Kai HAN, Muqing LIU, Shenglong FAN, Haiping SHEN

Department of Light Sources and Illuminating Engineering, Engineering Research Center of Advanced Lighting Technology, Ministry of Education, Fudan University, China

Improved Electrical Measurement Method for Junction Temperature of Light Emitting Diodes

***Abstract**. The electrical test method (ETM) is used to measure the junction temperature T_j of high brightness LEDs. NI 5922 digitizer and Keithley S2400 source meter were used to build the measurement system. Various measurement currents were used under 1MHz sampling rate. Results of different measurement currents are found to be the same under the same sampling rate and measurement error can be found under low sampling rates. When sampling rate is down to 0.2kHz, measurement error is up to 13.7%.*

***Streszczenie.** Zaproponowano metodę pomiaru temperatury złącza diody LED. Określono błąd metody dla różnych częstotliwości próbkowania. (**Ulepszona metoda pomiaru temperatury złącza diody LED**)*

Keywords: LED; junction temperature; electrical measurement; sampling rate
Słowa kluczowe: diode LED, temperature złącza.

Introduction

As predicted by Hatiz's Law, the lm/lamp of white LED increases 20 times per decade and dollar/lm of white LED falls 10 times per decade [1]. From the world first 1W white power LED LUMILEDS Luxoen I fewer 20 lm/W released in 1999 to the highest lumen efficacy commercial available LED CREE XP-G series max to 132lm/W at cool white today, great breakthrough has been made due to the development of AlInGaN chip manufacture technology, phosphor system and device structure [2]. The improvement of white LED's lumen efficacy and LED's long life time have made LED a competitive green light source for general lighting. However as LED is a semiconductor device, these two advantages of LED greatly depend on temperature [3]. Although LED is known as a highly energy efficient light source, there're still about 2/3 of the input electric energy wasted and finally transferred into heat today. So thermal management of the LED system has always been and will remain the most critical issue in the near future. The junction temperature T_j of LED is the temperature of LED's active layer where carrier injection and photon emission occurs and thus directly affects LED's efficiency and life time. In thermal management, it is important to correctly measure the junction temperature of LEDs under working condition. As LED chip is fragile and well protected in packaging material, it is not easy to get the T_j directly such as using thermal couple. In this case, case temperature T_c which is the temperature of a reference point of the package such as soldering point has been introduced by industries to monitor LED's performance. The thermal resistance from the junction to the reference point is given as a critical device parameter and the temperature of the reference point can be directly measured by thermal couple thus the junction temperature can be calculated. It's a practical and easy way for LED device end users to estimate the junction temperature. But in a high precision situation, the accuracy of this method is not enough.

In addition to case temperature method, several methods have been reported including nematic liquid crystal thermography (NLCT), infrared thermal imaging, electroluminescence method (ELM) and electrical test method (ETM). Each method has its advantages and drawbacks. In NLCT method, the temperature distribution of LED surface is get while in ELM and ETM the measured T_j is average junction temperature. The temperature accuracy is within 1□ and the spatial resolution is high. But in NLCT, a liquid crystal layer needs to be applied onto the chip thus the measurement is usually conducted on a bared chip [4, 5]. Similar to NLCT, the infrared thermal imaging method also uses a CCD camera to catch the temperature distribution of the LED system but with a lower resolution and accuracy. So the former method is better in chip and package level and the later method is more suitable in system level. The emissivity should be carefully selected and could greatly affect the results [6]. LED's surface condition is important to both of the methods. If the LED is encapsulated or covered with phosphor, there will be difficulty in T_j measurement. Indirect methods are commonly used in this case. In these methods, a temperature sensitive parameter (TSP) of the device is selected first and then the relationship between TSP and temperature is found out. So we can get the temperature by measuring the TSP. For ELM, the TSP can be wavelength shift or W/B ratio [7, 8, 9, 10, 11]. For ETM, the TSP is an electrical parameter such as forward voltage V_f of LED. As T_j changes fast and optical TSP changes small, high sampling rate and accuracy is required for spectroradiometer. Electrical parameter is relatively easy to measure so ETM is used in this paper.

The conventional ETM is defined by JESD 51-1 [12]. For LED, the relationship between forward voltage and junction temperature at a certain forward current can be theoretically proved as [13]:

$$k = \frac{V_f}{T_j} = \frac{\sigma}{Q}\ln\left(\frac{I_f}{I_s}\right) \quad (1)$$

where: *k* – factor calibration, V_f – forward voltage, T_j – junction temperature, σ – Boltzmann constant, Q – electrical charge, I_f – forward current, I_s – reverse saturation current.

The V_f is linear with the T_j and the slope k is constant with a fixed forward current. To get k of a certain measurement current I_m, *k* factor calibration is produced. The selected measurement current is applied to LED and V_f is measured at different temperature which is usually provided by oven. In the calibration, I_m is selected small enough to avoid heating the chip and large enough to tell from the noise so the oven temperature can be considered to be T_j. Finally to measure the T_j of LED in working condition, current step is applied to LED and V_f response is measured. See Fig.1. First, forward current is stepped up to I_m to measure the V_{f0} which is the forward voltage at ambient temperature. Assuming I_m doesn't heat the chip, the ambient temperature is considered to be the junction temperature corresponding to V_{f0} and record as T_{j0}. Then, forward current is stepped up to I_H which is the working current to heat the LED system long enough to reach thermal stabilization and provide the working condition. Finally, forward current is stepped down to I_m to measure the V_{f1} which is the forward voltage in working condition and the junction temperature in working condition T_{j0} can be calculated through the following equation:

$$k = \frac{V_{f0} - V_{f1}}{T_{j0} - T_{j1}} \qquad (2)$$

where: V_{f0} – forward voltage at ambient temperature, T_{j0} – junction temperature corresponding to V_{f0}, V_{f1} – forward voltage in working condition, T_{j1} – junction temperature corresponding to V_{f1}.

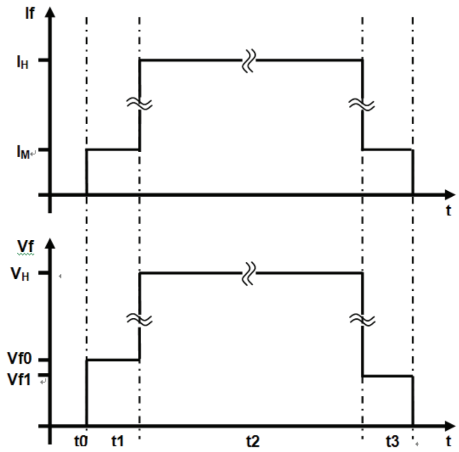

Fig. 1. Test waveform.

However, in practical measurement there are many non-ideal factors. The DC power supply is not ideal, it takes time to step the forward current from I_H down to I_m. Even the forward current steps instantly, there's measurement delay (td) due to the limitation of voltage sampling rate. The V_{f1} sampled is the forward voltage corresponding to the state that the chip has already cooled for at least td. We try to avoid heating effect in calibration and in V_{f0} measurement by selecting small I_m, but there's cooling effect in V_{f1} measurement. Let's consider the other extreme condition. If I_m is I_H, there will be no cooling effect in V_{f1} measurement. But on the other hand, heating effect in calibration and V_{f0} measurement will occur. The cooling and heating effects occur in either or most of time both ends of the measurement. The cause of these two effects is the same. In the chip and package level, the thermal capacitance and resistance are very small thus the T_j changes instantly when injection power steps. These non-ideal factors are inevitable by selecting proper I_m, but can be taken care of by fast measurement and proper data process. If the voltage sampling is not fast enough, the T_j could be underestimated.

T3ster is developed from the JEDEC ETM by a Hungary research team, which uses fast measurement and unique data processing. The whole thermal resistance capacitance structure of the system can be extracted. it is too expensive for most of LED device end users such as luminaire manufacturers. The powerful data processing software and fast data collector are two major part of the cost. Actually the sampling rate and resolution of T3ster's data collector may beyond necessary. Among all the results extracted by T3ster software, only junction temperature in the working condition is concerned most of the time [14].

In this paper, another data process method is established to deal with non-ideal factors and get the real T_j. Various measurement currents are used to study the relationship between I_m and measurement results. By data decimation, results of various measurement delays are got to find out how sampling rate affects the measurement error.

Measurements

Experimental setup

The experimental setup is shown in Fig.2. 1W white LED samples were used in our experiment. The LED sample was soldered on hexagon MCPCB board and then fixed on an aluminum heat sink. Silica gel was used as thermal paste to provide better interface contact between heat sink MCPCB and MCPCB LED. In k factor calibration, the LED system was put into the temperature controlling case and heated at different temperature. When testing the junction temperature in working condition, the LED system was put into a 0.5m×0.5m×0.5m plastic case to provide a still air working condition and the ambient temperature was set at 25□. Keithley S2400 sourcemeter was used as DC power supply to drive the sample LED and the forward voltage data of LED was collected by NI 5922 digitizer with 24-bit flexible resolution and sampling rate up to 16MHz. All the temperatures in the experiment including ambient temperature, oven temperature were measured by Keithley S2700 and K type thermal couple.

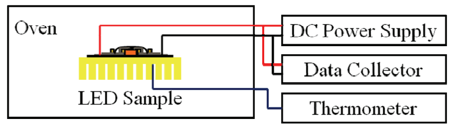

Fig. 2. Schematic diagram of the experimental setup.

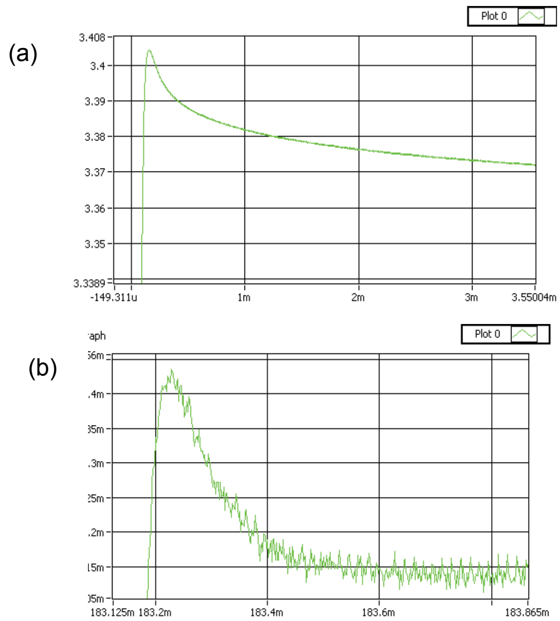

Fig.3. V_f (a) and I_f (b) after I_f stepped to I_m.

Measurement theory

In this paper, the *k* factor calibration and T_j measurement is processed according to JEDEC's standard and a data process method is developed. Take heating process in *k* factor calibration and V_{f0} measurement for example, the LED system is heated thus forward voltage drops after forward current is stepped to measurement current and we can see this process in Fig.3.(a) which is captured directly by NI5922 digitizer at a sampling rate of 1MHz. The 1MHz is chosen and used in the following measurements in this paper because it is fast enough to capture the whole heating process and at higher sampling rates 24bit resolution can't be achieved.

We can see from Fig.3.(a) in the first 500us, the V_f drops sharply. In order to find out whether this is caused by the thermal RC structure of LED system itself or other non-ideal effects, a small cement resistor is applied in the measurement system and serial with the LED to detect the current by measuring the voltage drop with digitizer. The result is shown in Fig.3.(b) and overdrive is found. This is because when we step the current to I_m, the current rises quickly and takes time to be stable at I_m. This is a negative feedback process and stable time, overdrive percentage are limited by the performance of DC supply.

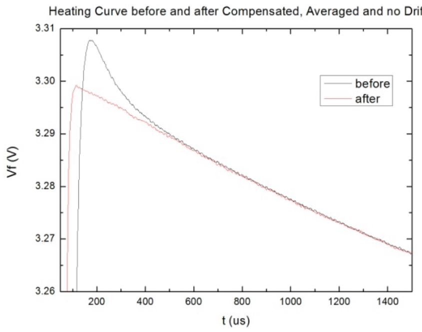

Fig.4. Forward voltage heating curve before and after current overdrive compensation.

However this effect can be eliminated by capture the forward current overdrive, calculate the overdriven V_f and deduct it from measured V_f and the Fig.4. shows the forward voltage before and after compensation and in the first 1ms, V_f drops linearly. According to the theory of thermal RC network, V_f decays exponentially with time. But when time is much smaller than the smallest time constant, V_f decay can be considered to be linear. The result fits the theory very well.

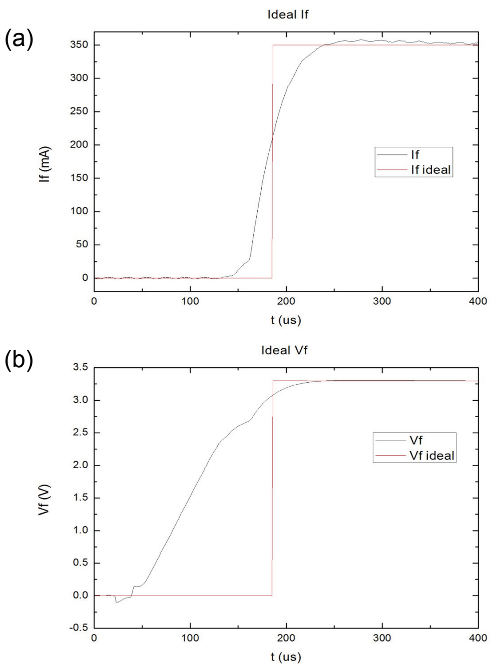

Fig.5. Ideal and measured (a) I_f and (b) V_f.

If we expand the time axes, another non-ideal effect is found with the current step. As shown in Fig.5.(b) It takes S2400 about 200us to rise and stablize the current from 0 to I_m and during this time period, the LED can already be heated and the V_f before being heated or ideal V_f can never be measured. In some papers, two DC supplies and a fast MOS switch are used to realize much shorter swtich time, but this may introduce parasitic osillations if the switch electrocurcuit is not perfectly made and installed. In this paper, the problem is solved by data processing. The idea is that we use a ideal current step with no rising time to replace the measured one shown in Fig.5.(a). The step moment or zero point of the new current step is calculated to make both current step have the same heating effect on the LED or in other words to ensure the same amount of energy being injected to the LED by both current steps before the current stablized and both of them heating the LED exactly the same after that. Thus the V_f at the swtich moment without being heated or the ideal V_f can be aquired by fitting the measured V_f data according to thermal RC network theory [15]. In this paper, only 5000 points after V_f stabilized are used in fitting, these data only reveals the property of several layers near the chip. On the other hand, a one order model is too simply and not accurate enough. Considering the accuracy and fitting time, a two exponential decay is used for fitting.

$$T_j = ae^{\left(-\frac{t}{t_1}\right)} + be^{\left(-\frac{t}{t_2}\right)} + c \tag{3}$$

where: a, b, c, t_1, t_2 – undetermined coefficients.

All data processing including overdrive compensation and fitting are realized by NI LabVIEW 2009 directly after data fetching. In order to study the sampling rate's effect on test results, V_f of 100us, 1ms, 5ms are recorded as well as the ideal V_f.

K factor calibration

In k factor calibration, the LED sample is tested at seven different temperature from 30-90℃ with a step of 10℃. There is an interval of 30 minutes between each two measurements. At the end of a day's measurement, the oven was set to another temperature for next day's work to ensure enough time for the LED system thermally stabilized at the new temperature. A K type thermal couple is attached to the heat sink of the LED system and the temperature of the heat sink recorded is considered by S2700. This is very important in K factor calibration. For the temperature distribution in the oven is not even and the temperature read from the oven panel is just the temperature of a small area around the oven's thermal senor. As it is placed near the heat source the panel temperature is always higher than the LED system's temperature especially in a low temperature such as 30℃, the error can be up to 5℃. Thus the temperature from the panel can't be always trusted and assuming in such a small dimension as the LED system, the temperature distribution is even, thus the recorded heat sink temperature can be considered to be the junction temperature of the LED sample. All the measurements are made three times and mean values are used in calculation.

Junction temperature measurement

In junction temperature measurement, the LED system is placed in the center of a 0.5m×0.5m×0.5m plastic shell on the insulated table to provide a still air working condition. A K type thermal couple is attached to the shell and the temperature is recorded as ambient temperature. The measurement proceeds according to JEDEC standard, ambient temperature is recorded after V_{f0} measurement as T_0 and after V_{f1} measurement to calculate the temperature rise from ambient to junction. As ambient temperature may change slightly during the measurement, the temperature rise is more suitable for later comparison. When different measurement current is applied, there's a interval of 30 minutes to ensure the LED system reach thermal stabilization again after last measurement. All the measurements are made three times and mean values are used in calculation.

Results and discussions

To study the sampling rate's effect on test results, V_f of 100us, 1ms, 5ms delay and ideal V_f were recorded which are correlated to test at a sampling rate at 10kHz, 1kHz, 0.2kHz and high enough respectively. Different measurement currents from 10mA to working current 350mA were used in the measurements to study whether all the currents can be used in thermal measurement when data is properly processed.

Results of different measurement currents

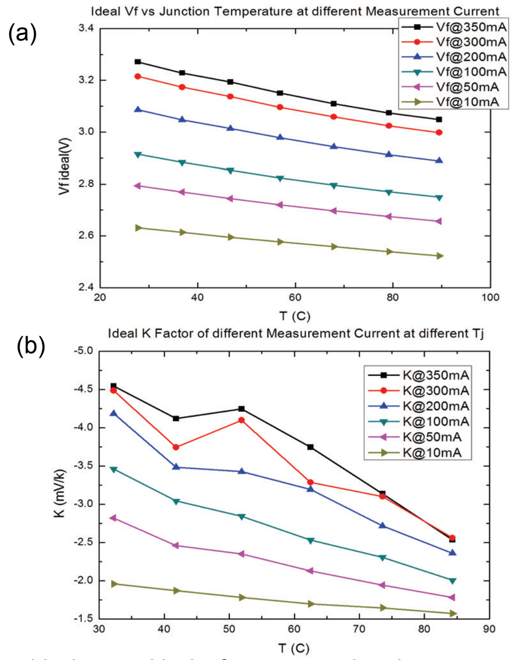

Fig.6. (a) Ideal Vf, (b) ideal k factor versus junction temperature at different measurement current

The results of *k* factor calibration are shown in Fig.6. In Fig.6.(a), the V_f -T_j relationship seems to be linear under all six applied measurement current within the temperature range between 30℃ to 90℃ and the slope is slightly flatter in the case of smaller measurement current. But this is only partly right. The slopes of each two adjacent points of all six curves in Fig.6.(a) are calculated. Since they represent the k factors of the certain temperature areas defined by each two points, the mean values of the temperature of each two points are calculated to represent these temperature areas and the calculation results is shown in Fig.6.(b). From this figure, we know LED have smaller k factor when measurement current is higher but k increases with the increase of T_j in all measurement current conditions especially in a large measurement current condition. So it will be more accurate to define the V_f -T_j relationship by using a series of k factors of different temperature range than a single k factor especially when large measurement current is applied. The junction temperature in working condition was measured with different measurement current. The results at different sampling rate were calculated in the form of junction temperature rise so that results with different measurement current measured in different ambient temperature can be compared together and shown in Fig.8.(c). To reach higher accuracy, series of k factors were used in calculation. In the ideal case, the difference of T_j rise of all six measurement currents is within 0.2. In the case of 10 kHz, 1 kHz and 0.2 kHz, the difference is within 0.4, 1.6 and 1.8 respectively. It is proved that when sampling rate is high enough and data is properly processed, the T_j measurement results is the same with all six measurement currents range from 10mA to 350mA. In other words, all the measurement current can be used to measure T_j when data is processed by the method developed in this paper. This means we can directly use working current to measure T_j and in T_j measurement, there's only one current step. We can monitor the T_j by directly measure the forward voltage, there will be no step down to measurement current and cooling effect. The Vf measured can be used as a feedback to directly control the T_j. The comparison experiment between our method and T3ster will be done in the future if funding permits.

Results of different sampling rate

The V_f -T_j curves of 350mA at different sampling rate are shown if Fig.7. The measured value of forward voltage decreases with the decrease of sampling rate. Assuming the ideal V_f is the real V_f, then the value of V_f was underestimated by 1.62mV, 13.7mV and 42.1mV when sampling rate is down to 10kHz, 1kHz and 0.2kHz *respectively*. The V_f -T_j curves of different measurement current at different sampling rate are linearly fitted and slopes are extracted to represent the k factor of each condition. The result is shown in Fig.8.(a). From this figure, we can see that the underestimation of k factor becomes larger in higher measurement current case and can be up to 0.8%, 4.9% and 13.7% at 10kHz, 1kHz and 0.2kHz respectively, when the measurement current is 350mA. From Fig.8.(a), the junction temperature rise is 0.4, 3.6 and 11.6 underestimated at 10kHz, 1kHz and 0.2kHz. The result agrees well with result got from Fig.7.

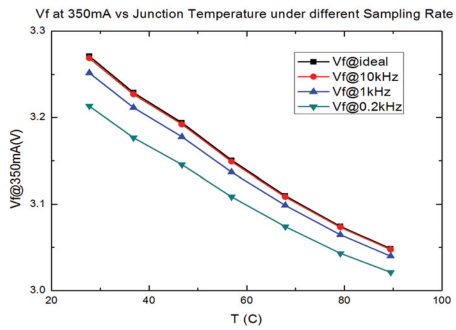

Fig.7. Forward voltage at 350mA versus junction temperature at different sampling rate

In all three figures, the ideal curves were measured at 1MHz and properly processed thus they can be considered to be curves of the real values and the other three groups of curves are curves of measured values. The measured values approach to real values when sampling rate increases. The higher sampling rate is used the smaller measurement error is caused. But the sampling rate is not always the higher the better. There is a tradeoff between voltage sampling rate and accuracy for a voltage measurement instrument. For what we actually measure in T_j measurement is not V_f but V_f shift which is counted by mV, the accuracy requirement is very high. Although only 1MHz is enough for T_j measurement and in some application the sampling rate of oscilloscope can reach GHz level easily, 1MHz is still expensive to reach with an mV level accuracy. As there's no room for negotiation about accuracy, the only way to cost down the expense of T_j

measurement is to test at lower sampling rate. It is found after sampling rate increased above a certain value, the improvement of measurement error can be neglected. For example, the T_j rise measurement error at 10kHz is 0.4. This means no matter how high sampling rate is used, the room to improve the measurement is only 0.4 in this case while the accuracy is also 0.4. Thus 10 kHz is considered to be enough for LED thermal measurement of this package.

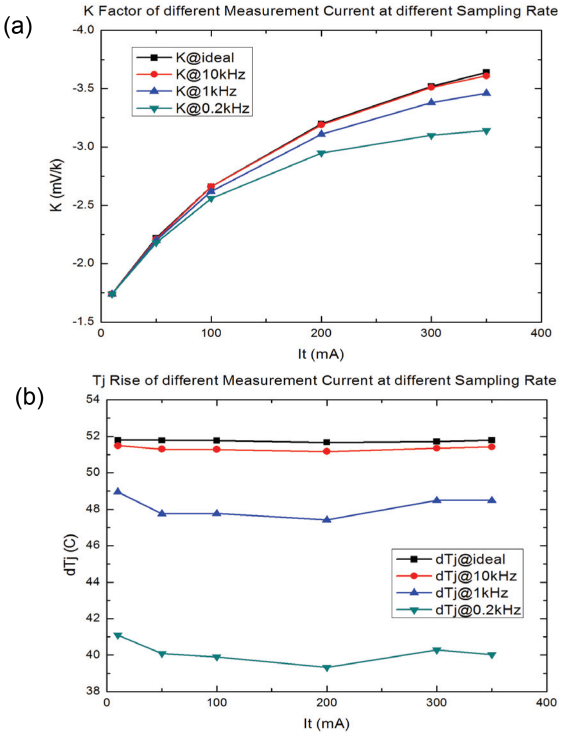

Fig.8. (a) K factor, (b) Junction temperature rise of different measurement current at different sampling rate

From Fig.8.(b), we can find that the measurement error is almost irrelevant to measurement current and only depended on sampling rate. With the same sampling rate, the measurement error is almost a constant. This is because the measurement error is caused by heating and cooling of LED during measurement and theoretically it only depends on the thermal RC structure of the system being measured and sampling rate. So for a certain LED device, if the measurement error of a low sampling rate such as 0.2kHz is given, we can compensate that error after the measurement at that sampling rate. By this method, even sourcemeter like Keithley S2400 with sampling rate only 200Hz is possible to measure the real T_j.

Conclusions

A data process method is established based on JEDEC ETM and thermal RC network theory. In this method, the beginning part of the heating and cooling process is captured, the current overdrive is eliminated and the ideal V_f is obtain by two exponential decay fitting thus the real T_j is acquired. By using different measurement current and calculation results at different sampling rate, this study demonstrates that if the voltage sampling rate is high enough and the data is properly processed, all the measurement currents can be used in LED Tj measurement. Thus working current can be used in T_j measurement and T_j can be monitored directly by measuring the V_f. It is also proved that 1MHz is high enough to get the real T_j and T_j of the sample can also be measured with slight measurement error at 10kHz. At a lower sampling rate the T_j will be greatly underestimated especially in the high measurement current case. Measurement error only depends on the thermal RC structure of the system and sampling rate. Different LED devices have different sampling rate requirements. For a certain LED device, even at a very low sampling rate, real T_j can be got at that sampling rate if the corresponding error is given.

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Corresponding author: *Dr. Haiping Shen, Fudan University, No. 220 Handan Road, Shanghai 200433, China. Tel: +86-21-55664541, Fax: +86-21-55665163, E-mail: shenhaiping@fudan.edu.cn*