STATE OF THE ART IN LED THERMAL CHARACTERIZATION

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MECHANICAL ANALYSIS

WHITEPAPER

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INTRODUCTION

Using the JEDEC standard static test method for transient thermal measurements in accordance with JESD51-14 and CIE 127-2007 has increased the level of accuracy in light-emitting diodes (LEDs) thermal characterization. These higher standards have resulted in increased customer confidence and market share. In compliance with these standards, the Mentor Graphics T3Ster system can complete more than 100 LED thermal measurements in a single day, and it is the most accurate. The T3Ster post-processing software fully supports the latest thermal testing standard (JEDEC JESD51-14) for junction-to-case thermal resistance measurement. This paper discusses the importance of more accurate thermal characterization to the rapidly evolving marketplace and how the T3Ster and TERALED systems are meeting this challenge for lighting manufacturers and their customers.

INDUSTRY TRENDS – THE LED REVOLUTION

McKinsey & Company report that general lighting, automotive lighting and backlighting are the three largest sectors in the lighting industry, and general lighting accounts for approximately 75% of the world market [1]. Almost all sectors of the lighting industry are undergoing an unprecedented change to solid state lighting (SSL) solutions based on LEDs. A number of factors have contributed to this change, including legislation, greater efficiency, and rapidly reducing prices.

The U.S. Energy Independence and Security Act of 2007 requires general-purpose light bulbs that produce 310–2600 lumens (lm) to be 30% more efficient than incandescent bulbs, with the aim of replacing 100 W incandescent bulbs in 2012 and 40 W bulbs in 2014. Many other legislative efforts around the world also will effectively ban incandescent light sources. LEDs are increasingly being used in DRLs (daytime running lamps), which are mandated for new car production in the European Union beginning in 2011–2012 (Figure 1). OEMs also are increasingly using LEDs as a competitive edge in branding their products.

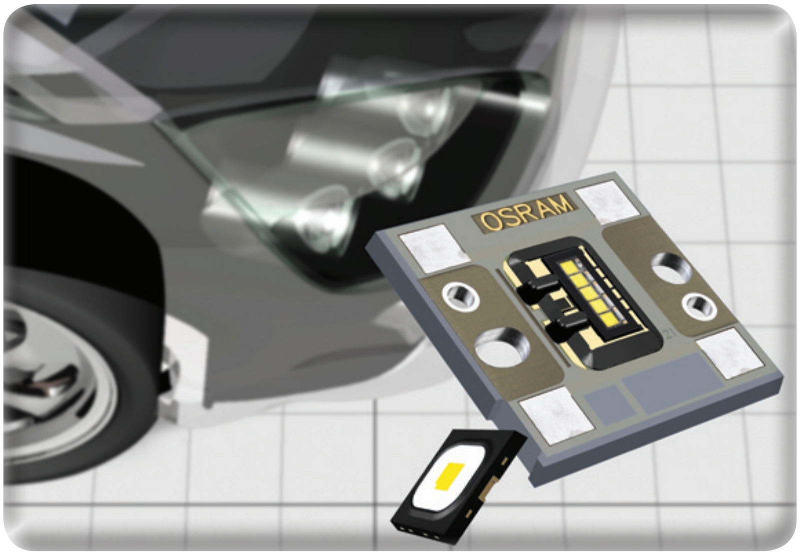

Figure 1: *The EU has mandated that LEDs be used for daytime running lights in new cars produced as of 2011–2012.*

The CAGR of revenues from >300 lm LEDs between 2009 and 2016 will be more than 40%, and high-brightness LEDs (HBLEDs) is the fastest growing subsector, according to IMS Research [2]. This growth is anticipated in spite of a projected significant decrease in unit costs. Vantage Point CEO, Alan Salzman, says he expects LED prices to fall from 1 cent-per-lumen in mid-2011 to 0.25 cents-per-lumen by the end of 2012 to 0.10 cents-per-lumen by 2015. He further speculates that LEDs will account for 50% of all general purpose lighting by 2016 [3] (Figure 2).

NEED FOR ACCURATE THERMAL METRICS

Metrics used to define the thermal performance of electronic parts are considered during the design process to select the most appropriate part for the application—the various benefits and drawbacks of one part versus another are weighed against their respective costs.

The published metrics are part of the commercial agreement between vendors and customers. If parts are found not to perform as advertised, the financial effects on profits can be severe, with vendors facing huge product recall and warranty costs, as well as substantial negative publicity. On the other hand, publishing correct metric values and providing accurate thermal models enhances LED sales, increases prestige, and maintains customer loyalty.

DELIVERING THE NECESSARY ACCURACY

Fortunately, accurate thermal performance *can* be measured. The Joint Electron Devices Engineering Council (JEDEC) has established a new standard, JESD51-14 [4], for junction-to-case thermal resistance measurement based on the latest transient measurement techniques. The junction-to-case resistance is the most appropriate metric for packaged LEDs because it characterizes the heat flow path from where the heat is generated at the PN-junction down to the bottom of the case—exactly how LED packages are designed to be cooled.

The method uses a “dual interface” approach in which the part is measured against a cold plate with and without thermal grease. The junction-to-case resistance is determined by examining where the two measurements differ. Very high measurement repeatability is required because the thermal impedance curves for the two measurements must be identical to the point where the heat starts to leave the package and enter the thermal interface between the package and the cold plate. This ensures that the point where the curves deviate is clear.

LEDs – SIMPLE ELECTRONICALLY, YET THERMALLY COMPLEX

From a semiconductor standpoint, LEDs seem to be simple PN-junctions. Thermal test equipment such as the Mentor Graphics MicReD T3Ster can be used to characterize far more complex packaged semiconductor products, so it follows that LEDs should be easier to measure but actually they are not.

LEDs present a number of thermal characterization challenges. They are often very small, and measuring them unmounted is difficult. Fortunately, the dual interface measurement principle can be applied by mounting the parts onto two different substrates. A greater challenge is that LEDs, unlike other semiconductors, emit light.

Figure 2: *High brightness LEDs are expected to be highly profitable over the next four years.*

For LEDs, emitting light is at the heart of the definition of thermal resistance. For the majority of semiconductor devices, thermal resistance can be calculated by simply dividing the temperature rise by the electrical power applied to the package. This is because all of the supplied electrical power is converted to heat. However, this is not the case for LEDs because a significant proportion of the supplied energy is converted into and emitted as light—thus, LEDs are used as light sources. This energy conversion efficiency can be as high as 30–40%, depending on the type of LED.

Using the efficiency figure above, if the supplied electrical power rather than the correct (heating) power is used to calculate the package's thermal resistance, the thermal resistance figure is significantly lower, suggesting that the package (of a less efficient LED) is far better at dissipating the heat generated in the LED than happens in reality.

PROVIDING SOLUTIONS — STATE OF THE ART IN LED THERMAL CHARACTERIZATION

T3Ster uses a "smart" implementation of the JEDEC static test method (JESD51-1) that allows for almost continuous measurement during a heating or cooling transient, which also forms the basis of the JESD51-14 test method. The result is far richer data that is measured from much earlier in the transient than possible with other techniques.

Figure 3: *T3Ster—the thermal transient tester from Mentor Graphics.*

The T3Ster system can complete more than 100 JESD51-1/ JESD51-14–compliant LED thermal measurements in a single day, which is the fastest possible thermal testing available on the market today (Figure 3). It is also the most accurate, capturing the transient response of a LED after just 1 µs (1 x 10^{-6} seconds), with a temperature resolution of 0.01 °C. This means that the earliest possible part of the LED's thermal response is captured; thus, you can see the influence of key constructional features close to the heat source within the LED package, such as the thermal resistance of the die attach after a short time.

The T3Ster post-processing software fully supports the JESD51-14 standard for junction-to-case thermal resistance measurement, allowing the temperature versus time curve obtained directly from the measurement to be re-cast as "structure functions" (described in JESD51-14 Annex A), and then automatically find the value of the junction-to-case thermal resistance.

The graphs in Figure 4 show the magnitude of all the thermal resistances in the heat flow path from the die through the package assembly to the cold plate used in the test setup. Deviation of the cumulative structure functions obtained for the two measurements (with two different qualities of the thermal interface at the package's case surface), forms part of the JESD51-14 methodology.

The challenge of correct LED thermal characterization is compounded because an LED's efficiency is adversely affected by the junction temperature. This presents a challenge for both LED vendors and SSL

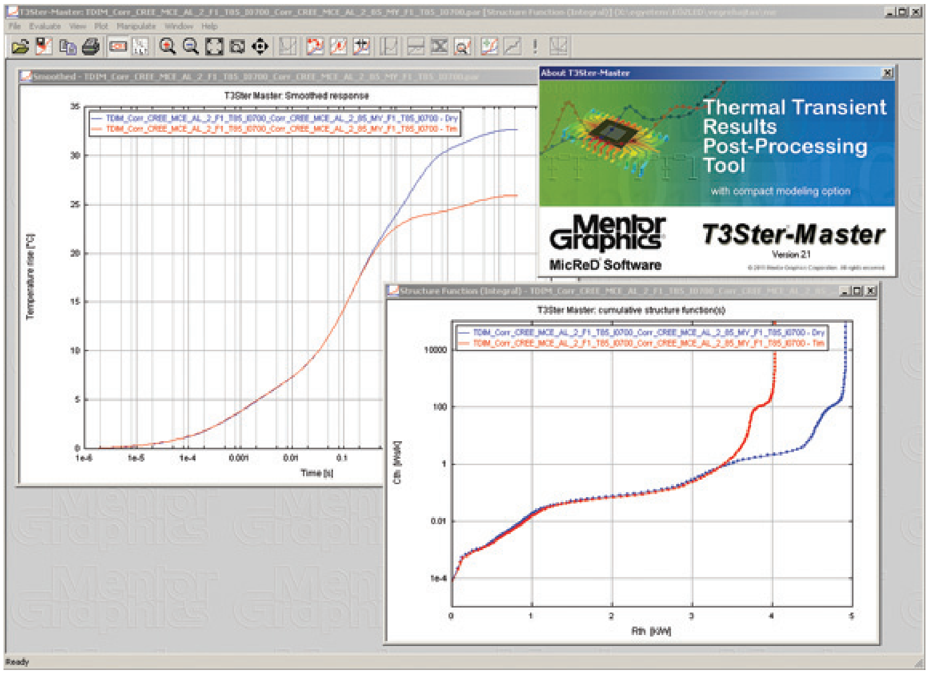

Figure 4: These graphs in show the magnitude of all the thermal resistances in the heat flow path from the die through the structure to the cold plate used in the test.

designers. Therefore, the LED's light output, junction temperature, and power draw need to stabilize before measurements are taken. Consequently, the static measurement method used to capture the cooling curve is the only correct approach to characterize LEDs.

PROVIDING SOLUTIONS — CORRECTLY ACCOUNTING FOR THE LIGHT OUTPUT

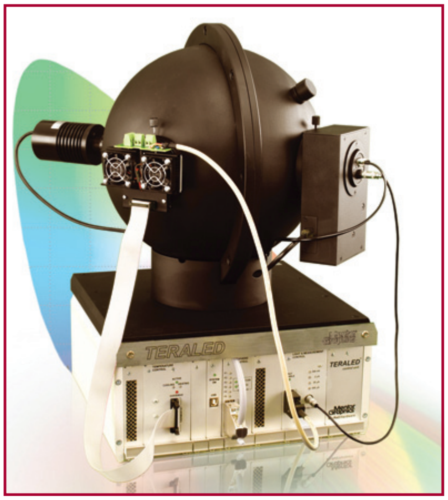

Figure 5: TERALED is a CIE 127:2007–compliant total-flux measurement system with temperature control.

One requirement is to correctly account for the light output when calculating thermal metrics. The light output from an LED is normally characterized in an integrating sphere, using detectors to measure the LED's total radiant power, luminous flux, and other light output properties.

The LED under test must be mounted onto a temperature-controlled cold plate to ensure that the light output and the dissipation of the LED being measured do not change. This way the LED's emitted optical power together with its other light output properties and its thermal impedance can be measured together, in a self-consistent way. If the measurements are performed at various temperature values, the temperature dependence of the energy conversion efficiency and the luminous flux, etc. can also be determined.

The MicReD TERALED from Mentor Graphics is a CIE 127:2007–compliant total-flux measurement system with temperature control (Figure 5). When used together with T3Ster, TERALED is a comprehensive LED testing station, performing self-consistent thermal and radiometric/photometric characterization for HB LEDs and LED assemblies. Full automation of the measurements allows extremely fast operation: for example, the LED under test can be characterized at about 100 operating points (forward current and temperature combinations) in approximately 2 hours.

STANDARDIZATION IS STILL NEEDED

We are actively pursuing standardization in LED thermal characterization [4] through international standardization and technical committees; but as yet, no published standards exist that describe how thermal and optical testing should be best combined to produce correct thermal and light output metrics for LEDs. A need for such standards is clear, and this need is increasing as LED semiconductor and packaging technologies continue to develop and the effects of not correctly accounting for the power emitted as light increases.

BUSINESS BENEFITS OF LED THERMAL MEASUREMENTS

One of the key benefits of the accurate transient measurement data to be obtained from T3Ster is that information about important thermal interfaces such as the die-attach thermal resistance can be quantified. Measurements can help manufacturers determine the optimum process window, minimizing die-attach cure times and helping accelerate the time it takes to push the part into full-scale production.

T3Ster also can be used in large-scale (high-throughput) reliability testing of single LEDs, LED lines, and arrays to check for thermally significant degradation caused by simple aging at elevated environment temperature (such as during LM80 life-time testing) or thermal cycling, optionally with high humidity, causing the die to detach for example [5] (Figure 6). Voids increase the thermal resistance of the die attach, which leads to substantially increased junction temperature and hence further accelerates aging. Longevity of the parts can be assured by confirming that the rate of die-attach degradation is acceptable before full-scale production.

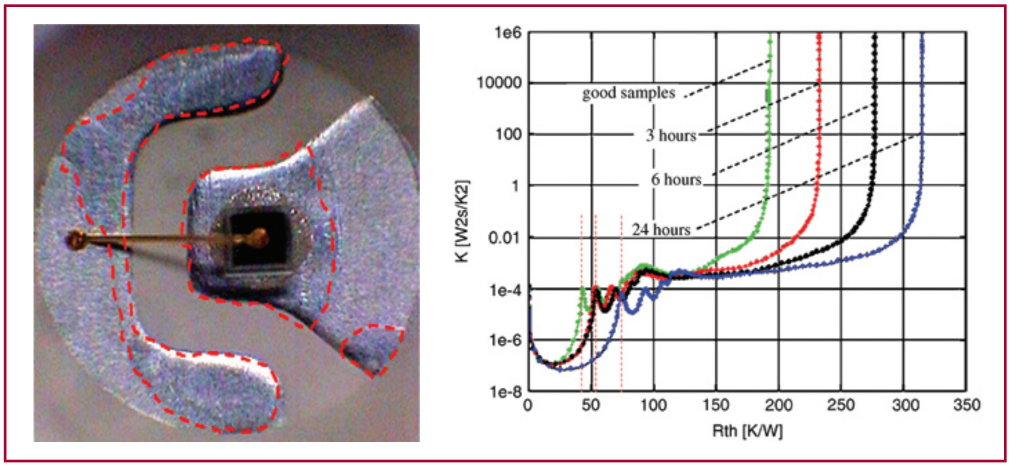

Figure 6: Damaged die attach and the resulting shift in the differential structure function [5].

As part of the production process, T3Ster is suitable to calibrate in-line die-attach testing equipment, which is used to detect unacceptable die-attach thermal resistance during production (go/no-go test). The effect of process window variations on product thermal performance can be checked, minimizing the substantial costs associated with inventory write-off and the disposal of defective products.

During full-scale production, the high throughput of measurements allows T3Ster to be used for testing of samples of parts from production batches, thereby ensuring that no bad parts get into the market. This alone saves millions of dollars each year in potential product-recall costs.

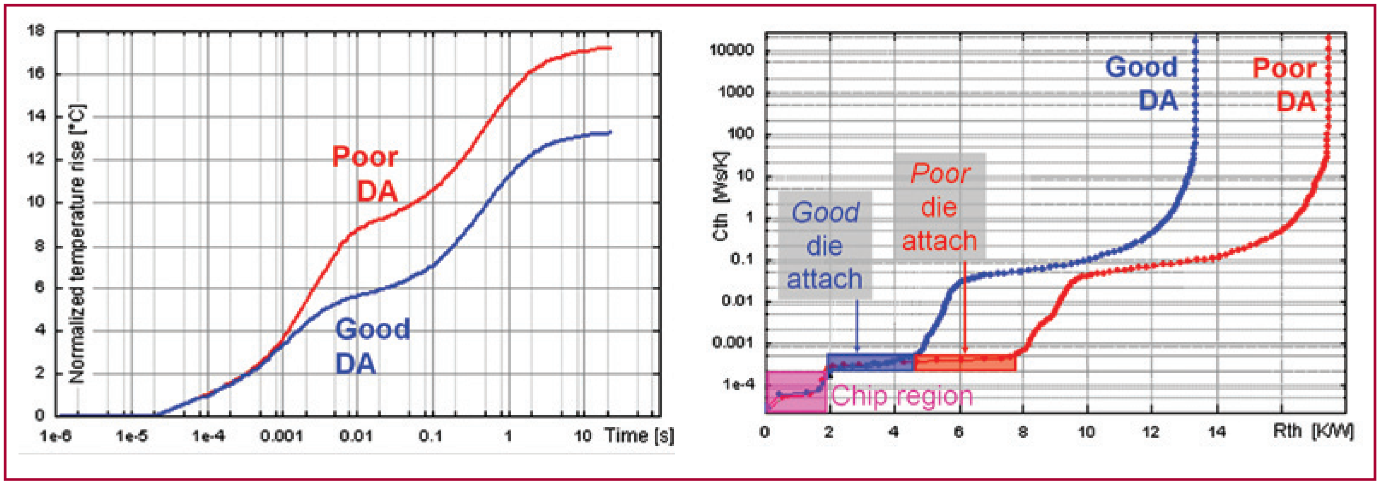

Figure 7: Comparison of good and bad die attach of LEDs for the purpose of setting limits for a go/no-go test. Left: Measured transient. Right: Structure functions that prove that increased thermal resistance is caused by poor die-attach quality.

Parts returned from the field can be tested and structurally analyzed with T3Ster. Information about failures obtained this way contributes to minimizing future warranty costs by providing feedback to production. Similarly, competing products can be tested, allowing LED vendors to keep track of innovations by competitors.

COMPLETING THE SUPPLY CHAIN

Accurate thermal metrics are essential if the correct LED is to be selected for a particular application. They are also used in early pre-design "sizing" calculations for potential cooling solutions.

SSL designers need accurate thermal models to produce the optimal thermal design for a product. These can now be produced directly from measurements using structure functions derived from the JESD51-14 junction-to-case resistance measurements. And when designers use T3Ster and TERALED together, they can be sure that the measured thermal data are scaled in the actual thermal resistance of an LED.

In the past, when accurate thermal models were needed for design, a detailed thermal model of the package that included all the thermally significant

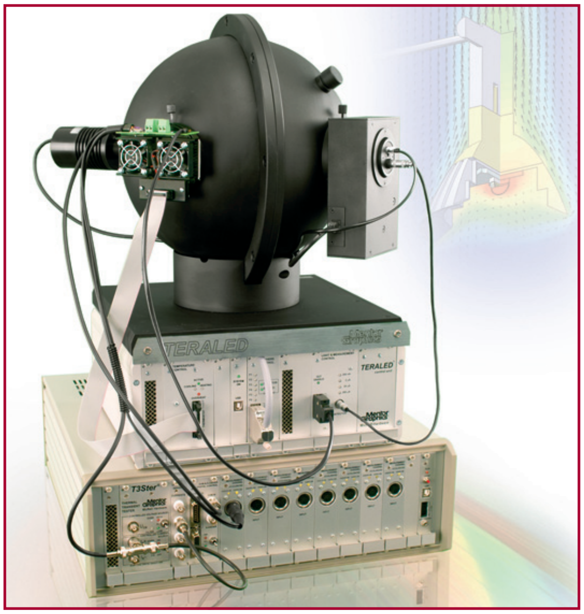

***Figure 8:** T3Ster and TERALED together provide a comprehensive solution for LED testing [4].*

internal geometry and material properties was necessary. Today, measurement-based thermal models are reducing this need.

Where they are still required, for example to represent an LED light engine, these detailed models can be validated using T3Ster. The designer can measure the actual part in different thermal environments, exercising different heat flow paths from the junction to the ambient and comparing the structure function response to that of the detailed model when simulated in the same environment. This allows detection of any errors in the model's construction and tuning of thicknesses and material properties in the model to ensure near-perfect model accuracy.

SUMMARY

Accurate transient thermal measurements according to the latest JEDEC-standardized techniques are having far-reaching effects in LED design, pilot manufacture, and volume production. The unprecedented accuracy resulting from using JEDEC standard static test method for transient thermal measurements in accordance with JESD51-14 has raised the bar in LED thermal characterization. These higher standards result in increased customer confidence and market share.

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