steady-state methods.

In addition, single-die thermal metrics are being extended to encompass multi-die packages (i.e., stacked die) or SiP with lateral arrangements. Development of measurement standards for power LEDs is also on the agenda in both the JEDEC committees and CIE (International Committee of Illumination). Several new thermal testing standards are expected to emerge from JEDEC in 2010 and 2011.

Thanks to these trends in standardization, thermal measurements (including thernal transients) are likely to become a routine part of almost every design project that uses semiconductor components.

6. PUBLISHING ACCURATE, VERIFIABLE PRODUCT DATA

Semiconductor end-users rely on device performance data published by the manufacturers of the products they use. A component data sheet promises certain bandwidth and edge rates, timing and amplitude values, and even physical dimensions. With the advent of new thermal standards, data sheets will also need to disclose a new, deeper level of detail about thermal characteristics, especially for power LEDs. Thermal simulation tools that can work with compact thermal models of packages are becoming more common in the market. Engineers no longer need leave this critical data to the manufacturer's discretion.

By selecting a complete and integrated thermal measurement solution, a semiconductor vendor will have the means to acquire, analyze, document, and easily publish accurate thermal performance data. Information can be ported from the measurement system to the analysis software and to spreadsheets and databases to generate the tables and graphs that end-users need when designing components into their emerging system-level products.

7. SUPPORTING MANUFACTURABILITY AND PRODUCTION

Thermal measurements are a valuable tool for process optimization, and can speed an emerging product toward full-scale production. Issues with parameters such as die attach quality are quickly revealed by the structure functions explained earlier, allowing process steps to be refined before production begins. It is even possible to adapt a thermal measurement system to perform in-line die attach testing if necessary, as in the case of components aimed at high-reliability applications or stressful environments. In such an instance it is sometimes desirable to build high-throughput, multi-channel thermal testing into the manufacturing flow.

The measurements are also useful for detecting and tracing lot-to-lot variations and yield crashes, and for analysis of related products and processes from suppliers and other manufacturers.

8. CONTROLLING ENVIRONMENTAL VARIABLES

Attempting to characterize the thermal performance of a device in an open room is like characterizing a CPU by plugging it into a socket in a PC. If it works, then functionality is confirmed for only one narrow set of operating conditions. If it doesn't work, then the problem might be due to external effects. Where there are indeed many measurements that don't care about their surroundings, some types of tests are completely invalid unless they are conducted under very specific, controlled conditions. To develop a reliable compact thermal model of a device, it is necessary to conduct measurements within a stable, known environment. And many compliance regimes define the test environment in great detail. One example is the DELPHI methodology for generating compact thermal models. JEDEC has released compact modeling guidelines that contain a comprehensive description of definitions and procedures needed to produce usable semiconductor device package models.

LED characterization is a shining example of the need to control environmental variables. An LED's color actually shifts when the component heats up. Purely thermal readings are essential but there is also a need to observe and measure the consequent shifts in color and device efficiency, which would be very difficult to detect in the stark overhead lighting of a typical lab. External lighting conditions must not be allowed to corrupt the readings. So characterization of light output requires not only the current and heat of a thermal measurement, but also a meticulously-controlled miniature "darkroom" of the type included with the MicReD TERALED system that appears in Figure 4. Within this realm the LED's light is undisturbed by outside influences. The darkened environment is essential for accurate measurements of luminous flux, chromaticity coordinates and energy conversion efficiency.

Figure 4: TERALED – a dedicated test environment for power LEDs. The system uses a built-in coldplate to provide hard thermal boundary conditions for measurements. The integrating sphere also allows the light output characteristics of LEDs to be measured in an undisturbed environment.

The movement of ambient air is another concern when making thermal measurements. Even the lightest ambient breeze can carry heat away from a device junction, potentially affecting T_J measurements and the resulting cumulative structure function plots. Full-featured measurement systems such as the MicReD T3Ster offer a host of environmental solutions, including both JEDEC-compliant still-air chambers and fixturing to orient a Device Under Test (DUT) as needed.

9. KEEPING PACE WITH POWER TRENDS

The demand for true high-power measurements is growing steadily. With the exception of specialized power transistors, thermal measurements on most components have until recently been a relatively low-current affair. Even with high-power devices, many measurements have been performed by acquiring readings at relatively low power levels and extrapolating the results.

Today's product developers need to validate motor driver components for electric vehicles, large-area ICs such as video devices, large LED arrays, and more - all of which can require kilowatts of instantaneous power. To characterize the thermal response of a high-power device and its heat flow path it is necessary to excite the path with very large (though momentary) currents.

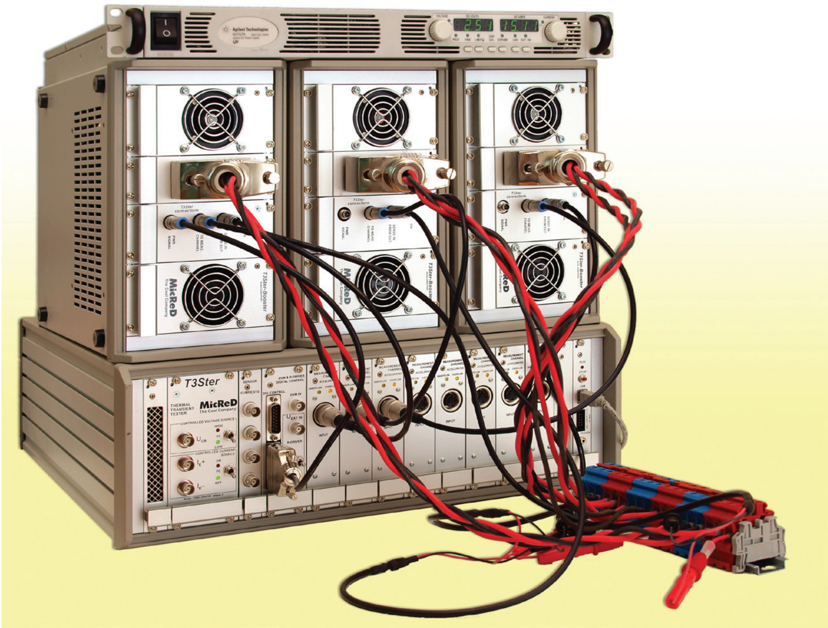

Figure 5: A T3Ster system with three high-current boosters, which allows simultaneous measurement of three power semiconductors. Alternatively, if the boosters are connected in parallel, their currents are additive, providing high power levels reaching into the kilowatts range. This is essential for reliability testing.

Measurement system requirements for this application are stringent. With the large voltages and currents involved, tests must be performed not only efficiently, but also safely. And of course accuracy must remain uncompromised. These requirements call for a scalable system whose core measurement features can be transparently augmented with high-voltage, high-current peripherals, as shown in Figure 5. The system's architecture supports high-power acquisition and analysis extending to hundreds of volts and amps.

10. INVESTING IN QUALITY

Users of semiconductor devices will inevitably become more aware of thermal performance as their platforms' power demands increase and thermal issues get more coverage in conference papers and industry magazines. Thermal perfomance will become a sought-after dimension of product quality, since it can impact everything from reliability to clock rate.

A manufacturer's commitment to a rigorous thermal characterization program, and to publishing accurate thermal data, is part of a larger message of product quality. Those who lead this thrust, investing in thermal measurement tools, skills, and strategies, will be positioned to meet the needs of their customers for years to come.

ABOUT MENTOR GRAPHICS MECHANICAL ANALYSIS DIVISION

The Mechanical Analysis Division of Mentor Graphics Corporation (formerly Flomerics) is a world leader in the computer simulation of engineering design processes involving heat transfer and fluid flow. Our customers eliminate mistakes, reduce costs as well as accelerate and optimize their designs by applying our simulation software and consultancy services before building physical prototypes. Using our advanced Computational Fluid Dynamics (CFD) software, we help increase efficiency in your mechanical design process, saving valuable time and money. For more information, visit www.mentor.com/mechanical or contact:

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