Is the Thermal Resistance Coefficient of High-power LEDs Constant?

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Is the Thermal Resistance Coefficient of High-power LEDs Constant?

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ABSTRACT

In this paper, we discuss the variations of thermal resistance coefficient from junction to board ($R\Theta_{jb}$) for high-power light-emitting diodes (LEDs) as a result of changes in power dissipation and ambient temperature. Three-watt white and blue LED packages from the same manufacturer were tested for $R\Theta_{jb}$ at different input power levels and ambient temperatures. Experimental results show that $R\Theta_{jb}$ increases with increased input power for both LED packages, which can be attributed to current crowding mostly and some to the conductivity changes of GaN and TIM materials caused by heat rise. With increasing ambient temperature, $R\Theta_{jb}$ increased but not as much as what was observed with drive current increase.

Keywords: light-emitting diode, LED, thermal resistance coefficient, junction temperature, life

INTRODUCTION

The global lighting community expresses no doubt that high-power light-emitting diodes (LEDs) will play a major role in general lighting applications in the near future. Since its first demonstration in 1994, white LED technology has rapidly evolved and has now reached a stage that it can compete with traditional light sources in some niche lighting applications. However, thermal management is one of the major issues to be improved for implementing LEDs into lighting fixtures because heat affects the performance and reliability of those fixtures and LEDs. When it comes to the thermal management of an LED, thermal resistance is an important device performance parameter, indicating the obstruction of the heat flow from the p-n junction to the ambient during operation. Manufacturers of high-power LEDs have been exploring and using components with high thermal conductivity within the LED package to lower the thermal resistance from the p-n junction to the LED board, so that the junction will be at a lower temperature during operation. Therefore, measuring junction temperature is one way to evaluate the performance of an LED. To the first order, junction temperature is a good predictor of LED life.[1] It has been a common practice in the industry to use the following one-dimensional heat transfer equation for conducted heat to estimate junction temperature, T_j:

$$T_j = T_b + R\theta_{jb}(P) \tag{1}$$

where T_b is the board temperature, $R\Theta_{jb}$ is the junction-to-board thermal resistance coefficient, and P is the total power dissipated at the junction of the LED. When using the above equation, it is assumed that $R\Theta_{jb}$ is a constant, independent of how the LED is driven or where it is used. However, in an earlier study we reported that for high-power white LEDs, $R\Theta_{jb}$ is not a constant and changes with power dissipation, ambient temperature, and the amount of external heat sink provided to the LED.[2] More recently, a few more publications have indicated that $R\Theta_{jb}$ for high-power LEDs is not a constant and is affected by factors such as power, ambient temperature, and applied pressure at different interfaces.[3 – 5]

The objective of the study presented in this manuscript is to expand our previous study to understand and explain the reasons behind these experimental observations, namely, the change in thermal resistance coefficient as a function of power dissipation and ambient temperature.

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EXPERIMENT

As shown in equation (2), the thermal resistance, $R\theta_{jb}$, from the junction to board of a high-power LED can be estimated by measuring the junction temperature, T_j, and the board temperature, T_b, for a given power dissipation, P:

$$R\theta_{jb} = (T_j - T_b)/P \tag{2}$$

If we consider only the power that is not turned into radiant energy, then equation (2) becomes:

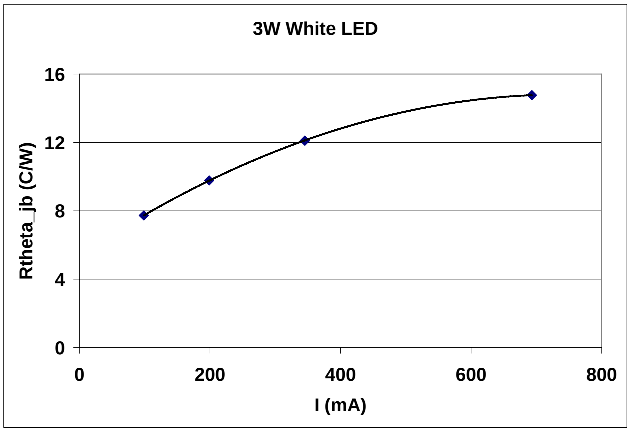
$$R\theta_{jb} = (T_j - T_b)/(P - P_o) \tag{3}$$

where P_o is the radiant optical power emitted by the LED.[6]

The junction temperature of a high-power white LED can be determined by measuring the potential across the p-n junction, which changes as a function of temperature. The experimental setup and procedure in this study were similar to the one explained in our previous paper.[2] The 3-watt white and 3-watt blue LEDs used in this study came from the same manufacturer. These LEDs were attached to aluminum heat sinks, 5 cm × 5 cm × 0.64 cm (2 in. × 2 in. × 0.25 in.). For each of the LEDs, a J-type thermocouple was attached to the LED board to measure the board temperature. For each of the LEDs, the current was changed while holding the ambient temperature constant, and at each point the junction temperature was estimated and the corresponding board temperature was measured. The same procedure was repeated for several ambient temperatures. In addition to the board temperature measurements, at each measurement point the radiant power emitted by the LED was measured.

RESULTS

The thermal resistance coefficient from junction to board, $R\Theta_{jb}$, was calculated using equation (2). Figure 1 illustrates $R\Theta_{jb}$ as a function of drive current at constant ambient temperature, 25°C, for the 3 W blue and 3 W white LEDs. $R\Theta_{jb}$ increased as the drive current to the LED increased for both types of LED. For the 3 W blue LEDs, $R\Theta_{jb}$ changed from 5°C/W to 10°C/W when the current changed from 100 mA to 700 mA. For the 3 W white LEDs, $R\Theta_{jb}$ changed from 8°C/W to 15°C/W when the current changed in the same range. Other studies have suggested that the $R\Theta_{jb}$ change as a function of drive current is due to the fact that part of the power dissipation at the junction is in the form of visible radiation, which changes nonlinearly with drive current,[3] and thus needs to be accounted for in the equation. Therefore, the thermal resistance coefficient from junction to board was calculated using equation (3) for 3 W white LEDs, which included the radiant power correction, $(P - P_o)$. Figure 2 illustrates $R\Theta_{jb}$ as a function of drive current at constant ambient temperature, 25°C, for the 3 W white LEDs calculated according to equations (2) and (3). For both cases, when considering P and $(P - P_o)$, the trend for $R\Theta_{jb}$ as a function of drive current was similar to the findings above, but the absolute values were slightly higher when optical power was taken into consideration. This shows that even though it is necessary to include radiant power correction to obtain accurate values for $R\Theta_{jb}$, it is not the reason why $R\Theta_{jb}$ changes as a function of current. From now on, in this paper the $R\Theta_{jb}$ value calculations will include the optical power loss, $(P - P_o)$, for 3 W white LEDs.



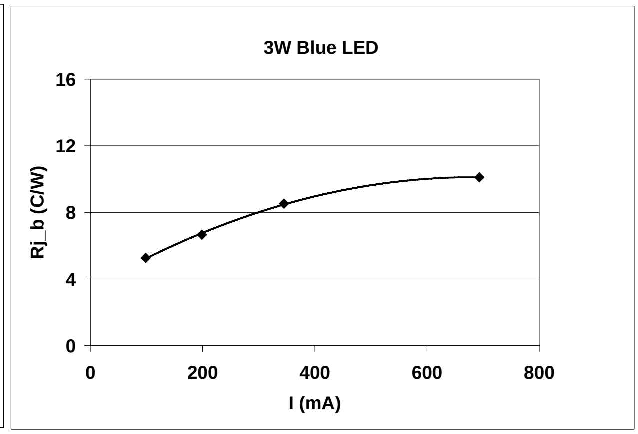


Fig. 1. $R\Theta_{jb}$ as a function of drive current at constant ambient temperature, 25°C, for the 3 W white and 3 W blue LEDs.

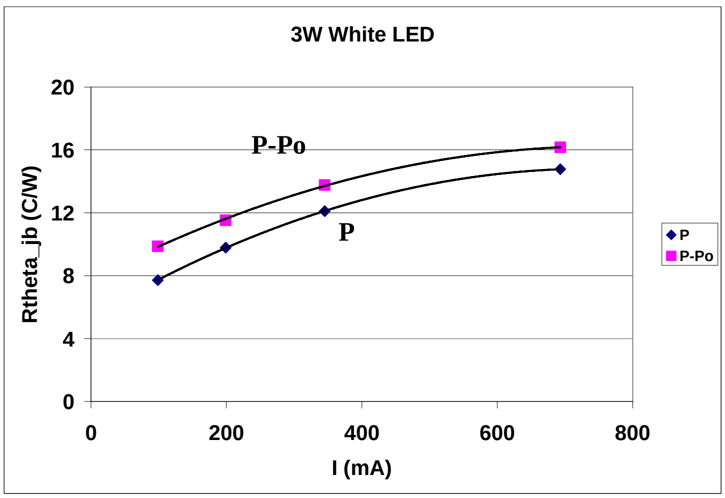


Fig. 2. $R\Theta_{jb}$ as a function of drive current at constant ambient temperature, 25°C, for the 3 W white LED calculated according to equations (2) and (3).

The estimated $R\Theta_{jb}$ values for the 3 W white and blue LEDs as a function of drive current at different ambient temperatures are shown in Figures 3 and 4, respectively. As before, the upper limit for the drive current is 700 mA for both types of LED. At any ambient temperature, the $R\Theta_{jb}$ change with change in drive current follows the same pattern for both LEDs tested in this study.

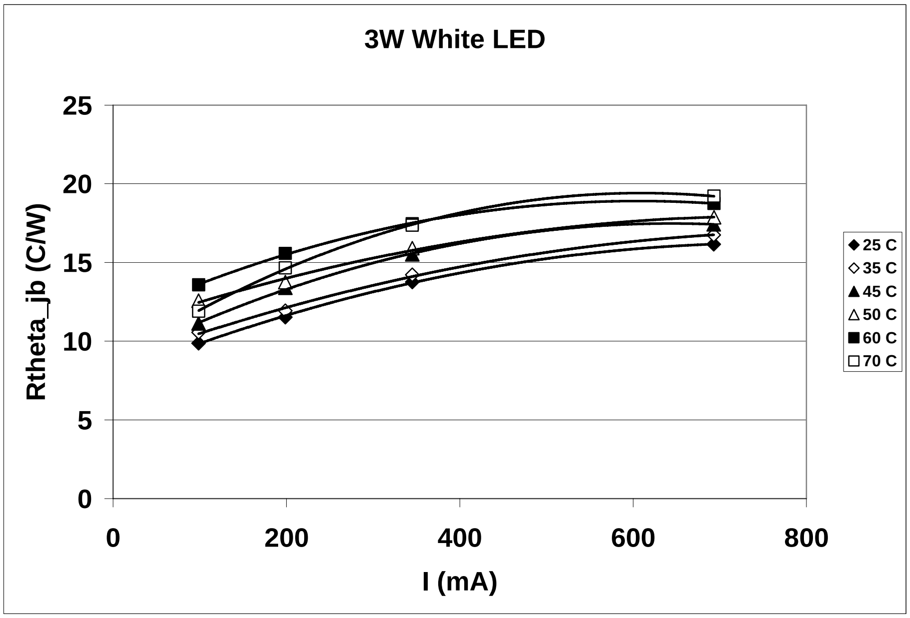


Fig. 3. $R\Theta_{jb}$ variation with drive current at different ambient temperatures for 3 W white LED.

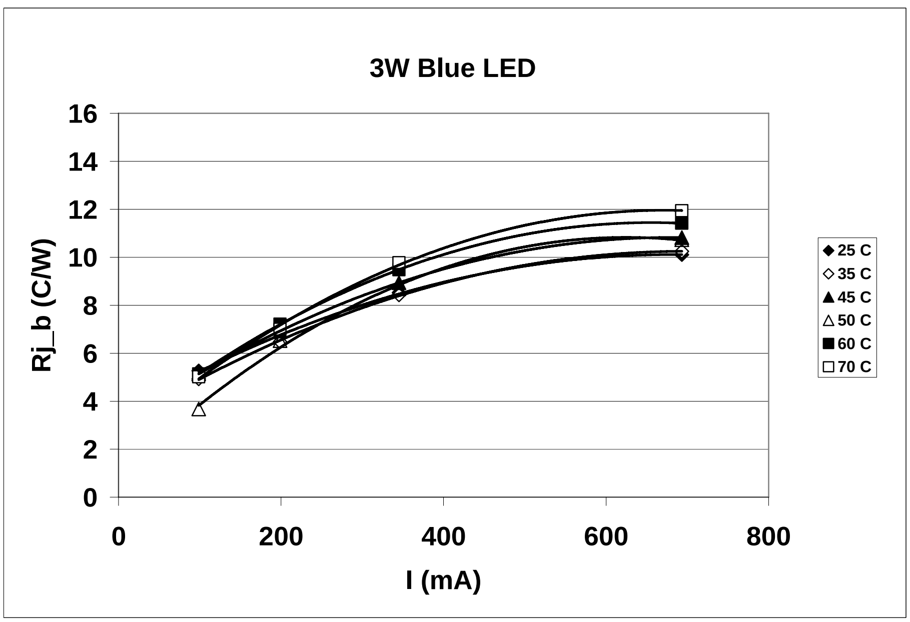


Fig. 4. $R\Theta_{jb}$ variation with drive current at different ambient temperatures for 3 W blue LED.

To illustrate the implication of $R\Theta_{jb}$ changing at different current values, the junction temperatures of 3 W blue and white LEDs were calculated. The following table shows the calculated junction temperatures of both types of LED using thermal resistance coefficient values given by the LED manufacturer (17°C/W) and the measured junction temperature values at 25°C ambient temperature. The difference between calculated and measured junction temperatures was up to 10°C.

Table 1. T_j values for 3 W blue and white LEDs. The $R\Theta_{jb}$ value given by the manufacturer was used for the calculated T_j values.

Drive Current (mA)	3W Blue LED		3W White LED	
	Measured T_j (°C)	Calculated T_j (°C)	Measured T_j (°C)	Calculated T_j (°C)
100	30.5	33.9	32.4	35.7
200	36.8	43.1	40.8	46.4
350	48.1	57.3	55.4	62.9
700	76.5	92.1	94.7	104.4

DISCUSSION

There were two main observations in this study. First, for both LED packages, 3 W white and blue LEDs tested in this study, $R\Theta_{jb}$ increased when the input power increased at constant ambient temperature (Figures 1 and 2). Second, at constant input power, $R\Theta_{jb}$ for the 3 W white and blue LED packages increased when ambient temperature increased. However, for the blue LED package the thermal resistance change with ambient temperature (Figures 3 and 4) was small.

The increased thermal resistance as a function of drive current can be attributed mostly to current crowding phenomenon and some to the conductivity changes of GaN and TIM materials caused by heat rise. Several past studies have shown that for semiconductor devices, current crowding takes place at high current densities.[7–9] In 1988, Siegal explained that current crowding results in a reduced effective power dissipation area, and thus causes the thermal resistance of semiconductor diodes to increase.[10] In addition, several studies have shown that thermal conductivity, K, of GaN changes with temperature. In one study it was shown that K reduced from 2.0 to 1.6 W/cmK when the temperature changed from 25°C to 125°C.[11] Another group has also observed thermal conductivity variation of GaN from 2.50 to 1.75 W/cmK within the temperature range of 25°C to 175°C.[12] Therefore, thermal conductivity variation in the LED chip area could be playing a role in the changing thermal resistance coefficient of the LED, since $R\Theta_{jb}$ is inversely proportional to thermal conductivity. In addition, one study shows that the thermal conductivity of thermal interface materials (TIM) changes with temperature.[13] When temperature increases, surface contacts between two surfaces where TIM are applied could be better or worse, and consequently the thermal resistance variation of a package may increase or decrease.

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