Methods for estimating junction temperature of AC LEDs

Asiri Jayawardena, Yi-wei Liu, and Nadarajah Narendran

Lighting Research Center
Rensselaer Polytechnic Institute
21 Union St.
Troy, NY 12180, USA
www.lrc.rpi.edu/programs/solidstate

Jayawardena, A., Y. Liu, and N. Narendran. 2011. Methods for estimating junction temperature of AC LEDs. *Eleventh International Conference on Solid State Lighting, August 22-25, 2011, San Diego, CA, Proceedings of SPIE* 8123: 81230I.

Methods for Estimating Junction Temperature of AC LEDs

Asiri Jayawardena, Yi-wei Liu, Nadarajah Narendran
Lighting Research Center, Rensselaer Polytechnic Institute
21 Union St., Troy, NY 12180 USA
Tel: +1 518 687-7100 | email: jayawa@rpi.edu | web: www.lrc.rpi.edu/programs/solidstate

ABSTRACT

Light-emitting diodes operating on alternating current (AC) are gaining popularity in lighting applications. The junction temperature of an LED significantly influences performance. Although there are many proven methods for estimating the junction temperature of direct current (DC) LEDs, only a few methods have been proposed for AC LEDs. Two different methods were investigated and analyzed for their accuracy in estimating AC LED junction temperature: a low reference current pulse used to measure the voltage across the junction, and an active cooling system to recover the first half cycle current (rms). Method details are provided. The results suggest that the voltage drop method for AC LEDs is a viable method to estimate junction temperature.

Keywords: AC LED, alternating current, light-emitting diode, thermal resistance, junction temperature

1. INTRODUCTION

Light-emitting diodes (LED) are gaining popularity among consumers as an energy-efficient alternative for general illumination. LEDs are typically powered using a direct current (DC) source; therefore, they require an alternating current (AC) to DC converter when connected to a power grid. The monolithic integration of multi-junction arrays to form an LED package that could be directly connected to an AC power supply has the potential to improve system efficiency, increase reliability, and reduce luminaire sizes while reducing the cost of the LED lighting system. These potential benefits have given AC LED packages greater recognition within the lighting community.

The junction temperature of an LED package affects its light output, color, and reliability. Junction temperature cannot be measured directly. Temperature-sensitive parameters such as forward voltage of the diode or peak emission wavelength are used to estimate the junction temperature. The users of LED packages rely on the thermal resistance value specified by manufacturers between the junction and the reference point on the LED package to predict junction temperature using the one-dimensional heat conduction equation:

$$\mathbf{T_j = T_{pin} + R_{\theta J\text{-}P} * P} \qquad \textbf{(Eq. 1)}$$

$$\mathbf{P = P_{electrical} - P_{optical}} \qquad \textbf{(Eq. 2)}$$

Where:
T_j : Junction temperature (°C)
T_{pin} : Pin temperature (°C)
P: Thermal power dissipation in the junction (W)
$R_{\theta J\text{-}P}$: Thermal resistance between the junction and pin (°C/W)

There are few studies in literature that have looked at the junction temperature measurement of AC LEDs. [1,2,3,4] Hwu et al. in 2009 correlated the junction temperature and the board temperature of an AC LED at different input power levels at DC operating conditions. [1] The mean junction temperature was estimated by measuring the board temperature at AC operation. The assumption was that the thermal resistance between the junction and the board of the package remain constant at all input power levels. However, according to literature, for high-power DC LEDs the thermal resistance changes with input DC current due to series electrical resistance in the package. [5,6]

Eleventh International Conference on Solid State Lighting, edited by Matthew H. Kane, Christian Wetzel, Jian-Jang Huang,
Proc. of SPIE Vol. 8123, 81230I · © 2011 SPIE · CCC code: 0277-786X/11/$18 · doi: 10.1117/12.904056

Zong et al. in 2009 estimated the junction temperature of an AC LED by recovering the first half cycle of current (rms) using an active heat sink. [2] This method is referred to as the first half cycle current recovery method in this paper. The assumption in Zong et al.'s study was that during the first half cycle there is no significant heating occurring in the junction; however, thermal simulation studies reveal that a significant temperature rise occurs during the first half cycle. [1,4] Liu et al. in 2010 suggested a method based on the voltage drop of the AC LED to measure its thermal resistance. [3] Poppe et al. in 2011 used transient thermal testing to obtain the thermal impedance curve in the frequency domain. [4] The junction temperature curve was obtained using thermal impedance and power dissipation functions.

2. OBJECTIVE

In 2010, researchers at the Lighting Research Center proposed a method to estimate the junction temperature of an AC LED by inserting a small reference current pulse at the non-conduction time interval (current dead-zone). [3] When they compared the thermal resistance value calculated using the voltage drop method with the thermal resistance value they calculated using the method proposed by Zong et al., [2] there was a wide discrepancy. It was hypothesized that this discrepancy is due to the heating in the first half cycle of current that Zong et al. did not account for in their method. However, no proof was given to validate this assumption. The objective of this follow-up study was to validate this assumption by estimating the temperature rise in the junction during the first half cycle of current.

3. METHOD: VOLTAGE DROP METHOD FOR AC LEDS

A GaN-based, phosphor-converted white AC LED was measured using the voltage drop method for AC LEDs [3] followed by recovery of the first half cycle using the active heat sink method. [2] A schematic diagram of the measurement setup for the voltage drop method is given in Figure 1. The control circuit was used for calibration and to insert the reference current pulse at the current dead-zone. Electrical input power was measured using a power meter. The electrical power measurements were obtained after completing the junction temperature measurements.

A reference DC current of 0.06 mA was used to obtain the calibration curve. The I-V analysis of the AC LED revealed that at this current, the AC LED is forward biased. It was assumed that the current is not large enough to cause significant heating in the junction. A J-type thermocouple was attached at the center of the board using thermal epoxy to measure the pin temperature. The AC LED was attached to a thermoelectric cooler using mechanical screws. The reference DC current was applied and the voltage across the AC LED was measured by adjusting the temperature of the active heat sink in 5°C steps from 25°C to 75°C. The calibration curve is given below in Figure 2.

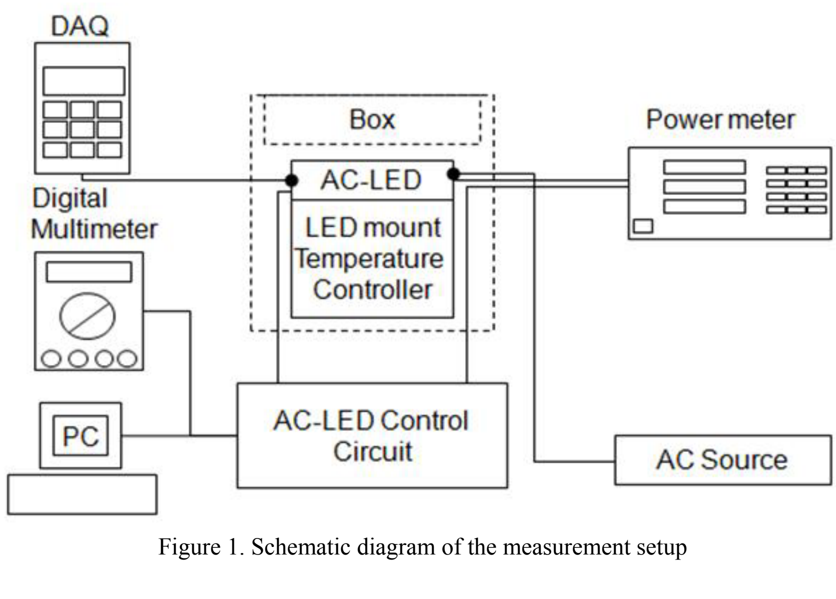

Figure 1. Schematic diagram of the measurement setup

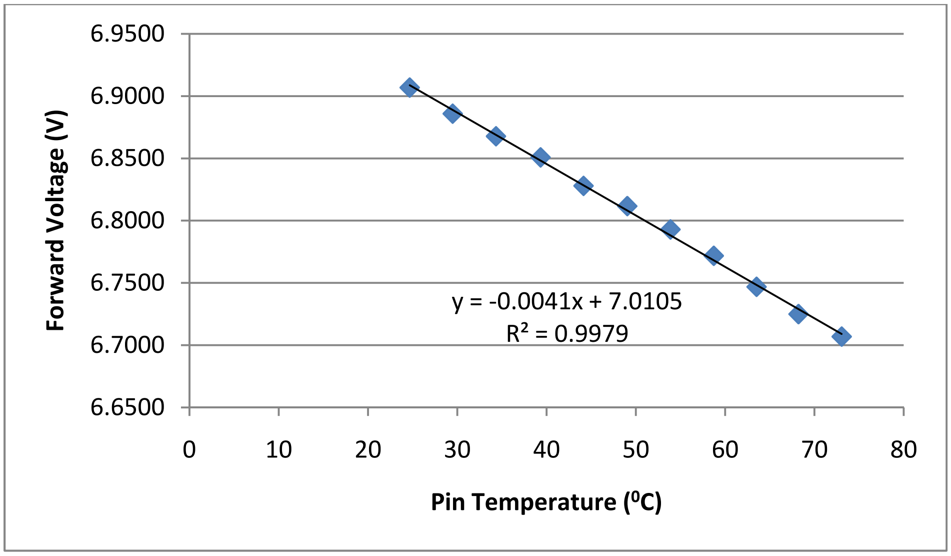

Figure 2. Calibration curve of the AC LED

During the AC operation, a pulse of 1.5 ms was inserted at the current dead-zone. When the package reached thermal stability, the voltage drop at the instance when the current pulse is applied was measured. Thermal stability was defined as the point when the variation among five pin temperature samples obtained at every one-minute interval was less than 0.1°C. The junction temperature was measured at three thermoelectric cooler temperature settings. The initial temperature setting of the voltage drop method was chosen to be within ±2°C of the temperature setting at which the first half cycle rms current is recovered. The optical power was measured using an 8-inch integrating sphere setup at every temperature setting. The thermal resistance was calculated using the following formula:

$$R_{J-P} = \frac{(Junction\ Temperature - Pin\ Temperature)}{(Input\ Electric\ power - optical\ power)} \qquad \textbf{(Eq. 3)}$$

4. METHOD: FIRST HALF CYCLE CURRENT RECOVERY METHOD

The thermal resistance of the same AC LED mounted in the thermoelectric cooler was measured using the method proposed by Zong et al. [2] The schematic diagram of the measurement setup is given in Figure 3. The AC input power to the sample was provided using a precision AC power supply (California Instrument: Model 1001P) in both methods. The control circuit was used to apply the AC voltage from the zero-phase angle. The first half cycle of current was captured using a 16-bit waveform digitizer with a sampling speed of 250 ks/S. The LabView 2009 software from National Instruments was used to control instruments and compute the root mean square (rms) value of the acquired data.

The temperature of the thermoelectric cooler was adjusted until the rms value of the current was equal to the first half cycle current (rms). When the first half cycle (rms) value was recovered, optical power measurements were obtained using an 8-inch integrating sphere setup. The thermal resistance of the sample was measured at three different initial temperature settings of the thermoelectric cooler.

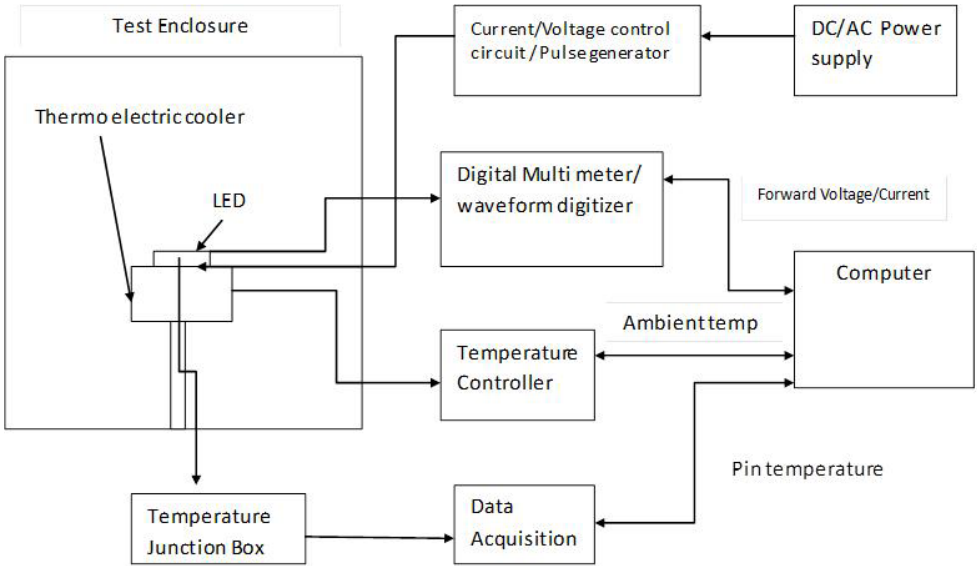

Figure 3. Schematic diagram of the measurement setup for first half cycle current recovery method

The temperature rise during the first half cycle of current in the junction was estimated by inserting the reference current pulse at the very end of the first half cycle of current. The measured voltage at this instance was converted to junction temperature using the calibration curve in Figure 2. The temperature rise in the first half cycle was estimated for each temperature setting, since the temperature rise in the junction depends on the initial temperature. The thermal resistance was estimated using equation 4.

$$R_{J-P} = \frac{(\text{Initial Temperature} + T_J \text{ rise in first half cycle} - \text{Pin Temperature})}{(\text{Input Electric power} - \text{optical power})} \qquad \textbf{(Eq. 4)}$$

5. RESULTS

The thermal resistance calculations for the AC LED package using the voltage drop method and the first half cycle current recovery method are given in Table 1 and Table 2. The estimated thermal resistances for the AC LED package for different temperature settings are plotted in Figure 4. The difference in thermal resistance values could be explained using the measurement uncertainty of the two measurement setups. The measurement uncertainty of the voltage drop method for the AC LED is 0.4°C\W. The uncertainty of the measurement setup that measured junction temperature using the first half cycle current recovery method was 0.7°C\W. Therefore, the thermal resistances measured using the two methods agree when heating during the first half cycle is accounted.

Table 1. Thermal resistance calculated using voltage drop method

Cold plate temperature (°C)	35	55	60
Junction temperature (°C)	53.3	75.1	81.1
Pin temperature (°C)	35.8	55.1	59.8
Temperature difference (°C)	17.5	20.0	21.3
Electric input power (W)	2.79	2.98	3.02
Optical power (W)	0.209	0.205	0.204
Thermal input power (W)	2.58	2.77	2.82
Thermal resistance (°C/W)	6.8	7.2	7.6

Table 2. Thermal resistance calculated using first half cycle current recovery method

Initial cold plate temperature (°C)	50	70	75
T_j after first half cycle (°C)	54.2	74.8	80.3
Recovered pin temperature (°C)	37.4	56.9	59.8
Temperature difference (°C)	16.8	17.9	20.5
Input electric power (W)	2.60	2.68	2.81
Optical power (W)	0.209	0.205	0.204
Thermal input power (W)	2.4	2.5	2.6
Thermal resistance (°C/W)	7.0	7.2	7.9

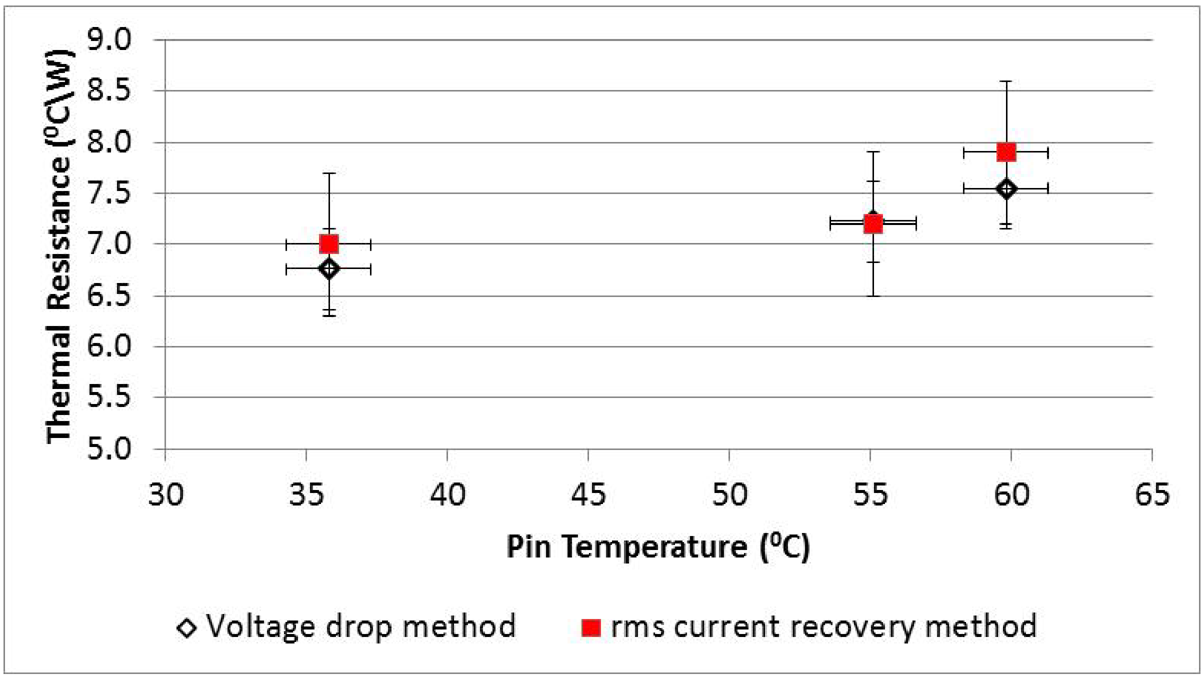

Figure 4. Comparison of results for the AC LED obtained using the voltage drop method and the first half cycle current recovery method using active heat sinks [7]

6. DISCUSSION

The converging results suggest that the voltage drop method is a viable method to estimate the junction temperature of AC LEDs. This method is easy to implement with slight modification to source measurement units available in the market. The method involves measuring voltage, which is a parameter that could be easily measured with high precision. However, implementation of this method as an in-line measurement method would require a batch calibration to determine a calibration factor (V/°C) unique for a batch of AC LEDs. If the variation of calibration factors within the batch is small, then this method could be implemented with a single calibration factor for a batch. The optical pulse method currently employed by the LED industry for binning purposes requires around 10 ms for measurement. This would mean approximately half of a cycle for an AC LED. If the DC current pulse is inserted at the beginning and at the end of the half cycle of the AC current waveform, the junction temperature rise could be estimated during binning.

The thermal simulation analysis in literature reveals that junction temperature oscillates with time and with fixed amplitude at steady state. [1,4] The amplitude of oscillation is determined by the thermal capacity. There is a phase delay in junction temperature rise with thermal power dissipation due to thermal capacitance effect. [4] The thermal capacitance ensures that the junction cools down at a slow enough rate so that the sampled voltage at the current dead-zone is closer to the maximum temperature in the junction. [7] A shorter sampling delay time means that the estimated junction temperature would be closer to the peak of the junction temperature. However, a sufficient sampling delay time is needed to ensure that the sampled voltage is free from any electrical transients.

ACKNOWLEDGMENTS

This study was sponsored by the Alliance for Solid-State Illumination Systems and Technologies (ASSIST) and the Federal Aviation Agency (FAA/05-C-AT-RPI Mod#12). We would like to thank Lite-on, Inc., for providing the testing samples. We would also like to thank Terence Klein and Yiting Zhu of the Lighting Research Center for their assistance in the experiment set up.

REFERENCES

[1] Hwu, F-S., Sheu, G-J., Lin, M-T., and Chen, J-C., "Method for determining the junction temperature of alternating current light-emitting diodes," *IET Sci. Meas. Technol.* 3(2), 159–164 (2009).

[2] Zong, Y., Chou, P-T., Lin M-T., and Ohno Y., "Practical method for measurement of AC-driven LEDs at a given junction temperature by using active heat sinks," *Proc. SPIE* 7422, 742208-742208-7 (2009).

[3] Liu, Y., Jayawardena, A., Klein, T.R., and Narendran, N., "Estimating the junction temperature of AC LEDs.," *Proc. SPIE* 7784, 778409 (2010).

[4] Poppe, A., Siegal, B., and Farkas. G., "Issues of thermal testing of AC LEDs," *27th IEEE SEMI-THERM Symposium*, 297-303 (2011).

[5] Yang, L., Kim, L., Hu, J., and Shin, M.W., "Variation of thermal resistance with input power in LEDs," *Physica status solidi (c)*, 2187-2190 (2006).

[6] Kuo, S-L. et al., "Characteristics of Thermal Resistance for High Power LEDs," *Electronics Packaging Technology Conference*, 149-154 (2008).

[7] Jayawardena, A., "Characterizing the Thermal Resistance of Alternating Current Light Emitting Diodes," Rensselaer Polytechnic Institute, Troy, NY, Master's Thesis (2011).