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Achieving Accurate Electro-Optical-Thermal Measurements of High-Power LEDs

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Abstract

High-power Light Emitting Diode (LED) generates significant amount of heat fluxes that can affect the temperature-dependent properties of the device. This self-heating effect can upset the measurement setup and produce inaccurate readings, leading to misinterpretation of results such as electrical and thermal resistances. Optical, electrical and thermal performances of high-power LED packages were analysed under different temperature feedback controls. The results of these experiments demonstrate the importance of the temperature control module in the measurement setup affecting the device's properties such as the series resistance R_s and the thermal resistance R_{th}. In the electrical current-voltage measurements, the temperature control module cannot control the self-heating effect effectively, resulting in a lower R_s compared to when the measurements are made manually. In transient thermal measurements, it was found that lower R_{th} values are obtained when the controller operates in closed-loop adaptive temperature control compared to when it operates in open-loop adaptive temperature control. This paper recommends the manual electrical and open-loop thermal measurement methods for accurate parametric LED analyses.

Introduction

As lighting constitutes 20% of energy consumption worldwide, there is a growing need for new lighting technologies to improve energy conservation and at the same time, reduce carbon emission. One such emerging lighting technology is the Gallium Nitride (GaN) based light-emitting diode (LED) which has the potential to become the next-generation light source due to its high luminous efficacy, long expected lifetime and low expected cost of ownership. However, only about 20% of the electrical input power is converted into visible light, while the remaining 80% is dissipated as waste heat [1]. Thermal management therefore is a key issue due to the significant heat flux generation within the LED package especially for high power applications. Parameters such as junction temperature and thermal resistance are typically used as comparative measures of its thermal performance. These parameters not only limit its maximum temperature of operation, but also negate its lifetime. LED system designers also rely on these parameters to ensure the LED design is within safe operational limits [2]. The junction temperature influences the optical power and luminous efficacy of the LED [3] while the thermal resistance is a measure of the LED heat dissipation capabilities and indicates changes in the heat transfer path causing uneven buildup of junction temperature leading to early failure or increased degradation [4]. Thermal resistance may also be used as a gauge of GaN or thermal interface material changes with heat rise as their conductivity changes as a function of drive current or temperature [5]. Furthermore, the series resistance parameter is associated with thermal effects [6, 7] of LEDs in that thermal degradation with increased current is observed to be consistent with increased series resistance. The series resistance also plays a role in the LED conversion efficiency with increased temperature [8]. In addition, the series resistance is used as an indicator of the maximum chip size and power density limits that the LED can operate effectively [9]. Due to the significance of the aforementioned parameters, it is important that the measurement techniques used to derive these quantities are able to do so as accurately as possible so as to produce reliable data.

As the industry demand for higher power density applications increases, larger LED chip size and higher LED packing density such as Chip-on-Board (COB) packaging architectures are employed. These high power density applications have significant thermal challenges as the input power to the LED is controlled by the maximum temperature rating of the materials in the LED package and the intended application environment of the luminaire. As the technological advancements in high power device fabrication/processes have gathered pace over the years, there is a need for LED characterization and measurement techniques to also keep up in order to produce reliable data. Lighting consultants and integrators rely on manufacturer datasheets to provide lighting solutions for their customers while the end-customers/adopters themselves use this information for product comparisons. In the event of data mis-specification, the published data will be of limited practical use as the accuracy of the expected performance and reliability estimation cannot be trusted. Poppe and Lasance [10, 11] discussed the need for more sophisticated thermal characterization and standardization of LEDs and LED-based products. This paper discusses the issues faced in optical, electrical and thermal characterization of high-power LEDs and proposes additional measures in order to produce accurate measurement results.

Experimental Procedures

To study the optical-electrical-thermal properties of the LED, a measurement station was assembled as shown in Fig. 1. This LED measurement station comprises a 20" integrating hemi-sphere system, a peltier-based temperature controller (TEC), a source measure unit and a transient thermal analyzer. To ensure traceable optical measurement, a reference lamp calibration and absorption correction were conducted prior to the measurements. The LED is placed onto a temperature-controlled cold plate in order to achieve the same thermal environment during optical measurements and thermal testing. In the transient thermal measurements, a cooling measurement mode is adopted.

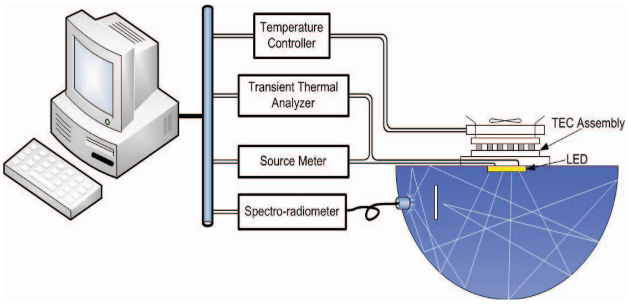

Fig. 1. Schematic diagram of LED measurement station.

In this experiment, Cree CXA1304 COB LED package with a maximum rating of 1A was used. The LED array in the COB LED package is arranged with 4 parallel paths with 3 LEDs connected in series for each path. A thermistor was attached onto the T_j test point of the LED package to provide temperature feedback for its controller to regulate the temperature. Two types of temperature feedback control – open-loop (pulsed) and close-loop (adaptive) – are used to regulate its specified temperature. In the open-loop approach, the temperature controller supplies a constant pulsed input power under a fixed duty cycle in order to attain its specified temperature. For the close-loop approach, the thermistor provides constant temperature feedback at 10 Hz to its controller. A data acquisition (DAQ) unit was used to monitor the supply inputs into the TEC module and LED as well as to monitor the surface temperature of the LED, cold plate of the TEC, and its ambient.

Results

A. Optical Measurements

The optical performance of the COB LED was measured at various temperature and drive current conditions. As shown in Fig. 2(a), the radiant flux and luminous efficacy decrease as temperature increases. On the other hand, the heat flux from the LED $Q_{LED\text{-}heat}$, which was calculated from the electrical input power minus the total radiant flux, has a reciprocal response to the radiant flux with respect to temperature. This shows that a higher heat load is generated at elevated operating temperatures. The higher heat load was due to an increase of non-radiative recombination processes and increased leakage currents in the quantum wells of the LED at higher operating temperatures [12, 13]. Contrary to the effect of temperature, an increase in power increases the quantum efficiency causing higher radiant flux output while generating significantly higher heat (Fig. 2(b)). This substantial heat in turn results in a more significant decrease in luminous efficacy with power input [14]. As the drive current increases, the accompanying device self-heating effect leads to a higher amount of non-radiative recombination processes, which causes the light output to reduce with power. The effect of luminous efficacy reduction with increasing power has been linked to mechanisms such as the current leakage [15, 16] which is also associated with higher series resistances at higher current levels. It is also possible that the Auger recombination process occurs at high current densities [17]. The high heat load generated by the LED at elevated temperatures and under high power driving conditions may alter the temperature conditions during measurement hence changing the derived parameters from the measurement. This will be elaborated further in the subsequent sections.

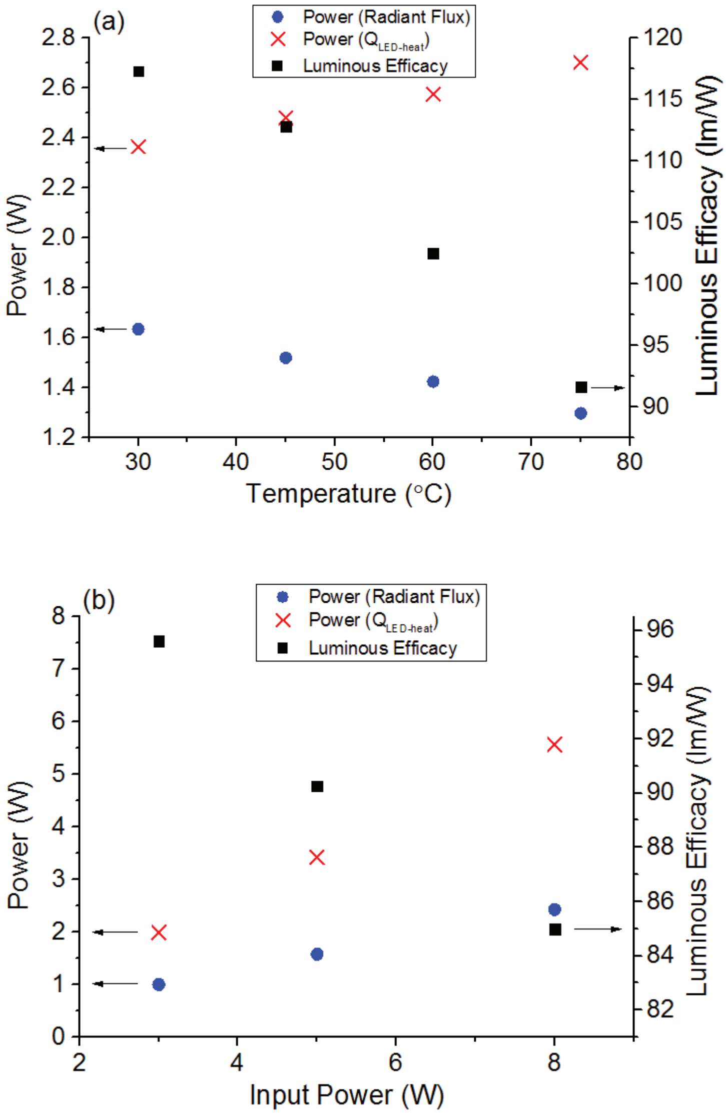

Fig. 2. Radiant flux, heat flux and luminous efficacy of the LED under different (a) temperature (b) input power.

B. Electrical Measurements

Electrical current-voltage (IV) measurements are conducted to understand the electrical characteristics of the LED device. From these measurements, the temperature dependent series resistance of the LED can be derived from the high voltage region of the IV curve. During measurement, the LED is usually placed onto a peltier-controlled plate to ensure that the device under test is maintained at a constant temperature while a voltage sweep is applied. However, high-power LEDs can generate significant amount of heat during voltage sweep measurement. As shown in Fig. 3, the surface temperature on the LED package increases within the measurement cycle. This temperature rise starts at about 7 s, reaching a peak of about 8 °C at about 12 s, after which it decreases due to the temperature regulation from the TEC. The heat generated from the LED causes the TEC to compensate for the additional heat load in order to regulate its specified temperature setting and adjust it back to its original operating temperature. However, it is observed that the TEC responds to this heat load by rising to 11 V only at about 10 s. The temperature controller has a delayed response to the heat generated by the LED and could not provide instantaneous temperature compensation back to its specified temperature effectively throughout the voltage sweep measurement. This implies that the LED package has not been kept at a fixed temperature throughout its entire measurement cycle. The LED temperature rise becomes negative as the TEC overcompensates initially to establish the original temperature. It is observed that the higher the operating temperature, the faster the temperature rise drops to a negative value. For 75 °C operating temperature, this negative drop occurs at 25 s whereas for 30 °C operating temperature, this occurs at 33 s. The higher heat flux from the higher operating temperature instigates the TEC to respond in a more aggressive manner to restore the original temperature.

A dip in voltage output indicates the TEC attempt to increase the temperature while an elevated voltage indicates the TEC attempt to decrease the temperature. The initial TEC voltage downswing at 17 s has the effect of slowing down the rate of temperature decrease as the temperature rise bottoms out at about 55 s. The difference in magnitude seen between the different TEC outputs is due to the higher heat flux generated by the LED at higher operating temperature. The temperature rise reaches a minimum of -3.5 °C for 75 °C operating temperature compared to -1 °C for 30 °C operating temperature due to the larger TEC output for the higher heat flux at higher temperatures. The TEC voltage subsequently alternates between upward and downward directions with the effect of gradually easing the LED temperature back to the original operating temperature.

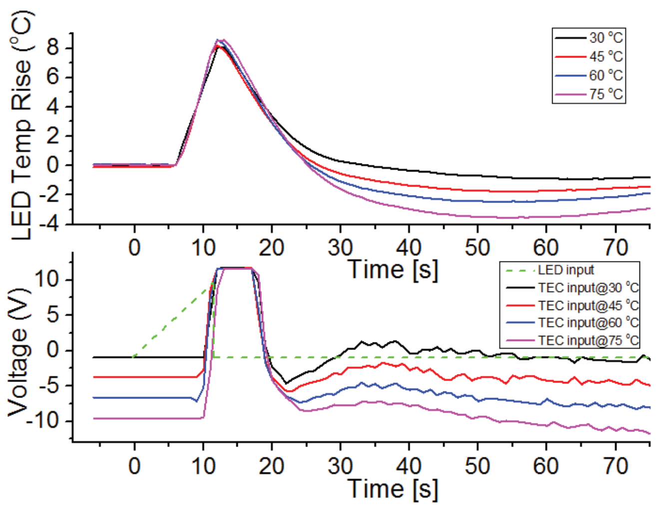

Fig. 3. TEC response (Bottom) during the voltage sweep of LED and the corresponding LED surface temperature rise (Top).

To further demonstrate this self-heating effect during the voltage sweep measurement, the IV characteristics of the LED was measured manually. This manual method allows for any device's self-heating to be compensated in order to attain its final steady state condition. Although this is a time-consuming approach, it provides a fixed temperature environment for the LED. As shown in Fig. 4, the IV characteristics of both approaches showed similar measurement readings at the diode region of the IV characteristics. However, at the high voltage region, the manual IV measurement approach exhibited a lower voltage drop as compared to the automated voltage sweep approach. In the diode region of the IV characteristics, the input power was less than 0.8W and the heat generated from the LED was small. However, at the high voltage region, the input power was more than 3W and the self-heating effect was significantly larger. Because of this self-heating phenomenon, a larger voltage drop is required under each current driving condition. From Table 1, it is observed that there is a decrease in series resistance with increasing temperatures for both approaches. This decrease in the series resistance is due to the higher acceptor activation occurring at elevated temperatures, resulting in the higher conductivity of the p-type GaN layer [18]. Comparing the difference in series resistance between both approaches for each operating temperature setting, R_s for the closed-loop approach is about 1 Ω lower than that for the manual approach. This is postulated to be due to the higher heat load generated from the LED in the closed-loop approach and the subsequent elevated temperature. Since the diagnosis of the diode is largely influenced by temperature, the instrumentation setup for an instantaneous temperature control is crucial to compensate for any self-heating effect in order to obtain accurate diagnoses of the device under test.

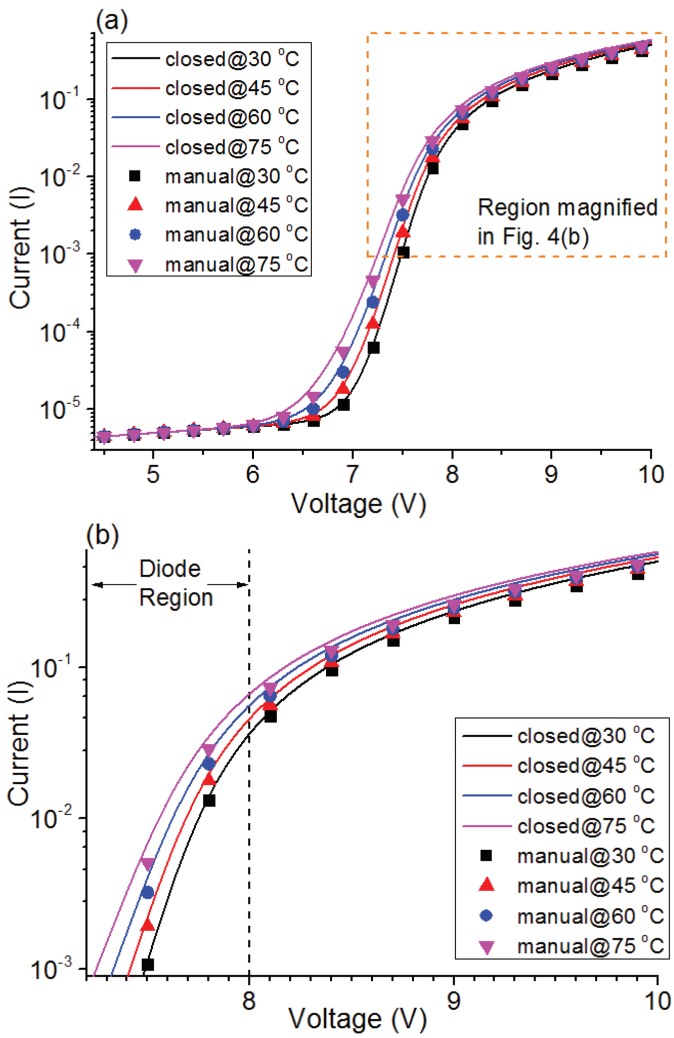

Fig. 4. (a) Comparison of IV characteristics of the LED under closed-loop and manual temperature control methods. (b) Magnification of high voltage region of LED IV characteristics under closed-loop and manual temperature control methods.

Table 1. Series Resistances R_s for closed-loop and manual temperature control methods at different temperature settings.

Operating Temperature	R_s (Manual Approach)	R_s (Closed-loop approach)
30 °C	5.0 Ω	4.0 Ω
45 °C	4.7 Ω	3.7 Ω
60 °C	4.5 Ω	3.5 Ω
75 °C	4.4 Ω	3.4 Ω

C. Thermal Measurements

For transient thermal measurement of the LED package, cooling measurement mode is adopted so that the radiant flux (described in Section A) can be considered in the thermal analysis. As illustrated in Fig. 5, the LED is switched on for a considerable amount of time until the junction temperature has reached steady state condition. Once thermal equilibrium is achieved, the LED is switched to 1 mA where the device's self-heating is minimal and the temporal difference of the junction temperature is calculated from the electrical test method. In order to provide an accurate estimate of the junction temperature rise in the LED, it is important that the thermal environment surrounding the LED i.e. Q_{TEC} be kept constant throughout the entire duration of the thermal measurement window. The typical thermal time constant for this LED package to cool to its ambient condition is 150 to 200 s. If the TEC reacts to the sudden change in heat flux caused by the LED at t=0 s within the measurement window, Q_{TEC} will not be constant and this will artificially alter the junction temperature estimate and thermal resistance of the package.

Fig. 6 shows the TEC responses when the LED is switched to 1 mA at t=0 s in a closed-loop temperature feedback control. The TEC input voltage drops instantaneously to negative voltage and the subsequent voltage fluctuations indicates that the TEC is compensating for the sudden loss of heat load from the LED. A higher LED power will generate higher heat flux and increase junction temperature. Accordingly, a higher TEC input voltage is required to accommodate for the higher heat flux with increased LED input power. The change in the TEC voltage polarity also indicates that the TEC is increasing the temperature of the LED (see Fig. 7).

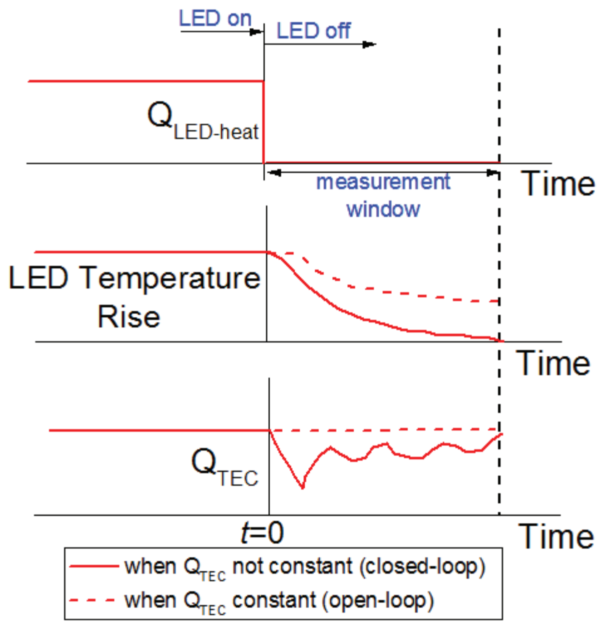

Fig. 5. Q_{TEC} remains constant throughout measurement cycle during open-loop measurement. TEC does not compensate for change in $Q_{LED\text{-}heat}$ and LED temperature. In closed-loop measurement, Q_{TEC} does not stay constant throughout the measurement cycle as the TEC compensates for change in $Q_{LED\text{-}heat}$ and LED temperature.

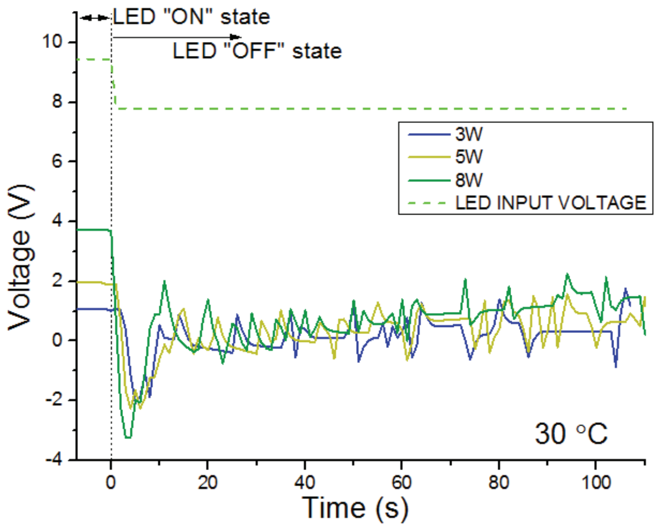

Fig. 6. TEC response during the transient thermal measurement for different power inputs. The TEC reacts to the sudden change of heat load from the LED in order to reach thermal equilibrium in a closed-loop system.

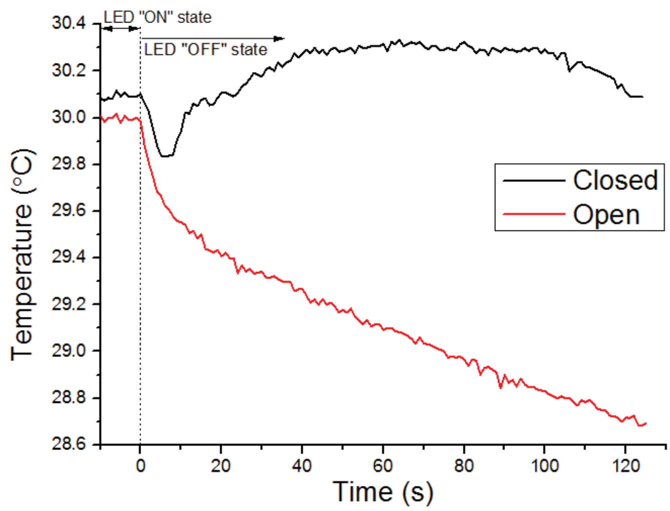

Fig. 7. LED temperature response in closed vs open-loop thermal measurement.

Fig. 7 shows the LED surface temperature response when tested under closed-loop and open-loop feedback control. As opposed to the closed-loop measurement where the TEC continuously regulates the temperature, by using a fixed duty-cycle mode of the TEC in the open-loop approach, the TEC does not compensate the temperature change thereby allowing for a constant Q_{TEC} flow. In closed-loop control, the sudden change of thermal load from the LED causes the TEC to compensate the change in $Q_{LED\text{-}heat}$ in order to maintain its specified temperature condition. The temperature in closed-loop initially drops due to the TEC overcompensation. The drop in temperature then prompts the TEC to increase the temperature accordingly in response. The temperature subsequently fluctuates between rise and fall as the TEC attempts to bring the temperature back to the original starting temperature. However, this compensation occurs during the thermal measurement window. As temperature rise is proportional to thermal resistance, this suppression of the temperature leads to inaccurate estimation of the thermal resistance, as will be shown later. In contrast, as there is no compensation in the open-loop measurement, the heat flow from the TEC Q_{TEC} is constant throughout the entire measurement cycle as the TEC is non-adaptive to the temperature change. As shown in Fig. 7, the LED temperature is therefore left unregulated and decreases gradually throughout the entire measurement window unrestricted, which allows for accurate thermal analysis of the LED package.

The cooling curves in Fig. 8 show a temperature rise of about 4.8 °C versus 5.8 °C at 30 °C temperature setting, and 5.8 °C versus 7.8 °C at 45 °C temperature setting for closed-loop and open-loop measurements respectively. These results translate to a marked difference in junction temperatures between open and closed-loop thermal performance, as summarized in Table 2. With increasing operating temperature, there is a greater increase in T_j for open-loop compared to closed-loop due to the higher heat flux generated which produces the ensuing higher temperature rise. In addition, Fig. 8 shows that the constant Q_{TEC} in the open-loop approach allows the temperature to be unregulated within the entire measurement window whereas in the closed-loop approach, the temperature is adjusted to its original setting within just a few seconds, which does not allow for accurate thermal analysis.

To analyse the impact of open and closed-loop temperature feedback control on the LED's thermal characteristics, the structure function of the LED package is derived as shown in Fig. 9. The structure function for the open loop temperature feedback control provides similar structure function characteristics as the closed-loop but with a larger thermal resistance value. The structure function graph diverges towards the tail end and is repeatable at elevated temperatures. At both temperature settings, it is observed that there is a distinct divergence at higher thermal resistances for open and closed-loop performance. At 30 °C temperature setting, this translates to a thermal resistance of about 2.1 K/W in closed-loop and 2.5 K/W in open-loop. At 45 °C temperature setting, the thermal resistance is about 2.6 K/W in closed-loop and 3.1 K/W in open-loop. These results are summarized in Table 2. In open-loop measurement, Q_{TEC} is kept constant throughout the span of the thermal measurement cycle, and there is a significant LED temperature change. In contrast, in closed-loop measurement, the temperature controller reacts to the change in heat flow to regulate the temperature, resulting in minimal temperature change. As thermal resistance is proportional to the change in temperature, the corresponding thermal resistance for open-loop measurement is higher than that for closed-loop measurement. The consequence of the closed-loop control is that the thermal resistance is erroneously suppressed. This in turn has the repercussion of inaccurate junction temperature projection for the LED.

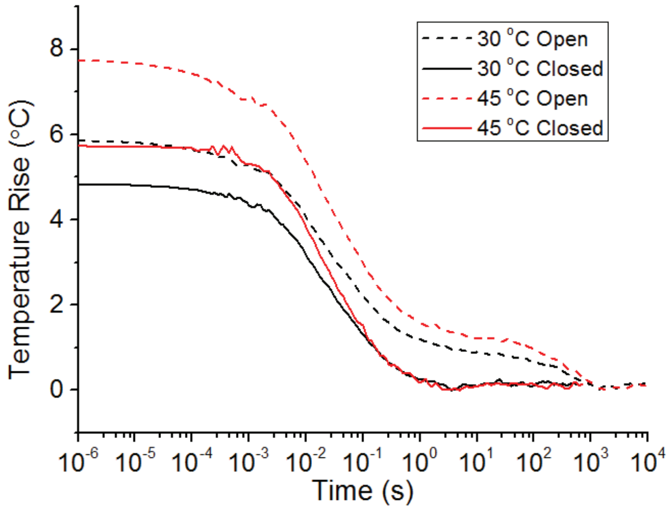

Fig. 8. Cooling curve response of LED package with different temperature feedback controls at different temperature settings.

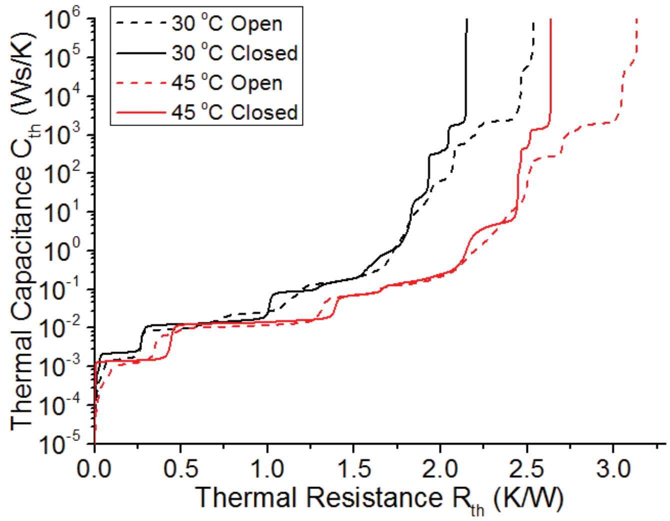

Fig. 9. Cumulative structure function of LED package with different temperature feedback controls at different temperature settings.

Table 2. Thermal resistances for open and closed-loop at different temperature settings.

Operating Temperature	TEC Open		TEC Closed	
	T_j (°C)	R_{th} (K/W)	T_j (°C)	R_{th} (K/W)
30 °C	35.8	2.5	34.8	2.1
45 °C	52.8	3.1	50.8	2.6

Conclusions

Temperature control of a measurement system is important especially in the analyses of high-power devices and assemblies. For electrical measurements, as the temperature controller has a delayed response to the heat load from the LED, the LED may not have been maintained at a constant temperature throughout the measurement cycle, resulting in a different R_s compared to when the LED IV measurements are made manually. A manual adaptive feedback system is recommended to compensate for any self-heating effect so as to provide more accurate diagnosis of the LED's electrical characteristics. In contrast, for transient thermal measurement, the LED should not be maintained at constant temperature and a constant heat flow Q_{TEC} is needed during the entire length of the thermal measurement window. An open-loop non-adaptive temperature control is recommended to provide such an environment. This will ensure proper evaluation of the thermal resistance and junction temperature compared to a closed-loop compensating approach. Although these experiments were conducted using LEDs, these measures are also applicable for other high-power devices and assemblies.

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