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An Improvement on the Junction Temperature Measurement of Light-Emitting Diodes by using the Peak Shift Method Compared with the Forward Voltage Method *

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The junction temperature of red, green and blue high power light emitting diodes (LEDs) is measured by using the emission peak shift method and the forward voltage method. Both the emission peak shift and the forward voltage decrease show a linear relationship relative to junction temperature. The linear coefficients of the red, green and blue LEDs for the peak shift method and the forward voltage method range from 0.03 to 0.15 nm/°C and from 1.33 to 3.59 mV/°C, respectively. Compared with the forward voltage method, the peak shift method is almost independent of bias current and sample difference. The variation of the slopes is less than 2% for the peak shift method and larger than 30% for the forward voltage method, when the LEDs are driven by different bias currents. It is indicated that the peak shift method gives better stability than the forward voltage method under different LED working conditions.

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With the breakthrough of III–V nitride-based blue light emission, light emitting diodes (LEDs) have been widely used in many fields. They are expected to replace incandescent or fluorescent bulbs eventually. It is probable that LEDs will be used in general illumination in the near future. However, LED efficiency is still low and great efforts have been made to improve both LED efficiency and reliability, including using surface roughing processes, photonic crystal structures, surface plasma, patterned substrates, electrical structure optimization, and so on.[1−8] In addition, the lifetime of LEDs is far less than the theoretical expectation value of 100000 h, because of the low quantum efficiency. The lower the efficiency, the more Joule heat will be generated and the shorter the lifetime of the LED will be. Among the optical, electric and thermal parameters of LEDs, the junction temperature (JT) is one of the most dominant factors related to their performance. However, the JT of an LED is hard to obtain, especially in LED lamps with complex structures and electric connections. Many methods have developed to obtain the JT. The electrical measurement method is based on the JT-dependent forward voltage (FV) of the LED.[9] The optical measurement method of Raman spectroscopy, infrared thermal imaging, the slope of the high-energy portion of the electroluminescence (EL) peak and/or the shift of the EL peak are used to measure the JT of LEDs.[10−13] The FV method is most commonly used and it is considered to be the most precise method of JT determination.

However, the main difficulty of the FV method is that it is time consuming, because the calibration curve used to determine the JT of LEDs is different from sample to sample. Moreover, the calibration curve will be changed by the operating current for the same LED sample. The calibration curve error directly affect the precision of JT determination. It is interesting to find a method with good calibration curve stability. An improved JT measurement method has been developed by using the peak shift (PS) method.[14] When referring to the PS method, it should be considered that this method was proposed a long time ago and it was applied well in JT measurement of laser diodes (LDs).[15−17] However, as we know, the line width of LDs is narrow with a typical value of less than 1 nm and the sharp peak position is easier to obtain. For example, the line width of Fabry–Pérot laser diodes in Ref. [17] is only about 0.2 nm. In LEDs, especially for the GaN-based LEDs, the spectrum is very broad with a typical value of 20–30 nm, and large random variation around the peak position, due to the limitation of the spectrum measurement ability. Therefore, it is not assumed that the PS method, which was used well in narrow spectrum systems (like LDs), can also be used well for a wide spectrum system (such as LEDs). In fact, the accuracy of the PS method applied to LEDs is quite low, and the limited accuracy is larger than 15℃.[16,18] Based on this reason, an improved PS JT measurement method for LEDs with broad spectrum is pro-

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posed and it shows preferable stability and precision than in our previous study.[14] However, there is still an open question about the application of this improved PS JT measurement method. The most widely accepted useful method to measure the JT of LEDs is the FV method. The question is how the advantage of the improved PS JT measurement method relates to the FV method. In this Letter, we will make a direct comparison between the PS method and the FV method. It is found that the PS method will give better performance than the FV method.

The JT measurement system and measurement process by the PS method are well described elsewhere.[14] This method is studied in comparison with the FV method. The FV method is carried out by using the same instrument. Both methods of JT measurement consist of two steps. The calibration of the peak shift vs temperature coefficient and the voltage-temperature coefficient is achieved in the first step. In order to improve the comparability, the EL spectrum and the voltage are measured synchronously. The second step is the determination of the JT in LEDs under working conditions. In this step the calibration trend line is used to convert the measurement parameter to JT. The uncertainty of the calibration coefficient is considered in the most dominant uncertainty factor in the JT measurement.[19] Therefore, we concentrate on the calibration coefficient determination.

Table 1 Parameters A and B for Eqs. (1) and (2) to the data in Fig. 2.

	LED	A (nm/℃)	B (nm)	R^2	$\Delta T/\Delta\lambda$ ($\Delta\lambda/\Delta T$)
Peak shift method	1WR	$(134\pm0.6)\times10^{-3}$	$(-54.7\pm0.4)\times10^{-1}$	0.9999	7.5℃/nm(0.13 nm/℃)
	3WR	$(150.7\pm0.4)\times10^{-3}$	$(-61.3\pm0.3)\times10^{-1}$	0.9999	6.6℃/nm(0.15 nm/℃)
	1WB	$(51.3\pm0.5)\times10^{-3}$	$(-21.1\pm0.4)\times10^{-1}$	0.9995	19.6℃/nm(0.051 nm/℃)
	3WB	$(54.3\pm0.7)\times10^{-3}$	$(-22.3\pm0.5)\times10^{-1}$	0.9992	18.5℃/nm(0.054 nm/℃)
	1WG	$(31.5\pm0.6)\times10^{-3}$	$(-12.9\pm0.4)\times10^{-1}$	0.9984	32.1℃/nm(0.031 nm/℃)
	3WG	$(6.1\pm0.1)\times10^{-2}$	$(-25.3\pm0.8)\times10^{-1}$	0.9982	16.8℃/nm(0.060 nm/℃)
		A(V/℃)	B (V)	R^2	$\|\Delta T/\Delta V\|$ ($\|\Delta V/\Delta T\|$)
Forward voltage method	1WR	$(-3.56\pm0.25)\times10^{-3}$	$(21.2\pm0.2)\times10^{-1}$	0.9763	2.8×10^2℃/V(3.59 mV/℃)
	3WR	$(-2.28\pm0.20)\times10^{-3}$	$(21.8\pm0.1)\times10^{-2}$	0.9644	4.3×10^2℃/V(2.34 mV/℃)
	1WB	$(-3.55\pm0.11)\times10^{-3}$	$(328.0\pm0.8)\times10^{-2}$	0.9956	2.8×10^2℃/V(3.54 mV/℃)
	3WB	$(-1.31\pm0.05)\times10^{-3}$	$(366.0\pm0.3)\times10^{-2}$	0.9943	7.5×10^2℃/V(1.33 mV/℃)
	1WG	$(-3.56\pm0.31)\times10^{-3}$	$(36.4\pm0.2)\times10^{-1}$	0.9713	2.9×10^2℃/V(3.47 mV/℃)
	3WG	$(-3.51\pm0.30)\times10^{-3}$	$(36.7\pm0.2)\times10^{-1}$	0.9655	2.8×10^2℃/V(3.57 mV/℃)

Table 2. Parameters A and B for Eqs. (1) and (2) to the data in Fig. 3 with different bias currents.

	Bias current (mA)	100	200	300	350
Peak shift method	A (nm/℃)	$(13.5\pm0.1)\times10^{-2}$	$(13.41\pm0.06)\times10^{-2}$	$(13.33\pm0.04)\times10^{-2}$	$(13.45\pm0.04)\times10^{-2}$
	B(nm)	$(-54.4\pm0.7)\times10^{-1}$	$(-54.7\pm0.5)\times10^{-1}$	$(-54.2\pm0.3)\times10^{-1}$	$(-55.1\pm0.4)\times10^{-1}$
	R^2	0.9997	0.9999	0.9999	0.9999
	$\Delta T/\Delta\lambda$ ($\Delta\lambda/\Delta T$)	7.5℃/nm (0.13 nm/℃)	7.5℃/nm (0.13 nm/℃)	7.5℃/nm (0.13 nm/℃)	7.5℃/nm (0.13 nm/℃)
FV method	A (V/℃)	$(-19.1\pm0.5)\times10^{-4}$	$(-26\pm2)\times10^{-4}$	$(-33\pm2)\times10^{-4}$	$(-36\pm2)\times10^{-4}$
	B (V)	$(154.0\pm0.4)\times10^{-2}$	$(178\pm1)\times10^{-2}$	$(201\pm2)\times10^{-2}$	$(212\pm2)\times10^{-2}$
	R^2	0.9961	0.9782	0.9790	0.9763
	$\|\Delta T/\Delta V\|$ $\|\Delta V/\Delta T\|$	5.2×10^2℃/V (1.9×10^{-3}V/℃)	3.8×10^2℃/V (2.6×10^{-3}V/℃)	3.1×10^2℃/V (3.3×10^{-3}V/℃)	2.8×10^2℃/V (3.6×10^{-3}V/℃)

In this study, commercial LED samples with red, green and blue colors are studied. Figure 1(a) shows that the EL spectra of red, green and blue LEDs are not symmetric with a typical full half bandwidth of ∼30 nm at rated currents 350 mA and 700 mA for 1 W and 3 W LEDs, respectively. Detailed spectrum analysis of the peak shift method can be found in our previous study.[14] The current pulse width is 500 µs with a duty cycle of 0.1%. In order to ensure the LED operate at a rated current and to avoid the effect of the rising edge of the current pulse, the data collection is started after a 10 µs delay from the turning-on of the LED lights. Considering the random measurement fluctuation, we employ the mean value of the 13 points' values of forward voltage to calibrate the temperature-dependent voltage curve.

The dependence of the peak shift and forward voltage of the high power red, green and blue LEDs on JT at rated current are shown in Figs. 2(a) and 2(b), respectively. The experimental results reveal that the dependence of the experimental emission PS (or FV) $\Delta\lambda$ (or ΔV) on the temperature T is very close to a linear relationship. They can be fitted by the equations:

$$\Delta\lambda = A(T_0 + \Delta T) + B, \quad (1)$$

$$\Delta V = A(T_0 + \Delta T) + B, \quad (2)$$

where ΔT is the difference of ambient temperature T relative to the initial T_0. A and$B$ are fitting parameters. Since the duty cycle of the pulsed current is 0.1%, the Joule heat generated by the pulsed current can be neglected. The JT can be assumed to be equal to the ambient temperature.

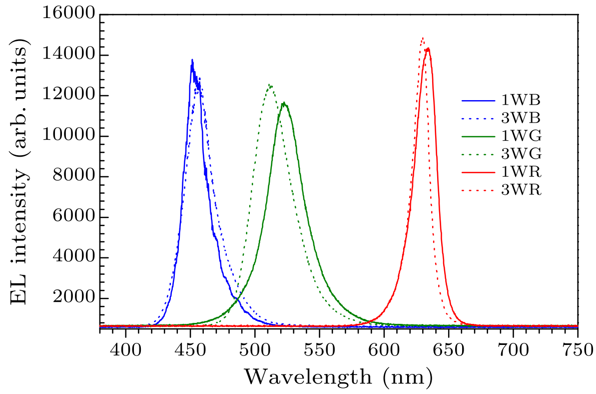

Fig. 1. The electroluminescence spectra of LEDs. The solid lines for 1 W LEDs and the dotted lines for 3 W LEDs.

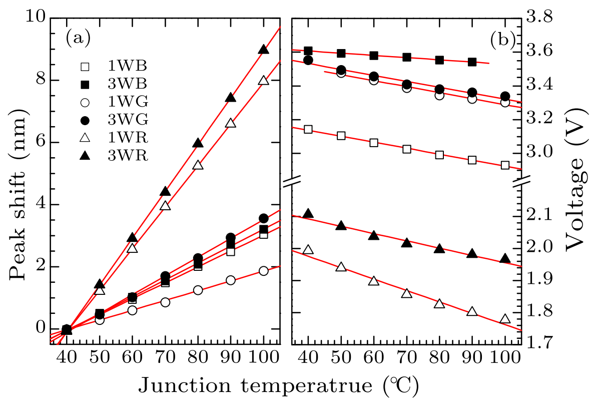

Fig. 2. Calibrated curves of the emission peak shift method (a) and the forward voltage method (b) for high power LEDs at rated current. The red lines are linear fits for the experimental data.

The parameters A and B for each LED are summarized in Table 1. These parameters are similar to the other reports.[9,12,20–23] The determination coefficient R^2 for the all trend lines are larger than 0.998 for the PS method. On the other hand, the coefficient of determination R^2 for the FV method are all less than 0.996. Furthermore, the peak wavelength shift and FV decreasing of red LEDs are sensitive to JT compared to the other kinds of LEDs. The slope of the emission peak shift of the red LEDs is about 2-times of that of other colors of LEDs. It results from the difference of materials for LEDs. The red LED is made of the AlGaInP quaternary alloy material, and then, the InGaN ternary alloy material is used for blue and green LEDs. The red LED is a simple p–n junction and the other kinds of LEDs are usually composed of multiple quantum wells (MQWs) between a p–n junction. The discrepancy between blue and green LEDs can be attributed to the difference in composition of indium in quantum wells. The similar consideration of the FV decreasing is much less than the peak shift between the red, green and blue LEDs. The decreasing of the FV in the red LED is slightly larger than green and blue LEDs. This can be ascribed to the electrical connection and the structural difference. It is known that the JT measured by the FV method is the average temperature of the diode, including the effect of the wire bond and series resistance.

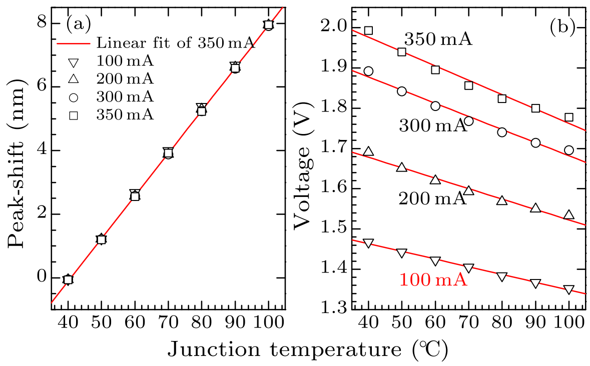

Fig. 3. Junction temperature dependence on peak shift (a) and voltage (b) for 1 W red LEDs under different currents.

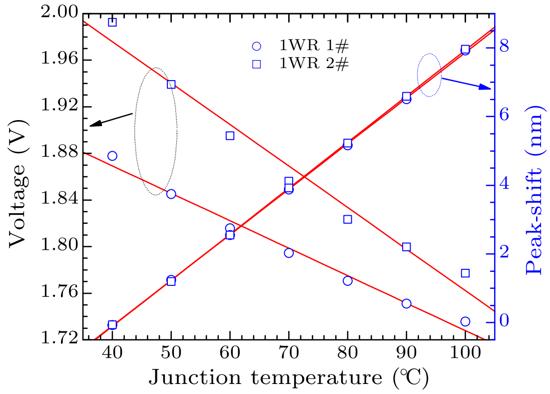

Fig. 4. Calibration curve comparison on junction temperature dependence on peak shift and voltage for different red LEDs.

As the important properties, the stabilization of calibration trend line on the variation of LED operation condition and the coefficient of determination R^2, are compared between both the methods. The calibration trend lines of the 1 W red LED using the PS and FV methods are shown in Fig. 3. The LED was driven by the same current pulse technique but different current magnitudes. Figure 3(a) shows the result of the non-contact peak shift method. The red line is the linear fit of the experimental data under 350 mA, which shows a very good linear correlation ($R^2 = 0.9999$) between JT and peak shift. Similar results are obtained, when the magnitude of the current pulse is changed to 100 mA, 200 mA and 300 mA. As listed in Table 2, the slopes of the linear dependence of the calibration trend lines for the LED at different bias currents are almost the same. The change of slope and intercept parameters (A and B) are less than 0.9%. This indicates that the calibration trend lines are almost independent of the LED bias current in the range 100–350 mA by using the peak shift method. Also as listed in Table 2, the change of slope and intercept parameters obtained by the FV method are as large as 46% and 37%, respectively. From this example, we find that the stability of calibration trend line by the peak shift method is more than 30 times better than that of the FV method. Moreover, the coefficient of determination R^2 is larger than 0.9997 for all bias currents in the peak shift method. The R^2 value is less than 0.997 for the FV method. For a further comparison, another 1 W red LED of the same production type was measured. Figure 4 provides the calibration curve of the two red LEDs. It is shown that the calibration trend line of the peak shift method is much more stable than that of the FV method for different samples. For the peak shift method, the variation of slope and intercept are 2% and 3%, respectively, with $R^2 = 0.9999$. These variations for the FV method are 34% and 7%, with R^2 less than 0.984. As we know, the FV method is a contact method and much more dependent on the package, electrical connections of the LED and the resistance in series. The FV changes with the resistance. For the peak shift method, the emission peak of the LED is exclusively dependent on JT, once the injection current is fixed.[24] Obviously, another advantages of the peak shift method is that it can be easily realized in remote measurement and monitored by an optical fiber. The FV method, however, can induce additional resistance if long wires are used for remote measurement. In our samples, the peak shift method gives improved performance as compared with the FV method in the behavior of calibration trend line.

In conclusion, the non-contact peak shift method has a better performance over the contact FV method in the JT measurement of LEDs. The peak shift method gives preferable representability on the calibration trend lines. Moreover, the peak shift method is convenient for remote determination and avoiding the influence of complex electrical connections and harsh LED environments.

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