Thermal testing of LEDs: emerging standards

András Poppe, PhD

Mentor Graphics MicReD Division, Budapest, Hungary
Why to deal with thermal issues in case of LEDs?

- Reliability is connected to thermal issues
  - life time (failure mechanisms are thermally assisted)
  - mechanical stress
- Optical properties strongly depend on temperature
  - spectra
  - emitted flux / efficiency / efficacy

No doubt that **reliable thermal data** is a must for power LEDs: widely accepted **standards are needed**

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Spectral power distribution [µW/nm]

- 20 °C
- 30 °C
- 40 °C
- 50 °C
- 60 °C
- 70 °C

I_F = 300 mA

**λ [nm]**

- 560
- 570
- 580
- 590
- 600
- 610
- 620
- 630
- 640
- 650
- 660
- 670
- 680
- 690

**Lifetimes [ks]**

- 350 mA
- 400 mA
- 500 mA
- 600 mA
- 700 mA

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**I_F [mA]**

- 100
- 200
- 300
- 400
- 500
- 600
- 700
- 800
- 900
- 1000

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**n_e [radiant efficiency [%]]**

- 30
- 25
- 20
- 15
- 10

**T_ref [°C]**

- 15°C
- 25°C
- 35°C
- 45°C
- 55°C
- 65°C
Standardization status at CIE (from Y. Ohno)

LED chips/packages

(low power)
CIE 127:2007
CIE TC2-46

(high power)
IES LM-80
Lumen maintenance
IES TM-21
IESNA new project
CIE TC2-63, 64

SSL products
(Integrated LED lamps & LED luminaires)
IES LM-79 Photometric meas.
ANSI C78.377 Chromaticity
CIE TC1-69 Color rendering

TC2-63 Optical measurement of High-Power LEDs (Y. Zong, USA)
TC2-64 High speed testing methods for LEDs (G. Heidel, Germany)

clusters and arrays

LED light engines
(ASSIST Recommends ..)
IESNA new project

Definitions (terminology)
IES RP-16 addendum a
IEC TS 62504

Safety
UL 8750
CIE TC2-58 radiance/luminance
Several projects in IEC TC34A
Approach of the JEDEC JC15 committee

- Overview document (not yet accepted)

JEDEC JC15 committee actively works on these:

THERMAL MEASUREMENT
- Electrical Test Method
- Guideline for Estimation Measurements (as proposed by NIST)
- Guideline for combining CIE 127-2007 measurements with thermal measurements
- Measurement of AC LEDs
- Measurement of $R_{th}$ during LM80 tests

THERMAL ENVIRONMENT
- Heat Sink
- Natural Convection
- Forced Convection

COMPONENT MOUNTING
- Heat Sink Mounting
- Thermal Test Board
- Test Luminaires

COMPONENT CONSTRUCTION
- Single Light Source LED
- Multi-Light Source LED

APPLICATION GUIDELINES
- Terms, Definitions & Units Glossary
- Additional thermal guidelines for IESNA LM80 tests

MODELING
- Dynamic Compact Thermal Model for single light source single heat-flow path LEDs
- Model validation procedures

Today we shall cover these

- Drafts
  - Issue identified which is dealt with
  - Recently identified issue which is dealt with
  - Yet to be identified and/or to be dealt with

Each box represents recommendations for a particular problem.
- New modules can be easily added
A few words about thermal resistance of LEDs

- Original definition in the JEDEC JESD51-1 document

2. MEASUREMENT BASICS

The thermal resistance of a semiconductor device is generally defined as:

\[ R_{JX} = \frac{T_J - T_X}{P_H} \]

where \( R_{JX} \) = thermal resistance from device junction to the specific environment (alternative symbol is \( \theta_{JX} \)) \([\text{°C/W}]\)

\( T_J \) = device junction temperature in the steady state test condition \([\text{°C}]\)

\( T_X \) = reference temperature for the specific environment \([\text{°C}]\)

\( P_H \) = power dissipated in the device \([\text{W}]\)

- Classically, for Si semiconductor diodes: \( R_{th-el} = \Delta T_J / (I_F \times V_F) \)
  Accurate; the questions are:
  — what is the dissipated power of an LED? \( \text{Subtract radiant flux} \)
  — what is the \( T_X \) reference temperature \( \text{Use cold plate!} \)

- For LEDs, consider the radiant flux: \( R_{th-r} = \Delta T_J / (I_F \times V_F - P_{opt}) \)

- Both \( R_{th-el} \) and \( R_{th-r} \) are correct, if proper power is used to calculate \( T_J \)
Importance of the definition of $R_{th}$ for LEDs

- Traditionally: $R_{th-el} = \Delta T_J / P_{el} = \Delta T_J / (I_F \times V_F)$

- Due to high efficiency, radiant flux must be considered:
  
  $$R_{th-r} = \Delta T_J / (P_{el} - P_{opt})$$
  $$= \Delta T_J / (I_F \times V_F - P_{opt})$$

By neglecting $P_{opt}$ vendors report much nicer data than reality

**EXAMPLE:**

- Let us assume two $\eta_e$ -s
  $\Delta T = 50^\circ C$, $P_{el} = 10W$

  - $\eta_e = 0\%$ (electrical only)
    \[ "R_{th-el}" = \Delta T / P_{el} = 50/10 = 5 \text{ K/W} \]

  - $\eta_e = 25\%$
    \[ R_{th-r} = \Delta T / (P_{el} - P_{opt}) = \Delta T / [P_{el} \cdot (1-\eta_e)] = 50/(10 \cdot 0.75) = 6.67 \text{ K/W} \]

  - $\eta_e = 50\%$
    \[ R_{th-r} = \Delta T / (P_{el} - P_{opt}) = \Delta T / [P_{el} \cdot 1-\eta_e] = 50/(10 \cdot 0.5) = 10 \text{ K/W} \]
Junction temperature — performance indicator

- Calculation: \( T_J = R_{\text{thJ-X}} \cdot P_H + T_X \)
  - \( R_{\text{thJ-X}} \) junction-to-reference\(_X\) thermal resistance supplied by the LED vendor
  - \( P_H \) heating power measured/calculated by the LED user
    - How?
  - \( T_X \) reference temperature (un)specified by the LED user

- Used in the design process to decide if the foreseen cooling is sufficient or not...
  - Not enough: in case of LEDs, prediction of “hot lumens” is also required

Differential formulation of the thermal resistance

\[
R_{\text{thJ-X}} = \frac{T_J - T_X}{P_H} = \frac{[\Delta T_J]_X}{P_H}
\]

Instead of spatial difference (temperature values at junction and reference point) temporal difference of the junction temperature can be used
How do we know $\Delta T_J(t)$?

- The LEDs’ forward voltage under forced current condition can be used as a very accurate thermometer.

- The change of the forward voltage (TSP – temperature sensitive parameter) should be carefully calibrated against the change of the temperature (see JEDEC JESD51-1 and MIL-STD-750D)
  - In the calibration process the $S_{VF}$ temperature sensitivity of the forward voltage is obtained.

- Forward voltage change due to temperature change is measured using a 4 wire setup (Kelvin setup).
The measurement waveforms

Time window for the CIE 127-2007 compliant measurement of the light output

heating

stable

cooling

measurement

Hot device biased by heating current

ΔV_F[mV]

Electrical transient

Thermal transient

Cool device biased by measurement current

Hot device biased by measurement current

1e-6 1e-5 1e-4 0.001 0.01 0.1 1 10

t[s]

t_MD
t_M

t=0

t_H

V_F

V_H

V_Ff

V_Fi

ΔV_F

I_F

I_H

I_M

V_H

V_Ff

V_Fi

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Comprehensive LED testing solution:

CIE 127-2007 compliant photometric & radiometric measurement system

Photometric/radiometric measurements in thermal steady-state

Steady-state electrical powering

The JEDEC JC15 committee deals with these issues. A set of documents is prepared and is being discussed (how to apply JESD51-1 & CIE 127-2007)
Some details of the test environment

The JEDEC JC15 committee deals with these issues. A set of documents is prepared and is being discussed (how to apply JESD51-1 & CIE 127-2007).

CIE TC2-63 deals with optical testing of high power LEDs, considering also the effect of the junction temperature.
The Mentor Graphics MicReD implementation:

Special LED booster: allows high voltage across a LED line (overall forward voltage can reach 280V – needed for AC mains driven LEDs).

It can be added to the system in a plug&play manner if the voltage of the base tester is not sufficient.
What temperature to report?

- The same luminous flux measurement results shown as function of reference temperature and junction temperature

The junction temperature is the one which determines the light output, this is the relevant quantity.
Case study:
10W white LEDs with their thermal properties and light output characteristics as function of forward current and junction temperature
Results for 10W white LEDs

- Measured at 700 mA and 85 °C
  - Structure functions of 3 samples, power corrected with $P_{opt}$

- $R_{thJC}$ is identified in a way similar to the \textit{transient double interface method}, a new standard: JEDEC JESD51-14

![Graph showing thermal test results for 10W white LEDs]
The transient dual interface method for $R_{thJC}$

- Original idea from 2005, standard JESD51-14 published in November 2010
- Change of thermal interface quality at the ‘case’ surface
- Divergence point in measured structure functions: ‘case’ surface

Change at the case: insulator inserted
Measurement of 2 setups (2x3 min), structure functions

Dirk Schweitzer - Harvey Rosten Award (24 March 2011)

SEMI-THERM 2005 Best Paper Award
Methodology for single-chip and lateral or stacked multi-chip structures
SEMI-THERM 21, March 15 – 17, 2005, San José, California

Oliver Steffens1, Péter Szabó2, Michael Lenz2, Gábor Farkas2
1Infineon Technologies AG, Ratisbon, Germany
2MicReD Ltd., Budapest, Hungary
3Infineon Technologies AG, Munich, Germany

Never stop thinking.
Results for 10W white LEDs

- Measured at 350/700 mA & between 15 °C and 85 °C
  - Structure functions of sample AL-2, power corrected with $P_{opt}$

**What thermal resistances did we measure?**

- $R_{thJC}$-package + $R_{th}$-MCPCB + $R_{th}$-grease

Changes in TIM quality contribute to light output variations

$R_{thJC}$-package + $R_{th}$-MCPCB + $R_{th}$-grease $\Rightarrow$ for "hot lumen" estimates
\( \Phi_V(T_{ref}) \) plots for two cases \( (I_F=350\,mA) \)

Variation of \( R_{th} \) means, the device characteristics scaled in reference temperature will be different

No need for a sophisticated control of the TEC in the integrated sphere

Re-scaling for junction temperature eliminates the effect of the different thermal resistance values
Further problems:
Thermal issues in short-pulse testing and in LM80 tests,
AC LEDs
Short pulse measurements

- During in-line testing photometric/colorimetric properties are measured with a short pulse
  - $T_J = T_{\text{ref}} = \text{constant}$ is assumed, **THIS IS NOT TRUE**: In 10 ms significant junction temperature change may take place

**Graph**

- 1W white LED measured in free air without any cooling assembly
- During 10 ms $T_J$ changes almost by 5 °C
- Question is if this causes big problems or not…

**Addressed by CIE TC 2-64**
Example: 10W white LED

- $P_{\text{heat}} \approx 3W @ 350mA$
- $R_{\text{th-r}} \approx 20K/W$

Junction Temperature Response:
- $\Delta T_J \approx +30^\circ C$ for $I_{\text{f}}=700 mA$
- $\Delta T_J \approx +15^\circ C$ for $I_{\text{f}}=350 mA$

Time [s] vs. Temperature:
- $\Delta T = 15^\circ C$
- $\Delta T_{CC} \approx +22 K$ for $\Delta T_J=15^\circ C @ 350 mA$
- $\Delta T_{CC} \approx +50 K$ for $\Delta T_J=15^\circ C @ 700 mA$

Luminous Flux vs. Temperature:
- $\Delta \Phi_V \approx 18 \text{ lm}$ for $\Delta T_J=15^\circ C @ 350 mA$
- Slope $\approx -1.2 \text{ lm/}^\circ C$

Addressed by CIE TC 2-64
In-situ thermal measurements during LM80 tests

LM80 test chamber with all the LEDs assembled

All measurements are done in-situ to eliminate any $R_{th}$ change which is NOT due to ageing.

In-situ thermal transient measurement

In-situ light output measurement
Recent results from LM80 test of different LEDs

- In cooperation with University of Pannonia, Veszprém (Hungary), prof. J. Schanda’s group within the KöZLED project of the Hungarian Government

### Relative Luminous Flux

<table>
<thead>
<tr>
<th>Vendor O, $I_F = 350$ mA</th>
</tr>
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<tbody>
<tr>
<td>85%</td>
</tr>
<tr>
<td>90%</td>
</tr>
<tr>
<td>95%</td>
</tr>
<tr>
<td>100%</td>
</tr>
<tr>
<td>105%</td>
</tr>
<tr>
<td>110%</td>
</tr>
</tbody>
</table>

**Structure functions taken at**
- 0h
- 500h
- 1000h

**Time [h]**
- 0h
- 200
- 400
- 600
- 800
- 1000
- 1200
- ave

**Sample #**
- 41
- 42
- 43
- 44
- 45
- 46

**Ligh output drop likely due to increased $R_{th}$ caused by TIM degradation, not by LED degradation**

**No change inside the LED package**

- 8 different kinds of LEDs from 4 vendors, so far 6500h burning time, processing measurement data in progress
Recent results from LM80 test of different LEDs

Results after 3000h:

- All HK LEDs have already died

**TIM ageing:** external to the LED – LM80 measurement results must be compensated for this

**Delemination from the MCPCB:** a failure inside the LED assembly, its contribution to light output degradation is part of the LM80 test result
Problems of testing AC LEDs: what “Z\text{th}” to use?

- For AC LEDs instead of the classical time-domain representation of Z\text{th} we need its frequency domain representation.

\[ Z_{\text{th}}(\omega) = \frac{1}{P_{\text{diss DC}}} \int_{0}^{\infty} a(t)e^{-j\omega t} \, dt \]

\[ Z_{\text{th}}(\omega) = \frac{1}{j\omega C_{\text{th}1}} \times \left( R_{\text{th}1} + \frac{1}{j\omega C_{\text{th}2}} \times \left( R_{\text{th}2} + \left[ \frac{1}{j\omega C_{\text{th}3}} \times \left( R_{\text{th}3} + Z_{\text{th-cooling ass}} \right) \right] \right) \right) \]

AC LED assembly

\[ P_{\text{diss AC}} \]

\[ \frac{1}{j\omega C_{\text{th}1}} \times \left( R_{\text{th}1} + \frac{1}{j\omega C_{\text{th}2}} \times \left( R_{\text{th}2} + \left[ \frac{1}{j\omega C_{\text{th}3}} \times \left( R_{\text{th}3} + Z_{\text{th-cooling ass}} \right) \right] \right) \right) \]
Problems of testing AC LEDs: dissipation, $Z_{thAC}$

- The AC dissipation for voltage generator driven LED:

$$P_{dissAC}(\omega) = U_{MAX}^2 \cdot \frac{I_0}{mU_T} \cdot \frac{1}{1!} \sin^2 (\omega t) + U_{MAX}^3 \cdot \frac{I_0}{(mU_T)^2} \cdot \frac{1}{2!} \sin^3 (\omega t) + U_{MAX}^4 \cdot \frac{I_0}{(mU_T)^3} \cdot \frac{1}{3!} \sin^4 (\omega t) + ...$$

- Multiple frequencies

- How to define a single number thermal metric?

$$Z_{thAC-max} = \frac{T_{JAC-max}}{P_{dissAC-mean}}$$

$$Z_{thAC-mean} = \frac{T_{JAC-mean}}{P_{dissAC-mean}}$$

See details in our paper in the LED session of SEMI-THERM
Conclusions

- Brief overview of standardization needs and recent activities was given
- Measurement setup for consistent measurement of thermal and light output metrics of power LEDs was shown
  - Based on existing standards (JEDEC JESD51-1, CIE 127-2007)
  - Therefore with some new measurement guidelines it is easily implemented
    - Such guidelines are being developed by the JEDEC JC15 Committee on Thermal Standards of Packaged Semiconductor Devices
- Merits of such a combined thermal/radiometric LED testing station were shown by a case study
  - Importance of changing properties of thermal interface materials and their effect on light output was shown
- Combined thermal transient and photometric measurements suggest that the constant junction temperature assumption in short pulse in-line testing is not valid
- To eliminate effect of variations (ageing) of TIM during LM80 tests, in-situ measurements are suggested, combined with thermal transient measurements
- Problems related to the “AC thermal impedance” as a single number thermal metric for AC mains driven LEDs were raised