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Can thermocouple measure surface temperature of light emitting diode module accurately?

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ABSTRACT

Thermocouple is often used to measure surface temperature of light emitting diode (LED). However, it was found that the method was not accurate in this work. An experiment was conducted to prove this in the first part. In the experiment, the air temperature above a lit LED chip was measured by a thermocouple, and it was found the measurement temperatures were higher than the LED junction temperatures. When the drive current was 1000 mA, the deviation reached as much as 148.61%, which proved that the temperature measured by the thermocouple was not accurate. The reason for the inaccuracy was supposed to be the absorption of the optical energy by the thermocouple. Theoretical derivation was conducted and it was found that the measurement temperature was related with the local luminance around the thermocouple and the optical absorption coefficient of the thermocouple. Comparison experiments were conducted and qualitatively validated the supposition.

1. Introduction

Light emitting diode (LED), as a new solid-state light source with a series of advantages such as high efficiency, low consumption and long life time, has been being widely used [1–3]. LED junction temperature, as a critical parameter which affects performances and reliability of LED product, needs to be obtained for performances and life evaluation [4–8]. Generally, there are three methods to measure the temperature of LED, which are electrical method, optical method, and physical contact method [9].

Electrical method bases on the theory that electrical properties of semiconductor devices can be strong functions of temperature. It is the most accurate way to measure the junction temperature [10–12]. Optical method, using the optical properties as a thermometer, is the better choice for measuring the junction temperatures of array packaging LEDs [13–16]. Both the electrical method and the optical method can accurately measure the junction temperature of LED. However, they need expensive instruments and professional operators.

Physical contact method like thermocouple measurement is often used to measure temperature of LED in the industry because of its low cost and easy maintenance. Because the thermal resistance between the junction and the LED surface is not big, the surface temperature sometimes is used to roughly evaluate the junction temperature, especially for the conventional LED chip. Therefore, the temperatures of the phosphor layer or silicone layer coating on the LED chip are measured to estimate the junction temperature or just obtain the temperatures of themselves [17–19].

Thermocouple can be used to measure the surface temperature of LED. However, is this measurement accurate? In this work, a simple experiment was conducted and proved such a measurement was not accurate and it was strongly affected by optical irradiation. A model was developed and a comparison experiment was conducted to validate the supposition.

2. Experiment

To simplify the judgment of thermocouple measurement accuracy, we measured the air temperature above a bare LED chip packaged on the leadframe. The measurement system is shown in Fig. 1. As shown in the figure, a bare LED chip was mounted on a leadframe, and no phosphor layer or silicone was coated on the chip. A K-style thermocouple was vertically hanged above the center of the chip, and materials for each thermocouple wires are alumel and chromel, respectively. The diameter of the thermocouple wire and bead are 0.3 mm and 0.5 mm respectively. The distance between the top surface of LED chip and the thermocouple bead was about 0.8 mm. The measurement system, including the thermocouple and the LED module, was placed in a close glass box to avoid the disturbance from surrounding.

When measuring the air temperature above the bare LED chip, we also measured the LED junction temperature with a commercial electrical junction tester at the same time. Eight groups of measurement data were obtained with the drive current changing

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Nomenclature

A	optical absorption coefficient of thermocouple
B_i	Biot number, $B_i = hd/\lambda$
c	heat capacity of thermocouple, J/(kg K)
$c1$, $c2$	undetermined parameters in general solution
d	diameter of the idealized thermocouple, m
h	idealized convective coefficient, W/(m^2 K)
$h(z)$	convective coefficient function around thermocouple, W/(m^2 K)
$I(z)$	luminance distributed function around thermocouple, W/m^2
$J(z)$	quadratic integral function of $-I(z)$, $J(z) = -\int\left[\int I(z)dz\right]$
$J'(z)$	first derivative of $J(z)$
m	user-defined variable, $m^2 = 2h/(\lambda r)$
n	user-defined variable, $n = \frac{\lambda m J(0)+\lambda J'(0)-I(0)}{\lambda m-h}$
Q_h	heat exchanged through convection, W
Q_o	heat transferred from optic energy, W
Q_r	heat exchanged through radiation, W
Q_v	internal energy increment of the infinitesimal element, W
Q_z	heat flowing into the infinitesimal element through conduction, W
Q_{z+dz}	heat flowing out of the infinitesimal element through conduction, W

Greek symbols

ρ	density of thermocouple, kg/m^3
ε	emissivity of thermocouple
σ	Stefan–Boltzmann constant, W/(m^2 K^4)
τ	time, s
r	radius of the idealized thermocouple, m
t	temperature of thermocouple, °C
t_a	ambient temperature, °C
t_b	temperature of the thermocouple bead, °C
θ	temperature access, $\theta = t - t_a$, °C
λ	thermal conductivity, W/(m K)

Subscripts

a	ambient
b	bead of thermocouple

from 300 mA to 1000 mA with an increment of 100 mA, which is listed in Table 1. The LED powers correspondingly increase from about 0.86–2.86 W with an increment of about 0.29 W.

It was found that the measurement temperature above the LED chip was higher than the LED junction temperature. If this is true, the heat will flow from the air to the LED chip based on the second law of thermodynamics. However, this is impossible and, undoubtedly, the real temperature of the air above the LED chip is lower than the LED junction temperature. So we can conclude that the temperature of air above the LED chip measured by thermocouple is not accurate.

3. Supposition, model development and validation

How does the inaccuracy of the thermocouple measurement come from? The thermocouple had been calibrated and rightly used, and the data acquisition instrument also normally worked, so the inaccuracy could not result from the incorrect use of thermocouple or instrument failure. We analyzed the energy exchange of the thermocouple, as shown in Fig. 2. Energy exchange happened between the thermocouple and the ambient through convection and radiation, while these wouldn't lead to a high measurement temperature. It was noticed that the thermocouple was irradiated by the light emitted from the LED chip. If part of light, which contains energy, was absorbed by the thermocouple and transferred to heat, it would bring a high thermocouple temperature and show an inaccurate measurement result.

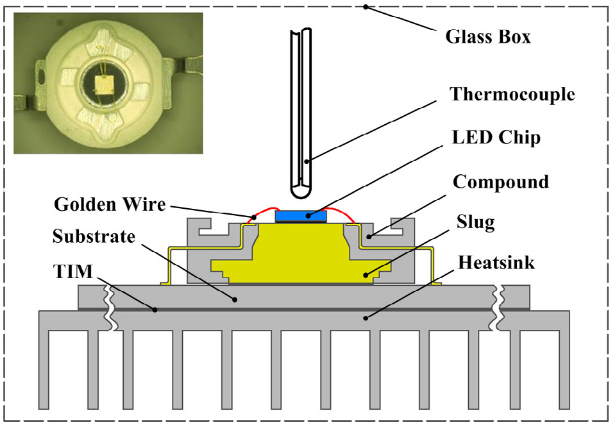

Fig. 1. Sketch of measurement system.

We suppose that the inaccuracy of the thermocouple measurement results from the absorption of optical energy by the thermocouple. If this is true, the measurement temperature of the thermocouple will change when the absorbed optical energy varies. To validate this supposition, we conducted the theoretical derivation based on the energy balance of the thermocouple. To simplify the theoretical derivation, the thermocouple model is idealized as an entire columnar structure, as indicated in Fig. 3. Then we focus on an infinitesimal element to analyze the temperature field.

Because the Biot number of the thermocouple $B_i = hd/\lambda = 9.7 \times 10^{-5}$ (Assuming $h = 5$ W/(m^2 K), $d = 0.0005$ m. $\lambda = 27$ W/(m K)) is quite small, the thermocouple temperature can be regarded as uniform at the same height. Therefore, the thermal conduction can be considered as one dimensional in the length direction.

The energy balance equation for the infinitesimal element is shown as following,

$$Q_z + Q_o = Q_v + Q_{z+dz} + Q_h + Q_r \tag{1}$$

where Q_z is the heat flowing into the infinitesimal element through conduction, Q_o is the heat transferred from optic energy, Q_v is the internal energy increment of the infinitesimal element, Q_{z+dz} is the heat flowing out of the infinitesimal element through conduction, Q_h is the heat exchanged through convection, Q_r is the heat exchanged through radiation. They can be obtained with the equations as following,

$$Q_z = -\lambda\pi r^2 \frac{dt}{dz} \tag{2}$$

$$Q_o = aI(z)2\pi r dz \tag{3}$$

$$Q_v = \rho c \pi r^2 dz \frac{dt}{d\tau} \tag{4}$$

Table 1
Measurement results of junction temperature and air temperature.

No.	Drive current (mA)	LED junction temperature (°C)	Measurement temperature above LED (°C)	Deviation rate (%)
1	300	34.92	71.6	105.05
2	400	37.78	82.8	119.15
3	500	39.84	93.8	135.46
4	600	42.87	104.6	144.00
5	700	46.72	114.8	145.71
6	800	50.33	124.0	146.40
7	900	53.85	133.2	147.35
8	1000	57.08	141.9	148.61

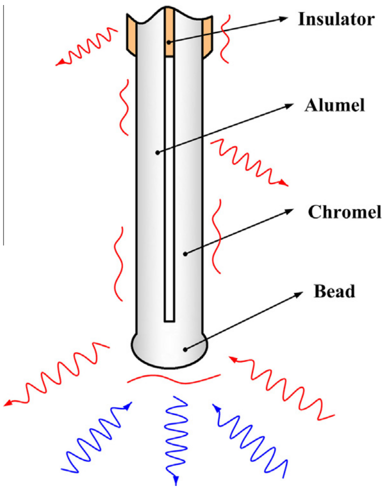

Fig. 2. Energy exchange schematic of thermocouple above lit LED chip.

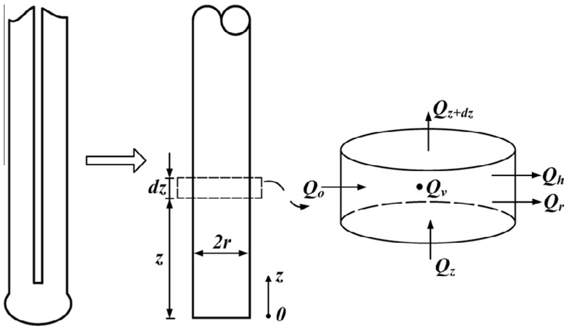

Fig. 3. Skecth for theoretical derivation.

$$Q_{z+dz} = Q_z + \frac{dQ_z}{dz}dz = -\lambda\pi r^2\frac{dt}{dz} - \lambda\pi r^2\frac{d^2t}{dz^2}dz \tag{5}$$

$$Q_h = h(z)(t - t_a)2\pi r dz \tag{6}$$

$$Q_r = \varepsilon\sigma 2\pi r dz(t^4 - t_w^4) \tag{7}$$

where λ is the thermal conductivity of the thermocouple, a is the optical absorption coefficient of the thermocouple, $I(z)$ is the luminance distributed function around the thermocouple, ρ is the density of the thermocouple, c is the heat capacity of the thermocouple, $h(z)$ is the convective coefficient function around the thermocouple, t_a is the ambient temperature, ε is the emissivity of the thermocouple surface, σ is the Stefan–Boltzmann constant, t_w is the wall temperature around the measurement system.

For the steady state, Q_v always equals to 0. The temperature of the thermocouple is not high, so the radiant energy can be neglected. Then the Eq. (1) can be expressed as

$$\frac{dt^2}{d^2z} = \frac{2h(z)}{\lambda r}(t - t_a) - aI(z) \tag{8}$$

The temperature gradient is not large in this work, so $h(z)$ is assumed as a constant h. Supposing $\theta = t - t_a$, $m^2 = \frac{2h}{\lambda r}$, Eq. (8) can be expressed as

$$\frac{d\theta^2}{d^2z} = m^2\theta - aI(z) \tag{9}$$

The general solution of Eq. (9) is

$$\theta = c_1e^{mz} + c_2e^{-mz} + aJ(z) \tag{10}$$

where

$$J(z) = -\int\left[\int I(z)dz\right]dz \tag{11}$$

The boundary conditions are

$$\theta = 0, \quad at \quad z = \infty,$$

$$-\lambda\frac{d\theta}{dz} = h\theta - aI(z) \quad at\ z = 0 \tag{12}$$

Thus,

$$c_1 = 0, \quad c_2 = \frac{haJ(0) + \lambda aJ'(0) - aI(0)}{\lambda m - h}$$

$$\begin{aligned}\theta &= \frac{haJ(0) + \lambda aJ'(0) - aI(0)}{\lambda m - h}e^{-mz} + aJ(z)\\ &= \left(\frac{hJ(0) + \lambda J'(0) - I(0)}{\lambda m - h}e^{-mz} + J(z)\right)a\end{aligned} \tag{13}$$

$$t = \left(\frac{hJ(0) + \lambda J'(0) - I(0)}{\lambda m - h}e^{-mz} + J(z)\right)a + t_a \tag{14}$$

The temperature of the thermocouple bead is

$$t_b = \frac{\lambda mJ(0) + \lambda J'(0) - I(0)}{\lambda m - h}a + t_a = na + t_a \tag{15}$$

where $n = \dfrac{\lambda mJ(0) + \lambda J'(0) - I(0)}{\lambda m - h}$.

λ, m and h depend on the thermocouple material, dimension and thermal boundaries, and they are approximate constant for the same thermocouple in the measurement, so the value of n mainly varies with the local luminance around the thermocouple. Because the ambient temperature t_a is fixed, it can be seen form Eq. (15) that the shown temperature is related with the local luminance around the thermocouple and the optical absorption coefficient of the thermocouple. When the local luminance is fixed, the shown temperature of the thermocouple is in proportion to the

Table 2
Thermocouple measurement temperatures before and after blackening treatment.

No.	Current (mA)	Measurement temperature before treatment (°C)	Measurement temperature after treatment (°C)	Change (%)
1	300	71.6	78.1	9.08
2	400	82.8	90.8	9.66
3	500	93.8	102.8	9.59
4	600	104.6	113.9	8.89
5	700	114.8	124.1	8.10
6	800	124.0	134.1	8.15
7	900	133.2	144.0	8.11
8	1000	141.9	153.6	8.25

optical absorption coefficient a. Also, when the optical absorption coefficient a is fixed, the shown temperature mainly depends on the local luminance.

To qualitatively validate Eq. (15), we conducted a comparison experiment. The surface of the same thermocouple was sprayed with carbon coating to obtain black surfaces. In the spraying process, once the relative position between the thermocouple and the LED module changed, it was difficult to recover and would lead to a meaningless comparison experiment. Therefore, we covered the LED module and carefully treated the thermocouple surface without any move of the thermocouple and LED module. After the blackening treatment, the optical absorption coefficient must be increased. Then the same thermocouple measurements at different LED input currents were conducted. Obviously, different LED input currents denote different luminances. The results are listed in Table 2.

In Table 2, the temperature change varies with input current (luminance) and thermocouple treatment (optical absorption coefficient). For the same current, which means the same luminance, the measurement temperatures increase after the thermocouple was blackening treated, and the temperature increase rate appears in a narrow range (between 8% and 10%). This validates that the measurement temperature is nearly linear with optical absorption coefficient, which fits the Eq. (15) well.

Combining Tables 1 and 2 to analyze, it can be seen that the difference between thermocouple measurement result and the real junction temperature increases with the increment of the input current (namely local luminance). This proves that the measurement error also depends on the local luminance. Therefore, it can be concluded that the thermocouple measurement inaccuracy results from the optical absorption. Since the thermocouple measurement error is caused by the absorption of optical energy, there are two methods to reduce the deviation. One is decreasing the optical absorption coefficient, for example, making a polish of the thermocouple surface. The other one is decreasing the thermocouple diameter, which reduces the optical absorption area and leads to less optical absorption. It should be noted that for the common use of thermocouple, because the luminance is very low, the error caused by the optical absorption can be neglected.

4. Conclusions

The thermocouple is often used to measure the LED surface temperature. In this work, we investigated the accuracy of such a measurement method. A measurement experiment was designed and it was found that the temperature of air above the LED chip measured by the thermocouple was higher than the LED junction temperature, which is unreasonable. This proved that such a measurement is not accurate. It was supposed that the inaccuracy resulted from the absorption of optical energy. Theoretical derivation was presented and comparison experiment was conducted to validate this supposition. The results showed that the measurement error depends on the local luminance around the thermocouple and the optical absorption coefficient of the thermocouple.

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