Two characteristic parameters for the junction temperature of white LED*

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This paper proposes a method for characterizing the junction temperature of light-emitting diodes (LEDs) by using two parameters, and the selected reference method is used to eliminate the self-heating effect of white LEDs. The constant current source is used to drive, which improves the practicability and reduces the measurement cost. The junction temperature of cold and warm white LED is measured with a small current of 50—400 mA as the driving current. The studied ambient temperature range is 30—80 °C. The results show that the relationship between the spectrum valley value of the calibration function, the full width at half maximum (*FWHM*), driving current, and junction temperature can be combined with a high degree of the fitting. Compared with the measurement results of the forward voltage method, the maximum error of the measurement of the two-parameter joint characterization junction temperature method is only 2.38 °C. It is a low-cost, practical, and effective junction temperature measurement method for white LEDs.

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Light-emitting diode (LED) is a common light-emitting device[1]. Because of its advantages of energy saving, green, long life, and good color rendering, it is gradually replacing traditional lamps and becoming a widely used lighting source[2]. However, a large amount of electrical energy is converted into thermal energy during LED luminescence, which makes the LED have significant problems in thermal performance[3]. Junction temperature is the basic thermal parameter of LED devices. Generally, with the increase in LED junction temperature, the recombination rate of effective carriers in the device will decrease, and the outgoing photons will decrease immediately, resulting in a decrease in luminous flux. At the same time, the energy loss inside the LED is one of the main reasons for the increase in the PN junction temperature. Excessive junction temperature directly affects the lighting quality and reliability of LED products[4-6].

Currently, the methods of measuring LED junction temperature mainly include contact type and non-contact type. A typical contact measurement method-forward voltage detection is a benchmark method for measuring LED junction temperature, which has been written into international standards[7]. However, this method requires fast and error-free contact with the LED pin when measuring the voltage, which has high technical requirements, and it is difficult to contact the pins in the measurement due to the limitations of the finished LED in terms of housing and package. There are many non-contact measurement methods, for instance, infrared thermal imaging[8], blue-white ratio method[9], peak wavelength shift method[10], full width at half maximum (*FWHM*), relative radiation intensity method, centroid wavelength method, center wavelength method[11], relative radiation intensity method, etc. Since the non-contact measurement method does not need to destroy the finished LED package structure and contact the pins, the demand and practical value of the non-contact measurement method are more extensive.

In 2004, HONG et al[10] proposed to characterize the junction temperature of AlGaInP-based LEDs with peak wavelength offsets. In 2012, LIN et al[12] proposed to characterize the junction temperature of GaN-based LEDs with centroid wavelengths or *FWHM* in combination with drive currents. In 2013, QIU et al[13] found that the radiation intensity of white LED radiation at a wavelength of 485 nm has a minimal value, and the radiation intensity of this wavelength has an excellent linear relationship with the LED junction temperature. In 2014, GU et al[14] found that the value of the blue-white ratio W/B was linearly related to the junction temperature. In 2016, KE et al[9] used the spectral decomposition method to optimize further the blue-white ratio method, which can more accurately measure the junction temperature of dual phosphor conversion white LEDs. In 2020, RAO et

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al[15] used the forward voltage method to measure the junction temperature of the dual phosphor conversion white LED when measuring different substrate temperatures and different current drives, and at the same time, selected the blue spectrum of the chip to obtain a pattern of changes between the centroid wavelength, *FHWM*, drive current and junction temperature. In the same year, JIANG et al[6] designed an LED junction temperature test system based on characteristic spectral parameters by analyzing the spectrum valley characteristics of YAG-type white LEDs using conventional visible light spectrometers and temperature control systems.

The above measurement methods primarily use a pulse power supply to provide pulse current, significantly increasing the measurement cost. The junction temperature is usually closely related to the drive current, in the case of driving current change, the calibration function of *FWHM* and valley is used to characterize the junction temperature of cool and warm white LED in this paper, and the two-parameter value can intuitively find the corresponding junction temperature.

Junction temperature cannot be inferred from the surface temperature. Therefore, the selected reference state method[6] reduces the self-heating effect of LEDs caused by the constant current power supply. The spectral parameters refer to *FWHM* and valley value of the LED luminous spectrum. *FWHM* is the difference between the longer wavelength and the shorter wavelength at the luminous spectrum of the blue light chip, which is the wavelength interval corresponding to 1/2 of the maximum spectral radiation power:

$$FWHM = \lambda_L - \lambda_S, \tag{1}$$

where λ_L is the longer wavelength, and λ_S is the shorter wavelength. *FWHM* reflects the degree of concentration of the spectral distribution of white LEDs, and it is better to characterize it with *FWHM* than the centroid wavelength[12].

The luminescence principle of fluorescent white LEDs is to produce white light by mixing part of the blue light that transmits the phosphor with the yellow light excited. From the perspective of the entire spectral curve, the valley (P) is formed by the intersection of the luminescence spectrum of the blue light chip and the yellow light spectrum generated by the excitation phosphor, which can reflect both the performance of the yellow light and the blue light temperature and can more fully reflect the temperature of the LED[9,16].

In order to eliminate the influence of the self-heating effect and the accuracy of the temperature control system in the measurement process and improve the linear fit of the spectral parameters and the junction temperature, the state at a certain temperature is selected as the reference state. Set the corresponding base junction temperature as T_b. The base full width at half maximum is $FWHM_b$, the basic spectral intensity of the spectral valley point is P_b, and i is the current driving value at that time. The formula is applied as follows:

$$\Delta T_j = T_{j(i)} - T_b, \tag{2}$$

$$\Delta FWHM_{(i)} = FWHM_{(i)} - FWHM_b, \tag{3}$$

$$\Delta T_j = f(\Delta FWHM_{(i)}). \tag{4}$$

The difference between the junction temperature $T_{j(i)}$ and $FWHM_{(i)}$ with their base values are given as Eq.(2) and Eq.(3), respectively, and Eq.(4) is obtained by fitting, that is, the calibration function of the junction temperature and the *FWHM* is obtained.

$$\Delta P_{(i)} = P_{(i)} - P_b, \tag{5}$$

$$\Delta T_j = g(\Delta P_{(i)}), \tag{6}$$

$$\Delta FWHM_{(i)} = \varphi(\Delta P_{(i)}). \tag{7}$$

The difference between $T_{j(i)}$ and the valley value $P_{(i)}$ with their base values are given as Eq.(2) and Eq.(5), respectively, and after fitting Eq.(6), the calibration function g of the junction temperature and the valley value is obtained. Select the state at the same temperature as the basic state, that is, the ΔT_j in Eq.(4) and Eq.(6) are equal, and Eq.(7) can be derived.

The measurement samples were selected from the typical CREE LED products on the market for experiments with five LEDs of each color temperature[17]. The rated current is 350 mA, the rated power is 1 W, the color temperature of cool white LED is 6 500 K, and the color temperature of warm white light is 4 500 K.

The experimental system for two-parameters joint characterization of LED junction temperature measurement is mainly composed of SPD3303X constant current source, Labsphere USB-2000 optical fiber spectrometer[18], LFC software, integrating sphere, and thermostat, where the constant current source provides a stable constant current drive for the LED test samples with a current error of ±0.1 mA. The thermostat provides a stable ambient temperature for the LED with an error of less than 1 °C. The integrating sphere and fiber optic spectrometer are used to quickly and accurately analyze the LED spectral data, and the experimental schematic diagram and physical diagram are shown in Fig.1.

The operating steps of the two-parameters joint characterization LED junction temperature measurement system are as follows.

(1) First, the spectrum and luminous flux of the LED lamp beads at 250 mA are measured with the integrating sphere and spectrometer system.

(2) Fix the LEDs in the thermostat, adjust the position of the fiber, and keep the fiber fixed, so that the spectrum and luminous flux measured are the same as in step (1).

(3) The thermostat keeps the temperature stable at 30 °C for 30 min to make the LEDs reach a thermal equilibrium state, with the drive current as the variable, and the driving current was set from 50 mA to 400 mA with a 50 mA increment so that the LEDs emit light, and the spectrometer quickly measures the data.

(4) Adjust the thermostat to keep at 40 °C, 50 °C, 60 °C, 70 °C, and 80 °C, respectively. Repeat the constant current operation in step (3) above, so that the LEDs emit

light, and the spectrometer quickly measures the spectral data and records the data.

(5) The relationship between *FWHM*, valley, and junction temperature under different drive currents is obtained by data collation, and $\Delta FWHM_{(i)}=\varphi(\Delta P_{(i)})$ is obtained by combining the selected reference state method.

(6) ΔP combined with the selected reference state method is taken as the abscissa, and $\Delta FWHM$ is taken as the ordinate to mark the data points, iso-temperature lines and iso-current lines.

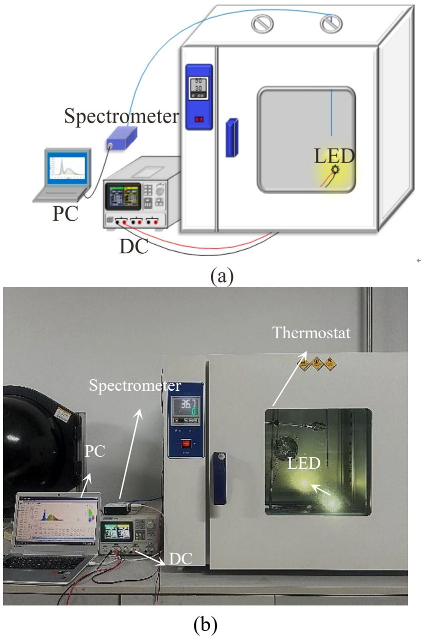

Fig.1 (a) Schematic diagram and (b) physical diagram of a two-parameter joint characterization LED junction temperature measurement system

The state under 50 °C is randomly selected as the reference state. Tab.1 shows the calibration function, *R*-squares, and root mean square error (*RMSE*) of *FWHM* and junction temperature fitting of cool white LED under the driving current of 50—400 mA. It can be seen from Tab.1 that the fitting results of *FWHM* and junction temperature under each driving current are in line with the linear relationship, and *R*-squares are all greater than 0.974, indicating a high degree of the fitting.

Tab.1 Calibration function, *R*-squares, and *RMSE* of fitting *FWHM* and junction temperature under different driving currents

Current (mA)	$\Delta T_j=f_1(\Delta FWHM_{(i)})$	*R*-squares	*RMSE*
50	$Y=0.123x+0.534$	0.984	1.482
100	$Y=0.121x+0.164$	0.983	1.454
150	$Y=0.134x-0.135$	0.996	1.336
200	$Y=0.134x-0.087$	0.989	1.003
250	$Y=0.131x+0.197$	0.980	1.113
300	$Y=0.125x-0.344$	0.996	1.121
350	$Y=0.120x-0.182$	0.974	0.817
400	$Y=0.126x+0.135$	0.995	1.142

Fig.2(a) is made from the calibration function given in Tab.1, which is the relationship between ΔT_j and $\Delta FWHM$ under the driving current of 50—400 mA. It can be seen that under different driving currents, the maximum slope span of the calibration function is from 0.119 to 0.134, and the change is less than 0.015.

Similarly, the research object was changed to the warm white LED, and the state under 50 °C was selected as the benchmark state. *R*-squares of 0.991 can be obtained from $\Delta T_j=f_2(\Delta FWHM_{(i)})$ through fitting. *R*-squares are all close to 1, indicating that the fitting degree of the above two cases is high.

As can be seen from Fig.2(a) and (b), an excellent linear relationship between ΔT_j and $\Delta FWHM$ of high and low color temperature LEDs is not significantly related to the change of driving current.

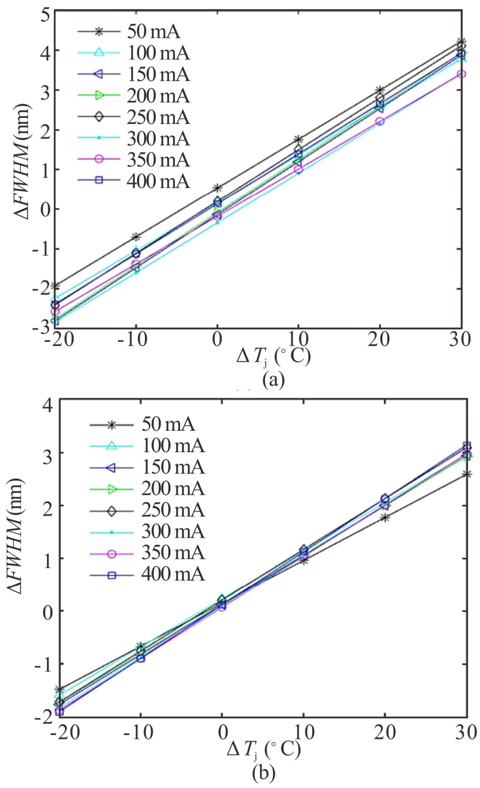

Fig.2 Δ*FWHM* versus ΔT_j of (a) cool white LEDs and (b) warm white LEDs under different currents

The cool white LED is lit at a drive current of 50 mA, with a randomly selected state at 30 °C as the reference state. The difference between the junction temperature T_j and the valley value P was obtained by the difference from the reference value T_{jb} and $P_b=0.345\times10^3$ W/nm, respectively, to get ΔT_j and $\Delta P_{(50\text{ mA})}$.

After selecting the base state, the experimental data are fitted. As shown in Fig.3(a), it can be seen that the slope of the calibration function of the valley value and junction temperature increases with the increase of the current, because the yellow light emitted by the phosphor increases with the increase of the junction temperature, and the valley between the blue light and the yellow light increases more significantly with the increase of the junction temperature. As the drive current increases, the valley value changes faster and faster.

By fitting the original spectral data to obtain the calibration function $\Delta T_j=g(\Delta P_{(i)})$, Tab.2 is the calibration function of the valley and junction temperature fitting and R-squares for the warm white LED in different driving currents, it can be intuitively seen that the fitting R-squares are above 0.96, and Fig.3(b) is obtained from the data in Tab.2.

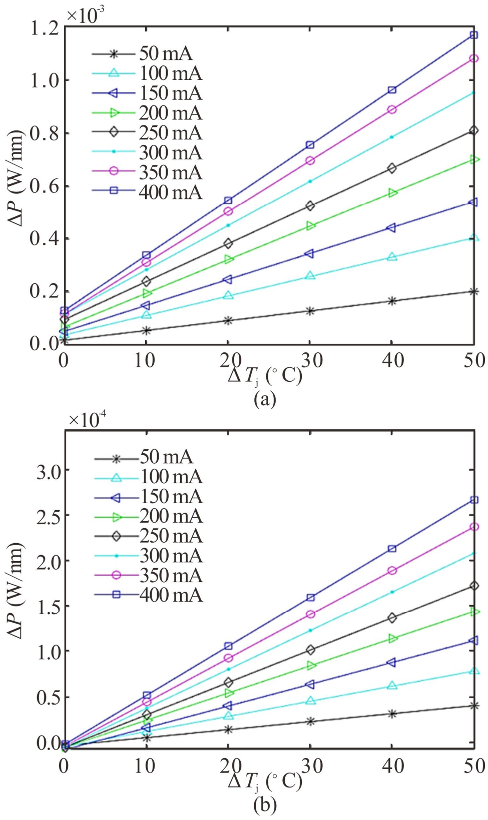

Fig.3 Δ*P* versus Δ*T*j of (a) cool white LEDs and (b) warm white LEDs under different currents

Tab.2 Calibration function and *R*-squares of the trough and junction temperature fitting of warm white LED under different driving currents

Current (mA)	$\Delta T_j=f_1$ ($\Delta FWHM_{(i)}$)	R-squares
50	Y=0.876×10⁻⁶x−3.587×10⁻⁶	0.980
100	Y=1.657×10⁻⁶x−4.662×10⁻⁶	0.989
150	Y=2.389×10⁻⁶x−7.975×10⁻⁶	0.985
200	Y=2.984×10⁻⁶x−5.487×10⁻⁶	0.993
250	Y=3.550×10⁻⁶x−5.251×10⁻⁶	0.988
300	Y=4.264×10⁻⁶x−5.199×10⁻⁶	0.991
350	Y=4.825×10⁻⁶x−4.273×10⁻⁶	0.990
400	Y=5.386×10⁻⁶x−2.150×10⁻⁶	0.964

In Fig.3(a) and (b), it can be intuitively seen that the valleys of white LEDs of different color temperatures increase with the current drive increase at the same junction temperature.

The relationship between the calibration function of the white LED, $\Delta FWHM_{(i)}=\varphi(\Delta P_{(i)})$, and the driving current and junction temperature are shown in Fig.4(a) and (b).

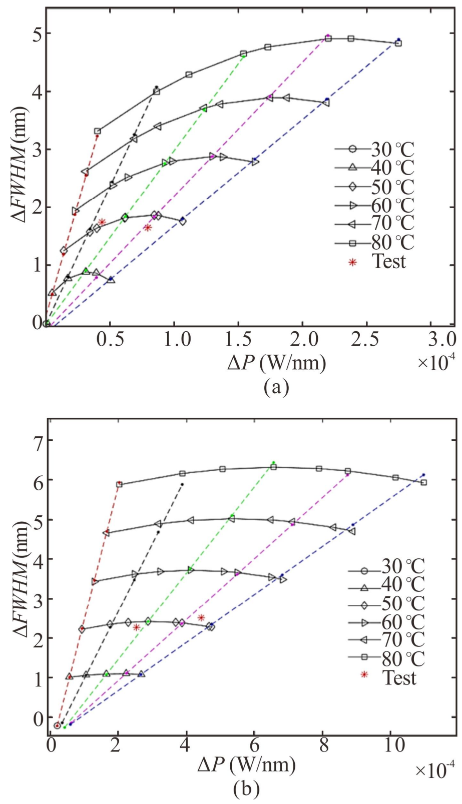

Fig.4 Δ*FWHM* versus Δ*P* of (a) cool white LEDs and (b) warm white LEDs under different junction temperatures

The solid lines with the symbols mark in Fig.4(a) and (b) are fitted iso-temperature lines, corresponding from bottom to top at 30 °C, 40 °C, 50 °C, 60 °C, 70 °C, and 80 °C, respectively. The dashed part of the figure from left to right is the iso-current line with drive currents of 50 mA, 100 mA, 200 mA, 300 mA, and 400 mA, respectively. The test with the star symbol mark in the figure is the test point when the test LED is lit, and the corresponding junction temperature can be calculated by using the linear interpolation method according to the coordinates of the test point in the figure. Tab.3 shows the comparison of the test results by using this method and the forward voltage method Mentor Graphics T3ster test instrument. The following table compares the cool and warm white LED test point test junction temperature, estimated junction temperature, and difference.

Tab.3 Test values, estimated values, and differences of cool and warm white LED test points

Test object	$T_{j\,(\text{Test by T3ster})}$ (°C)	$T_{j\,(\text{This method})}$ (°C)	ΔT_j (°C)
Cool LED	51.10	52.00	0.90
	49.63	48.20	-1.43
Warm LED	50.97	48.89	-2.08
	48.72	51.10	2.38

The data in Tab.3 shows that compared with the forward voltage method measurement used by Mentor Graphics T3Ster, the maximum junction temperature error is 2.38 °C. The maximum current measurement error is 30 mA, and the above errors are within the acceptable range, indicating that the novel method has a specific practical application value and can accurately measure the junction temperature and real-time drive current of LEDs of different color temperatures.

In this paper, the selected reference method was used to eliminate the effect of self-heating due to the use of constant current power and the accuracy of the temperature control system. Moreover, junction temperature under different drive currents was studied, and the relationship between valley value, *FWHM*, drive current, and junction temperature was established. It was a simple and practical LED junction temperature measurement method that did not need to destroy the packaging structure of LED products.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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