Evaluation of current and temperature effects on optical performance of InGaAlP thin-film SMD LED mounted on different substrate packages

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The relationship between the photometric, electric, and thermal parameters of light-emitting diodes (LEDs) is important for optimizing the LED illumination design. Indium gallium aluminium phosphide (InGaAlP)-based thin-film surface-mounted device (SMD) LEDs have attracted wide attention in research and development due to their portability and miniaturization. We report the optical characterization of InGaAlP thin-film SMD LED mounted on FR4, 2 W, and 5 W aluminum (Al) packages. The optical and thermal parameters of LED are determined at different injection currents and ambient temperatures by combining the T3ster (thermal transient tester) and TeraLED (thermal and radiometric characterization of power LEDs) systems. Analysis shows that LED on a 5 W Al substrate package obtains the highest luminous and optical efficiency.

Keywords: light-emitting diodes (LEDs), surface-mounted device (SMD), InGaAlP, luminous efficiency

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1. Introduction

Indium gallium aluminium phosphide (InGaAlP) light-emitting diodes (LEDs) are devices of high efficiency and long-wavelength region of the visible spectrum, which will play a vital role in various solid-state lighting applications.[1] Thin-film LEDs offer high light extraction efficiency due to the existence of a dielectric coated metal reflector between the active region and the substrate. Hence, this will help to avoid the absorption of emitted light from the active region by the substrate.[2] Following the miniaturization development in microelectronics, surface-mounted device (SMD) LEDs have been employed in today's technology. Currently, InGaAlP thin-film SMD LEDs are the material of choice in research and development due to their portability and miniature size.[3] Their advantages comprise low power consumption, less heat production, a wide viewing angle, long lifespan, and capability of producing saturated colors with high luminous efficiency.[4] The luminous efficiency is a significant parameter for evaluating the light source.[5] The LED junction temperature depends on the heat source such as current and temperature.[6,7] The luminous efficiency of the light emission drops with the increase in the LED junction temperature.[8–12] The photometric, electric, and thermal parameters of the LED device are dependent on each other.[13] To obtain higher efficiency and light output, the LED chip temperature needs to diminish.[14] Dissipation of the heat generated from the chip to the ambience is the key to reducing the junction temperature. The heat produced in the LED chip should be transferred efficiently to the board and then to the atmosphere to cool the LED system. A good design of the board is one of the solutions to dissipate the heat. A dielectric material in the metal-core printed circuit board (MCPCB) with higher thermal conductivity can improve the thermal characterization and the optical performance of the LED package. Not much work has been found in the literature on evaluating the optical performance of InGaAlP thin-film low power LEDs. Therefore, it is important to investigate the optical performance of the InGaAlP Thinfilm low power LED.

In this study, we present the optical characterizations of InGaAlP thin-film SMD LED mounted on different substrate packages. The substrate packages are FR4 and two types of Al substrate packages with thickness of 1.6 ± 0.16 mm. Thermal conductivities of dielectric layers in Al packages are 2 and 5 W/m·K. The optical and thermal parameters of the LED on different substrates are measured via the integration of T3Ster and TeraLED systems. Measurements are analyzed using the T3Ster TeraLED-View evaluation software.

2. Experimental work

LED of amber color and power 0.1855 W was used in this work (LA E67F, Osram Opto Semiconductors). This LED can handle more than its maximum ratings of forward current and ambient temperature (indicated in the manufacturer's website).[15] The characteristics of the LED under test are demonstrated in Table 1.

Before the measurements, the LED was attached to the substrates which were FR4 and two Al substrate packages (Fig. 1) using solder paste. The materials data of the substrate packages and experiment conditions are illustrated in Table 2. A small sensor current of 1.0 mA (to produce a negligible

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Table 1. Characteristics of the LED under test.

Technology	InGaAlP thin film
Color	Amber
Chip size	300×300 μm
Package geometry	$3.4 \times 3.0 \times 2.1$ mm
Luminous intensity (Max.)	3550 mcd

amount of heat) and temperature range of 25–75 °C by an increment of 10 °C were applied to determine the calibration factor of the LED through the T3ster system. Radiometric and thermal measurements were achieved via the combination of T3ster and TeraLED systems (Mentor Graphics Corp.). In accordance with the recommendations of the International Commission on Illumination (CIE),[16] the LED module was fixed on a Peltier-cooled fixture of a mounting area 40×40 mm^2 that is attached to a 300 mm integrating sphere using a thermal pad with thermal conductivity of 3 W/m·K and thickness 0.35 mm (Fig. 2). The Peltier-cooled fixture stabilized the temperature of LED during the optical measurements and was employed as a cold-plate in thermal measurements. Under thermal and electrical steady-state conditions, the optical parameters of the LED were recorded at various values of current and temperature. When the LED was switched on for 900 s, the emitted light was captured by a detector connected to the integrating sphere of TeraLED. As the LED was switching to the sensing mode, the cooling transient curve was recorded by T3Ster equipment for another 900 s.[17] The optical and thermal test reports were attained using the T3ster TeraLED-View evaluation software.

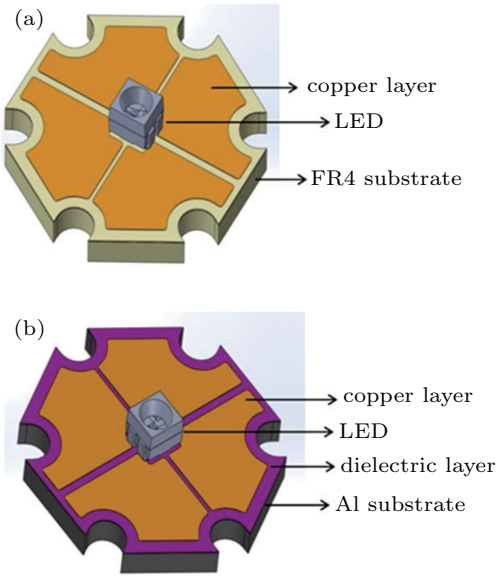


Fig. 1. (color online) InGaAlP thin-film SMD LED mounted on (a) FR4 and (b) Al substrate packages.

Table 2. Materials data and experiment boundary conditions.

Substrate data and boundary conditions	Variable
Substrate material	FR4/Al core
Substrate thickness	1.6 ± 0.16 mm
FR4 package	1.093 W·m^{-1}·K^{-1}
Al substrate (Al 6063)	201 W·m^{-1}·K^{-1}
Dielectric layer of 2 W Al package	2 W·m^{-1}·K^{-1}
Dielectric layer of 5 W Al package	5 W·m^{-1}·K^{-1}
Copper material	383 W·m^{-1}·K^{-1}
Injection current	50–100 mA at 25 °C
Ambient temperature	25–75 °C at 50 mA

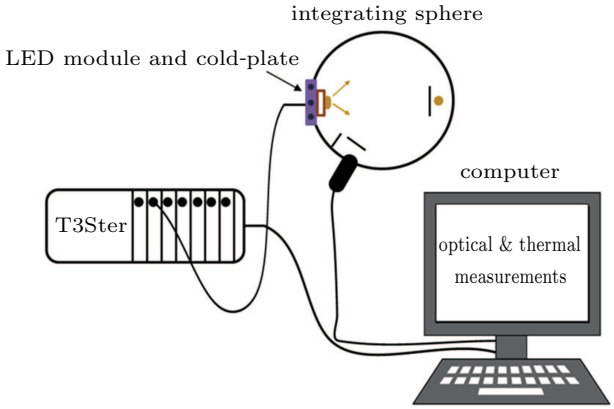


Fig. 2. (color online) Experimental setup of optical and thermal measurements.[18]

3. Results and discussion

K-factor is the LED calibration factor that can be obtained using the slope of the forward voltage versus ambient temperature curve. For the measurement of K-factor calibration, a sensor current of 1.0 mA and temperature range of 25–75 °C with an increasing step of 10 °C were utilized. The K-factor is calculated by[19]

$$K = \frac{\Delta V_{\mathrm{f}}}{\Delta T_{\mathrm{A}}}, \tag{1}$$

where ΔV_{f} and ΔT_{A} are the changes of the forward voltage and ambient temperature, respectively. As shown in Fig. 3, the calibration factor of the LED on FR4, 2 W, and 5 W Al packages are −1.63, −1.66, and −1.65 mV/°C, respectively. Therefore, the calibration factor of the LED under test is about −1.65 mV/°C.

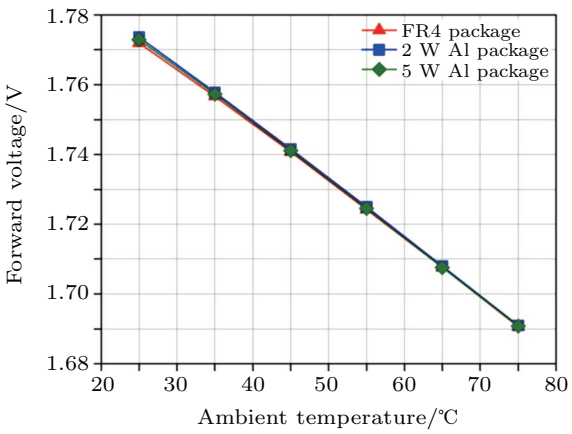


Fig. 3. (color online) The calibration curve of InGaAlP thin-film SMD LED.

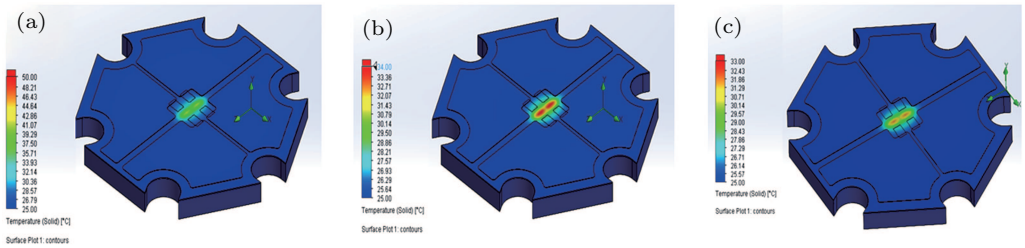


Fig. 4. (color online) Heat distribution for (a) FR4, (b) 2 W Al, and (c) 5 W Al packages at 50 mA and 25 °C.

Figure 4 shows the heat distribution in the substrate packages at 50 mA injection current (I_f) and ambient temperature (T_A) of 25 °C. It can be observed that the dissipation of heat for FR4 (Fig. 4(a)) is less due to its lower thermal conductivity compared to Al packages. However, the dielectric layer in Al substrates is diminished the LED junction temperature and the substrate package temperature, as shown in Figs. 4(b) and 4(c).

The luminous efficiency (η_v) reduces with the increase of the junction temperature (T_J). The relationship between luminous efficiency and junction temperature is linear as follows:[13]

$$\eta_v = \eta_{vo}\left[1+k_e\left(T_J-T_o\right)\right], \tag{2}$$

where η_{vo} is the luminous efficiency at rated temperature T_o (typical value is 25 °C in LED data sheets), and k_e is a negative coefficient which indicates the relative reduction of luminous efficiency with the rise in junction temperature.

From Fig. 4, it is clear that η_v of the LED is highest in the case of using 5 W Al substrate. η_v is a function of I_f and T_A.[11,12] The change in η_v of the LED with I_f and T_A is shown in Fig. 5. When I_f and T_A increase, η_v decreases. A reduction in efficiency due to the injection current is called efficiency droop.[20,21] Figure 5(a) displays that as I_f increases from 50 to 100 mA at 25 °C, the relative increase in η_v ($\Delta\eta_v$) is about 1% and 4% between FR4 and 2 W Al packages. Likewise, $\Delta\eta_v$ of FR4 and 5 W Al packages are approximately 5% and 10%, respectively. In addition, figure 5(b) shows that as T_A increases from 25 °C to 75 °C at 50 mA, the $\Delta\eta_v$ are about 2% and 7% between FR4 and 2 W Al packages. Similarly, $\Delta\eta_v$ between FR4 and 5 W Al packages are about 5% and 11%, respectively. Reduction in η_v with increasing I_f can be from the non-radial composition at the potential well that causes radiation decay.[22] Furthermore, a drop in η_v due to the rise in T_A may be attributed to the drop in external quantum efficiency and the spectral shift.[23] It can be seen that the drop in η_v due to T_A is higher than I_f. For example, in Fig. 5(a), the η_v of the LED mounted on 5 W Al package reduces from 105 lm/W to 87 lm/W as I_f increases from 50 mA to 100 mA. Similarly, as T_A increases from 25 °C to 75 °C, η_v decreases from 105 lm/W to 68 lm/W as shown in Fig. 5(b). This means that low power LED T_J is more affected by the ambient temperature.[24,25]

Optical efficiency (η_w) is another parameter that can be used to evaluate the LED optical performance.[26,27] From Fig. 6 we find that η_w drops due to the rise in I_f and T_A. As I_f increases from 50 mA to 100 mA, $\Delta\eta_w$ between FR4 and 2 W Al packages are about 2% and 4%, respectively. In the same way, $\Delta\eta_w$ between FR4 and 5 W Al packages are almost 4% and 7%. In addition, when T_A increases from 25 °C to 75 °C, $\Delta\eta_w$ are about 2% and 8% between FR4 package and 2 W Al package. Also, $\Delta\eta_w$ are approximately 3% and 10% between FR4 and 5 W Al packages, respectively.

The drop of η_w can result from different mechanisms, such as auger recombination, current leakage, and built-in piezoelectric fields.[28,29] η_w can be calculated by the ratio between optical output power and electrical input power as follows:

$$\eta_w = \frac{P_{opt}}{P_{el}} = \frac{P_{opt}}{I_f \times V_f}, \tag{3}$$

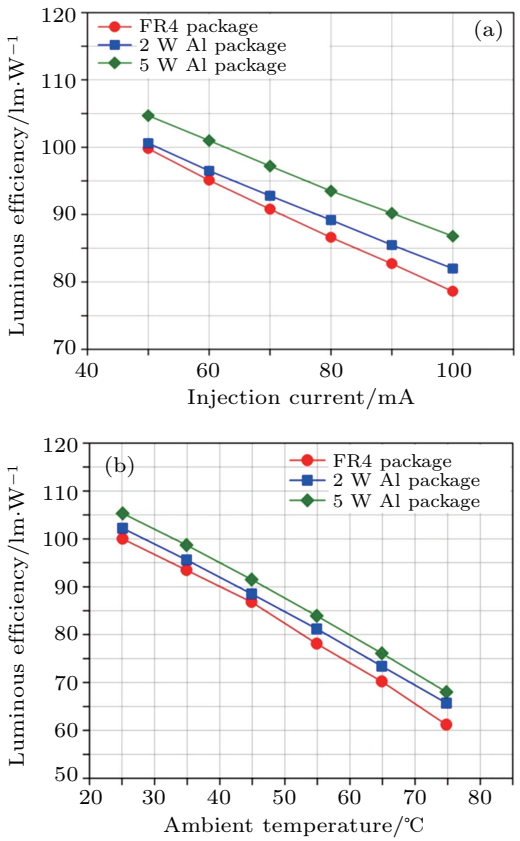


Fig. 5. (color online) Luminous efficiency of InGaAlP thin-film SMD LED versus (a) injection current and (b) ambient temperature.

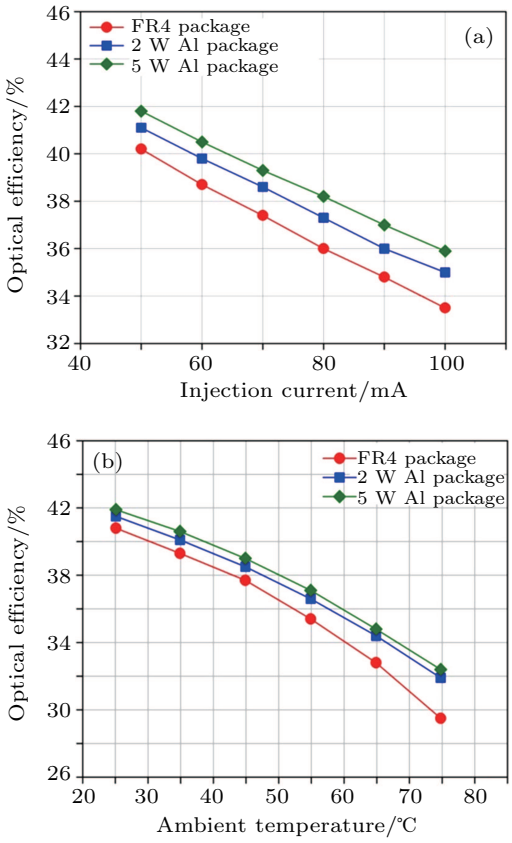


Fig. 6. (color online) Optical efficiency of InGaAlP thin-film SMD LED versus (a) injection current and (b) ambient temperature.

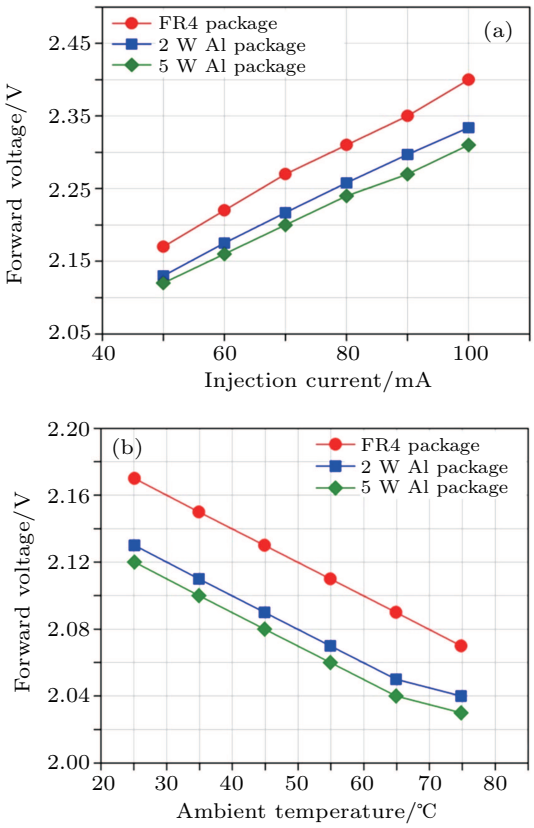


Fig. 7. (color online) Forward voltage of InGaAlP thin-film SMD LED versus (a) injection current and (b) ambient temperature.

where P_{opt} is the optical output power and P_{el} is the electrical input power, which is the product of injection current and forward voltage ($P_{el} = I_f \times V_f$). This means that η_w reduces at higher V_f.[30] The forward voltage is linearly proportional to T_A and I_f.[31] V_f as a function of I_f and T_A is shown in Fig. 7. Apparently, V_f of the LED mounted on 5 W Al substrate package is lowest with increasing I_f and T_A. In the I–V curve, as the temperature increases, the forward voltage decreases.[32] This is due to the shrinkage of the bandgap energy in the active region with increasing junction temperature.[33–35] As a result, the electrical power and the heat dissipation will reduce.[36] Moreover, the forward voltage falls at higher junction temperature because of the reduction in internal series resistance which is attributed to the higher acceptor activation and results in higher conductivity of the p-type layer and active layers.[23,32]

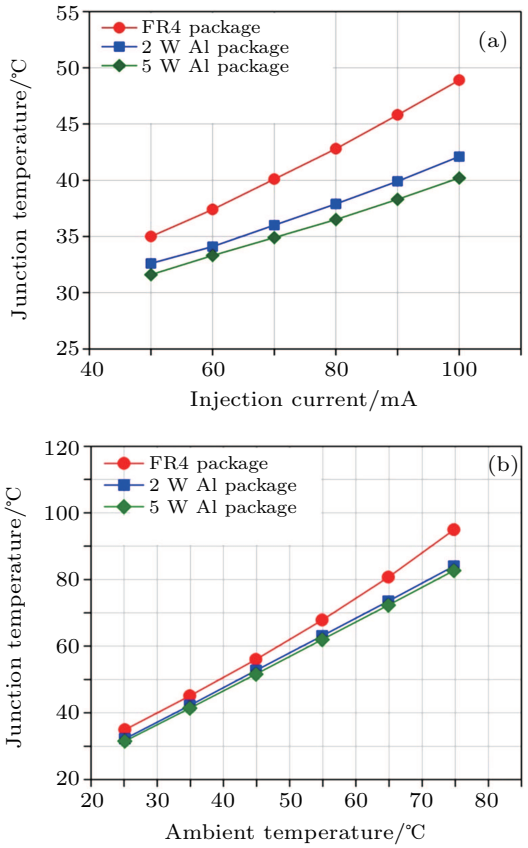


Fig. 8. (color online) Junction temperature of InGaAlP thin-film SMD LED versus (a) injection current and (b) ambient temperature.

The LED junction temperature affects internal efficiency, maximum light output, and peak wavelength.[37] The forward voltage falls as the junction temperature increases. This is due to the Joule heating effect that derives the relation between the forward voltage and junction temperature. Figure 8 illustrates the change of the junction temperature with I_f and T_A. It is noticeable that the smallest value of T_J is for the 5 W Al substrate package.

Figure 9 shows that the heat dissipation (P_{heat}) is higher with increasing ambient temperature than injection current. The heat dissipation is the subtraction of optical output power

from the electrical input power and given by[38–40]

$$P_{\text{heat}} = P_{\text{el}} - P_{\text{opt}} = P_{\text{el}}\,(1-\eta_{\text{w}})\,. \tag{4}$$

We find from Eq. (4) that when η_{w} drops with I_{f} and T_{A} (Fig. 6), $(1-\eta_{\text{w}})$ increases and thus P_{heat} increases (Fig. 9). Obviously, the heat dissipation for the 5 W Al package is lower than the other substrate packages. This also confirms that the emitted optical power and other photometric parameters are higher for the 5 W Al substrate package.

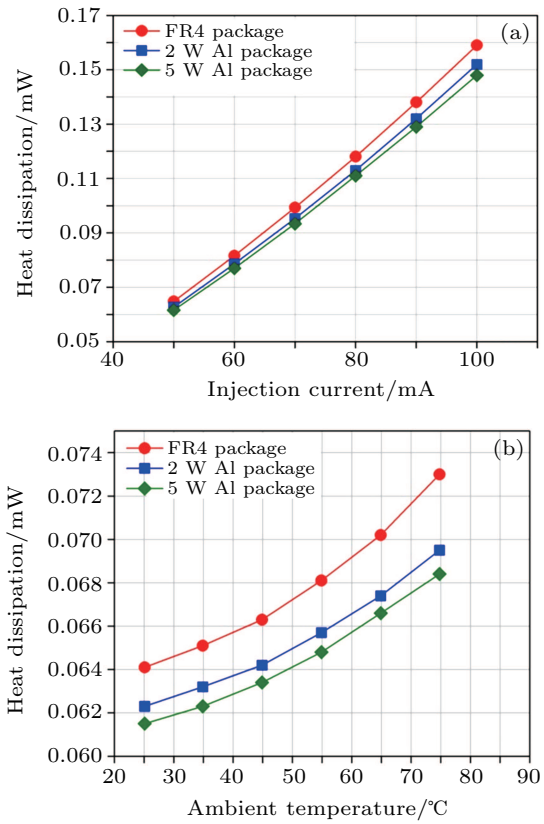


Fig. 9. (color online) Heat dissipation of InGaAlP thin-film SMD LED versus (a) injection current and (b) ambient temperature.

Real thermal resistance from junction to ambient ($R_{\text{thJA-real}}$) describes the thermal properties of the LED system.[41] The increase of the LED junction temperature causes the increase in $R_{\text{thJA-real}}$ as follows:

$$R_{\text{thJA-real}} = \frac{T_{\text{J}} - T_{\text{A}}}{P_{\text{heat}}} = \frac{T_{\text{J}} - T_{\text{A}}}{P_{\text{el}}\,(1-\eta_{\text{w}})}. \tag{5}$$

Equation (5) shows that P_{heat} increases with the temperature gradient $(T_{\text{J}} - T_{\text{A}})$. Therefore, $R_{\text{thJA-real}}$ can be considered as the proportionality factor that includes the heat dissipation characteristics of the LED device. Moreover, this equation connects thermal, electrical, and optical parameters of the LED with each other.

Figure 10(a) demonstrates that $R_{\text{thJA-real}}$ decreases with the increasing injection current. This is due to the changes in the LED active area with the injection current. At low I_{f}, the power is dissipated through a small conducting area. This will cause $R_{\text{thJA-real}}$ to increase since thermal resistance is inversely proportional to the cross-sectional area of the heat source.[39] With increasing I_{f}, the junction area becomes more conducting and the active area expands. Therefore, the power is dissipated more across the active region and subsequently the thermal resistance decreases.[42,43] Figure 10(b) shows the increase in $R_{\text{thJA-real}}$ with T_{A}, which is due to the increase in LED T_{J} (see Eq. (5)). The LED T_{J} is linearly proportional to T_{A} at constant I_{f}. A higher T_{J} will lead to more defects and non-radiative recombination in the LED chip.[44] Hence, the current crowding phenomenon may occur which generates heat and causes the increase in total thermal resistance.[42] A higher T_{J} diminishes the LED light output, luminous efficiency, and reliability.[45–49]

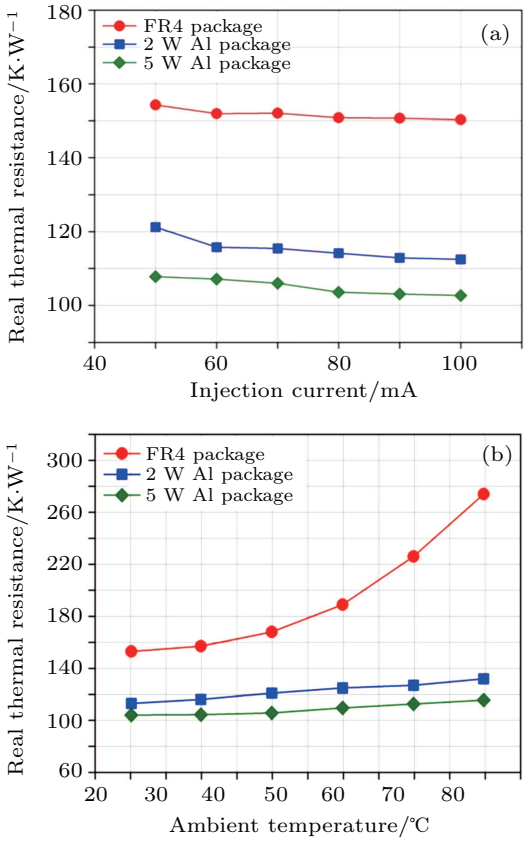


Fig. 10. (color online) Real thermal resistance of InGaAlP thin-film SMD LED versus (a) injection current and (b) ambient temperature.

We also observe from Fig. 10(b) that the FR4 package is more sensitive to T_{A} and displays much quicker increase in $R_{\text{thJA-real}}$ than Al substrate packages. Particularly, at high T_{A}, the $R_{\text{thJA-real}}$ changes quickly in the FR4 package. When T_{A} is below 45 °C, the $R_{\text{thJA-real}}$ increases linearly. However, if T_{A} is above 45 °C, the $R_{\text{thJA-real}}$ rises exponentially with T_{A}. This indicates that the FR4 package is only appropriate for low T_{A}. For Al substrate packages, the $R_{\text{thJA-real}}$ increases linearly with lower values compared to the FR4 package. As T_{A} varies from 25 °C to 75 °C, $R_{\text{thJA-real}}$ for FR4 differs from 153 K/W

to 274 K/W. In addition, $R_{\mathrm{thJA-real}}$ change from 113 K/W to 132 K/W and from 104 K/W to 115 K/W in 2 W and 5 WAl substrate packages, respectively. This demonstrates that even at high T_{A}, the $R_{\mathrm{thJA-real}}$ of the LED attached to the Al package keeps in a convenient range.

4. Conclusion

The optical performance of InGaAlP thin-film SMD LED mounted on different substrate packages is investigated. The optical and thermal parameters of the LED are determined using the combination of T3ster and TeraLED instruments. The LED optical behavior at various injection currents and ambient temperatures is studied and compared among FR4, 2 W Al, and 5 W Al substrate packages. We find that as the injection current increases from 50 mA to 100 mA at ambient temperature of 25 °C, the luminous efficiency is improved from 5% to 10% between FR4 and 5 W Al substrate packages and from 4% to 6% between 2 W and 5 W Al packages, respectively. For the same range of injection current, the variation in optical efficiency between FR4 and 5 W Al substrate packages is about 4% to 7%. Likewise, the relative increase in optical efficiency between 2 W and 5 W Al packages is approximately from 2% to 3%. In addition, at 50 mA and ambient temperature 25–75 °C, the luminous efficiency is enhanced by 5%–11% between FR4 and 5 W Al packages. Similarly, the relative increase of the luminous efficiency between 2 W and 5 W Al packages is about 3%–4%. Furthermore, the optical efficiency increases from 3% to 10% between FR4 and 5 W Al packages and from 1% to 2% between 2 W and 5 W Al packages, respectively. Apparently, the LED attached to the 5 W Al substrate package shows the highest luminous and optical efficiency, due to its higher thermal conductivity of the dielectric layer, which allows effective dissipation of heat generated and subsequently improves the optical performance of the LED device.

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