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Measuring the thermal resistance of LED packages in practical circumstances

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ABSTRACT

In this paper, a new evaluation method for thermal resistance of LED packages is proposed. The method is based on the electrical test method and the time constant theory. The temperature difference of junction-to-case is obtained by the appropriate inflection point on thermal transient response, which is calculated by the minimum point of the 1st derivative curve. Since the method only requires a natural convection heat sink, the thermal resistance of LED packages can be measured quickly and conveniently. The theoretical and experimental results show that it is an effective approach to the measurement of thermal resistance of LED packages in practical situations.

1. Introduction

In recent years, due to rapid development of high power LEDs, thermal management and heat dissipation become essential [1–3]. For the LED modules with the electric power up to 120 W, since large amount of heat is generated, the thermal problem is a bottleneck to limit their lifetime and optical properties [4]. The mechanical computer-aided design (MCAD) in thermal simulation provides an effective way for both the design and optimization of the thermal flow path [5]. However, when it comes to real devices, some unpredictable factors, such as bad die attach, would probably reduce the thermal performance. Therefore, an accurate and convenient method to identify the thermal resistance is required. Among various methods of measuring the thermal resistance, electrical test method (ETM) is one of those recognized by (Joint Electron Devices Engineering Council) JEDEC. In ETM, the junction temperature is gained by detection of forward voltage of the junction, for the linear relationship: $T_J = T_C + \Delta T_J = T_C + K^{\bullet}\Delta V_F$, where ΔT_J and ΔV are the change of junction temperature and forward voltage respectively, T_j is the junction temperature, and K is the voltage–temperature coefficient. Thus, the thermal resistance from junction to case is $R_{th} = \Delta T_J/P_h$, where P_h is power dissipated in the device. Although ETM cannot give the same temperature distribution of the chip surface as IR thermal image determination does, it is still the most convenient way and has wide applications in LED thermal analyses [6,7]. Additionally, since the p–n junction functions both as a heat source and a thermal sensor, no extra senor is needed compared to those use thermocouples [8]. In the past decade, with the development of data processing techniques, some researchers have begun to pay attention to the transient forward voltage response for a unit-step power excitation, which is recorded by a high-speed data acquisition system [9–11]. When analyzing thermal transient data, Sofia has proposed a viewpoint that the different response time of each layer on thermal flow path could be used to define the boundaries between layers [9]. However, he simply equated each time constant to the product of resistance and capacitance of each cell in the Cauer equivalent, ignoring Foster–Cauer approximation. This has been proved inappropriate in the successive papers [10,11]. Based on the transient response theory, Szekely has developed the structure function theory which is the map of thermal resistance and thermal capacitance of every layer along the heat flow path. It could be calculated from the data processing of thermal transient response [11]. Thus, the thermal measurement based on this theory is superior to the steady-state ETM and has been developed in the use of top thermal analysis instruments. However, it is still imperfect and inconvenient in practical thermal resistance measurement. First of all, an accurate temperature-controlled heat sink is required, which can hardly be achieved in many labs, not to mention the commercial LEDs in the real working environment. If the natural convection heat sink was employed to replace the temperature-controlled one, the capture time would be long, even up to 10 min to wait it reached steady state [12]. Secondly, given the fact that the thermal resistance shifts while the junction temperature changes [13], it is more difficult to measure the thermal resistance of LED packages working in practical circumstances such as road lamps, rather than on temperature-controlled heat sinks. Thirdly, the data processing is quite complicated. Moreover, the

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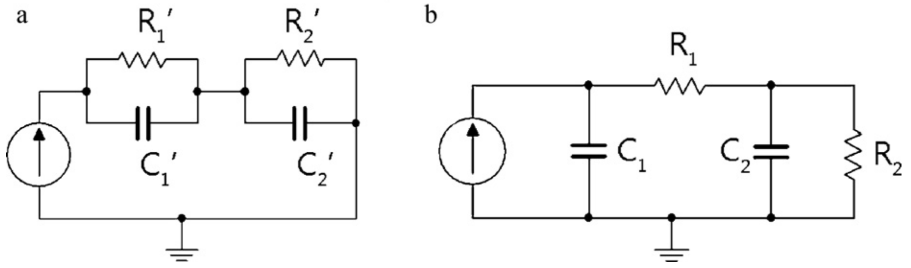

Fig. 1. The two equivalent simulation circuits. (a) The Foster equivalent and, (b) the Cauer equivalent.

thermal resistance of LED packages cannot be obtained until we calculate the structure function.

In order to solve the problem, we exploit a method based on the time constant theory [9,11] to measure the thermal resistance of LED packages quickly in practical circumstances. The LED package is mounted on natural convection heat sink instead of a temperature-controlled one. After analyzing the relationship among time constants, we find that their coupling would be largely attenuated if an appropriate heat sink was employed. In our method, this effect has been considered as the system error. Various LED package experiments and simulations of lumped-element circuits have been performed to prove it as a robust and reproducible method with relative low testing error.

2. Basic theory

When light up, the LED conducts a heat flow path from the chip to the heat sink. The detail of the heat-flow can be analyzed using the lumped-element circuit, in which every layer of the heat flow path is considered as a resistor/capacitor (RC) cell, as illustrated in Fig. 1. Hence, the thermal step response is equivalent to the voltage transient response of the RC circuit excited by step current $I(t) = I_0 \cdot u(t)$, with the amplitude I_0. According to Ref. [11], when transformed to logarithmic time scale, its 1st derivative can be expressed as the result of convolution of the time constant spectrum and a weighting function

$$\dot{T}(z) = R(z) \otimes W(z) \tag{1}$$

where $\dot{T}(z)$ is the 1st derivative of the transient response, $R(z)$ is the time constant spectrum, and $W(z) = \exp[z - \exp(z)]$ in logarithmic time scale ($z = \ln(t)$). Fig. 2 shows the typical time constant spectrum of a LED package.

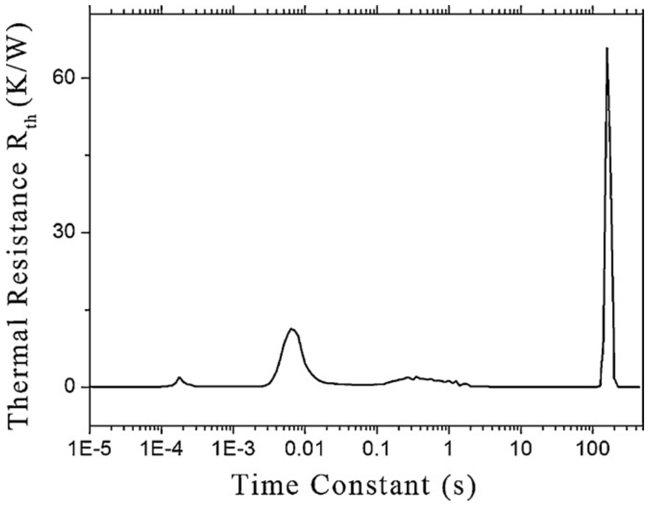

Fig. 2. The time constant spectrum.

In most cases, LEDs are mounted on heat sinks. In terms of the time constant, they can generally be divided into two parts. The first part is between 0 and 0.1 s, much smaller than the second part (about 10–100 s). The huge gap between the two parts could be used to determine the temperature difference between junction and case.

To simplify the problem, we merge the two parts respectively into two discrete time constants. Therefore, according to the Foster equivalent, it is a two-stage model, as illustrated in Fig. 1. The Foster equivalent would become more meaningful when it is transformed to the Cauer equivalent, where R and C are exactly equal to the thermal resistance and thermal capacitance of the LED package and heat sink. The impedance expressions of the Cauer and Foster equivalents are written by Eqs. (2) and (3), respectively.

$$Z_C(j\omega) = \frac{R + j\omega R_1 R_2 C_2}{1 - \omega^2 R_1 R_2 C_1 C_2 + j\omega(R_2 C_2 + C_1 R)} \tag{2}$$

$$Z_F(j\omega) = \frac{R + j\omega R'_1 R'_2 (C'_1 + C'_2)}{1 - \omega^2 R'_1 C'_1 R'_2 C'_2 + j\omega(R'_1 C'_1 + R'_2 C'_2)} \tag{3}$$

where $R = R_1 + R_2 = R'_1 + R'_2$, and ω is the frequency. Since above two equations are equivalent at any frequency, system of equations could be established:

$$\begin{cases} R_1 R_2 C_2 = R'_1 R'_2 (C'_1 + C'_2) \\ R_1 R_2 C_1 C_2 = R'_1 C'_1 R'_2 C'_2 \\ R_2 C_2 + C_1 R = R'_1 C'_1 + R'_2 C'_2 \\ R_1 + R_2 = R'_1 + R'_2 \end{cases} \tag{4}$$

After solving Eq. (4), we have:

$$\begin{cases} R_1 = \dfrac{(R'_2 \tau_1 + R'_1 \tau_2)(C'_1 + C'_2)}{\tau_1 C'_1 + \tau_2 C'_2} \\ C_1 = \dfrac{C'_1 C'_2}{C'_1 + C'_2} \\ R_2 = \dfrac{(\tau_1 - \tau_2)^2}{C'_1 \tau_1 + C'_2 \tau_2} \\ C_2 = \dfrac{(C'_1 \tau_1 + C'_2 \tau_2)^2}{(C'_1 + C'_2)(\tau_1 - \tau_2)^2} \end{cases} \tag{5}$$

where $\tau_1 = R'_1 C'_1$, and $\tau_2 = R'_2 C'_2$. Eq. (5) shows the relationship between two kinds of equivalents in terms of each R and C. In most cases, $\tau_2 \gg \tau_1$. Accordingly, the R_1 expression can be simplified by dividing τ_2 on both the numerator and denominator. We have:

$$R_1 = \frac{((R'_2 \tau_1/\tau_2) + R'_1)(C'_1 + C'_2)}{(C'_1 \tau_1/\tau_2) + C'_2} \approx \frac{R'_1 (C'_1 + C'_2)}{C'_2} \tag{6}$$

If $C'_2 \gg C'_1$, which is also satisfied in this problem, R_1 is slightly larger than R'_1, while C_1 approximately equals C'_1. Moreover, if the thermal capacitance of the heat sink was much larger than that of the LED package, R_1 and R'_1 were almost equal to each other, so the

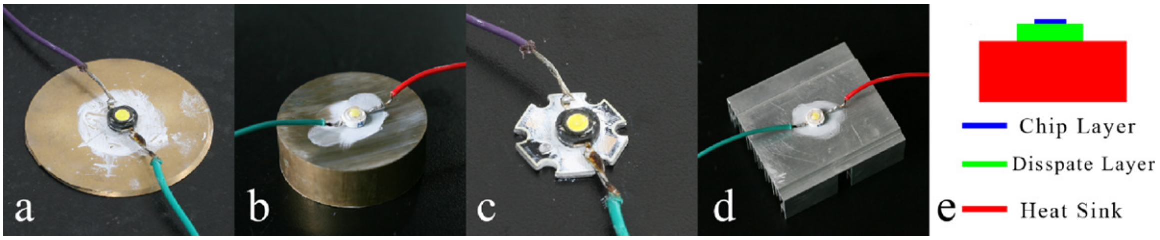

Fig. 3. Experiment setup. LED package mounted on heat sink. (a) Thin copper, (b) thick copper, (c) small Al, (d) large Al, and (e) sketch of LED structure.

time constant spectrum would directly indicate the structure information. It means that the part with the small time constant (about 0.01 s) is relevant to the LED package, and the other part is relevant to the heat sink. When measuring the transient response after being sufficiently heated, the process of cooling mainly occurs in the LED package during the first 10–100 times of the time constant of a LED package (i.e., 1 s), while the temperature of the heat sink remains almost constant. Then the temperature of the LED package almost equals that of the heat sink, and the temperature of the whole structure slowly falls to the environment temperature. Hence, there exists a moment during the transient process, at which the junction temperature is equivalent to the case temperature when the LED is working steadily. In our perspective, this moment of time can be derived from the 1st derivative thermal transient response and the time constant spectrum. As shown in Eq. (1), the 1st derivative thermal transient response is the convolution of the time constant spectrum and $W(z)$, so the 1st derivative curve is the blurred time constant spectrum by $W(z)$. Therefore, we define the time of the minimum point between the two peaks on the 1st derivative curve as the demarcation of the LED package and heat sink. Thus, the temperature difference of junction to case (on steady state) can be obtained from the temperature variation between 0 s and the demarcation on the thermal transient response. The temperature difference is divided by the heat flow power to get the thermal resistance of LED package. For the structure function method, the thermal resistance of LED package is mainly determined by checking the stage of integrated structure function manually. Obviously, the method proposed herein simplifies the calculation.

3. Experiments

In practice, our experiment consists in 4 steps:

Step 1: mount the LED package on a natural convection heat sink, and then turn on the LED with the heating current setting at 350 mA and waiting the device reaching stable (1–5 min). The experiment setup is illustrated in Fig. 3. Each of the three 1 W LEDs (labeled as #1, #2, #3) are mounted on different heat sinks every time. The environment temperature is 298 K.

Step 2: switch the current to 10 mA, and record the thermal transient response $T(z)$ immediately using the T3ster (Micred Co.). As mentioned above, set the capture time to 10–100 s.

Step 3: calculate the 1st derivative curve $\dot{T}(z)$. Smooth it and find the minimum point $(z_d, \dot{T}_d)$ around 0.1 s. Substitute z_d into the

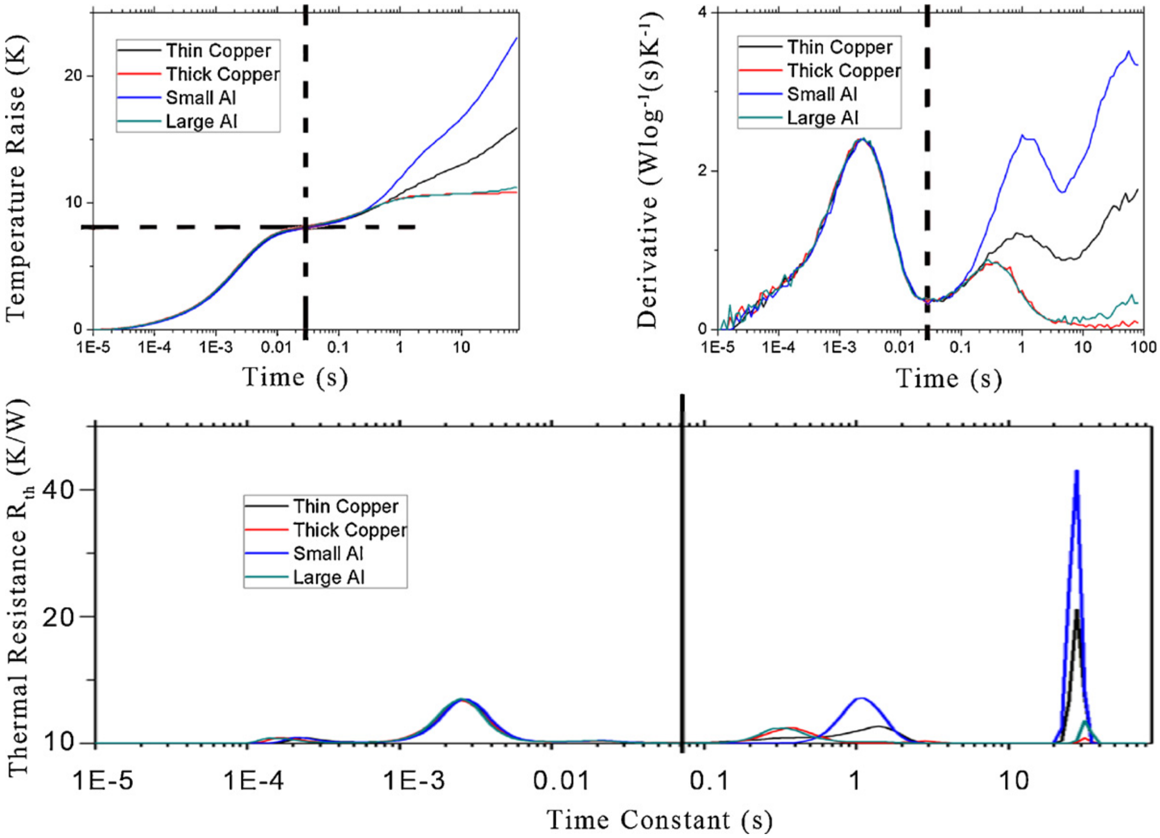

Fig. 4. The testing data with different heat sinks.

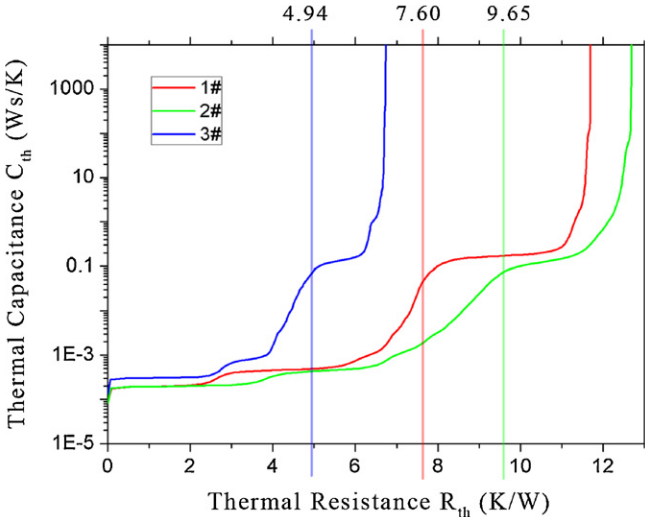

Fig. 5. The structure functions of 3 LEDs under test. The color vertical lines show the LED package boundary respectively.

Table 1
The thermal resistances of 3 different types of LEDs mounted on 5 heat sinks.

Heat sinks		Thin copper	Thick copper	Small Al	Large Al	T control
Thermal resistance (K/W)	#1	7.62	7.71	7.76	7.64	7.60
	#2	9.35	9.79	9.42	9.75	9.65
	#3	4.90	5.01	4.87	4.97	4.94

transient curve. $T_d = T(z_d)$ is the junction-to-case temperature difference.

Step 4: get the thermal resistance from Eq. (7). P_h is the power of heat flow.

$$R_{th} = \frac{T_d}{P_h} \tag{7}$$

Fig. 4 shows the thermal transient responses (for our convenience, we set the K factor to its modulus, so the curves are monotonically increasing, which would not influence the results), 1st derivative curves and the time constant spectrums of #1 LED on 3 heat sinks, respectively. The black dotted line shows the demarcation: $T_d = T(z_d)$. A comparative measurement is done with the very same LEDs mounted on a temperature-controlled heat sink with temperature kept at 298 K. The structure functions are shown in Fig. 5. All the results of the thermal resistance of 3 LEDs are listed in Table 1.

From Table 1, we can deduce that the results are almost consistent with different heat sinks. And the relative error is less than 3.2% with temperature-controlled results as references. From Fig. 4, we can also construe that although the heat sink changes, the time constant spectrum remains stable during 0–0.1 s (left part of the vertical line), whereas, those larger than 0.1 s (right part of the vertical line) vary significantly. That reconfirms the theory that the time constant spectrum, in the case, would directly indicate the structure information.

4. Analysis and discussion

4.1. Simulation and error analysis

In this section, the equivalent circuit is employed to simulate the experiment and analyze the relative error. As mentioned above, the LED package with heat sink should always have two or three main time constant peaks. Those with time constants smaller than 0.1 s represent the LED package, and others represent the heat sink, as illustrated in Fig. 4. To simplify the simulation, we used only two discrete time constants to represent the whole spectrum. Equivalently, two-cell equivalent circuits, as illustrated in Fig. 1, are used for simulating the thermal transient response. It is an one-port network, and the current source represents the heat source with power P_h. The output voltage represents junction temperature. If we capture the voltage transient from $t = 0$ s as the input current signal set to $I(t) = I_0 \cdot u(t)$, that means the heat flow would have the same input as $P_h(t) = P_{h0} \cdot u(t)$, where P_{h0} is the power excitation amplitude. The transient response is described by the system of differential equations below. T_1 and T_2 are the voltages (temperatures) to ground of C_1 and C_2 respectively.

$$\begin{cases} \dfrac{T_1 - T_2}{R_1} = -C_1 \dot{T}_1 \\ \dfrac{T_2 - T_1}{R_1} + \dfrac{T_2}{R_2} = -C_2 \dot{T}_2 \end{cases} \tag{8}$$

If the two functions are merged, a differential function of T1 is generated.

$$R_1 C_1 C_2 \ddot{T}_1 + \left(C_1 + C_2 + \frac{C_1 R_1}{R_2} \right) \dot{T}_1 + \frac{T_1}{R_2} = 0 \tag{9}$$

With the initial condition:

$$\begin{cases} T_1 \Big|_{t=0} = 0 \\ \dot{T}_1 \Big|_{t=0} = \dfrac{P_{h0}}{C_1} \\ R_1 + R_2 = R'_1 + R'_2 \\ C_1 = \dfrac{C'_1 C'_2}{C'_1 + C'_2} \end{cases} \tag{10}$$

The analytical solution is:

$$T_1 = P_{h0} \left[(R'_1 + R'_2) - R'_1 \exp\left(\frac{-t}{\tau_1} \right) - R'_2 \exp\left(\frac{-t}{\tau_2} \right) \right] \tag{11}$$

where R'_1 and R'_2 are the resistances of the Foster equivalent. Set $z = \log_{10}(t)$ and $\zeta = \log_{10}(\tau)$. The functions above are transformed to logarithmic scale and the junction temperature $T = T_1$.

$$T(z) = P_{h0}(R'_1 + R'_2) - P_{h0} R'_1 \exp(-10^{z-\zeta_1}) - P_{h0} R'_2 \exp(-10^{z-\zeta_2}) \tag{12}$$

$$\begin{aligned} \dot{T}(z) = {} & P_{h0} R'_1 \ln(10) \exp(-10^{z-\zeta_1}) 10^{z-\zeta_1} \\ & + P_{h0} R'_2 \ln(10) \exp(-10^{z-\zeta_2}) 10^{z-\zeta_2} \end{aligned} \tag{13}$$

$$\begin{aligned} \ddot{T}(z) = {} & P_{h0} R'_1 \ln^2(10) [\exp(-10^{z-\zeta_1})(10^{z-\zeta_1} - 10^{2(z-\zeta_1)})] \\ & + P_{h0} R'_2 \ln^2(10) [\exp(-10^{z-\zeta_2})(10^{z-\zeta_2} - 10^{2(z-\zeta_2)})] \end{aligned} \tag{14}$$

Eqs. (12)–(14) show the formations of thermal transient response, 1st derivative function and 2nd derivative function respectively. In principle, we can get the minimum point of Eq. (13) around 0.01 s by substituting the solution of $\ddot{T}(z) = 0$ to Eq. (12). Unfortunately, Eq. (14) is a transcendental equation which could not give us an analytical solution, so we would have to seek for a numerical solution using Matlab. When R'_1, R'_2, and the time constant values are changed, the relative error changes correspondingly. In our simulation, we set $R'_1 = 1$ K/W, $\tau_1 = 0.01$ s as constants, and increase R'_2 from 1 to 6 K/W by the step of 1. The trend of the relative error versus τ_2 is plotted and illustrated in Fig. 6.

Fig. 6 shows that (1) the larger the time constant of heat sink, the smaller the relative error; (2) the smaller the thermal resistance of

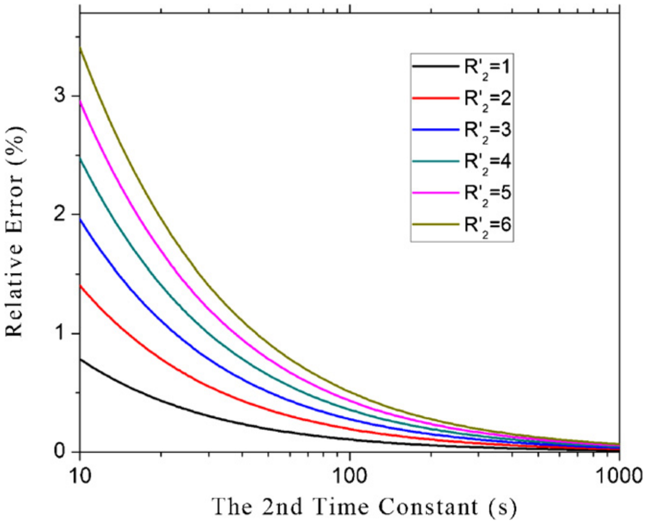

Fig. 6. The error trend curves.

heat sink, the smaller the relative error becomes. Therefore, a heat sink with small thermal resistance and larger thermal capacitance is essential to reduce testing error.

4.2. Relationship between thermal resistance and temperature

Yang reported that LED's thermal resistance varies while the temperature of heat flow path changes[13]. It mainly due to the following two reasons: First, the thermal conductivity of material changes with the temperature; second, the volume and pressure changing cause by thermal expansion and contraction. That means if we put a same LED package on different heat sinks and light it up, the LED's junction temperatures are different, so does the LED's thermal resistance, even though the heat flow power stays the same. Hence, to obtain the accurate thermal resistance, the LED package should be tested in the real circumstance. This makes our method more useful in practice. Obviously, LEDs cannot always be put on a temperature-controlled heat sink in a practical environment, so it is difficult to reproduce the accurate operating temperature of the package when measuring the thermal resistance. The method proposed herein could be operated directly in the real circumstance exactly on the operating temperature.

5. Conclusions

In this paper, we present a practical method of measuring the thermal resistance of LED packages based on the division of the time constant spectrum. It has the following advantages. The temperature-controlled heat sink is not a necessity, provided that the LED packages are mounted on natural convection heat sinks. For most LED packages, it only took about 10 s to finish the measurement. Moreover, according to the approximation based on the huge gap in the time constant spectrum, the system error could be limited to less than 1% if employing the large thermal capacitance and small thermal resistance heat sink. On the other hand, it should be noted that there are still some limitations to this method. The K factor should be known or tested in advance. However, it is easy to measure or be replaced with those of other same type of LEDs. As we pointed out, if the gap in the time spectrum between the heat sink and LED package is less than 2 magnitudes, the approximation of Eq. (6) is no longer valid, causing the relative error to rise rapidly. Fortunately, a moderate heat sink would meet the approximation, so this scenario rarely occurs in practice.

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