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Dynamic junction temperature measurement for high power light emitting diodes

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Junction temperature of high power light emitting diodes (LEDs), which is crucial for the thermal management of solid-state lighting, needs to be measured accurately. In this paper, a dynamic junction temperature measurement system for LEDs was proposed and the calibration including instrument calibration and factor K calibration were presented. The influence of the fast switch time in dynamic junction temperature test was analyzed and measurement errors caused by sampling delay were quantified. To prove the accuracy of the present system, comparison experiment was conducted. It shows a good agreement between the experimental data and reference value. Experiments also show that the measurement accuracy of the instrument can be up to 0.1 °C, and the standard error of temperature measurement can be controlled within 1%. © *2011 American Institute of Physics*. [doi:10.1063/1.3624699]

I. INTRODUCTION

Light emitting diodes (LEDs) have been widely used in many applications as a new solid-state light source due to its advantages in energy-saving and long life. For LEDs, even with the rapid technology development, there is still more than 70% of electrical power converted into heat due to the still relatively low internal quantum efficiency and light extraction efficiency. The heat makes the chip junction temperature significantly increase, which accelerates the deterioration of electro-optical property of LEDs. Meanwhile, packaging materials will be also degraded to cause device failure because of high junction temperature. Therefore, to achieve high reliability of LED, LED junction temperature should be effectively monitored. Accurate measurement for LEDs junction temperature is a challenging issue in the development of high-power LEDs.

Many methods have been provided to measure LED junction temperature recently. Link *et al.*[1] used the stokes and antistokes shift to measure temperature change, and different Raman scattering spectra were divided with different microregions of the chip to conduct measurement of the junction temperature distribution. Raman scattering spectra proposed in their paper for testing junction temperature needs to take the optical lens away which may damage the LED package. Xi *et al.*[2] had an excellent work for LEDs measurements and they established the relationship between the LED peak wavelength shift and the increase of junction temperature, obtained the function between peak wavelength and junction temperature, and calculated the junction temperature after calibration. Actually, for LED chip with various materials, its peak wavelength is the complex function of junction temperature and can vary significantly with the change of the junction temperature. Lee *et al.*[3] proposed a method by which they implanted a flexible micro-temperature sensor between the LED chip and the lead frame of LED, and junction temperature is typically measured using a thermal resistance measurement approach. However, it is difficult to embed with such sensors due to the cost and other issues.

Evaluation of LEDs junction temperature using electrical testing has extensive applications. The method is to calibrate temperature sensitive parameters (TSP) of LED, and an external heating source is provided to elevate LED temperature at thermal equilibrium, and junction temperature corresponds to the fluctuation of associated electrical parameters. Keppens *et al.*[4] revealed a linear dependence of temperature on the forward voltage if the drive current was chosen within a rather limited range, it provides an important work for junction temperature measurement with electrical testing method. Zong *et al.*[5,6] presented a pulse method to test dc and ac LED thermal resistance. By adjusting heat sink temperature of LED, the forward voltage or current is consistent with the previously loaded pulse voltage or current. The temperature fluctuating amplitude of heat sink is correlated with LED junction temperature. Rencz *et al.*[7] made use of the thermal transient

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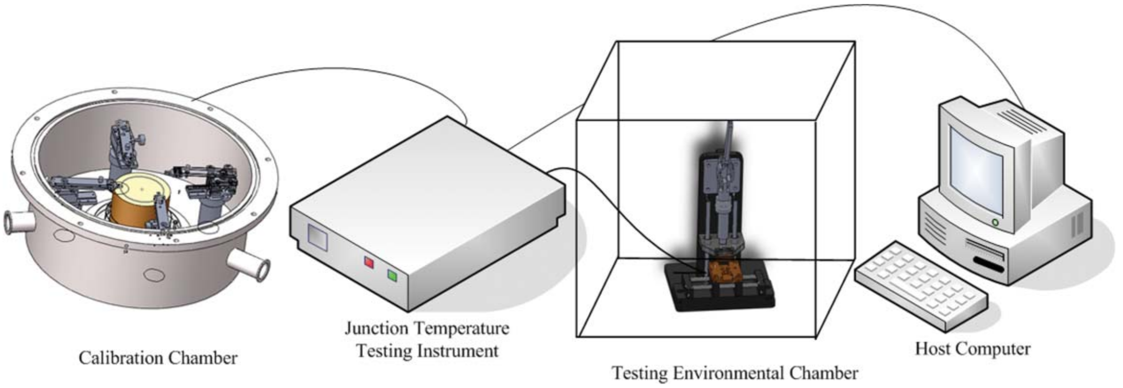


FIG. 1. (Color online) Configuration of junction temperature measurement system.

measurement method to capture the voltage change during the process of heating or cooling, and they used thermal material parameter measurement method based on a structure function to calculate thermal resistance and thermal capacitance, and chip junction temperature can be estimated reasonably by such a proposed method.

Recently, the thermal resistance measurement system has found wide applications in semiconductor industry. They can be used to measure the junction temperature of LED after measuring system thermal resistance. Two famous companies provide such kinds of products. Analysis Technology Incorporation provides a thermal resistance measurement apparatus. In this instrument, the transient testing[8] method was given for the thermal resistance and thermal impedance of power semiconductor devices. Micred Corporation also has an instrument for thermal testing,[9] by which the static testing is used to investigate the thermal characteristics of high power optical devices.

In our previous work, an instrument for transient measurement of LED's characteristic parameters, including photometric parameters, colorimetric parameters, and electrical parameters, was presented.[10]

In this paper, a portable junction temperature measurement instrument was proposed to measure junction temperature for high-power LEDs. A testing environmental chamber was designed to provide exact heat flux boundary condition for the mounted LEDs. A calibration chamber was used to accurately calibrate the factor K value within an extensive temperature ranges, and the accuracy of measurement can be up to 0.1 °C. The instrument is compact and portable with low power consumptions, which can be used to accomplish *in situ* measurement.

II. SYSTEM SETUP

Figure 1 demonstrates the junction temperature measurement system, which mainly consists of junction temperature testing instrument, calibration chamber, and testing environment chamber. The instrument provides the real-time temperature data to a host computer that is coupled to the interface device. Before the junction temperature is measured, the system must be calibrated first. LED module is placed in the calibration chamber where the temperature is rise up with a known step. A testing current is provided to measure the forward voltage drop, and the relationship of forward voltage drop versus junction temperature can be achieved and stored in flash memory of instrument. In the state of testing, a rated heating current is loaded to realize the instant heating for the tested LED. By fast switching method, a narrow testing pulse is provided to achieve signal sampling of the forward voltage drop during a heating period. The above heating and testing time are controlled by pulse width modulation method. In order to measure the various LED modules, some parameters (e.g., heating current, testing current, and heating time) are designed to be adjustable in a certain range.

Figure 2 shows the final prototype of the present system. The calibration chamber is shown in Fig. 2(d), the heat source is provided by the copper pillar heater, which temperature can be controlled from 0 °C to 400 °C, and the accuracy of measurement is up to 0.1 °C. The LED under calibration is placed in the surface of the copper pillar and is pressed by the manipulators. Two thermocouples are placed into this chamber to monitor the flat of temperature profile. One is placed in the inner of the copper pillar, and another is placed in the interface between the heat slug of LED and the upper of copper pillar, which is controlled by proportional integral differential controller.

To obtain the good data sheet for LED modules, a manual test fixture as shown in Fig. 3 is provided to fix on the

FIG. 2. (Color online) Junction temperature measurement system.

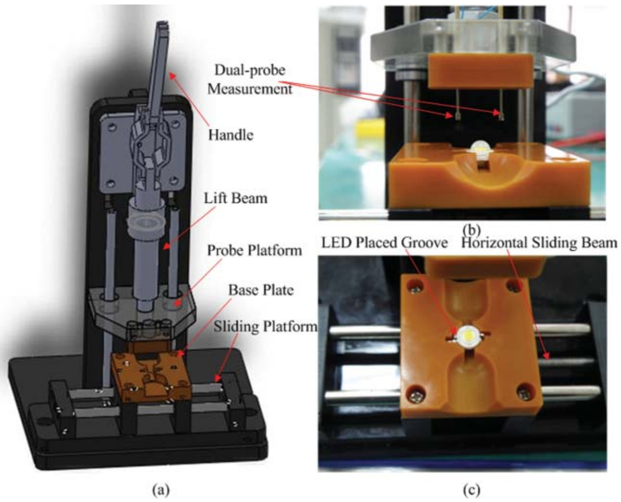


FIG. 3. (Color online) Manual test fixture for LED.

LED modules, and the fixture is inputted inside a cubic enclosure under still-air conditions. It is mainly made up of probe platform, base plate, and sliding platform. The tested LED is positioned into one specific groove of the base plate; the test probes are aligned with the lead frame of the LED for making electrical contact with circuits. The LED is then pressed downward against the test probes by the lift beam. The base plate is designed to allow for adjusting in horizontal direction, and it can be replaced for various packaged LEDs.

In this system, the junction temperatures shown on the panel of instrument are calculated as

$$T_j = T_0 + \Delta V_T / K, \tag{1}$$

where T_0 is the ambient temperature, and it can be obtained by the digital temperature sensor. ΔV_T is the output of TSP. The factor K is the function of the forward voltage with junction temperature, and is defined as

$$K = \left| \frac{V_H - V_L}{T_H - T_L} \right| \ \text{mV/°C}, \tag{2}$$

where T_H and T_L are high and low temperature which can be controlled by the calibration chamber, respectively, V_H and V_L is the corresponding TSP voltage. A micro-processing unit is provided to send the data to the host computer over the serial port at a baud rate of 115 200 bps, and the average effective transmission data rate is about 393 data per second.

It is emphasized that once the factor K value is determined and calibration is completed, the junction temperature testing instrument can work without the calibration chamber, environmental chamber, and the computer. This instrument can be applied for *in situ* measurement. It has the advantages of small volume and being portable.

III. SYSTEM CALIBRATION AND FAST SWITCHING

A. Instrument calibration

Before junction temperature is measured, the outputs of instrument must be calibrated. According to the experiments, the precision and the amplitude of testing current affect the calibration error of instrument. When the testing current variation reaches 1% from the selected value, the output of TSP will change about 4 mV, which corresponds to the measurement error of about 2 °C. Additionally, when the testing current is too large, it leads to the self-heating of chip, which will result in the zero offset change.

B. Factor K calibration

Factor K calibration is the main source of the measurement error in the system. Two factors will influence its precision, on the one hand, the curve of factor K achieved by linear regression have the deviation with the real data in the range of high temperature, on the other hand, the variations of factor K value in various LED samples with the same chip structures will result in the errors because average K value is applied to measure junction temperatures for the same type LEDs in this instrument.

In order to derive the relationship of the forward voltage (*Vf*) with junction temperature, we begin with the *I-V* characteristic of a forward-biased p-n junction diode considering the series resistance R_s,[11] the testing current in this system can be expressed as

$$I_f = I_s \exp\left[\frac{q(V_f - I_f R_s)}{nKT}\right], \tag{3}$$

where I_s is the reverse saturation current, n is the ideality factor, q and K are the constants. Solving the equation for Vf and substituting the corresponding parameters for I_s and R_s, Eq. (3) can be rewritten as

$$V_f = \frac{nkT}{q} \ln \frac{I_f}{CT^r} + nV_{g0} + I_f D T^{-3/4} \exp\left(\frac{-E_a}{2kT}\right), \tag{4}$$

where E_a is the acceptor activation energy, V_{g0} is the potential difference at the conduction-band and valence-band edges at temperature of absolute zero, r is decided by the temperature dependence of the minority carrier mobility, and C and D is the constant and decided by the junction area, dopants with

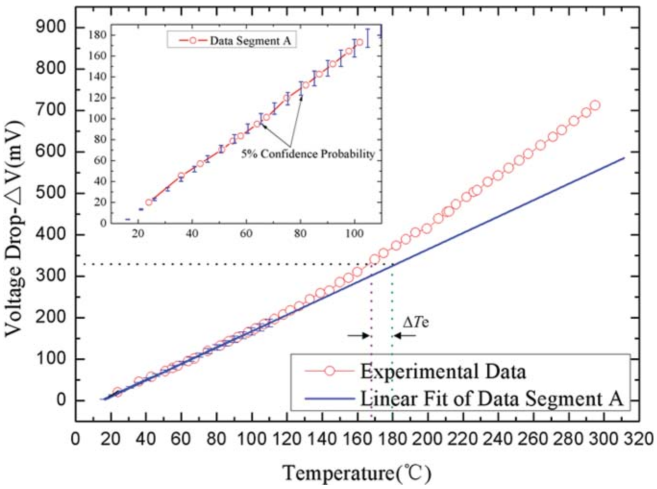


FIG. 4. (Color online) Measured forward voltage drop versus junction temperature.

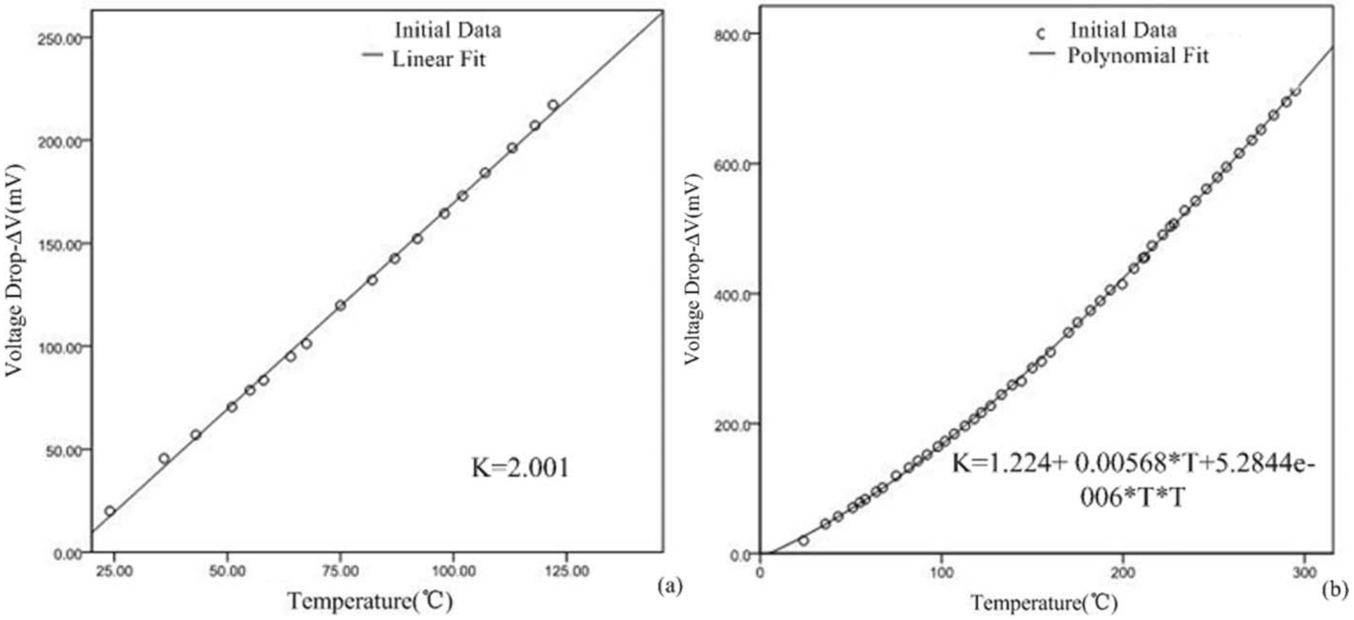


FIG. 5. (a) Linear fitting in the range of 20 °C to 120 °C, (b) polynomial curve fitting in the overall temperature range.

concentration and so on. This equation gives the fundamental temperature dependence of the forward voltage, executing the derivative yields

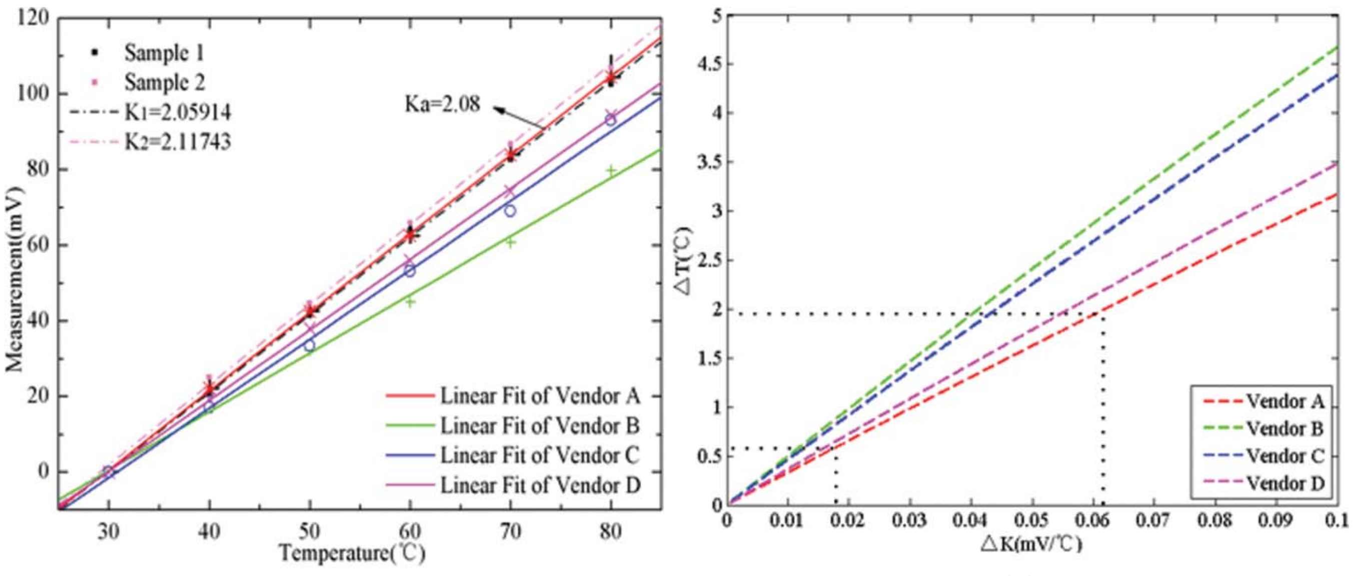
$$\frac{dV_f}{dT} = \frac{nk}{q}\ln\frac{I_f}{CT^r} - \frac{nkr}{q} - \frac{1.5kT + E_a}{2kT^2} I_f R_s. \qquad (5)$$

The above equation is the expression of the temperature coefficient of the forward voltage. When the temperature increases, the first summands on the right side of the equation will change in a direction opposite to the third summands, furthermore, the first summand is a logarithmic function of temperature, and it will decrease more quickly than the third command. Therefore, the factor K, which is the absolute value of the temperature coefficient, will gradually increase with the rise of temperature.

To solve precision problem of the factor K, some blue LED samples are experimentally investigated. The testing current of 650 μA was provided to inspect the changes of the forward voltage drops. Experimental results reveal that the relation between V_f and T is nearly linear in temperature ranges between 0 °C and 120 °C, as shown in Fig. 4, and can be fitted by the equation

$$V_f = a + KT_0, \qquad (6)$$

where T_0 is the oven temperature, the constant a and K are fitting parameters. However, when the temperature is more than



(a) (b)

FIG. 6. (Color online) (a) K calibration curves of four types LEDs, (b) temperature deviation arising from factor K errors.

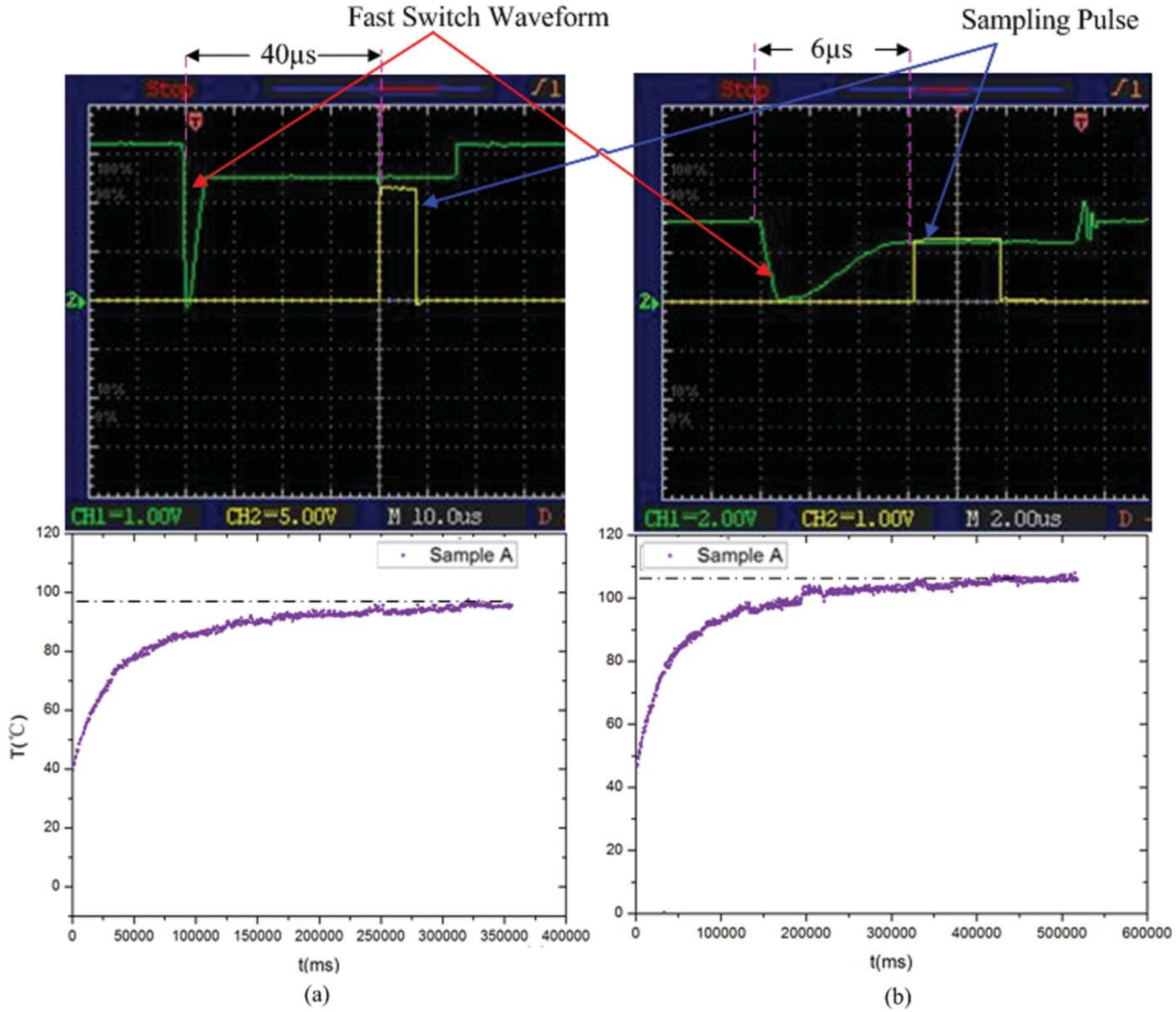


FIG. 7. (Color online) Sampling delays of TSP signal and curves of dynamic junction temperature.

120 °C, the coefficient K increases slowly with temperature. So the new method must be proposed to fit the data.

From Fig. 4, it can be seen that the calibration data keeps a good linearity until 120 °C, and then drifts upward slightly until 300 °C. Therefore, when junction temperature exceeds 120 °C, linear fitting is not suitable for the factor K calibration, the measured temperature is larger than the practical value. It is found that when we use the same constant at all the range, the temperature error ΔT_e will be up to 10 °C as the actual junction temperature is 170 °C.

Based on the curve of calibration, polynomial fit is the best for the data in the range of high temperature. A critical temperature of 120 °C is used to judge various fitting methods for calculating the factor K value. Figure 5(a) shows the linear fitting results which are achieved from the data in the range of low temperature, experiment data shown in Fig. 5(b) indicates

FIG. 8. (Color online) Three kinds of test environments for vendor A samples.

TABLE I. Junction temperature test results.

	T_j (°C)			
Cooling methods	Vendor A	Vendor B	Vendor C	Vendor D
(I)	118.2	116.5	111	86.3
(II)	81.4	82.1	78.2	63.8
(III)	50.1	67.5	61.2	52.5

that polynomial fitting using all of data are better than that just using the data of high temperature.

To evaluate the measurement errors by adopting the average factor K value for every sample, ten LED samples from every vendor were used for calculating K value, as shown in Fig. 6(a). The averaging K value of the vendor A is 2.08, and the standard deviation of the two samples, σ, are about 1% and 1.8%, respectively. When the sample 2 adopted the averaging K value, the tested junction temperature had the deviation of 0.6 °C, approximately.

The tested junction temperature can be expressed as Eq. (1). Its deviation caused by factor K value can be expressed as

$$\Delta T = T_c - T_m = -V_f \times \Delta K/(K_a K_c), \tag{7}$$

where $\Delta K = K_c - K_a$, T_c is the calculated temperature by using K_c, which is the real K value of some samples, T_m is the measured temperature, and it is calculated by K_a, which is the average K value.

Figure 6(b) shows that the deviation between K value and the junction temperature for every vendor. If $\sigma = 3\%$ for vendor A, ΔK is equal to 0.062 mV/°C, and the temperature deviation will be up to 2 °C.

C. Influence of the switching time

During a pulse measurement period, the time from the removal of heating current to the start of testing current is defined as the switching time, the junction temperature has the extremely rapid decrease in this switching time and this time is mainly decided by testing constant current sources and the junction capacitance of the LED. When test samples have considerable electrical rated power, the switching time will be prolonged because of the effect of LED junction capacitance. So sampling pulse must lag behind the switching time for obtaining the effective forward voltage drop. To prove the influence of the switching time, sample A is selected from 1 W GaN-based white light LEDs, 100 μA testing current and 350 mA input current are provided according to the *I-V* characteristic curve of the diodes,[12] sampling delays of TSP signal and curves of dynamic junction temperature in system are shown in Fig. 7, here the heating current provides the forward voltage about 3.2 V and the testing current provides the forward voltage about 2.4 V. The sampling delays are configured to 40 μs and 6 μs, as shown in Figs. 7(a) and 7(b), respectively.

Figure 7(a) shows the final result is about 94.3 °C at 40 μs sampling delay, however, there is a remarkable rise of junction temperature shown in Fig. 7(b), which reaches at 107.5 °C at 6 μs sampling delay.

The above results indicate that a loss of 12.3% of the junction temperature is caused by the 34 μs cooling time difference during the fast switching process. This phenomenon was approved by all of our experiments. So the suitable switch time is also very important for the measurement accuracy.

IV. EXPERIMENTAL TESTS

Some experiments were conducted to evaluate the present junction temperature measurement system. The LED samples from four vendors were selected in the experiments. Junction temperature is measured with three different cooling connections methods by the present instrument, which are shown in Fig. 8. Table I shows that the junction temperature is 118.2 °C in the way of cooling method (I), the tested temperature has a rapid drop accompanying with the increase of the heat sink size. This fits our common senses in the thermal management of LEDs.

In order to verify the accuracy of testing results, the temperatures at the bottom of heat slug in the cooling method (I) were measured with the thermocouples, and the resistance can be calculated by the formula as follows:

$$R\text{th} = (T_j - T_a)/P_d, \tag{8}$$

where P_d is the power dissipation which can be got by the *I-V* characteristic curve, and T_a is the temperature at the bottom of the heat slug. The calculating results are shown in Table II.

Generally, the reference thermal resistance value of the LED module based on the cooling method I can be achieved from the manufacturer, so we use these data for comparison with the results obtained by our instrument. From Table II, it is clear that the error between our tested result and the data provided by the vendors. Taking the sample from vendor D as an example, our calculated result of Rth is ~8.15 K/W, it has a good agreement with reference data by vendor D, in which the value of Rth is 8 K/W. This proves that the test results obtained by the present instrument are reliable.

TABLE II. Results of thermal resistance calculating at cooling method (I).

	T_a (°C)	Rth (K/W)		
Vendors	Heat slug	Calculating value	Reference value	Error
A	102.7	13.48	13.6	0.0088
B	101.4	13.14	13	0.0108
C	98.6	10.82	11	0.0164
D	76.9	8.15	8	0.01875

V. CONCLUSIONS

A portable dynamic junction temperature measurement instrument for LED was developed in this paper. The measurement parameters could be adjusted flexibly for various high power LEDs. The instrument can work independently for *in situ* measurement, and the accuracy of measurement can be up to 0.1 °C. A piecewise fitting method was proposed for reducing calibration error of factor K value. The influence of the fast switch time in dynamic junction temperature test was analyzed, it shows that 12.3% decrease of junction temperature is caused by the cooling time during the fast switch process. Comparison experiments were conducted to prove the present test instrument. Good agreement between the experimental data and reference value was found.

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