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A Method for Projecting Useful Life of LED Lighting Systems

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ABSTRACT

This study investigated a non-invasive method to determine the junction temperature of AlGaInP light-emitting diodes (LEDs) in a system. Because the primary cause for the AlGaInP LED degradation is junction temperature, this method can be used to predict LED life. Currently, life estimates of LED lighting systems quoted by manufacturers (commonly 100,000 hours) are based on the average life of a single LED measured under specific laboratory conditions. In reality, rates of degradation are much different for LEDs in a system than for those in a laboratory environment because the packaging and the environmental conditions in which the system operates can affect LED performance. Current practices for estimation require time-consuming life tests to accurately predict the life of LEDs. Therefore, a rapid estimation method for LED life is needed. Based on previous studies, the authors chose to focus on the measurement of junction temperature and its relationship to LED degradation.

The primary objective of this study was to verify that wavelength shift could be used to estimate accurately the junction temperature of 5mm epoxy encapsulated AlGaInP LEDs. In this study, the junction temperature was increased by changing the drive current while holding the ambient temperature surrounding the LED constant, and by changing the surrounding temperature while holding the drive current steady. Experimental results from this study showed that for commercial LEDs, peak wavelengths shift proportionally to junction temperature regardless of how the temperature is created at the junction, and that this linear relationship could be used as a direct measure of the junction temperature. Because the primary cause for the degradation of AlGaInP LEDs is junction heat, the light output degradation rate of these types of LEDs can be predicted by measuring the spectral shift. Therefore, LED systems can be evaluated without disassembly in their intended application.

Keywords: LED, degradation, life, lighting

1. INTRODUCTION

Light-emitting diode (LED) technology has been used increasingly during the last five years in various lighting systems such as exit signs, traffic signals, channel-letter signs, and other forms of displays. End users purchasing an LED system want an accurate estimate for how long a system will last. Unlike most traditional light sources, LEDs do not fail catastrophically. Instead, the light output of LEDs degrades over time. Therefore, the useful life of an LED lighting system can be defined by the time when it fails to provide sufficient light for an intended application.^{1,2,3} Hence, measuring the average light output degradation rate would provide the necessary information to estimate the useful life of the LED lighting system.

System life quoted by manufacturers, commonly 100,000 hours, is often based on the average lifespan of a single LED. However, the average performance of a single LED cannot be used as an indicator of the lifespan of an LED system, which may contain multiple LEDs, circuit boards, housing, lenses and other components that, when combined, affect performance. Therefore, system manufacturers have to perform life tests for their products to obtain a more accurate life value. Measuring the light output for a certain amount of time and extrapolating the data to determine system life is not only time-consuming, but by the time a life estimate is made, technologies would have changed and the results may not be applicable anymore. Therefore, the goal of this study was to develop a methodology that can be used to rapidly estimate the life of an LED system.

Different types of materials and packages of LEDs have different degradation mechanisms. As a starting point in this study, the authors used only the 5mm epoxy encapsulated AlGaInP type of LED, which is commonly used in a variety

of LED systems including traffic signals and exit signs. Past literature suggests that the main cause for long-term light output degradation in LEDs is the heating of the *pn*-junction.^{4,5}

One of the consequences of heating the *pn*-junction is that the output spectrum of the light is affected.^{6,7,8,9} Studies of AlGaInP LEDs have shown that the peak wavelength shifts as a function of junction temperature.^{6,8} This effect is attributed to two primary mechanisms: lattice dilation and lattice vibration.^{9,10,11} Since the peak wavelength shifts proportionally to the junction temperature, and the primary cause for the degradation of AlGaInP LEDs is junction heat, the light output degradation rate of the LED can be predicted by measuring the spectral shift. The junction temperature of an LED is affected by the electrical power that is dissipated at the junction and by the ambient temperature. One of the main objectives of this study was to verify that spectral shift is proportional to junction temperature, regardless of how the heat is generated at the junction.

Although there are other ways to measure junction temperature, all of them require access to the lead wires of the LEDs. In most cases, once the LEDs are packaged into a lighting system, gaining access to the lead wires is not possible. This is the reason why the spectral shift method, being a non-contact method, is an attractive way to measure the junction temperature of LEDs in a system.

2. EXPERIMENT

The primary objective of this study was to verify that wavelength shift could be used to accurately estimate the junction temperature of AlGaInP LEDs. Therefore, the first step was to select an alternate, reliable method for measuring the junction temperature. Past studies have demonstrated that at a given forward current, the forward voltage across AlGaAs and AlGaInP red LEDs decreases linearly with increasing temperature over the range of -55 to 100°C.^{6,12} Therefore, by comparing the LED potential to a reference condition, the junction temperature can be determined. The junction temperature, T_j , can be expressed as

$$T_j = T_0 + \frac{V_t - V_0}{K} \quad (\text{Equation 1})$$

where T_0 is the reference ambient temperature; V_t and V_0 are the forward potentials at the test condition temperature and the reference ambient temperature, respectively; and K is the temperature coefficient of the forward voltage.¹²

Equation 1 can be rearranged to obtain an expression for K , and is expressed as

$$K = \frac{V_0 - V_1}{T_0 - T_1} \quad (\text{Equation 2})$$

where V_0 and V_1 are forward potentials at two known ambient temperatures, T_0 and T_1 , respectively.¹² Therefore, the constant K can be determined by measuring the potential drop across the LED junction at two known ambient temperatures. The junction temperature of the LED can now be determined using Equation 1 by measuring the change in forward potential.

To implement this method of measuring junction temperature, an electronic circuit was built to power the individual LED and to measure the potential across the junction.¹³ The LED was placed inside the thermal chamber (see Figure 1) at a predetermined ambient temperature and was driven at five different current conditions of 10mA, 20mA, 40mA, 60mA and 80mA. The ambient temperatures used in this study are 25°C, 40°C, 55°C and 70°C. At regular intervals, at a duty cycle of 0.001, the current was stepped down to a value of 1mA using a very short (200-microsecond) square wave pulse. The potential across the junction was measured during this short stepped-down period. The assumption here was that the 1mA current provides negligible heat to the junction, and temperature drop is negligible during the short stepped-down pulse condition. This method was used in subsequent tests as the reference method for studying the peak wavelength shift as a function of junction temperature.

In the tests that followed, the goal was to measure and correlate the peak wavelength shift of LEDs as a function of junction temperature. Three LED samples, each from three different manufacturers, were tested and the results were compared. The experimental apparatus consisted of three parts: the thermal chamber, the heating system, and the drive circuit. In addition, an oscilloscope and a spectroradiometer were used to measure and record the electrical and spectral data, respectively. Figure 1 illustrates the schematic of the experimental setup used in this study. The thermal chamber

measured 9 inches square and was built out of 1/2-inch wood laminate. The inside of the box was painted with a matte-finish white paint to create a Lambertian surface. A one-inch-diameter aperture with a clear acrylic window was created in the box to allow for spectral measurements using a spectroradiometer. A small white baffle was placed in front of the aperture to block any direct radiation from the LED. The LED was mounted on a 1.5-inch-square circuit board inside the thermal chamber. Spacers were added to create a 1-inch gap from the surface of the chamber box to the surface of the circuit board. This board was mounted on a plane orthogonal to the plane of the aperture and on the same horizontal plane as the aperture. Then, the LED was connected to a power supply and a digital multimeter outside the box by routing the wires through a small hole. A 6-inch-square heating element was placed at the bottom of the box. A resistance temperature detector (RTD) measured the ambient temperature of the box and provided the feedback signal to maintain the temperature inside the box to within $\pm 1^\circ\text{C}$. A J-type thermocouple was used to monitor the pin temperature of the LED. The temperature data from the thermocouple was used in parallel with the temperature obtained from the RTD to determine thermal equilibrium. The LED drive circuit provided the necessary current to the LED. An oscilloscope monitored the drive current and potential across the LED.

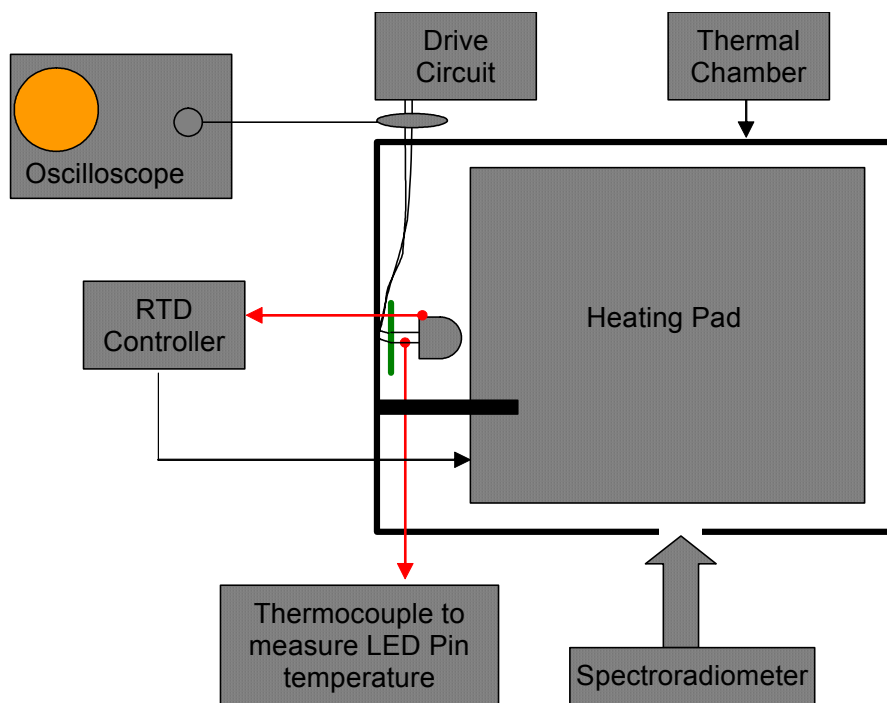
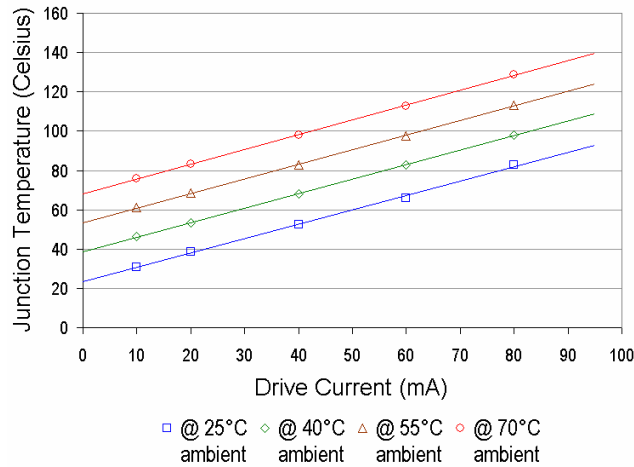


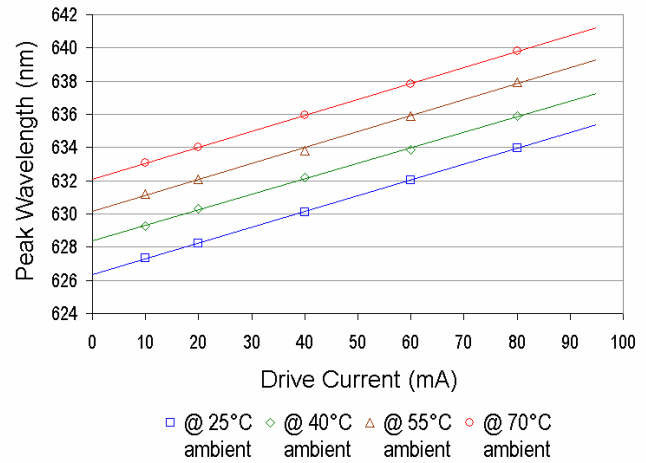
Figure 1: Schematic of experimental setup.

At each of the experimental conditions, the measured potential across the junction determined the junction temperature. The corresponding SPD was also measured. Finally, a comparison of the spectral results to the junction temperature determined the correlation of peak wavelength shift to junction temperature.

Figure 2a and Figure 2b show the results of one of the samples. As seen in these two figures, the junction temperature and the peak wavelength of the LED spectrum are both linearly proportional to the drive current at all four ambient temperatures.



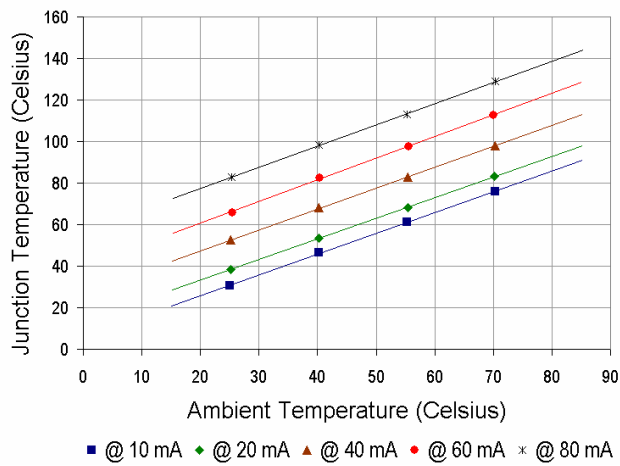
(2a)



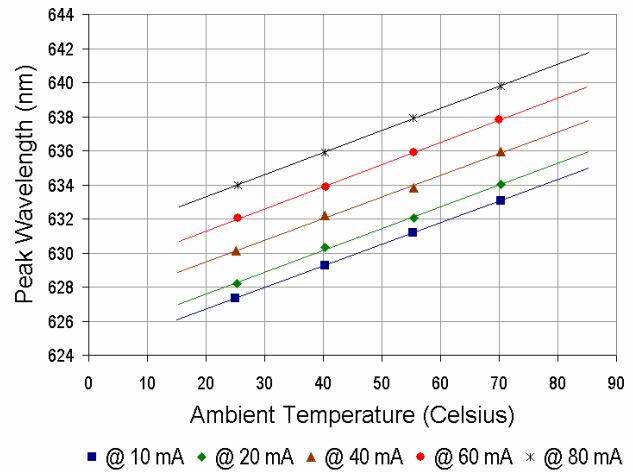
(2b)

Figure 2: a) The junction temperature and b) the peak wavelength of LED sample A1 as a function of drive current at four different ambient temperatures.

Similarly, Figure 3a and Figure 3b illustrate the linear relationship for junction temperature and ambient temperature, and for peak wavelength and ambient temperature, respectively.



(3a)



(3b)

Figure 3: a) The junction temperature and b) the peak wavelength of LED sample A1 as a function of ambient temperature at five different drive current values.

Figure 4 shows the final results of these four graphs, illustrating that peak wavelength is directly proportional to the junction temperature. Therefore, it can be concluded that the peak wavelength shift is proportional to the change in junction temperature, regardless of how the heat is generated at the junction.

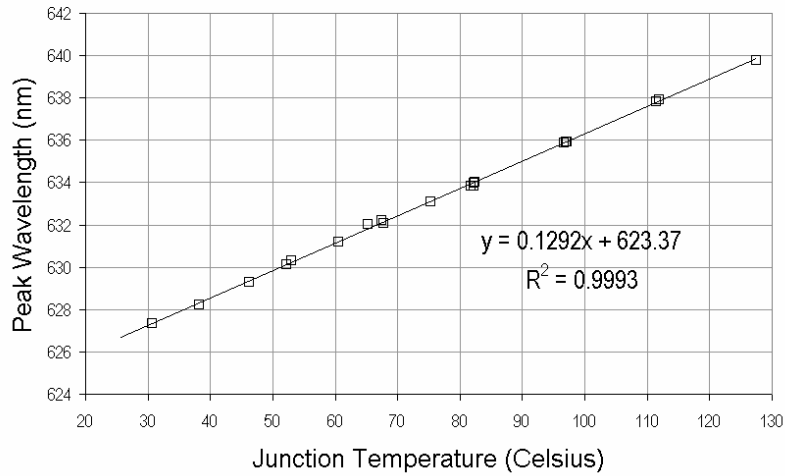


Figure 4: Peak wavelength as a function of LED junction temperature for LED Sample A1.

So far, only figures from one sample LED are shown to illustrate the relationships. Figure 5 illustrates the peak wavelength as a function of junction temperature for nine commercial LEDs.

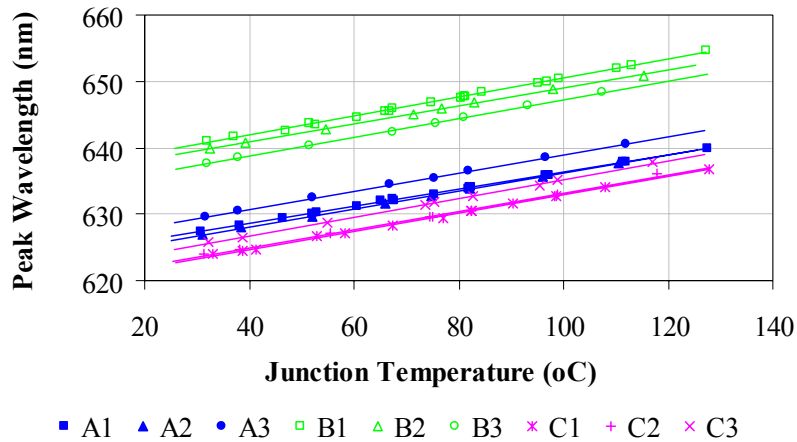


Figure 5: Peak wavelength versus junction temperature for nine commercial red LEDs (AlGaInP).

As seen in Figure 5, although the LEDs had different peak wavelengths at room temperature, their relative shifts were the same for similar changes in junction temperature. In these plots of peak wavelength versus junction temperature, linear regression lines are drawn through the data points. The average slope of all these regression lines is 0.1376 (nm/°C). Now, to elucidate the effect of peak wavelength shift on change in junction temperature, an aggregate of the relative shift in the peak wavelengths for all nine commercial LEDs is plotted against the aggregate relative increase in junction temperature (Figure 6). The dotted lines in Figure 6 illustrate the standard deviation of the nine trend lines.

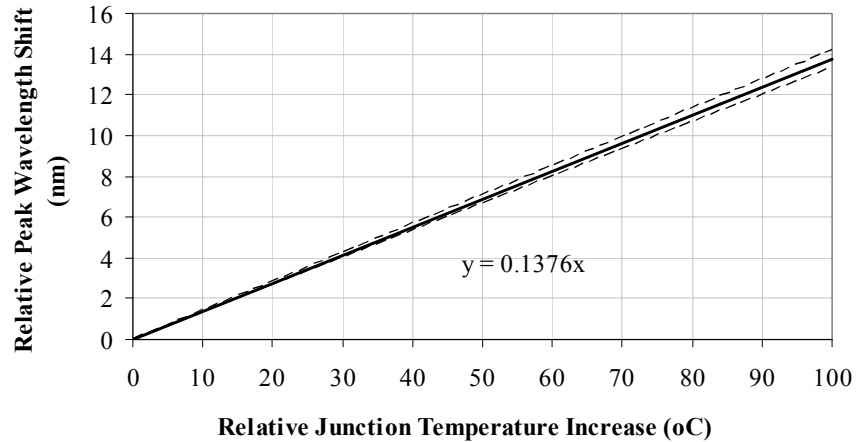


Figure 6: Relative peak wavelength shift as a function of relative junction temperature change. The solid line indicates the mean value, and the dotted lines indicate the standard deviation.

From the results of this experiment, it can be concluded that the peak wavelength of AlGaInP-type red LEDs shifts proportionally to junction temperature. The high correlation of the trend lines generated from the experimental data of the nine commercial LEDs validates that the observed relationship is indeed linear.

2.1 Discussion

As seen in Figure 5, the peak wavelength of the red LEDs may be different at the beginning. Therefore, in practice the LED system will be powered up, and the SPD of the emission spectra will be measured initially (at time zero) and after some time when the system reaches thermal equilibrium. Since the LED system was in thermal equilibrium with the initial ambient temperature prior to power up, it can be assumed that the LED junction temperature is equal to the ambient temperature. Therefore, the LED junction temperature, T_j , at operating condition can be determined from the following equation

$$T_j = T_a + \frac{\Delta\lambda_p}{K_p} \quad (\text{Equation 3})$$

where T_a is the ambient temperature of the environment (which is also the initial junction temperature), $\Delta\lambda_p$ is the magnitude of the peak wavelength shift from the initial condition to the final operating condition, and K_p is the slope of λ_p versus T_j plot for these types of LEDs. Using Equation 3, the LED junction temperature can be determined non-invasively for an LED in a system. The wavelength coefficient (K_p) is the rate of change of junction temperature (ΔT_j) to peak wavelength ($\Delta\lambda_p$). From the previous experiment, the wavelength coefficient was determined to be $0.1367 \text{ nm}/^\circ\text{C}$ ($+0.005 \text{ nm}/^\circ\text{C}$). Therefore, measurements of the peak wavelength shift and the initial ambient temperature are all that is needed to determine the junction temperature of the LED in steady-state operation.

The next step is to relate junction temperature to LED degradation rate. As part of ongoing research, these types of LEDs are presently being life tested. The results showing the relationship between junction temperature and light output degradation rate will be published at a later time when they become available.

This method demonstrates tremendous potential as a non-invasive technique to accurately determine the junction temperature for LEDs. However, the scope of this study was limited to 5mm type AlGaInP LEDs. The authors of this manuscript hope to expand this study to include other LED packages and materials such as nitrides. Further refinement in the technique and improvements in the instrumentation can lead to its application as a predictor of LED useful life.

3. SUMMARY

This study demonstrates the possibility of a non-invasive method to determine the junction temperature of AlGaInP LEDs in a system. The results show that peak wavelength shift can be used as a direct measure of the junction temperature. Therefore, LED systems can be evaluated without disassembly in their intended application.

Although literature suggests that device temperature has an impact on useful life, practical issues in determining the operating junction temperature may have pre-empted its consideration as a useful metric for determining LED life. Currently, determination of device temperature under operation is accomplished by using a thermal transfer algorithm with the thermal coefficients provided by the manufacturer. An accurate determination is dependent on an accurate characterization of the thermal operating environment of the LEDs. However, this is extremely difficult to achieve without introducing a confound to the closed thermal environment under consideration.

The non-invasive method suggested in this paper tackles these concerns. This method addresses the more important issue of device temperature under its intended operation. Because the method is non-invasive, the integrity of the LED system is maintained.

Questions still exist as to what causes certain LED technologies to degrade. Therefore, further research is needed to definitively link the spectral shift to the life of the LED. Isolating the spectral shift to the junction temperature of the LED is only the first step. Therefore, a life test is under way to determine if any interaction of drive current and ambient temperature exists on the gradual degradation of the AlGaInP LED.

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