A new method to measure the junction temperature of LEDs

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There are many available junction temperature measurement methods of LEDs. These methods depend on some characteristics of LEDs related to junction temperature. In this study, it has been taken advantage of the relative variation of radiant power with junction temperature characteristic of LED to measure junction temperature. The error ratio of the calculated junction temperature decreases in pulsed high currents.

(Received July 10, 2018; accepted February 12, 2019)

Keywords: LED, Junction temperature, Measurement method

1. Introduction

The life and reliability of LEDs depend on their junction temperature. The light colour temperature of LEDs varies with their junction temperature and the radiant power of LEDs decreases when the junction temperature increases. The available thermal impedance - and thermal resistance- measuring methods and reliability analyses require junction temperature measurements. Because of that, the measurement of the LED's junction temperature is very important and there are many new researches about it [1-15].

The forward voltage drop of LED linearly changes with the junction temperature. This characteristic has been used to measure the junction temperature by measuring the voltage drop of LED in traditional measuring methods (Fig. 1). Another traditional junction-temperature-measuring method uses the linearly changing junction temperature with spectral shifting (Fig. 2) [1, 2].

In this new method, some voltages are measured in an appropriate measuring circuit (Fig. 3) and used in a formula to determine the junction temperature. The relative radiant power-junction temperature characteristic, which is also linear, is used in this new method (Fig. 4).

2. Material and method

The equation used to calculate the junction temperature is as follows:

$$T_j(t) = \frac{[k_{pn}I_n - P_n(t)]}{k(k_{pn}I_n)} + T_a \quad (1)$$

Equation 1 is obtained in a pulsed high-current operation, where t is the pulse duration of the photodetector voltage; I_n is the amplitude of the current pulse of the LED; k_{pn} is the electro-optic converter between the current and the photodetector voltage at low LED currents, where the thermal effect of the LED is negligible and the LED radiant power varies almost linearly with the LED current. $T_j(t)$ is the junction temperature and T_a is the ambient temperature. k can be measured by putting the LED in a chamber and heating the chamber. The LED current is held constant during the measurement. The relative change in radiant power can be calculated by measuring different photodetector voltages for different chamber temperatures using a simple photodetector. Photodetector circuit must be outside of the thermal chamber. k is calculated using the relative variation of the LED radiant power with the junction temperature (Fig. 4) (for example k = 0.7% / °C) [16-19]. Because of k is a relative magnitude, there is no need to measure the radiant power of LED. Two measurements are enough (or three measurements to proof linearity changing of variation) to determine the slope of relative variation of radiant power (which is proportional to photodetector voltage) vs. junction temperature.

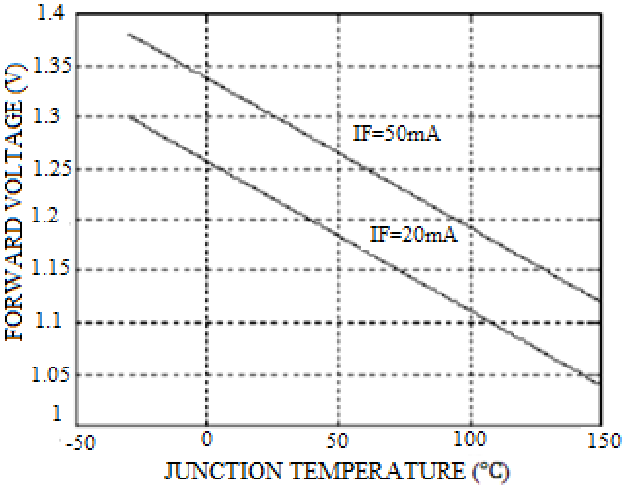

Fig. 1. Variation of the forward voltage of the LED with the junction temperature. (Philips Semiconductors Data Book, Part 8, September 1983)

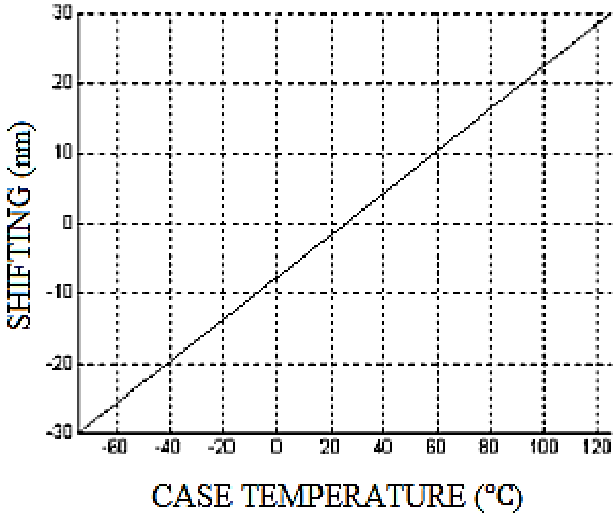

Fig. 2. Shift of the maximum radiation wavelength of a GaAs LED with the case temperature. (Texas Instruments, Optoelectronics and Image Sensors Data Book, 1990)

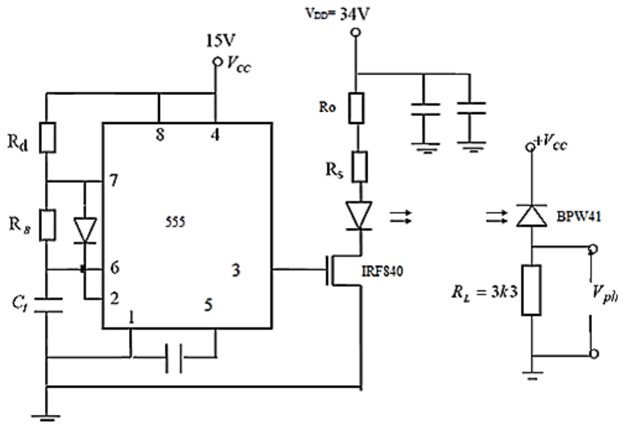

Fig. 3. Measuring circuit. An oscillator is formed by a 555 timer to produce current pulses for the LED, and a photodetector circuit is formed by a BPW41 photodiode connected in the photoconductive mode

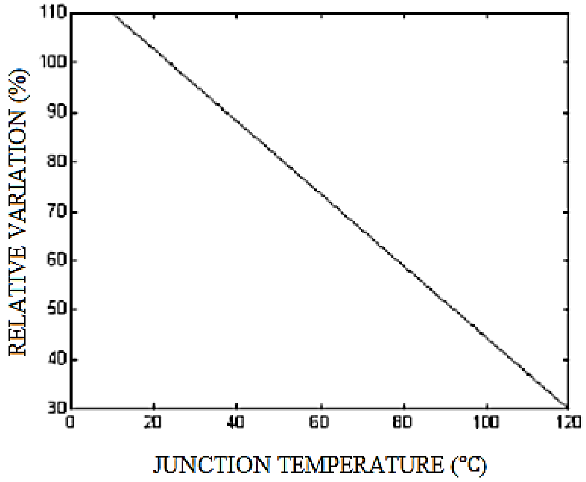

Fig. 4. Relative variation of the LED radiant power with the junction temperature. (Philips Semiconductors Data Book, Part 8, September 1983)

Fig. 5 was obtained by measuring the photodetector voltages $P_n(t)$ and LED currents I_n for different pulse durations [16]. Fig. 5 shows that the radiant power of the LED (SLR 932 A (Sanyo)) [20] increases with its current amplitude, but the rate of increase in radiant power decreases because of the self-heating of the junction. For the same reason, the radiant power also decreases with the pulse duration of the LED. The radiant power of the LED must be $k_{pn}I_n$ if the heating effect is negligible. However, the radiant power is less than this amount and is only $(k_{pn}I_n - P_n(t))$. This decreased value can be written relatively as $(k_{pn}I_n - P_n(t)) / (k_{pn}I_n)$. This ratio is divided by k (e.g., 0.7% / °C) to obtain the increase in temperature of the junction for the identical relative radiant power ratio, and junction temperature $T_j(t)$ is obtained by adding ambient temperature T_a to this ratio (Equation (1)).

Measuring circuit has been shown in Fig. 3 [16-19]. Using the circuit in Fig. 3, Fig. 5 is obtained by measuring the photodetector voltages and LED currents for different pulse durations [16-19].

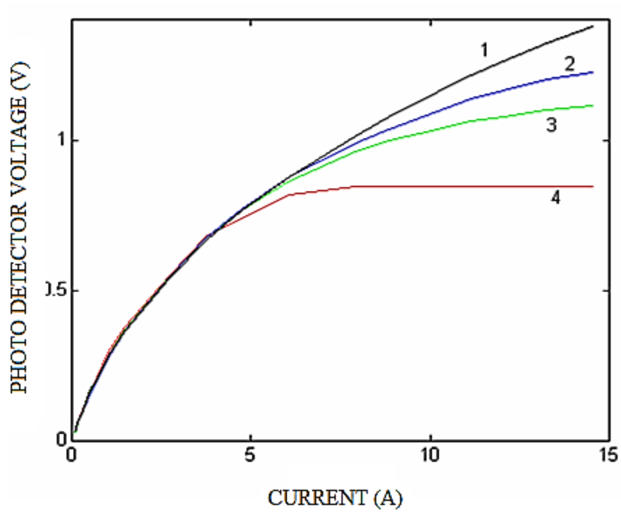

Fig. 5. Current-radiant power characteristics of an infrared LED (SLR 932 A (Sanyo)). The pulse durations of the curves are 1 - 3.5 µs; 2 - 6.5 µs; 3 - 9 µs; 4 - 18 µs

The measurement steps to determine the junction temperature of the LED are:

a. The pulse duration of the pulsed signal, which is produced by the oscillator circuit, must be adjusted as the duration of the junction temperature to be calculated. The space time of the periodic pulsed signal must be sufficiently long so that the LED junction can completely consume the heat gained during the pulse duration.
b. The distance between the LED and the photodiode must be sufficiently long so that the variation of the photodetector voltage with the LED radiant power can be linear.
c. The LED current amplitude must be adjusted to the requested value (I_n) by selecting the suitable serial resistance (R_s).

d. The voltage drop of the current measurement resistor R_o is measured by an oscilloscope.
e. The voltage drop on R_o is divided by the value of R_o to calculate the LED's current amplitude (I_n).
f. The voltage drop of the photodetector resistor (P_n) is measured by an oscilloscope. This photodetector voltage is proportional to the LED radiant power. This voltage must be measured after the current pulse duration when the current pulse is applied to LED.
g. The current limiter resistor (R_s) is increased so that the current amplitude of the LED is small and the thermal effect is negligible.
h. The voltage drop of the measurement resistor (R_o) is measured by an oscilloscope.
i. The voltage drop of the measurement resistor is divided by the value of the measurement resistor to obtain the LED current (I_n').
j. The voltage drop of the photodetector resistor, which corresponds to the LED radiant power, is measured when the LED current is equal to I_n'.
k. The electro-optic converter value is calculated using the calculated LED current in step i and measured photodetector voltage (P_n') in step j ($k_{pn} = P_n' / I_n'$).
l. Constant k is determined using the LED data sheet or a measurement.
m. The room temperature T_a, which must be stable during the measurement, can be measured using a thermometer.
n. The junction temperature is calculated using Equation 1 and the results of steps f, i, j, k, m and l.

3. Results and discussions

The measured values in Table can be used to obtain the change in error rate with the current pulse amplitude and current pulse duration.

Table. Measured values

N	I_n (V)	V_n (V)	P_n(V) (18 µs)	P_n(V) (9 µs)	P_n(V) (6.5 µs)	P_n(V) (3.5 µs)
1	13.1	8.35	1.39	1.65	1.74	1.82
2	11.95	7.96	1.38	1.60	1.69	1.75
3	10.9	7.5	1.36	1.54	1.61	1.66
4	10.15	7.29	1.34	1.515	1.56	1.595
5	9.30	6.97	1.315	1.445	1.47	1.50
6	7.30	6.1	1.21	1.29	1.305	1.305
7	5.585	5.2	1.08	1.12	1.12	1.10
8	4.47	4.57	0.973	0.980	0.977	0.966
9	3.55	3.915	0.840	0.840	0.840	0.819
10	2.615	3.215	0.686	0.683	0.677	0.670
11	1.455	2.29	0.435	0.423	0.417	0.410

Here, I_n is the voltage drop of measurement resistor R_o = (0.984 ± 0.16) Ω, whose nominal value is 1 Ω. The current pulse amplitude can be calculated as (I_n / 0.984) A. V_n is the voltage drop of the LED, which is not necessary in the junction temperature calculations. P_n is the measured photodetector voltage for four different pulse durations (18 µs, 9 µs, 6.5 µs, and 3.5 µs).

The absolute error can be calculated using Equation 1 as follows: k_{pn} can be calculated using a low current value, where the thermal effect is negligible and the error is small. The current amplitude is calculated using the voltage drop on the resistor, which is called the current measurement resistor and measured by an oscilloscope. The voltage drop is V_{Ro}=(0.675±0.006)V for the measurement resistor R_o=(0.984±0.002)Ω. The current amplitude is $I_n' = V_{Ro} / R_o$ =0.686A. The measured photo detector voltage is P_n'=(0.218±0.006)V for this current, and $k_{pn}=P_n'/I_n'$=0.3178. The error ratio of k_{pn} is found as follows:

$$\Delta I_n' = \left|\frac{\partial I_n'}{\partial V_{R\ddot{o}}}\right| \Delta V_{R\ddot{o}} + \left|\frac{\partial I_n'}{\partial R_{\ddot{o}}}\right| \Delta R_{\ddot{o}}$$

$$= \frac{1}{0.984} 0.006 + \frac{0.675}{(0.984)^2} 0.002$$

$$\Delta I_n' / I_n' = 0.0075 / 0.686 = 1.09\%$$

$$\Delta k_{pn} = \left|\frac{\partial k_{pn}}{\partial I_n'}\right| \Delta I_n' + \left|\frac{\partial k_{pn}}{\partial P_n'}\right| \Delta P_n'$$

$$= \frac{P_n'}{(I_n')^2} \Delta I_n' + \frac{1}{I_n'} \Delta P_n'$$

$$= \frac{0.218}{(0.686)^2} 0.0075 + \frac{1}{0.686} 0.006 = 0.0122$$

$$\Delta k_{pn} / k_{pn} = 3.84\%$$

$$k_{pn} = (0.3178 \pm 0.0122)$$

The error ratio of I_n is calculated as follows: the voltage drop is $V_{R\,o}$= (13.1 ± 0.16) V for R_o = (0.984 ± 0.002) Ω. Hence,

$$I_n = \frac{V_{Ro}}{R_o} = \frac{13.1}{0.984} = 13.31 \text{ A}$$

$$\Delta I_n = \left|\frac{\partial I_n}{\partial V_{R\ddot{o}}}\right| \Delta V_{R\ddot{o}} + \left|\frac{\partial I_n}{\partial R_{\ddot{o}}}\right| \Delta R_{\ddot{o}}$$

$$\Delta I_n = \frac{1}{0.984} 0.16 + \frac{13.1}{(0.984)^2} 0.002 = 0.1896 \text{ A}$$

$$\Delta I_n / I_n = 1.41\%$$

k_{pn} = (0.3178 ± 0.0122), I_n = 13.31 A, ΔI_n = 0.1896 A, Pn = (1.39 ± 0.01) V, t_1 = 18 μs, k = 0.7% / °C, Δk = 0.1% / °C. Using these values:

$$\Delta T_j(t) = \left|\frac{\partial T_j(t)}{\partial k}\Delta k\right| + \left|\frac{\partial T_j(t)}{\partial P_n(t)}\Delta P_n(t)\right| + \left|\frac{\partial T_j(t)}{\partial k_{pn}}\Delta k_{pn}\right| + \left|\frac{\partial T_j(t)}{\partial I_n}\Delta I_n\right|$$

$$\frac{\partial T_j(t)}{\partial k} = \left|-\frac{1}{k^2} + \frac{P_n(t)}{k_{pn} I_n k^2}\right| = |-20408.2 + 6706.36| = 13702$$

$$\frac{\partial T_j(t)}{\partial P_n(t)} = \left|-\frac{1}{k_{pn} I_n k}\right| = 33.77$$

$$\frac{\partial T_j(t)}{\partial k_{pn}} = \left|\frac{P_n(t)}{(k_{pn})^2 I_n k}\right| = 147.72$$

$$\frac{\partial T_j(t)}{\partial I_n} = \left|\frac{P_n(t)}{k_{pn} k (I_n)^2}\right| = 3.53$$

$T_j(t1)$ = (142.86 – 46.94) + 25 = 95.92 + 25 = 120.92°C

$\Delta T_j(t1) = (13702 \times 0.001) + (33.77 \times 0.01) + (147.72 \times 0.0122) + (3.53 \times 0.1896) = 16.5$ °C

The relative error of the junction temperature is:

$$\frac{[\Delta T_j(t1)]}{T_j(t1)} = \frac{16.5}{120.92} = 0.136$$

The variation of the junction temperature relative error according to the current for four pulse durations is shown in Fig. 6. In this graph, k = 0.7% / °C, Δk = 0.1% / °C, and Δk / k = 0.001 / 0.007 = 0.14 are selected. The error rate of the junction temperature depends on the error rate of k. The variation of the junction temperature relative error rate for Δk / k = 0.00007 / 0.007 = 0.01 according to the current is shown in Fig. 7. Fig. 6 and Fig. 7 show that the error rate decreases with the increase in current. The error rate is large at low currents. Therefore, the junction temperature can be measured at high currents using this method.

The variation of the junction temperature with the current for four different pulse durations according to Equation 1 is shown in Fig. 8. Only the variations at large currents are shown because the error rate is large at low currents. Fig. 8 shows that the junction temperature increases with the increase in current. The room temperature is assumed to be constant at 25 °C.

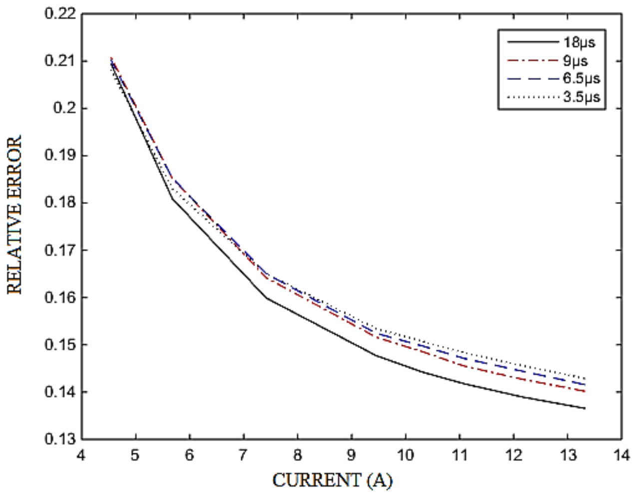

Fig. 6. Variation of the junction temperature relative error with the current for four pulse durations. In this graph, k = 0.7% / °C, Δk = 0.1% / °C, and Δk / k = 0.001 / 0.007 = 0.14

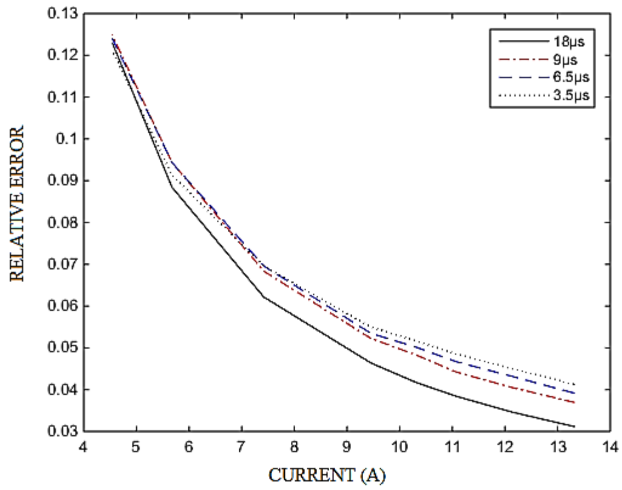

Fig. 7. Variation of the junction temperature relative error rate with the current for Δk / k = 0.00007 / 0.007 = 0.01

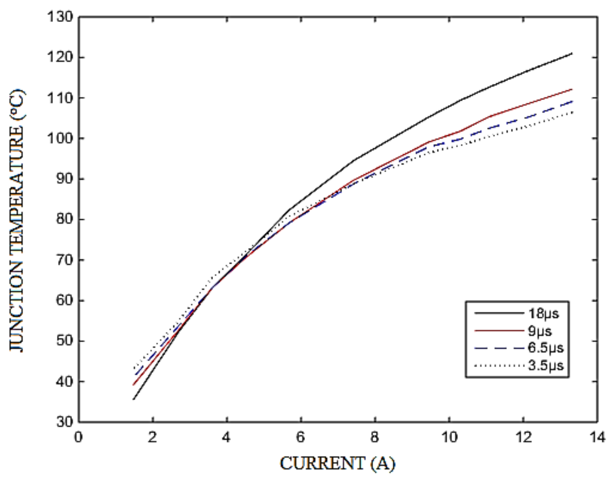

Fig. 8. Variation of the junction temperature with the current for four different pulse durations according to Equation 1

4. Conclusions

The junction temperature can be calculated by measuring some voltages. The thermal measurements and optical measurements are not necessary, even if the circuit has an LED and a photodiode. The photodetector voltage is used instead of the radiant power of the LED. Another advantage of this measurement technique is that the junction temperature can be calculated for microseconds.

The LED and photodiode are placed in a line, their positions must be stable during the measurements, and the distance between them must be sufficiently long to prevent the saturation of the photodiode. Equation 1 does not contain the distance and angle between the LED and the photodiode, so they are not involved in the junction temperature calculation.

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