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Characterization of Thermal Resistance Coefficient of High-power LEDs

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ABSTRACT

Heat at the junction of light-emitting diodes (LED) affects the overall performance of the LED in terms of light output, spectrum, and life. Usually it is difficult to measure junction temperature of a LED directly. There are several techniques for estimating LED junction temperature. One-dimensional heat transfer analysis is one of the most popular methods for estimating the junction temperature. However, this method requires accurate knowledge of the thermal resistance coefficient from the junction to the board or pin. An experimental study was conducted to investigate what factors affected the thermal resistance coefficient from the junction to the board of high-power LED. Results showed that the thermal resistance coefficient changed as a function of ambient temperature, power dissipation at the junction, the amount of heat sink attached to the LED, and the orientation of the LED with the heat sink. This creates a challenge for using one-dimensional heat transfer analysis to estimate junction temperature of LEDs once incorporated into a lighting system. However, it was observed that junction temperature and board temperature maintains a linear relationship if the power dissipation at the junction is held constant.

Keywords: light-emitting diodes (LEDs), junction temperature, thermal resistance coefficient, life

1. INTRODUCTION

The light-emitting diode (LED) has become a promising candidate for the replacement of incandescent and fluorescent lamps in general lighting applications. Many LED products mimicking traditional halogen/incandescent PAR and MR16 lamps are continuously appearing in the marketplace. When these lamps are used with lighting fixtures of different insulation ratings that are commonly found in residential and commercial applications, like insulated (IC) or non-insulated (Non-IC), their performance varies because the temperature around the lamps is different for each fixture environment. To understand the temperatures experienced by the individual LEDs when these lamps are used in the different types of fixtures, several commercially available LED PAR and MR lamps were evaluated in open air and IC rated recessed downlight fixtures. As an example, data for one of the LED PAR lamps is illustrated in figure 1. For this lamp, the board temperature stabilized at 150°C within the IC fixture. This is significantly high when compared with the board temperature measured during open-air operation, which is 60°C. It was also observed that the board temperature of the same PAR lamp increased almost 15°C when its orientation changed from a vertical to horizontal position (figure 2) in open air. Therefore, from these observations it is clear that one must pay close attention when LED fixtures are used in different applications, since LED light source performance is very much affected by temperature.

From past studies, it is also shown that heat at the junction determines the performance of LEDs in terms of light output, spectral shift, and light output degradation over time.¹⁻⁵ Accurately measuring junction temperature is of great importance in predicting the short-term and long-term performance of LED systems. Generally, it is very difficult to measure the junction temperature of an LED directly, and therefore it is estimated. One-dimensional heat transfer analysis is a common method for estimating junction temperature. This method requires knowing the thermal resistance coefficient from the LED junction to the electronics board where the LED is attached. The temperature of the board can be measured easily using a temperature sensor. However, the accuracy of the junction temperature estimate depends on the value of the thermal resistance coefficient. Although the thermal resistance coefficient is a constant for a given condition, it is not well known how it is affected by parameters such as ambient temperature, drive current, the amount of heat sink used in a package, and the orientation of the heat sink. Literature survey shows very few publications addressing the changes in the thermal resistance coefficient of high-power LEDs.

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Therefore, the objective of this study was to understand how the junction-to-board thermal resistance coefficient changes with different parameters such as ambient temperature, power dissipation, the amount of heat sink attached to the LED, and the heat sink orientation. Having good knowledge of the factors that influence the thermal resistance coefficient would allow for quantification of the uncertainties involved in estimating junction temperatures.

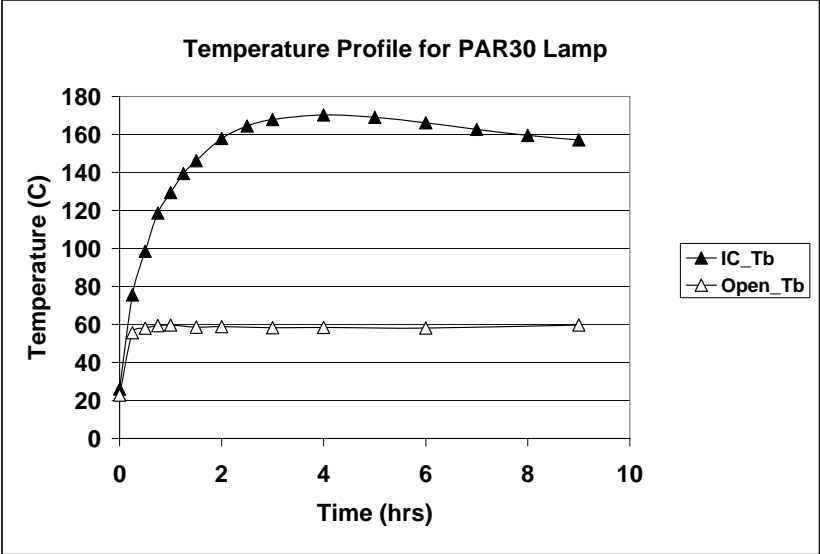


Fig. 1. Temperature profile for a mixed-color PAR30 LED lamp when operating in open air and within IC-rated fixture (Tb=board temperature).

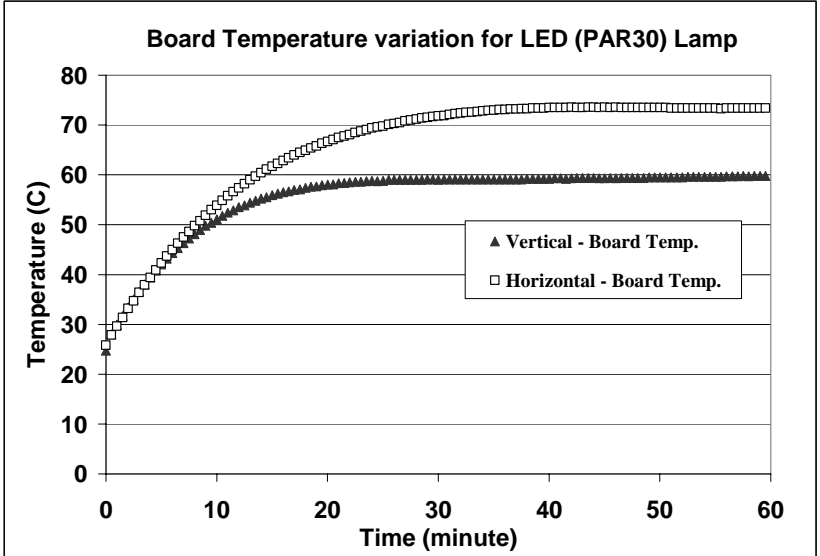


Fig. 2. Board temperature variation due to orientation of the lamp. Note that the board temperature increases almost 15°C due to the change of its orientation.

2. BACKGROUND

Although there are not many studies that have addressed the issue of thermal resistance coefficient variation for high-power LEDs and how it is affected, several studies have analyzed the thermal resistance variations of other types of power electronics devices, like heterojunction bipolar transistors (HBTs), that have similar structures including a semiconducting p-n junction.⁶⁻⁸ Some of these studies have evaluated the thermal resistance variations of HBT packages with ambient temperature, case temperature, and power dissipation. Menozzi et al. showed that in the range of power from 30 to 120 mW, the thermal resistance, R , (at base plate temperature $T_b = 25^\circ\text{C}$) varies from 400 to $800^\circ\text{C}/\text{W}$.⁶ In the same work, it was shown that R increases when the base plate temperature increases at constant power.⁶ Marsh studied a method to derive the junction temperature of HBTs.⁷ In his work, the simulation results showed that for fixed junction temperatures of 130°C and 188°C , the thermal impedance is a linear function of the ambient temperature of the base plate.⁷ Another study by Paasschens et al. investigated the dependency of thermal resistance on ambient temperature for HBTs.⁸ They estimated the thermal resistance using two different methods, showing that the thermal resistance for GaAs-based HBTs increased linearly with ambient temperature.⁸ All of the studies have shown that the thermal resistance of HBTs varies with factors such as ambient temperature, case temperature, and dissipated power. One manufacturer's application note for high-power LEDs shows how the thermal resistance coefficient changes with the size of the heat sink used and the orientation of the heat sink.⁹

Based on past studies, one can hypothesize that drive current or dissipated power at the p-n junction, ambient temperature, the amount of heat sink, and orientation of the heat sink would affect the thermal resistance of high-power LEDs.

3. EXPERIMENT

The goal for this study was to measure the thermal resistance variation of high-power LEDs with changing power, ambient temperature, amount of heat sink, and heat sink orientation. The first step was to select a reliable method to predict the junction temperature of an LED. Usually, the potential across the p-n junction changes with temperature. Therefore, a commonly used method for estimating the junction temperature of an LED is to compare the voltage across the p-n junction at a given temperature to a reference condition. Therefore, the junction temperature, T_j , can be expressed as:

$$T_j = T_0 + \frac{V_t - V_0}{K} \quad (1)$$

where T_0 is the reference ambient temperature, V_t and V_0 are the forward potentials at the test condition temperature and the reference ambient temperature, respectively, and K is the temperature coefficient of the forward voltage.¹⁰

By rearranging equation (1), K can be obtained as:

$$K = \left[\frac{V_0 - V_t}{T_0 - T_t} \right] \quad (2)$$

where V_0 and V_t are forward potentials at two known ambient temperatures, T_0 and T_t , respectively.¹⁰ First, K is determined by measuring the potential drop across the LED junction at two known ambient temperatures. Then T_j is obtained using equation (1).

Once the junction temperature is known, then the thermal resistance from the junction to the board, $R\theta_{j-b}$, can be estimated using the following equation:

$$R\theta_{j-b} = (T_j - T_b) / P \quad (3)$$

where T_b is the board temperature and P is the power.

3.1 Experimental setup and procedure

An electronic circuit was built to create the necessary current pulses to measure the voltage across the junction. Using the equations described above, the junction temperature of high-power LEDs was estimated. Figure 3 is a schematic of the

experimental setup. The LED was placed inside the thermal chamber to keep it at a constant ambient temperature. The temperature inside the thermal chamber was controlled by a heater controller, which received temperature information from the resistance temperature detector and turned the heater on and off.

A bare LED or an LED with a heat sink was attached to the top side of the test box. J-type thermocouples were attached to the LED cathode pin to measure the board temperature. Another thermocouple was added to the thermal chamber to measure the ambient temperature. A Yokogawa WT210 digital power meter was used to monitor the forward voltage, power, and current of the LED. At regular intervals and at a duty cycle of 0.001, the current was stepped down to a value of 1 mA using a very short (200 μ s) square wave pulse. The potential across the junction was measured during this short stepped-down period. The assumption here is the 1 mA current would provide negligible heat to the junction, and the temperature drop would be negligible during the short stepped-down pulsed condition. To measure K , one needs to measure the forward potential across the junction at two different ambient temperatures. LEDs operating at higher ambient temperatures have lower voltages across the junction than LEDs operating at lower ambient temperatures.

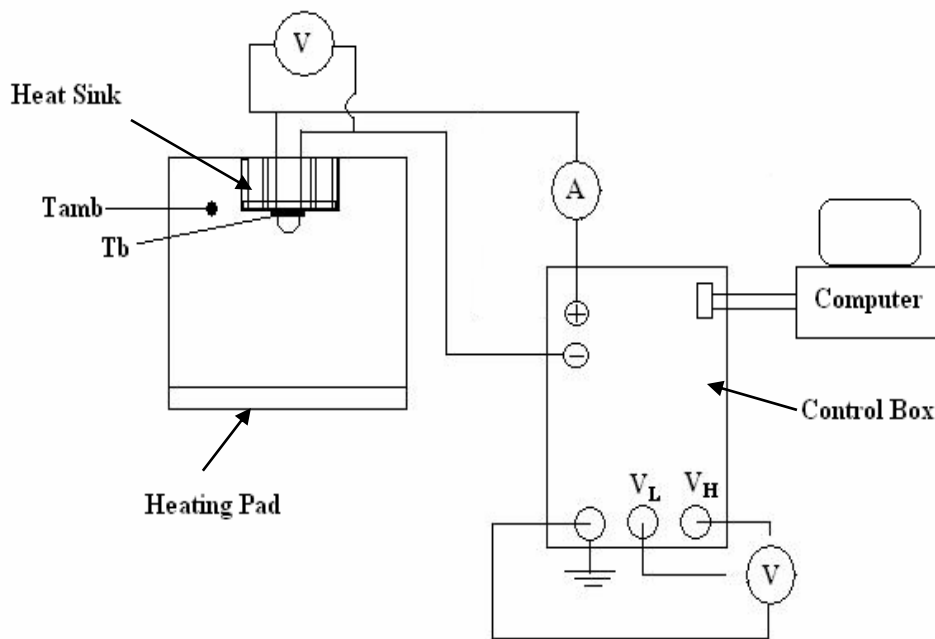


Fig. 3. Schematic of the experimental setup.

High-power 1 W and 3 W LEDs from the same manufacturer were used for the experiment. Anodized aluminum heat sinks with different surface areas (712 cm² [heat sink A], 250 cm² [heat sink B], 85 cm² [heat sink C], and 40 cm² [heat sink D]) were used to estimate the thermal resistance variations occurring with different heat sink surface areas. The LEDs were attached to the heat sinks using thermal conducting adhesive tape. A J-type thermocouple was attached to the cathode pin to measure the board or pin temperature. The LED with the heat sink was then placed inside the thermal chamber. For the 1 W LEDs, the thermal resistance from the junction to the board was measured for four different drive currents: 1, 100, 200, and 350 mA. For the 3 W LEDs, the applied drive currents were 1, 100, 200, 350, and 750 mA. The ambient temperatures used in this study were 25°C, 40°C, and 60°C. The experiment was repeated three times for each heat sink size, and data were collected for voltage, current, power, and pin temperature. For all of these measurements, the LEDs were kept horizontal, facing downward. It is essential to keep the orientation the same, or else the thermal resistance coefficient will be affected.⁹ One other issue that needed care was the LED attachment to the heat sink. The thermal conducting tape used to attach the LED to the heat sink contributes significantly to the thermal resistance variation. During attachment, any air bubbles created between the tape and the heat sink can significantly alter the thermal resistance.

4. RESULTS

The thermal resistance from the junction to the board was measured at 25°C to determine the uncertainty of the measurement system built for the experiment and the variation from LED to LED in the same manufacturing batch. Three 1 W LEDs from the same manufacturing batch were measured for four different conditions: no heat sink, heat sink B, heat sink C and heat sink D. The junction temperature of each 1 W LED was measured three times and the thermal resistance (°C/W) was estimated. The same procedure was repeated for the 3 W LEDs. The results obtained for the 1 W and 3 W LEDs with heat sink area 40 cm² (heat sink D) for 350 mA drive current are shown in Figures 4 and 5. Results indicate a 0.7°C/W difference among 1 W LEDs and a 0.6°C/W difference among 3 W LEDs for heat sink D. Overall, the measurement system uncertainty for all heat sinks was 1°C/W.

For the 1 W bare LED with no heat sink, the average thermal resistance value from nine measurements was close to the one provided by the manufacturer, indicating the reliability of the measurement system.

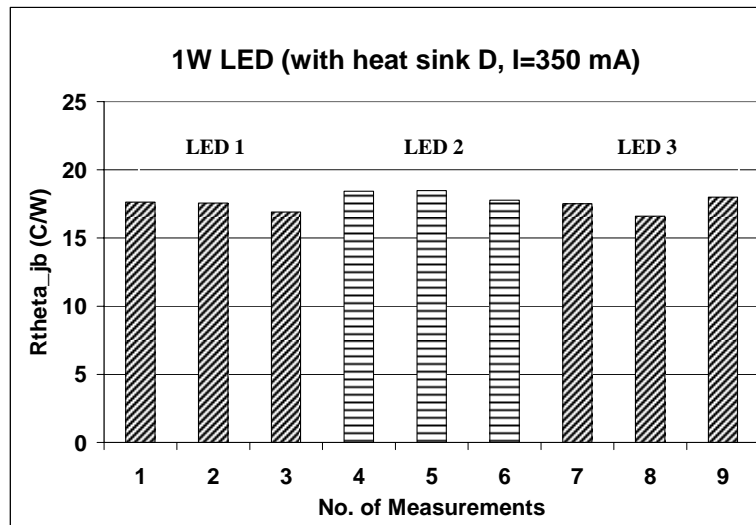


Fig. 4. Thermal resistance coefficients for three 1 W LEDs with heat sink D, measured three times for each case.

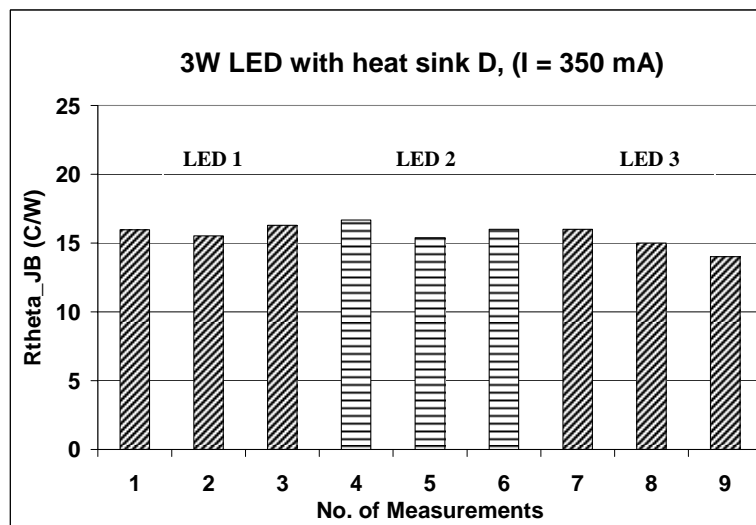


Fig. 5. Thermal resistance coefficients for three 3 W LEDs with heat sink D, measured three times for each case.

4.1 Thermal resistance variation with power dissipation at the junction

Since the LEDs had slightly different voltages, the power was used as the independent variable rather than the current. Figure 6 shows the variation of thermal resistance from junction to board with dissipated power for 1 W and 3 W LEDs with three different heat sink sizes at two different ambient temperatures. The results show that at a constant ambient temperature and constant heat sink size, the thermal resistance increases when the power increases.

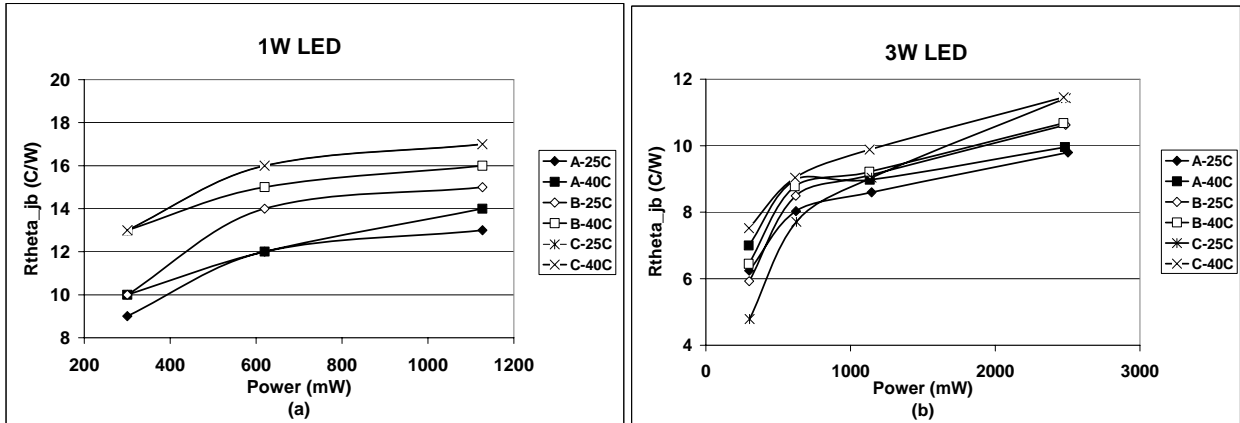


Fig. 6. Thermal resistance from junction to board as a function of dissipated power for (a) 1 W and (b) 3 W LEDs with three different heat sinks at two different ambient temperatures. Each point correlates to a drive current: 100, 200, and 350 mA for 1 W LEDs, and 100, 200, 350 and 700 mA for 3 W LEDs.

4.2 Thermal resistance variation with ambient temperature

Figure 7 shows graphs of the thermal resistance from junction to board at constant power when the ambient temperature changes for three different heat sink surface areas. For a given heat sink, there is no significant difference in thermal resistance for 1 W LEDs when the ambient temperature increases. However, for 3 W LEDs the thermal resistance from junction to board increases with ambient temperature for a given heat sink.

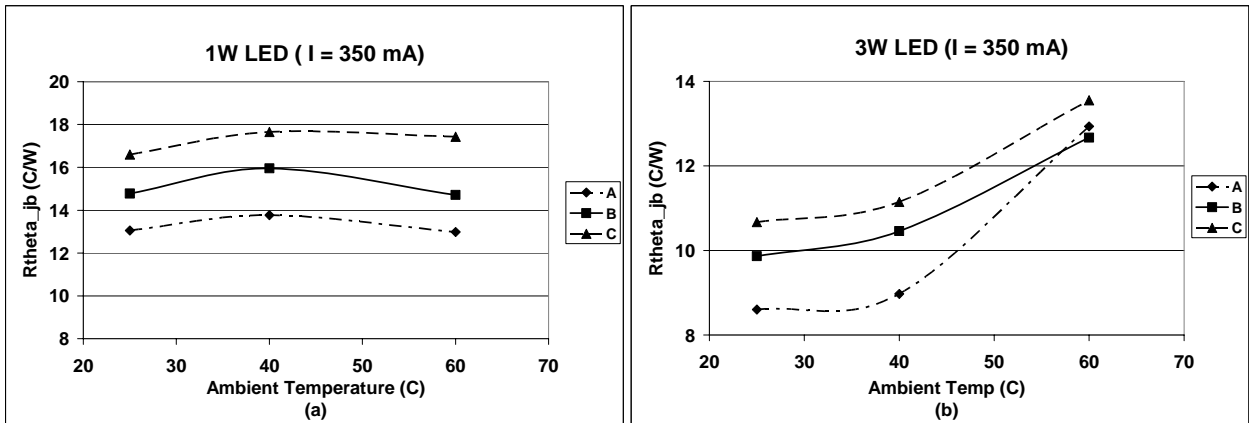


Fig. 7. Thermal resistance from junction to board as a function of ambient temperature for (a) 1 W and (b) 3 W LEDs with three different heat sinks. Note that A, B and C are heat sinks with three different surface areas.

4.3 Thermal resistance variation with heat sink surface area

From the data collected, thermal resistance variations were obtained for different heat sink surface areas. Figure 8 shows that the thermal resistance from junction to board decreases for both 1 W and 3 W LEDs when the surface area of the heat sink increases.

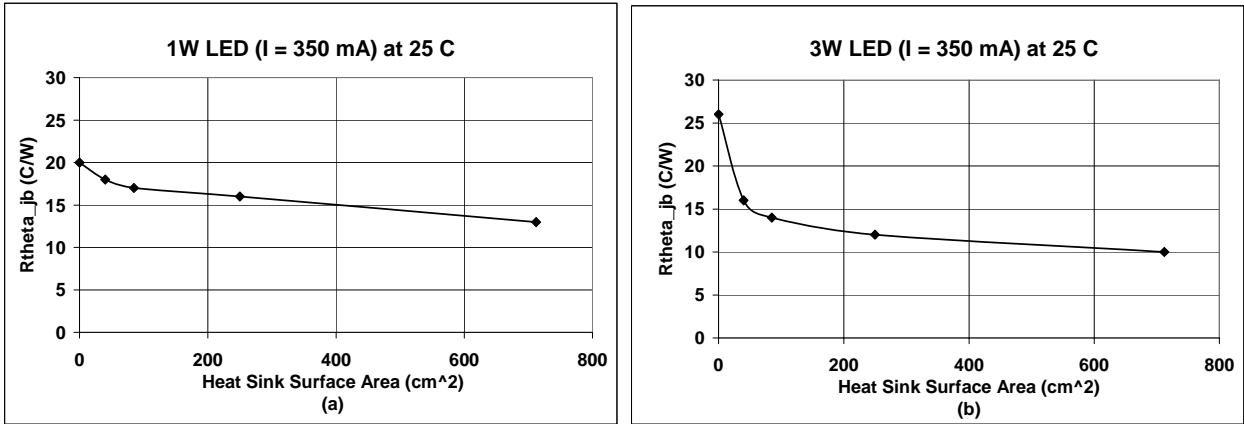


Fig. 8. Variation of thermal resistance from junction to board with different heat sink surface areas for (a) 1W LED and (b) 3W LED.

4.4 Thermal resistance variation with the heat sink orientation

The 1 W and 3 W LEDs were tested with a heat sink that was positioned horizontally (with LEDs facing downward) and vertically. The thermal resistance of the 1 W and 3 W LEDs from junction to board was measured in still air for both vertical and horizontal orientations. An LED was attached to a heat sink and placed with its fins upward (horizontal position) and fins parallel to the floor (vertical position). It was observed that the LED board temperature changed with lamp orientation. Figure 9 shows that there is a decrease in thermal resistance from junction to board when the heat sink attached to the LED changed from the vertical to horizontal position with the lamp facing down and fins up, consequently decreasing the junction temperature. Heat dissipation due to convection is the main cause for this variation. Results indicate that junction temperature changes 2–3°C at 350 mA for the 1 W LED, compared with 7–8°C at 700 mA for the 3 W LED. To explain what this heat rise means, for example, past studies show that a 10°C increase in junction temperature reduces LED life by half.

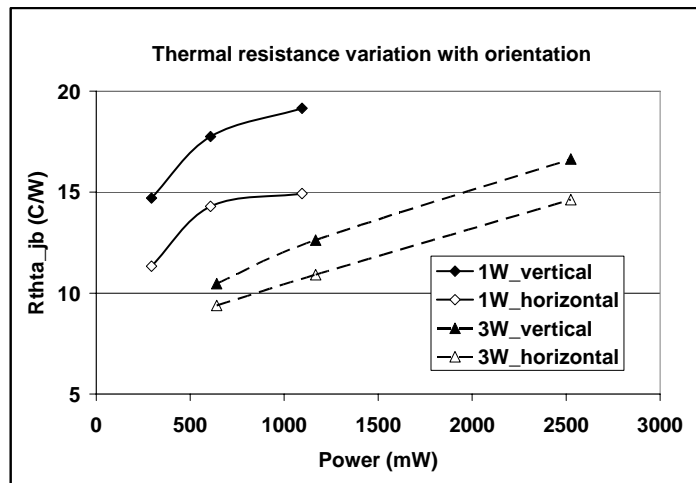


Fig. 9. Thermal resistance variation due to orientation change.

5. DISCUSSION

The results from the experiments indicate that the thermal resistance from junction to board of an LED depends on the power at the junction, the ambient temperature, heat sink surface area, and the orientation.

When an LED is attached to a heat sink with a certain amount of surface area and is operated within a limited temperature range, results indicate that the junction temperature changes linearly with the board temperature. Figure 10 illustrates the plot of junction temperature versus board temperature for LEDs with different heat sinks A, B, and C at three different ambient temperatures, 25°C, 40°C, and 60°C for a constant drive current. The solid lines in the figure represent linear regression lines, which show a linear correlation between junction temperature and board temperature. In this study, we observed that even with thermal resistance variation due to the change of ambient temperature and the amount of heat sink, junction temperature and board temperature tend to maintain a linear correlation. The linear correlation is only valid when the LED is attached to a heat sink. Tables 1 and 2 show experimentally determined and calculated junction temperature values for 1 W and 3 W LEDs. Results clearly show that one can estimate the junction temperature using the above linear relationship within a 5% margin of error.

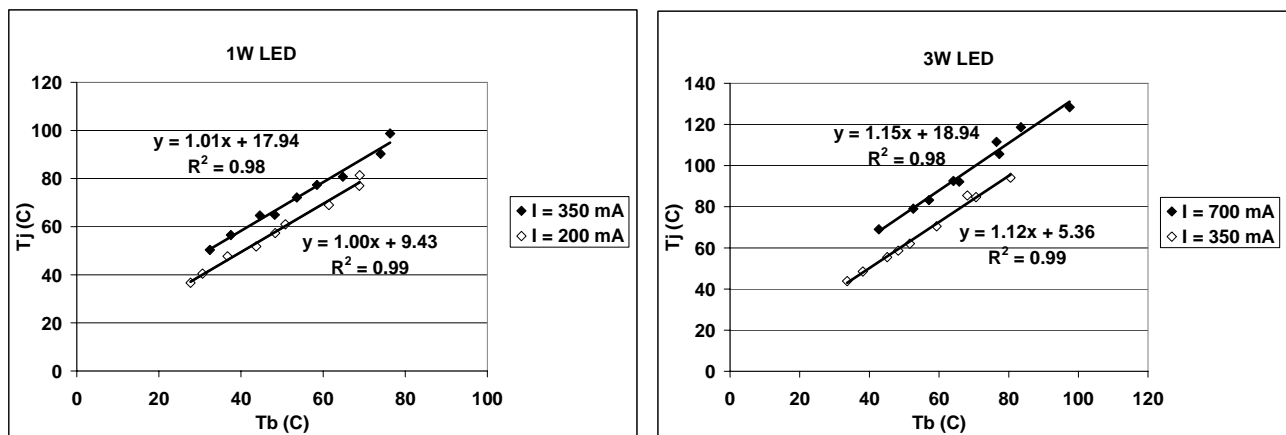


Fig. 10. Junction temperature as a function of board temperature for (a) 1 W and (b) 3 W LEDs for three different heat sink surface areas at three different ambient temperatures.

Table 1. Experimental and calculated values for 1W LED at 350 mA. Note that T_j values can be obtained within 4% margin of error

1W LED, I = 350 mA					
Heat Sink	Tamb (°C)	Tb (°C)	Tj (°C)	Tjcal (°C)	Error
A	25	33.6	43.8	43.0	2%
	40	48.3	58.6	59.5	-1%
	60	68.1	85.5	81.7	4%
B	25	38.1	48.5	48.1	1%
	40	51.6	62.0	63.2	-2%
	60	70.6	84.7	84.5	0%
C	25	45.1	55.5	55.9	-1%
	40	59.3	70.5	71.8	-2%
	60	80.5	94.1	95.6	-2%

Table 2. Experimental and calculated values for 3W LED at 700 mA. Note that T_j values can be obtained within 4% margin of error.

3W LED, I = 700 mA					
Heat Sink	T _{amb} (°C)	T _b (°C)	T _j (°C)	T _{j cal} (°C)	Error
A	25	42.7	69.0	68.1	1%
	40	57.1	83.2	84.6	-2%
	60	76.5	111.6	106.9	4%
B	25	52.6	79.0	79.4	-1%
	40	65.8	92.2	94.6	-3%
	60	83.5	118.7	115.0	3%
C	25	64.1	92.5	92.7	0%
	40	77.3	105.6	107.8	-2%
	60	97.5	128.4	131.1	-2%

6. CONCLUSIONS

This study demonstrated that the thermal resistance of high-power white LED packages varies with different parameters such as ambient temperature, power dissipated at the junction, heat sink area, and orientation of the heat sink. It was shown that when the drive current (power) was held constant, the board temperature and the junction temperature varied when the heat sink area or the ambient temperature was changed, and the two are correlated linearly. Therefore, if an LED's thermal resistance coefficient is measured with a large heat sink, then the junction temperature can be estimated using the board temperature, even if the ambient temperature or the heat sink are changed. This is very useful in measuring the junction temperature of LEDs in a LED fixture.

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REFERENCES

1. T. Egawa et al. "Optical degradation of InGaN/AlGaIn light-emitting diode on sapphire substrate grown by metalorganic chemical vapor deposition," *Applied Physics Letters* 69(6), 830 (1996).
2. T. Yanagisawa, "The degradation of GaAlAs red light-emitting diodes under continuous and low-speed pulse operation," *Microelectronics Reliability*, 38, 1627-1630 (1998).
3. L. Sugiura, "Dislocation motion in GaN light-emitting devices and its effect on device lifetime," *Journal of Applied Physics* 81(4), 1633-1638 (1997).
4. N. Narendran, and Y. Gu. "Life of LED-based white light sources," *IEEE/OSA Journal of Display Technology* 1(1), 167-171 (2005).
5. N. Narendran, Y. Gu, J.P. Freyssonier, H. Yu, and L. Deng. "Solid-state lighting: Failure analysis of white LEDs," *Journal of Crystal Growth* 268 (3-4), 449-456 (2004).
6. R. Menozzi et al. "A new method to extract HBT thermal resistance and its temperature and power dependence," *IEEE Transactions on Device and Materials Reliability* 5(3), 595-601 (2005).

7. S.P. Marsh, "Direct extraction technique to derive the junction temperature of HBT's under high self-heating bias conditions," *IEEE Transactions on Electron Devices* 47(2), 288-291 (2000).
8. J.C.J. Paasschens et al., "Dependence of thermal resistance on ambient and actual temperature," *IEEE BCTM* 5(1), 96-99 (2004).
9. Philips Lumileds Lighting, "Thermal design using Luxeon power light sources," Application Brief AB05 (2006).
10. Agilent Technologies, "LED thermal testing," Application Brief A05 (1999).