

Thermal resistance of high power LED on surface modified heat sink

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Abstract For 3 W green light emitting diode (LED), the top surface of commercial heat sink was machined with two different shapes (hole and ‘V’ shaped) and the thermal performance was tested. The contact surface area of the heat sink was increased by machining process. The observed junction temperature (T_j) from transient cooling curve was high for ‘V’ shaped surface for all driving currents. Hole shaped surface of heat sink did not influence much on the T_j values. In addition, total thermal resistance (R_{th-tot}) was not affected by the hole shaped surface compared to plain surface. Noticeable increases in T_j as well as R_{th-tot} were observed for ‘V’ shaped surface for all driving currents (100, 350 and 700 mA). The observed correlated color temperature (CCT) values were high for hole and ‘V’ shaped surfaces and the variation in CCT with respect to time was high for all surfaces measured at 700 mA. Increased lux for modified surface at high driving current (700 mA) was also observed. Very small variation in color rendering index (CRI) values could be observed.

Keywords light emitting diode (LED), surface modification, transient analysis, cumulated structure function, optical properties

1 Introduction

Apart from special illumination, high power light emitting diodes (LEDs) will soon be used in general illumination because of its distinctive advantages including high efficiency, good reliability, long life, variable colors and low power consumption. An expectation about high power LED is that it will be a dominant lighting technology by 2025 [1]. Theoretically, higher operating current delivers more light output from LED. Unfortunately, the light output power of the LED decreases as the increasing of

LED temperature [2]. It has been reported that the thermal problem is a main factor which is related to most of the main parameters of LEDs. Driving current and forward voltage are interdependent, and they influence the light output and the efficiency of LEDs. Optical power degradation occurred due to junction temperature (T_j) increasing, therefore, proper thermal management is a key issue in power LED based lighting applications [3]. When two solid surfaces are joined, asperities of each surface limit their actual contact to a very small fraction, perhaps it is just 1%–2% of the apparent area for lightly loaded interfaces. The flow of heat across such interfaces involves not only the conduction of solid-to-solid in the area of actual contact (A_c), but also the conduction through the fluid occupying the noncontact area (A_{nc}) of the interface. This constriction of heat flow is manifested as thermal contact resistance (R_c) at the interface [4].

The surface geometry of heat sink is important and influences the heat transfer from the LED package to ambient. Generally, air gaps restrict the heat flow in electronic packaging. Thermal interface material (TIM) is an alternative to avoid the effect of air gaps as well as to increase the contact surface area between metal core printed circuit board (MCPCB) and heat sink. The surface characteristics, such as flatness, waviness and roughness, have a major impact on the thermal contact resistance decreases with the increase in surface flatness. In contrast, thermal contact resistance decreases with decrease in waviness and roughness [5,6].

2 Experimental method

In this study, an effort has taken to reduce the thermal resistance (R_{th}) value and material quantity of heat sink as well as increasing the contact surface area between MCPCB and heat sink. As consequently, the surface of heat sink (top) is machined in different shapes and the thermal & optical properties of 3 W green LED with

respect to different operating currents are tested.

2.1 Theoretical background

The device junction temperature in the test condition can be determined by

$$T_J = T_{J0} + \Delta T_J, \quad (1)$$

where T_{J0} = initial device junction temperature ($^{\circ}\text{C}$), ΔT_J = change in junction temperature due to heater power application ($^{\circ}\text{C}$). It should be noted that the relationship between ΔT_J and power dissipation is usually linear under some specific conditions, and it may vary considerably at the extremes of device operation. The method itself is independent of the environment of the device under test (DUT), thus it is required to pay careful and detailed attention to environmental conditions in order to assure that the test produces significant results. Static mode was applied using still air box for all measurement, which applies heating power to the DUT on a continuous basis while the T_J was monitored through measurement of temperature-sensitive parameter.

The thermal contact conductance for joint between contacting solids is defined as

$$h_c = \frac{Q/A}{\Delta T} = \frac{Q/A}{T_1 - T_2} = \frac{Q}{A(T_1 - T_2)}, \quad (2)$$

where T_1 and T_2 are the temperatures of the bounding surfaces of the contact, and Q/A is the heat flow per unit area [7]. Bulk resistance of the two contacting surface (R_{bulk}) is given by the following relation

$$R_{\text{bulk}} = \frac{BLT}{k_{\text{TIM}}}, \quad (3)$$

where BLT is bond line thickness or thickness of applied TIM, and k_{TIM} is the thermal conductivity of TIM [8].

The total contact resistance of the interface material is given as follows

$$R_c = \frac{r_c}{A_{\text{int}}}, \quad (4)$$

where r_c is the contact resistance, and A_{int} is the total area of the interface material [9].

2.2 Experimental work

In order to test the surface influence, three identical heat sink (see Fig. 1) are selected ($23 \text{ mm} \times 25 \text{ mm} \times 9 \text{ mm}$). One among them is considered as plain surface, and the other two are machined as shown in Figs. 2(a) and 2(b). Figures 2(a) and 2(b) show the schematic diagram with specification of the hole and 'V' shaped surface, respectively. To understand easily, the terms 'hole' and 'V' shaped shapes are used for surface modified heat sink throughout this paper. The dia and depth of the hole made

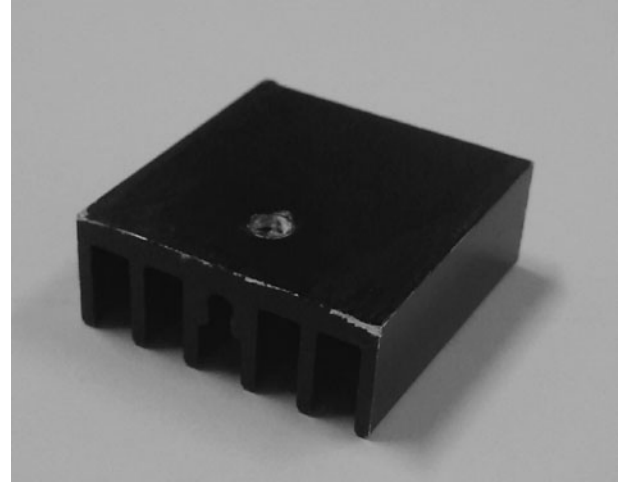


Fig. 1 Photograph of ideal heat sink used (plain surface)

on the surface of the heat sink are 1 and 0.5 mm, respectively. The top surface area of the heat sink is 575, 782 and 654 mm^2 for plain, hole and 'V' shaped surface, respectively.

In this study, 3 W green LED package attached with MCPCB was used for all measurements and placed over the heat sink as shown in Fig. 3(a). Alumina thermal paste was used as TIM in this study. The thermal transient characterization of the LED for three surface conditions described above was captured based on the electrical test method JEDEC JESD-51 [10]. The thermal behavior of the LED was measured by the Thermal Transient Tester (T3Ster) in still air box as given in photograph in Fig. 3(b).

In order to study the optical behavior with respect to input current, MK350 LED meter (Make:UPRtek) was used to record the parameters such as correlated color temperature (CCT), color rendering index (CRI), and brightness (Lux).

2.3 K-factor calibration

Before measurement, the LED was thermally calibrated using dry thermostat and T3Ster as the power supply. The product of K and the difference in temperature-sensing voltage (referred to as ΔV_F) produces the device junction temperature rise:

$$\Delta T_J = \Delta V_F K, \quad (5)$$

$$K = \Delta T_J / \Delta V_F. \quad (6)$$

During the calibration process, the LED was driven with lower operating current at 1 mA to prevent self-heating effect at the junction. The ambient temperature of the LED was fixed to 25°C and the voltage drop across the junction was recorded once the LED reached thermal equilibrium with the temperature of the thermostat. Later, the ambient temperature of the LED was varied from 35°C to 85°C with

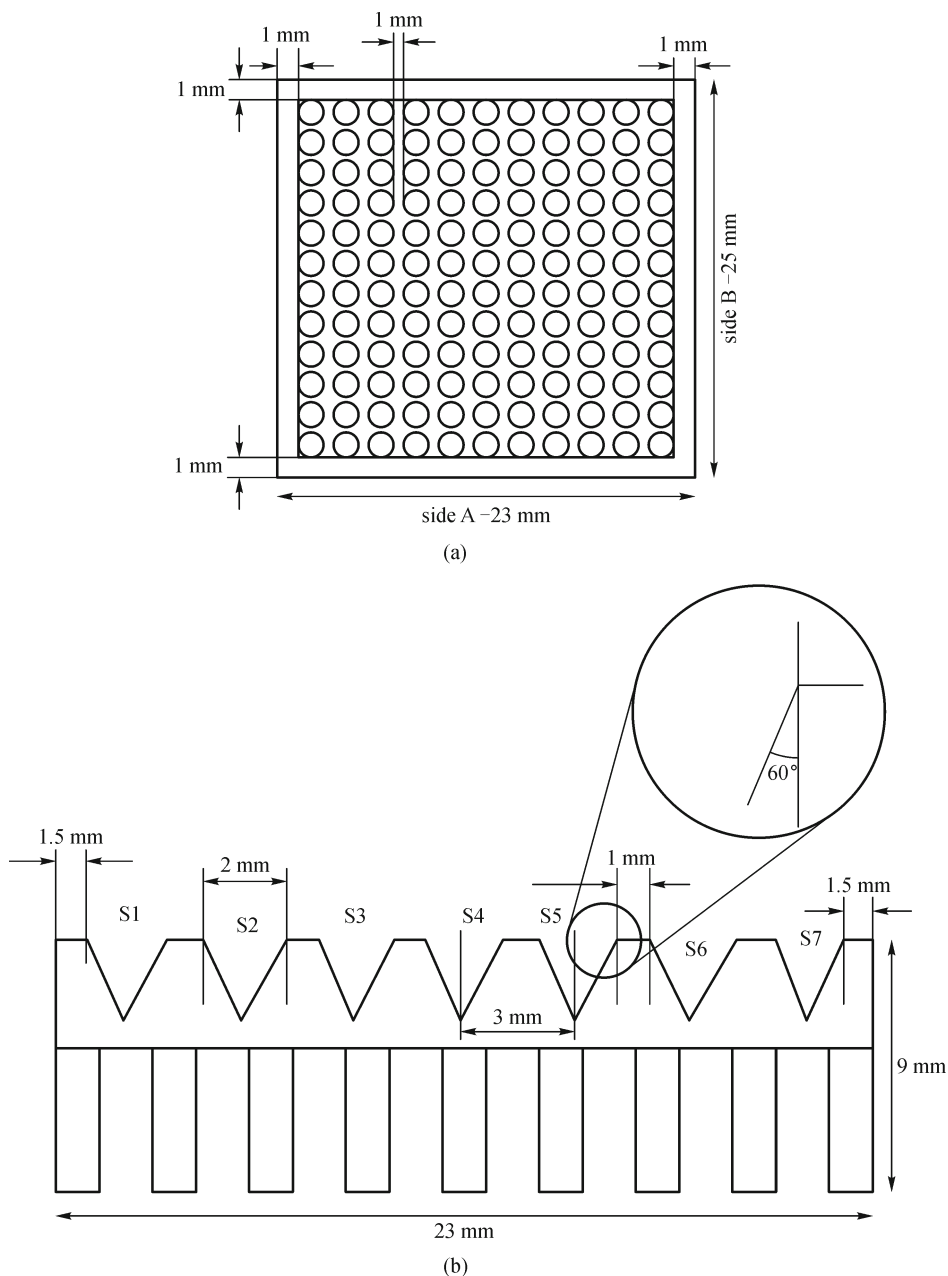


Fig. 2 Schematic diagram of surface machined as (a) hole shape and (b) ‘V’ shape on top surface heat sink

10°C increment and the voltage drop across the junction was noted at each ambient temperature. From the calibration process, the K -factor of the LED was determined as 2.289 from the graph of junction voltage (voltage drop) against ambient temperature as shown in Fig. 4.

2.4 Thermal transient analysis

During the thermal test, the LED was driven by three different currents 100, 350 and 700 mA in a still air chamber at room temperature of $25^{\circ}\text{C} \pm 1^{\circ}\text{C}$ as shown in Fig. 3(b). The LED was forward biased for 900 s. Once it reached steady state, the LED was switched off and the transient cooling curve of heat flow from the LED package

was obtained for another 900 s. The obtained cooling profile of the LED for plain, hole shaped and ‘V’ shaped surface of the heat sink was processed for structure functions using Trister Master Software.

3 Results and discussion

3.1 Cooling curve and cumulative structure function analysis

In order to study the effect of surface machining of heat sink on junction temperature of LED, transient cooling curve was recorded as given in Figs. 5(a)–5(c). Table 1

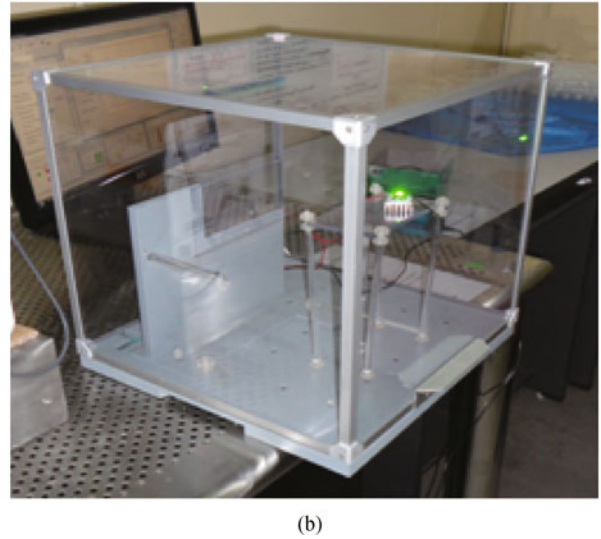
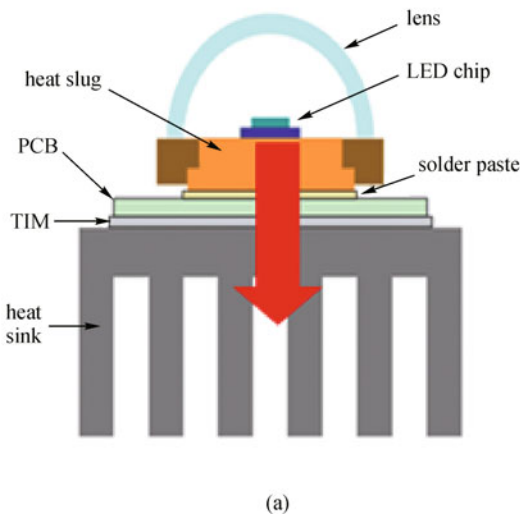


Fig. 3 (a) Schematic diagram of LED on heat sink and (b) measurement setup for thermal transient analysis of LED within still air chamber

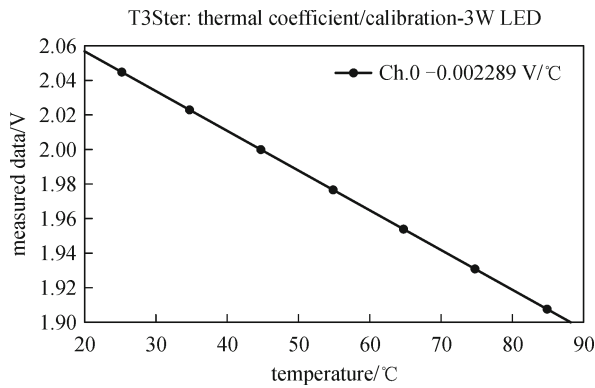


Fig. 4 K-factor calibration curve for given 3 W green LED

shows the variation of T_J value of 3 W LED for surface modified heat sink at various driving current. Figure 5 clearly indicates that the ‘V’ shaped surface affects the T_J noticeably and increases with driving current. It is understood that the volume of thermal paste applied at ‘V’ shaped surface is higher than that of the hole surface. Moreover, the surface contact area for ‘V’ shaped surface is comparatively small than that of the hole shaped surface and hence the thermal resistance at ‘V’ shaped surface is more. In addition, the higher driving current does not show much more influence on reducing T_J for hole shaped

surface (Fig. 5(c)) when compared to ‘V’ shaped surface. The total thermal resistance (R_{th-tot}) of the LED package at different driving current for surface modified heat sink was also studied by the cumulative structure function as given in Figs. 6(a)–6(c). It reveals that the ‘V’ shaped surface shows noticeable reduction in R_{th-tot} as the driving current increases from 100 to 700 mA. Eventhough, R_{th-tot} value of ‘V’ shaped surface is still higher when compared to plain and hole surface. It is due to the increased bond line thickness, that is to say, the heat transfer distance at ‘V’ shape portion is higher than that at the hole shape.

As per the Eq. (2) [7], the heat flux depends on the area of the material, hence the resistance increases with augment of the heat flux area through the applied TIM. The T_J and R_{th-tot} values for ‘V’ shaped surface at 100 mA are much higher than those for other two surfaces.

It is attributed to the effect of thermal barrier formed at the interface between MCPCB and heat sink. According to the Eq. (3) in Ref. [8], the BLT is directly proportional to the bulk resistance. From our studies, the BLT of applied TIM in ‘V’ shape is believed to be higher than that in the hole shape. Moreover, the thermal path distance is larger for ‘V’ shaped surface since it has high volume of thermal paste (TP) at the machined surface area compared with plain and hole surface. Furthermore, the noncontact area A_{nc} of the interface is higher compared to the actual contact

Table 1 Junction temperature and thermal resistance of plain and modified surface heat sinks from cumulative structure function

driving current/mA	plain surface			hole shaped surface			‘V’ shaped surface		
	100	350	700	100	350	700	100	350	700
$T_J/°C$	9.68	36.98	79.58	10.14	37.14	79.61	11.4	37.05	80.90
$R_{th-tot}/(K \cdot W^{-1})$	34.61	34.10	34.16	36.34	34.23	34.16	41.06	35.09	34.74
$R_{th-b-hs}/(K \cdot W^{-1})$	21.33	21.04	20.41	23.06	21.14	20.04	27.35	21.78	20.38

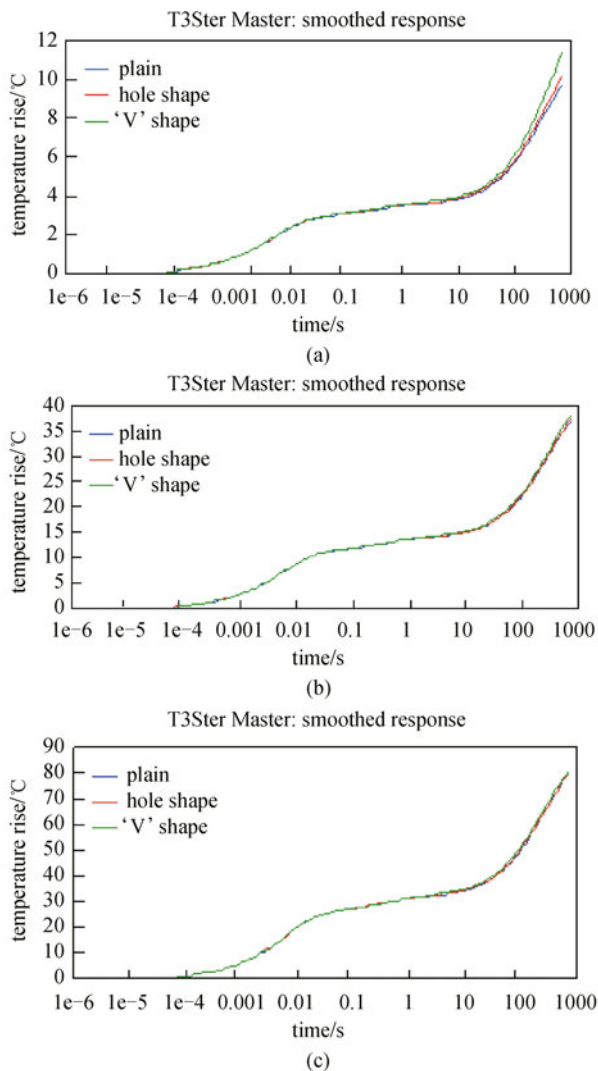


Fig. 5 Transient cooling curve of 3 W green LED for plain and surface modified heat sink recorded at (a) 100 mA, (b) 350 mA and (c) 700 mA

area A_c of the interface at the MCPCB board and heat sink surface area [4]. In addition, the difference in observed R_{th-tot} is not significant at higher driving current between hole shaped surface and plain surface (> 350 mA).

The interface resistance was also calculated by the structure function analysis, and it was found that as the value drastically decreased with the increase of driving current for 'V' shaped surface. According to the Eq. (4) given in Ref. [9], the total area of the interface material is higher in 'V' shaped heat sink, and hence the interface resistance is lower compared to other surfaces. Furthermore, the interface resistance is higher compared to plain and hole shaped surface since the 'V' shaped surface has bulk volume of thermal paste at machined surface [7]. The heat capacitance at the interface was also measured, and it

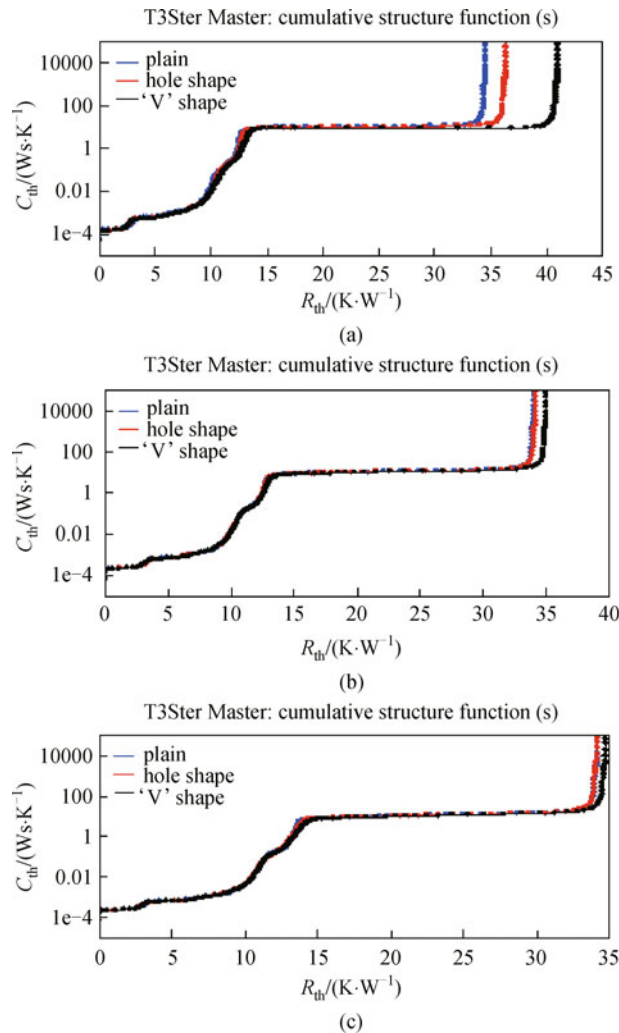


Fig. 6 Cumulative structure function of plain and surface modified heat sink recorded at (a) 100 mA, (b) 350 mA and (c) 700 mA

was higher for plain surface due to low BLT than those for other two surfaces. Particularly, the interface at MCPCB and 'V' shaped surface has low heat capacitance and high resistance.

3.2 Optical performance

The CCT of the given 3 W green LED was recorded and plotted against the LED burning time as given in Fig. 7. It clearly shows that CCT values are high for surface modified ('V' and hole shaped) heat sink at all measured driving currents. Particularly, 'V' shaped surface shows high value for lower driving currents (100 and 350 mA). No difference in CCT values is observed for the modified surface at 700 mA. The color temperature or CCT over 5000 K are called cool colors, while lower color temperatures (2700–3000 K) are called warm colors¹⁾.

1) <http://www.handprint.com/HP/WCL/color12.html>

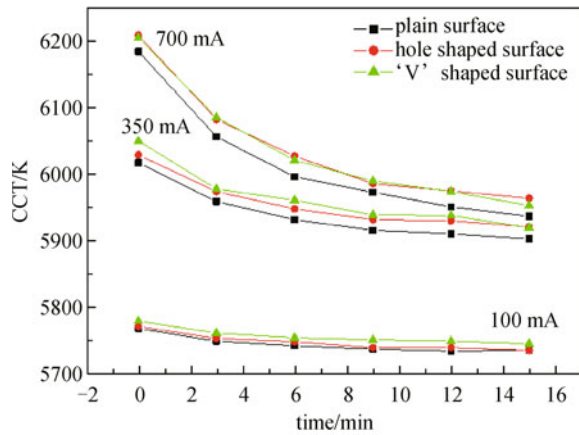


Fig. 7 Variation of CCT values with respect to measuring time for 3 W green LED fixed on plain and surface modified heat sink

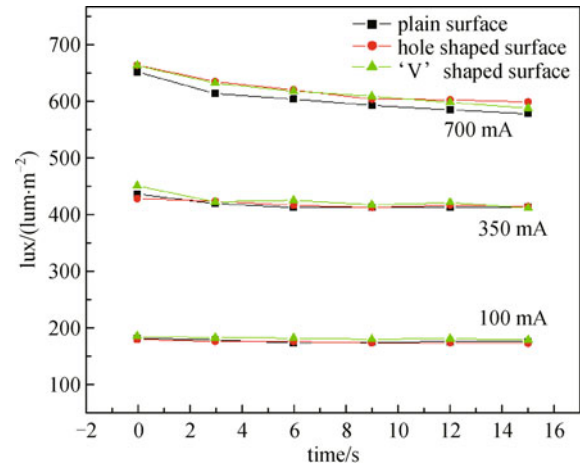


Fig. 8 Change in lux of 3 W LED against measuring time at various driving current for plain and surface modified heat sink

According to Wien's displacement law, the spectral peak is shifted towards shorter wavelengths for higher temperatures. The observed results are obeyed the Wien's concept and the CCT value increases as the current input increases and hence the λ peak is shifted to shorter wavelength from 542 to 539 nm [11,12]. Over all, the CCT values decreases as the driving times increases. It is due to the effect of increasing T_J as with light burning time increases.

In addition to CCT values, variation of lux as a result of surface modification for given LED was also recorded for various driving currents. The measured value is shown in Fig. 8. It reveals that the surface modification does not have much influence on the lux levels of the given LED for lower driving currents (100 and 350 mA). But noticeable increase in lux could be observed for both modified surfaces (hole and 'V' shaped) at 700 mA when compared to plain surface. It is attributed to the effect of lower thermal resistance in the modified surface than those in plain surface at high driving currents. This could be explained by the increased contact surface area by machining the top plain surface of heat sink [9].

CRI is a index of how accurately an artificial light source displays colors. The higher the CRI, the better the artificial light source is at rendering colors accurately. In order to study the influence of surface modification on CRI for 3 W green LED, the CRI values were recorded for modified surfaces at different driving currents and observed that the variation in CRI values are ± 3 . According to reported results¹⁾, the differences in CRI values of less than five points are not significant.

4 Conclusions

The surface of commercial heat sink was machined in two

different geometry (hole and 'V' shape) and the thermal performance of 3 W green LED was tested with modified surface. The observed T_J values was higher for 'V' shaped surface than that for hole surface since the contact surface area was small. The surface modification influenced the change in T_J , and it was high at higher driving current. R_{th-tot} values were also dependent on the modified surface, and it was higher for 'V' shaped surface. The interface resistance $R_{th-b-hs}$ was decreased even for reduced material quantity for hole shaped surface. The CCT and lux values for the given LED were high for the surface modified heat sinks at all driving currents.

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