Feasibility analysis of junction temperature measurement for GaN-based high-power white LEDs by the peak-shift method

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Transient thermal impedance of GaN-based high-power white light emitting diodes (LEDs) is created using a thermal transient tester. An electro-thermal simulation shows that LED junction temperature (JT) rises to a very low degree under low duty cycle pulsed current. At the same JT, emission peaks are equivalent at pulsed and continuous currents. Moreover, the difference in peak wavelength when a LED is driven by pulsed and continuous currents initially decreases then increases with increasing pulse width. Thus, selecting an appropriate pulse width decreases errors in JT measurement.

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The light emission efficiency and service lifetime of high-power white light emitting diodes (LEDs) rapidly decrease with increasing junction temperature (JT). Thus, measuring the JT of LEDs is an effective approach to determining efficiency and lifetime[1,2]. Peak wavelength, a key parameter of LEDs[3,4], is highly related to JT[5−7], which can be measured by the peak-shift method; this approach presents non-contact and convenience[8,9] and involves two steps. The first is the calibration of peak shift versus the JT coefficient at different ambient temperatures under narrow pulse widths and low duty cycle pulsed currents. JT is approximately equal to ambient temperature because the former increases to a very low degree under narrow pulse widths and low duty cycle pulsed currents. The peak shift can be calibrated against the JT coefficient by controlling ambient temperature. The second step is the calculation of peak shift to determine JT for a LED that works at continuous current. On the basis of these data, researchers proposed two hypotheses. Firstly, JT is approximately equal to ambient temperature when LEDs function under pulsed current, making the use of ambient temperature as control for JT possible. Secondly, peak wavelengths are approximately equal when LEDs function at pulsed and continuous currents at the same JT. Thus, peak versus ambient temperature can be used to determine JT for LEDs working at continuous current. Despite the progress made in research, previous studies have not analyzed the error caused by the approximation method. In this letter, we analyze such errors to confirm that they are negligible.

We simulate the rise in LED JT with increasing time, in which a LED is driven by a narrow pulse width and a low duty cycle pulsed current. JT rises at a very slow pace and such increase lasts for a short period, leading us to conclude that ambient temperature can be considered JT. We experimentally demonstrate that the peak shifts of LEDs driven by either pulsed or continuous currents are the same only under the same JT.

The structural diagram of our system is presented in Fig. 1. A GaN-based high-power white LED is installed in a temperature-controlled oven. Two trigger sources (thermal transient tester and pulsed current source) are used to drive the LED. The switch is used to alternate between the two trigger sources. A spectrometer is used to acquire the LED's emission spectrum, with which the peak shift of the LED is calculated.

The thermal transient tester (T3Ster) of Mentor Graphics Corporation uses the static test method defined by JESD51-1 to acquire LED transient temperature response curve at a temperature resolution of 0.01 °C. Using the original structure function method, we can build a model that represents transient thermal impedance from the heating PN junction to the radiator. Transient thermal impedance, which is related to time, can be equivalent to a series of thermal resistance and

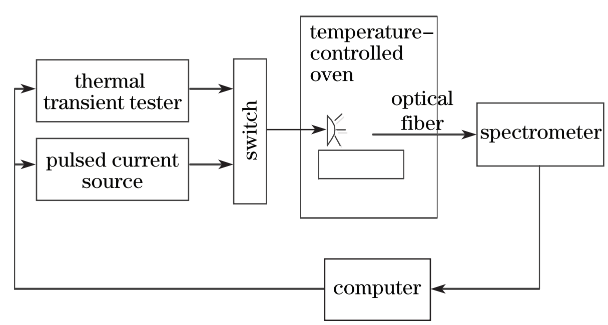

Fig. 1. Structural diagram of the system.

thermal capacitance values[10]. Transient thermal impedance is used primarily to analyze the inter heat variety of LEDs under different currents. In electro-thermal simulations, an electrical transmission line equivalent to a circuit diagram is built to model heat conduction properties[11−13]. In the circuit diagram (as mentioned above), the voltage of the current source (V_{source}) is equivalent to temperature rise. When driven by pulsed current with different pulse widths, V_{source} varies with increasing time. The transient curve of V_{source} is the JT transient rise curve under different pulsed currents. Simulations are conducted at a current amplitude of 350 mA, a repetition period of 400 ms, and different pulse widths (50 to 1 000 μs). The increase curve of JT is shown in Fig. 2.

JT rises during the "on" period of each pulse (Fig. 2). The pulsed current repetition period is 400 ms, much larger than the pulse width. When the current decreases to 0, therefore, the rise in JT reaches 0 before the next current pulse is applied. Thus, the junction of a LED that is driven by low duty cycle pulsed currents at a prolonged duration does not accumulate heat inside. The properties of JT increase are almost the same in any pulse cycle. The curve of JT increase of the LED in the first pulse cycle is shown in Fig. 3.

On the basis of Fig. 3, we conclude that JT rises with increasing pulse width (Table 1). The average temperature ($\overline{\mathrm{Temp}}$) can be calculated using

$$\overline{\mathrm{Temp}} = \frac{1}{T}\int_0^T \mathrm{temp}(t)\mathrm{d}t = \frac{1}{T}\sum_{t\to 0}^{T} \mathrm{temp}(t) \times \Delta t, \quad (1)$$

where T is the pulse width, t is the transient time, temp(t) is the transient JT increase at time t, and Δt is the time interval.

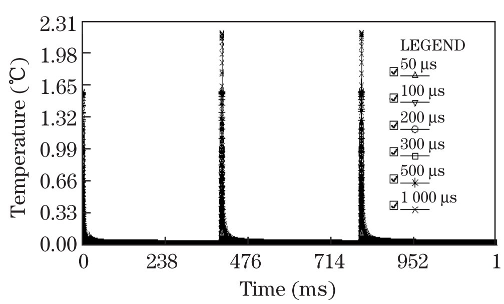

Fig. 2. Curve of the increase in LED junction temperature under different pulse widths.

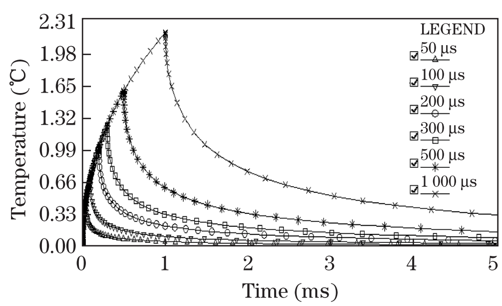

Fig. 3. Curve of junction temperature increase in the first pulse cycle.

Table 1. Increase in Junction Temperature with Increasing Pulse Width

No.	Pulse Width (μs)	Peak JT Rise (°C)	Average JT Rise (°C)
1	50	0.49	0.34
2	100	0.70	0.48
3	200	1.00	0.68
4	300	1.21	0.83
5	500	1.57	1.07
6	1 000	2.20	1.50

Table 2. Increase in Junction Temperature and Peak Wavelength for a LED Working at Continuous Current

No.	Ambient Temperature (°C)	JT (°C)	Peak (nm)
1	30	51.7	449.63
2	40	60.7	450.01
3	50	70.1	450.48
4	60	79.7	450.94

Table 1 shows that the average JT increases from 0.34 to 1.5 °C as the pulse width increases from 50 to 1 000 μs. Thus, if the pulse width is set below 500 μs, the average JT rise would be less than 1 °C. Ambient temperature is almost equal to JT when the LED is driven by a pulsed current with a low duty cycle and sufficiently short time. Consequently, we can control the JT by configuring the settings toward ambient temperature in the temperature-controlled oven.

Our system is used to compare the difference in peak wavelength when the LED is driven by continuous and pulsed currents (Fig. 1). The ambient temperature in the oven is initially increased from 30 to 60 °C at an interval of 10 °C; a 350-mA continuous current supplied by T3Ster is used to drive the LED. When the LED achieves thermal balance for 30 min, the driving current abruptly drops to 5 mA. The voltage drop of the LED is verified using T3Ster and the JT increase of the LED under current ambient temperature is calculated by the forward-voltage method[14]. The EL spectrum is acquired using a spectrometer and then the peak wavelength is calculated. Data are shown in Table 2.

JT increases to a minimal degree at a very narrow pulse width, and ambient temperature is approximately equal to JT when the LED functions under pulsed current. Temperature is controlled once JT is reached, as shown in Table 1. Once the LED achieves thermal balance, the spectrum is acquired when the LED works at pulsed current. Subsequently, the LED spectrum can be acquired at the current JT. The peak wavelength is compared with that obtained at continuous current to obtain the difference between pulse and continuous applications at the same JT. Figure 4 shows that pulse width (X-axis) increases from 50 to 1300 μs and that the Y-axis reflects the difference in LED peak wavelength between pulsed and continuous current applications at the same JT. The peak–wavelength difference curves for four different JTs are calculated (Fig. 4).

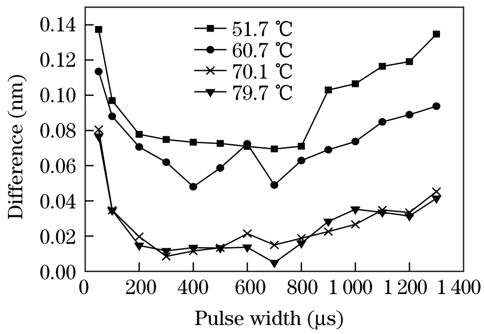

Fig. 4. Difference in LED peak wavelength between pulsed and continuous current at the same junction temperature.

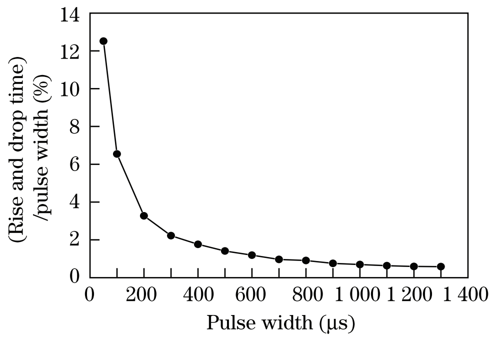

Fig. 5. Ratio of duration of increase and decrease to pulse width with increasing pulse width.

As shown in Fig. 4, the difference in LED peak wavelength between pulsed and continuous currents at the same JT first decreases and then increases with increasing pulse width. This phenomenon is influenced mainly by two effects. The first is that the pulsed current exhibits an increasing and decreasing trend with values lower than the maximum, i.e., 350 mA. Because the emission peak wavelength of the GaN-based LED increases with decreasing driving current[15], the emission peak wavelength of the LED is higher when the driving current increases or decreases than when it is at 350 mA. For a pulsed current source, the duration of increase and decreasing in driving current is almost constant and does not vary with pulse width. Thus, the ratio of this duration to pulse width decreases with increasing pulse width (Fig. 5). Moreover, peak wavelength decreases with increasing pulse width, but JT increases the peak wavelength with increasing pulse width–this phenomenon is the second effect.

In conclusion, the combined effects initially decrease and then increase the peak wavelength with increasing pulse width when the LED functions at pulsed current. Figure 4 shows that at an appropriately selected pulse width, the influence of the duration of increase and decrease, as well as that of increasing JT, can yield preferable results on peak wavelength. The difference in LED peak wavelength between pulsed and continuous currents is minimal. Table 2 indicates that the slope of LED peak wavelength versus JT is 0.04 nm/°C. For a pulse width of 200 μs, the maximum difference between peaks is 0.08 nm and the error is less than 2 °C.

A thermal transient tester is used to build a high-power white LED transient thermal impedance model. Using the electro-thermal simulation method, we analyze the transient response curve of JT increase for a LED that works under pulsed currents with different pulse widths and low duty cycles. At a pulse width less than 1 000 μs, the average JT increase is less than 1 °C, suggesting that ambient temperature is approximately equal to JT. Consequently, JT can be controlled by configuring the settings of a temperature-controlled oven to ambient temperature. Then, LED peak shift versus JT can be calibrated when a LED functions at pulsed current. We validate the difference in peak wavelength between pulsed-current and continuous-current spectra and find that the difference initially decreases and then increases. Thus, using an appropriate pulse width results in minimal difference. That is, the peak wavelength curve at pulsed currents is equivalent to that at continuous currents. In addition, the curve derived in this work exhibits good linearity. Overall, this curve can be used to measure the JT of LEDs by the peak-shift method.

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