STATE OF THE ART IN SOLID STATE LIGHTING THERMAL DESIGN

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MECHANICAL ANALYSIS

WHITEPAPER

HEAT — THE NEW ENEMY IN LIGHTING EFFICIENCY

Unlike incandescent lighting that relies on heat to cause a filament to glow and produce light as hot black body, light emitting diodes (LEDs) are semiconductors and as such must be kept cool. When LEDs produce light, heat is a by-product. Heat generated in an LED increases its temperature. As the LED's temperature increases, the light output decreases, the light changes color, and the lifetime of the LED reduces. Temperature adversely affects both the functional performance of the LED and its longevity. As a consequence, thermal management has become the most predominant issue in solid state lighting (SSL) design.

When designing an SSL solution with power LEDs, the importance of the thermal system design cannot be underestimated. As Rudi Hechfellner, technical marketing manager for Philips Lumileds Lighting Company, said, "Think thermal first."

IMPORTANCE OF ACCURATE THERMAL METRICS

Purchasing parts with poor thermal performance is a false economy because, in the end, a more efficient and costly cooling solution will be required. Selecting the best part for a particular application is critical to producing a commercially successful product, and thermal metrics are a key consideration when making that selection. Because these are the primary inputs to thermal design, the metrics must be accurate. Thermal performance of an electronic part is usually reported as a thermal resistance, which is an indication of how difficult it is for heat to flow out of the package. Thermal resistance is calculated as the temperature rise of the junction divided by the power heating the junction.

LEDs are complex because their thermal, optical, and electrical operations are interdependent. For example, the amount of electrical power that produces heat varies with temperature. Thermal metrics should be based on the actual heat dissipated in the LED rather than the supplied electrical power, which requires accurate measurement of the light output as a function of temperature and applied electrical current. If the supplied electrical power is used, the calculated thermal resistance is far too low; and the more efficient the LED, the more the error increases.

If the published metrics are optimistic, the likely result is either that an inadequate cooling solution will be designed or that a far more expensive cooling solution is required will be realized late in design, which increases the costs and lengthens the timescale of the design process. In either case, the commercial viability of the product will be in jeopardy.

LONGEVITY — THE KEY TO LED ADOPTION FOR GENERAL LIGHTING

Legislation regarding lighting efficiency is forcing the phasing out of incandescent bulbs. Compact fluorescent lamps (CFLs) are the other incumbent and cheaper competing lighting technology, but these are now regarded as being less green because they use mercury vapor. Now that the necessary brightness and efficiency levels are competitive, we are arguably close to the tipping point for the adoption of high-brightness (HB) LEDs for most general illumination applications.

However, adoption may be hampered by concerns over their longevity and the high initial cost of LED-based lighting solutions. Some early CFLs had shorter than expected lifetimes as a result of reliability issues with the ballast and ignition circuitry. This experience may act as a barrier to the adoption of LEDs in domestic lighting until longevity of the LED plus driver electronics as an integrated system is proven.

Currently, the wide adoption of LEDs is facing two particular challenges. Too many technical trade-offs have to be made for LEDs to replace incandescent bulbs in luminaires originally designed for incandescent. Ultimately, new luminaires are needed that are specifically designed for LEDs, for which no compromise has to be made with regard to thermal management. However, the bare LEDs that are to be used in such LED-specific designs are not interchangeable (plug-in compatible) with each other because of a lack of standards.

Good thermal designs that work well for unspecified thermal environments will be essential if LED-based retrofit products are to achieve anything close to the potential 40,000 hour useful lifetime, which is the level of consumer acceptance needed for LEDs to replace incandescent bulbs at anticipated rates.

BUSINESS BENEFITS OF LED THERMAL MEASUREMENTS

More efficient and brighter LEDs are finding new applications that have severe thermal challenges, such as LED car headlights, where product longevity is a must if excessive future warranty costs are to be avoided and the vehicles' safety requirements are to be maintained. As a result, the need for accurate metrics, and hence standardization, is growing rapidly. If vendors are not using accepted standards to ensure their metrics are both correctly based, and accurately measured, SSL designers are placing themselves at considerable business risk unless they verify the thermal metrics provided by vendors.

Fortunately, T3Ster's high measurement throughput enables systems integrators (for example, automotive lighting manufacturers, automotive OEMs, and customers in other safety-critical industries such as aerospace), to verify a vendor's thermal resistance data during design and to test incoming COTS parts before they are introduced into production.

DESIGNING WITH THERMAL METRICS

A long-established division of responsibility in the electronics thermal supply chain is that vendors should provide information that characterizes their part independent of any application environment in which they are used, and their customers are responsible for building products that provide an application environment in which the part can operate within specification.

The latest JEDEC standard covering junction-to-case thermal resistance measurement, JESD51-14 [1], is now regarded as *the* way to thermally characterize power semiconductor devices, including power and high-brightness (HB) LEDs. Correctly measured, with allowance made for the power emitted as light, the junction-to-case thermal resistance measured in accordance with JESD51-14 conforms to the above principle.

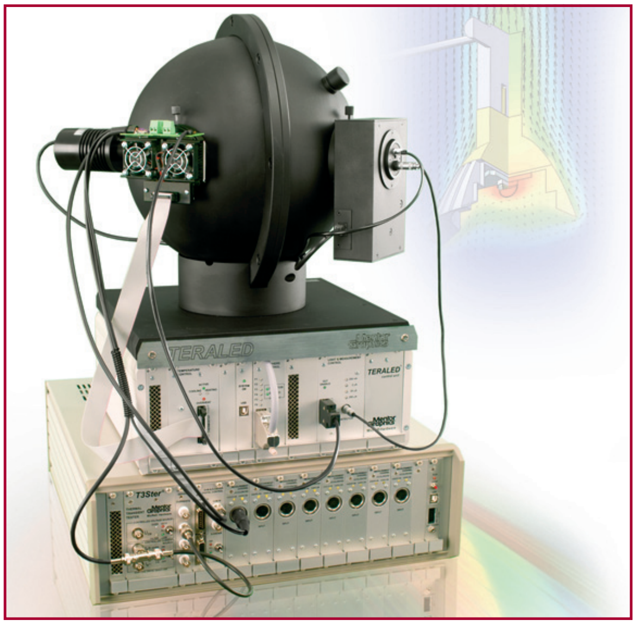

Figure 1: *T3Ster and TERALED together provide a comprehensive solution for LED testing [4].*

The Mentor Graphics thermal transient tester T3Ster uses a “smart” implementation of the JEDEC JESD51-1 static test method, and this measurement approach provides the fastest and most accurate thermal transient testing solution on the market. Using T3Ster together with TERALED, a CIE 127:2007–compliant total flux measurement system with temperature control, provides LED vendors a comprehensive LED testing station that enables them to perform self-consistent thermal and radiometric/photometric characterization of LEDs. The system is fully automated, allowing an LED to be characterized at approximately 50 operating points (forward current and temperature combinations), in an hour.

LED vendors often report thermal metrics at only one temperature; for example, for a junction temperature of 25 °C, which is far from the temperature at which LEDs normally operate. This data is supplemented by diagrams showing the relative light output as a function of junction temperature, but again no standardized method is used for obtaining these curves.

Using a junction-to-case thermal resistance at 25 °C to design a product is valid, but the lower efficiency caused by the higher temperature during operation must be factored in, recognizing that the light output will be lower. As the forward voltage also drops with temperature, light output and power consumption vary until LED reaches a stable operating temperature.

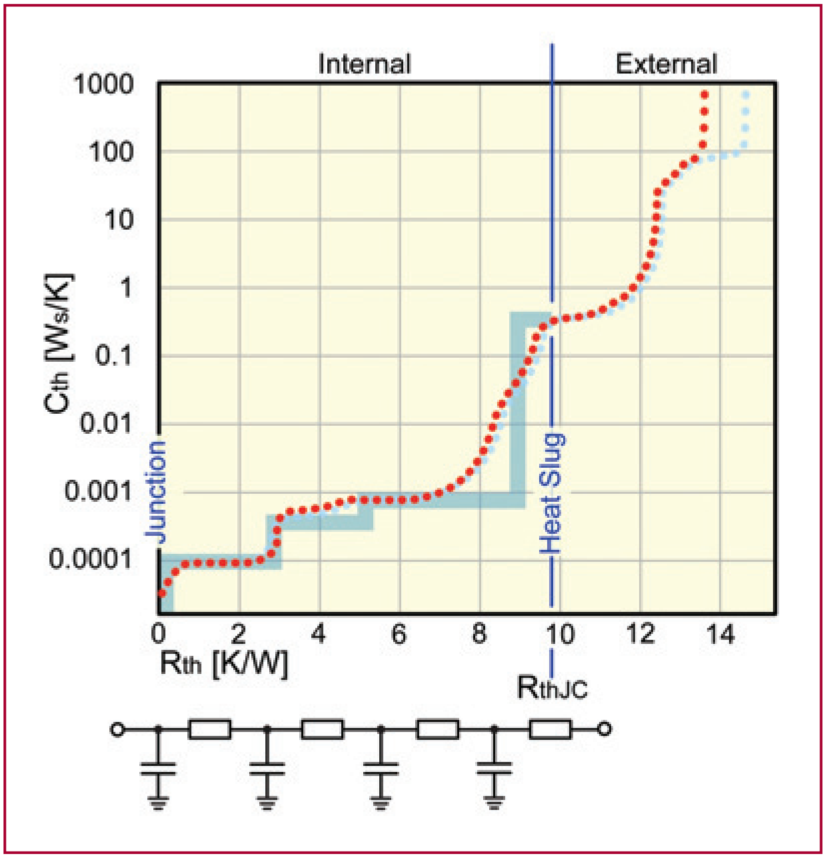

__Figure 2:__ A dynamic compact thermal model (DCTM) ladder when used in dynamic thermal simulations accurately reproduces the thermal response of the LED as a function of time.

With care, metrics can be used for early design calculations. Their use becomes more problematic the more complex the product. Placed close together, LEDs interact, each heating its neighbors as well as itself. Light generation, electrical power consumption, and heating have a complex, mutual interdependence. The junction-to-case resistance describes how self-heating affects the junction temperature, but does not capture the effect of heating from other LEDs, so this metric alone is unsuitable for designing complex multiple heat source products such as LED headlights.

THERMAL MODELS — CRITICAL TO SUCCESSFUL SSL DESIGN

Thermal models don't replace metrics, but within dedicated thermal design software such as FloTHERM from Mentor Graphics, they are far more useful in product design. Models allow designers to investigate the thermal interaction between multiple LEDs and to arrive at a product that delivers the desired light output at the anticipated operating temperature, while dissipating the heat produced. This means that the thermal design of the product can be optimized to minimize cost, weight, form factor, etc. while meeting the performance targets.

The T3Ster post-processing software allows the temperature versus time curve obtained during the JESD51-14–compliant transient junction-to-case thermal resistance measurement of a single LED to be re-cast as "structure functions" described in JESD51-14 Annex A. These graphs show the magnitude of all the partial thermal resistances in the heat flow path.

The structure function can be represented by a piecewise linear fit, separating the curve into a number of discrete thermal resistance and thermal capacitance steps. The resistance and capacitance values within the package provide a measurement-based thermal model that is computationally efficient and accurately captures the heat flow path. These dynamic compact thermal models (DCTMs), as they are known to thermal designers, can capture the thermal response of the LED as a function of time (Figure 2). When generated with T3Ster and TERALED, the models are consistent with the measured light output properties. Measurements that use the older "dynamic" test method are much slower to perform, do not provide the accuracy needed for JESD51-14–compliant thermal resistance measurements and to construct DCTMs, and, in the case of LEDs, are fundamentally incorrect for reasons which are outside of the scope of this article to discuss in depth[1].

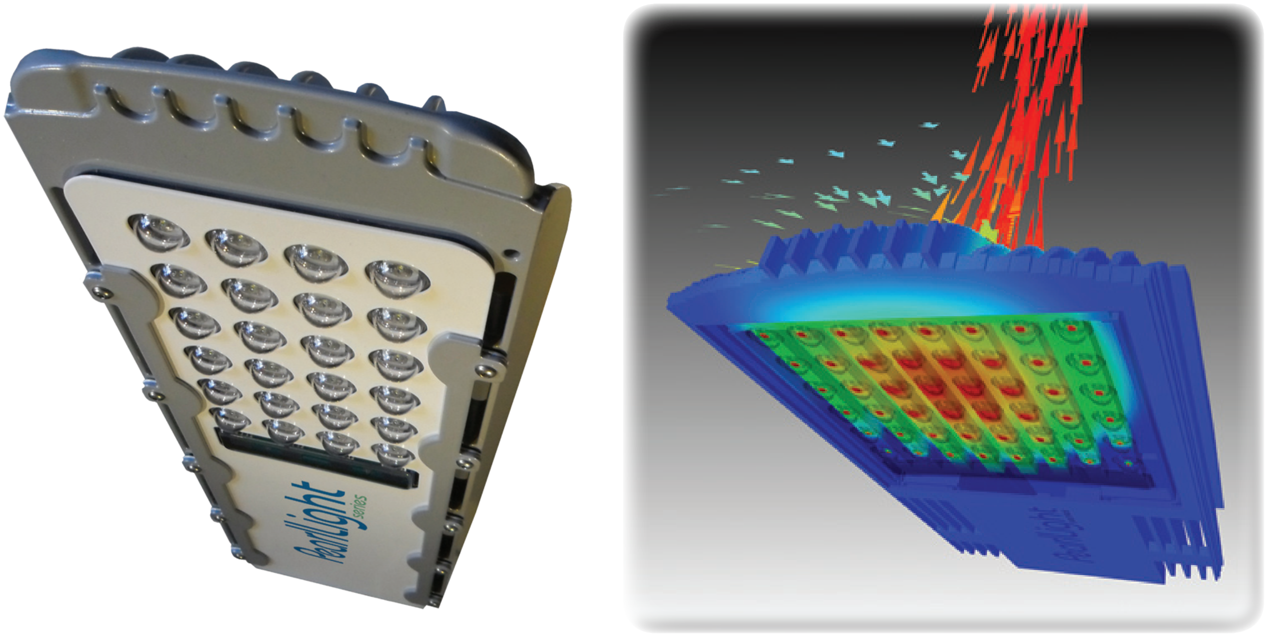

Figure 3: *Result in FloTHERM of an LED street-lighting luminaire using an LED compact model.*[2]

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. Accurate thermal models are needed to produce the optimal thermal design for a product, and they are available directly from measurements using T3Ster and TERALED. SSL designers can use these measurement-generated models in detailed design by importing them directly into FloTHERM (Figure 3).

In the past when accurate thermal models were needed for design, a detailed thermal model of the package that included all the thermally significant internal geometry and material properties would be needed. Today, measurement-based thermal models are reducing this need.

Where they are still required, for example to represent LED light engines or street-lighting luminaires, these detailed models can be validated by vendors using T3Ster and tuned to give near-perfect accuracy, increasing confidence in their use during product design.

SUMMARY

Thermal metrics and models resulting from accurate transient thermal measurements are improving the reliability of SSL design and helping to ensure the widespread adoption of LED-based lighting in applications as diverse as replacement domestic lamps, street lighting, and car headlights.

This unprecedented accuracy has “raised the bar” in thermal design, improving the quality of thermal information transferred across the supply chain. The end result is substantially increased confidence for SSL designers, leading to increased product quality, longevity, and profitability.

REFERENCE

1. JESD51-14 “Transient Dual Interface Test Method for the Measurement of the Thermal Resistance Junction to Case of Semiconductor Devices with Heat Flow through a Single Path,” November 2010, http://www.jedec.org/sites/default/files/docs/JESD51-14_1.pdf.

FOOTNOTES

[1] *Briefly: If an LED’s thermal metrics are measured in heating mode and its heating curve is composed from measurement results obtained by the JESD51-1 dynamic test method, each measured data point corresponds to a different operating point (different junction temperature, different actual heating power) of the LED under test. This violates the basic LED measurement principle that LEDs can be correctly characterized only in a stable state, as required also by CIE 127:2007, the LED light output measurement standard.*

[2] *Courtesy of HungaroLux Ltd. Budapest, Hungary.*

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