Practical Considerations in High Power LED Junction Temperature Measurements

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Abstract—Power densities approaching 500W/cm^2 in the coming commercially available illumination LEDs has moved thermal management of power dissipation to the forefront in most package development efforts for this kind of product. These development efforts require a simple, accurate junction temperature measurement approach that can be implemented in the laboratory and on the production line. This presentation will describe the alternative junction temperature measurement approaches, then focuses on the most practical one with some discussion of measurement issues often encountered.

1. Introduction

The alternative techniques include two optical approaches - light frequency shift with temperature and light power shift with frequency - and two electrical approaches - the change in diode forward voltage with temperature using two different pulsing alternatives. The apparatus requirements and the measurement procedures for each alternative are discussed to provide a background for the selection of the most practical approach.

2. Optical Test Methods (OTMs)

The light output of an LED is temperature sensitive in two ways – power and frequency. Each of these ways offer a way fo determining the junction temperature.

2.1. Light Power Output Method (POM)

The light power output of an LED is linearly proportional to its junction temperature (T_J). This attribute can be used to determine T_J if the relationship between T_J and the power output is known in advance. Unfortunately, this relationship is dependent not only on the process-dependent characteristics of the diode chip but also on the ability to get rid of the heat generated at the diode junction. The latter is a function of the chip package and the combination of chip attachment technique and material. The manufacturing variability in diode construction and materials make empirical determination the best approach to deriving the P_O vs. T_J relationship. Once K_P is known, the junction temperature can be determined as follows:

$$T_J = T_A + \Delta T_J \quad (1)$$

where

$$\Delta T_J = (P_O - P_{Oi})(K_P) \quad (2)$$

$\therefore$

$$T_J = T_A + (P_O - P_{Oi})(K_P) \quad (3)$$

Implementing this method requires a measurement setup as shown in Figure 1. The LED is contained in a temperature controlled environment and pulsed with a very short current pulse at a very low duty cycle to minimize self-heating. Under these conditions the LED junction temperature can reasonably be assumed to equal the environment temperature. The power output is measured each time the environment temperature is changed and allowed to reach a steady-state condition. The data can then be plotted as P_O versus T_J and the value of K_P determined from taking the reciprocal of the plotted line. In most cases the plotted line will actually deviate from a straight line by a few percent and a straight line regression must be used to determine the slope.

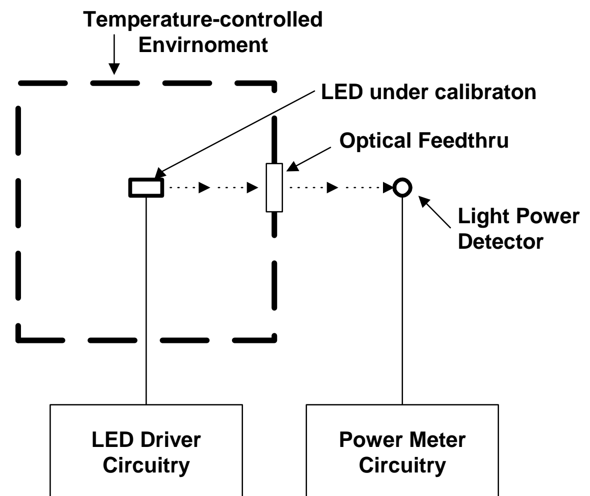

Figure 1 Light Power Output Measurement Setup

After K_P has been determined, the same measurement setup can be used to determine junction temperature rise under DC steady-state conditions. Power output (P_{Oi}) is measured the instant the DC power is applied and then

again when the power output (P_O) no longer changes with time (i.e., steady-state has been reached).

2.2. Wavelength Shift Method (WSM)

The other optical method makes use of the fact that the light output spectrum, primarily the center wavelength (λ_O), shifts linearly with device junction temperature with a positive slope. This method is particularly useful for narrow spectrum laser devices. Similar to the previous method, a calibration procedure is necessary to obtain the reciprocal of the slope, refereed to as K_λ. The value of K_λ is heavily dependent on the diode construction. Once K_P is known, the junction temperature can be determined as follows:

$$T_J = T_A + \Delta T_J \quad (4)$$

where

$$\Delta T_J = (\lambda_O - \lambda_{Oi})(K_\lambda) \quad (5)$$

$\therefore$

$$T_J = T_A + (\lambda_O - \lambda_{Oi})(K_\lambda) \quad (6)$$

The measurement setup and procedure for this method, shown in Figure 2, is very similar to that for the Power Output method. The only difference is the light measurement instrumentation. The procedure consists of applying short, low-duty cycle pulses and measuring the wavelength as the environment temperature is changed, making sure to allow sufficient time between temperature changes for stabilization at a steady-state condition. The measurement data is used to generate a plot of wavelength versus junction temperature from which the slope reciprocal produces K_λ. Then, junction temperature measurement is made by multiplying the K_λ by the wavelength shift from initial turn-on to the steady-state condition under application conditions.

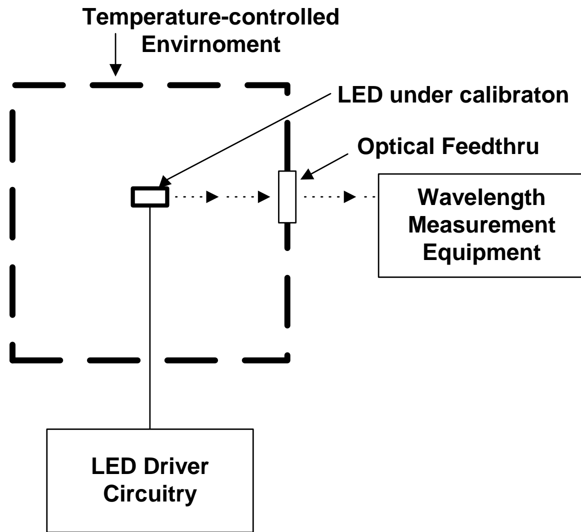

Figure 2 Light Wavelength Measurement Method Setup

Reference 1 discusses both of these methods in more detail.

3. Electrical Test Methods (ETMs)

Light emitting diodes, like most other semiconductor junction diodes, have a forward voltage characteristic that can be used for temperature sensing. The two alternative methods that make use of this attribute approach the voltage-temperature characteristic in different ways.

3.1. Single Current Method (SCM)

This method applies a fixed current to the LED and monitors the change in the forward voltage as a function of time. The LED forward voltage change at the fixed current must first be calibrated as function of junction temperature. This is done, in a manner similar to the Light Output Methods, measuring the forward voltage for very short, low-duty cycle pulses as the junction temperature is varied by external means in a temperature-controlled environment, using a setup shown in Figure 3.

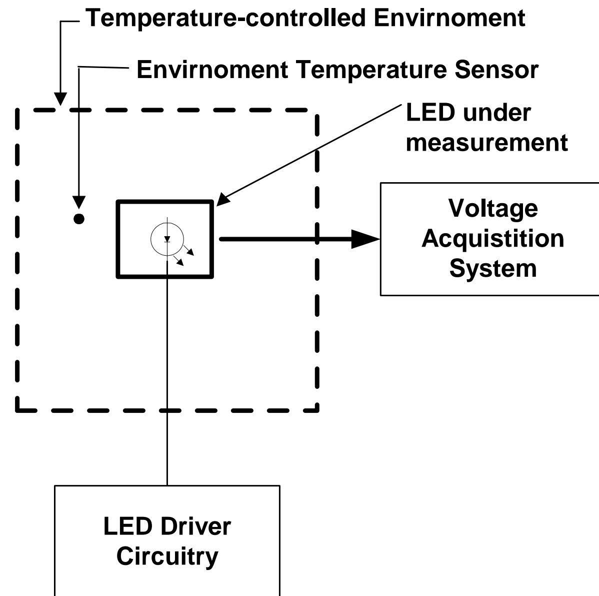

Figure 3 ETM-SCM setup for Junction Temperature measurement

The plotted calibration data will produce a nearly linear sloped line; the reciprocal of the slope is K. The LED is then put in a application or thermal standard environment and powered with an external current source. The change in forward voltage from the instant the current is applied to the device until some specific time (t_H), as shown in Figure 4, is then used to calculate junction temperature as follows: Although the slope is negative, K is always stated as a positive number:

$$\Delta T_J = (V_{Fi} - V_{Ff})(K) \quad (7)$$

$\therefore$

$$T_J = T_A + (V_{Fi} - V_{Ff})(K_P) \quad (8)$$

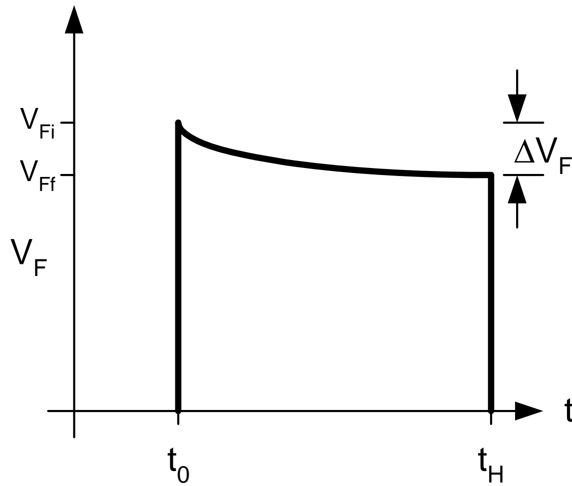

Figure 4 Heat-induced forward voltage change

3.2. Dual Current Method (DCM)

The disadvantages of the *Single Current Method* are that the calibration is done at a pulsed-current equal to the actual current that the LED is going to be used at, that this high current value produces sufficient slope variations from device-to-device to make calibration necessary on each individual diode, and that the calibration has to be repeated each time the current value changes. The *Dual Current Method* overcomes these issues by using separate currents for temperature sensing and for heating. This method is well documented[2,3,4] and is pretty much considered and industry standard..

The forward-bias current, referred to as Measurement Current (I_M) or Sense Current (I_S), must be large enough to turn the junction on over the range of temperature range of the measurement but not so large as to cause significant self-heating of the junction. Usual practice is to select a current value that is right around the knee of the diode forward characteristic as shown in Figure 5. The actual value is dependent on the specific device-under-test (DUT); 1mA to 10mA is sufficient

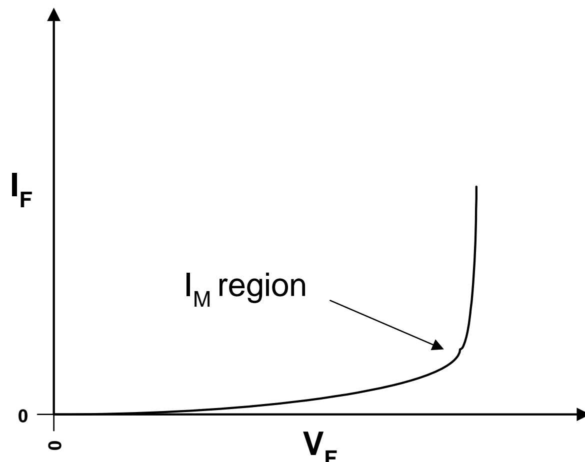

Figure 5 Measurement Current selected around the I_F-V_F curve knee

for most light emitting diodes, although high power output diodes may require 50 mA or more. As a general rule-of-thumb, the ratio of Heating Current (I_H) to I_M is 25:1 to 100:1; the exact value is dependent on the DUT and the test conditions during the T_J measurement.

Calibration of the V_F temperature characteristic requires a setup like the one shown in Figure 6. The low value of I_M insures that the environment and junction temperatures are the same. Note that because calibration requires only a constant current and a voltage measurement capability, multiple units can be calibrated at

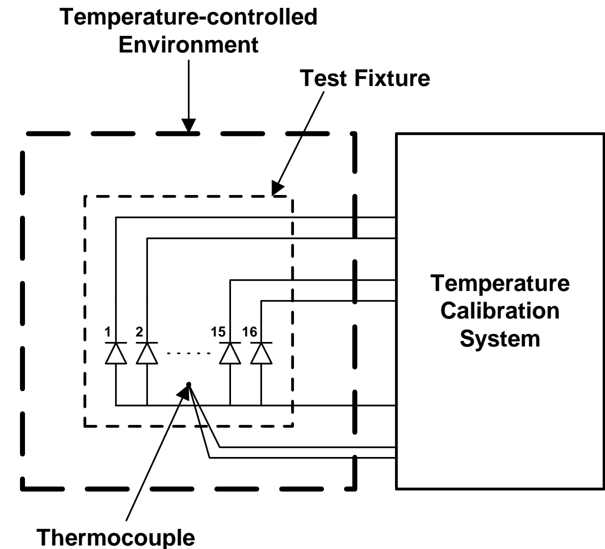

Figure 6 Equipment setup for Batch Calibration

the same time in a batch mode. The Temperature Calibration System shown contains the current source, voltmeter, a thermocouple meter and a multi-channel electronic switch.

The relationship between V_F and Temperature is, for most practical purposes, very linear and produces the curve shown in Figure 7. The calibration constant, K

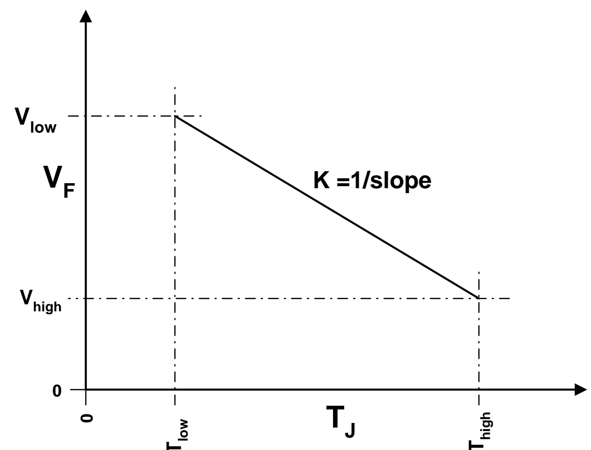

Figure 7 V_F -T_J calibration plot for determining K

Factor (or just K) is typically in the range of 0.5 °C/mV for silicon-based PN-junctions but can vary greatly

depending on the specific light emitting diode construction and materials, typically being in the 0.3 to 0.8 °C/mV range. The exact value of K is also dependent on I_M. Although the slope is negative, K is always stated as a positive number:

$$K = \left| \frac{T_{high} - T_{low}}{V_{low} - V_{high}} \right| \quad (9)$$

The batch calibration approach suggested in Figure 6 typically takes less than 1 hour to complete, depending on the type and size of the temperature-controlled environment. Equipment is commercially available for batch testing 48 units at a time, making the equivalent per unit calibration time in the range of 1.4 minutes each.

The *Dual Current Method* uses a three-step sequence of applied current levels to determine a change in junction voltage (ΔV_F) under Measurement Current (I_M) conditions. The setup for the measurement is shown in Figure 8. First, I_M is applied and the diode-under-test junction voltage is measured - the measurement value is referred

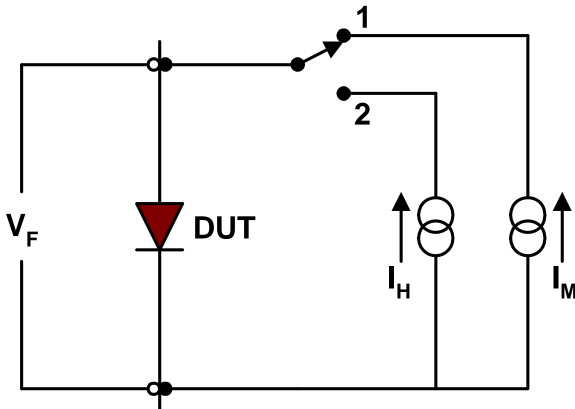

Figure 8 *ETM-DCM* setup for Junction Temperature measurement

to as V_{Fi}. Second, I_M is replaced with a desired amount of Heating Current (I_H) for a time duration (t_H) consistent with the steady-state or transient data required. During this time the diode voltage (V_H) is measured for determining the amount of power (P_H) being dissipated in the diode. Third, I_H is removed and quickly replaced with I_M and a final junction voltage measurement is be made - this voltage is referred to as $V_{Ff.}$ The three-step operation is shown graphically in Figure 9.

As discussed with the two previous methods, the ETM also requires the use of a temperature sensor (T_A) placed in the thermal test environment or on the diode mounting surface or package to determine T_J in absolute terms. This sensor, in conjunction with monitoring of V_F under I_M conditions before the start of the test, is also used to determine if temperature equilibrium conditions exist before the start of the test. Without power applied to the diode, the V_F reading will settle down to a value corresponding to the temperature of the external sensor. The value of T_J can then be calculated as follows:

$$T_J = T_A + \Delta T_J \quad (10)$$

where

$$\Delta T_J = (V_{Fi} - V_{Ff})(K) \quad (11)$$

$\therefore$

$$T_J = T_A + (V_{Fi} - V_{Ff})\left(\left| \frac{T_{high} - T_{low}}{V_{low} - V_{high}} \right|\right) \quad (12)$$

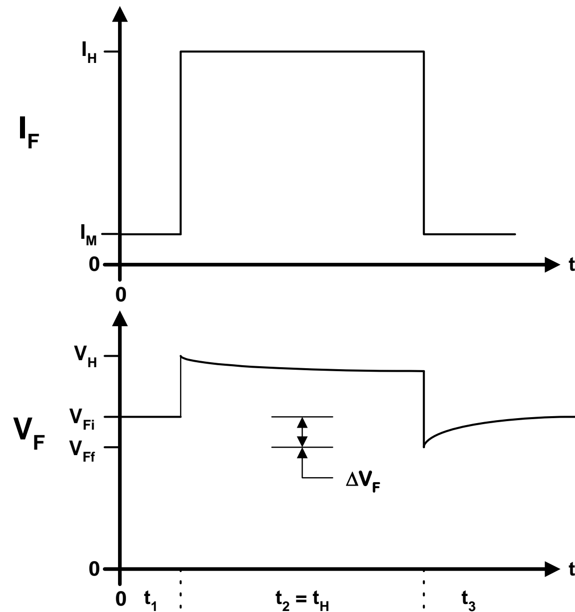

Figure 9 ETM-DCM measurement waveforms

4. Method Selection

Each of the junction temperature measurement methods discussed above has specific issues that set them apart from each other. The WSM is difficult to implement because LED light usually has a relatively broadband output making wavelength shift difficult to accurately measure. The POM requires an integrating sphere to accurately capture all the LED power output making thermal measurements in standard or application environment difficult to implement. The SCM is theoretically the easiest to implement but requires recalibration each time the Heating Current is changed. Further, the pulsed calibration requirement makes batch mode calibration difficult to implement. The DCM requires two accurate current sources and a relatively sophisticated electronic switch to properly implement. However, it does offer the advantage of calibration batch processing.

Table 1 summarizes the key attributes of each method based on a variety of factors. The table contents include:

O → Optical	C → complex	H → High
E → Electrical	S → Simple	M → Moderate
		L → Low

Comparison Item	POM	WSM	SCM	DCM
Type	O	O	E	E
TSP	P_O	λ_O	V_F	V_F
Calibration Type	Single	Single	Single	Batch
Calibration Setup	D	D	E	E
Calibration Cost	H	H	L	L
Measurement Setup	D	D	E	E
Measurement Cost	L	H	M	M
Automation Potential	M	L-M	H	H
Production orientation	L	L	H	H

Table 1 T_J Measurement Method Comparison

Based on the comparison table above, the two ETMs are a better choice than either of the OTMs. Of the two ETMs, the DCM has an edge because of batch calibration capability and from an historical and standards perspective.

5. Conclusions

As with all semiconductor devices, knowledge of junction temperature is necessary for predicting and improving reliability, for proper package design and selection, and for providing key product specifications to customers. The ETM-DCM satisfies the requirements of relatively simple implementation with capabilities for full thermal characterization[4,5].

References

[1] Siegal, B., “Laser Diode Junction Temperature Measurement Alternatives: An Overview”, Proceedings of PhoPack 2002, (July 2002).

[2] Mil-Std 750, Method 3101, U.S. Dept. of Defense.

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[4] “Integrated Circuit Thermal Measurement Method - Electrical Test Method (Single Semiconductor Device)”, *JESD51-1*, EIA JEDEC,.

[5] Hughes, J.J., Gilbert, D.B., and Hewrylo, F.Z., “Measurement of the Thermal Resistance of Packaged Laser Diodes”, *RCA Review*, Vol. 46, (June 1985), pp. 200-213.