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ABSTRACT

The goal of this study was to develop a non-contact method for determining the junction temperature of phosphor-converted white LEDs as a first step toward determining the useful life of systems using white LEDs. System manufacturers generally quote the same life values for their lighting systems that the LED manufacturers estimate for a single LED. However, the life of an LED system can be much different compared with the life of an LED tested under ideal conditions because system packaging can affect system life. Heat at the *pn*-junction is one of the key factors that affect the degradation rate, and thus the useful life, of GaN-based white LEDs. The non-contact method described in this manuscript, combined with LED degradation rates, can be used to predict white-LED system life without affecting the integrity of the lighting system or submitting it to long-term life tests that are time-consuming.

Different types of LED packages would have different degradation mechanisms. Therefore, as a first step this study considered only the 5mm epoxy encapsulated GaN+YAG Cerium phosphor white LED. The method investigated here explored whether the spectral power distribution (SPD) of the white LED could provide the necessary information to estimate LED junction temperature. Based on past studies that have shown that heat affects the radiant energy emitted by the InGaN blue LED and the YAG Cerium phosphor differently, the authors hypothesized that the ratio of the total radiant energy (W) to the radiant energy within the blue emission (B) would be proportional to the junction temperature. Experiments conducted in this study verified this hypothesis and showed that the junction temperature can be measured non-invasively through spectral measurements.

Keywords: Light-emitting diodes (LEDs), white light, degradation, life, junction temperature, spectral power distribution

1. INTRODUCTION

White light-emitting diodes (LEDs) are rapidly evolving for use in general illumination applications. LEDs are known to produce light for a long time. For LED lighting systems, original equipment manufacturers (OEMs) generally quote the same numbers the LED manufacturers quote for the life of individual LEDs, which are based on data collected under certain laboratory conditions. In reality, however, LEDs in a system would degrade at a much different rate depending on how the LEDs are packaged and powered. Presently, there is no easy way to estimate the life of white LED systems. Therefore, the greater goal of this study was to work toward developing a method that could be used to predict the life of white LED lighting systems rapidly, without subjecting them to long-term life tests.

One of the most common methods for producing white LEDs is to utilize a GaN-based blue emitter and a cerium doped yttrium aluminum garnet (YAG:Ce) phosphor, which are then embedded inside an epoxy resin. Different types of LED packages have different degradation mechanisms, and therefore, the light output depreciation rates of the various white LED packages are much different. As a starting point, this study considered only the 5mm epoxy encapsulated YAG:Ce phosphor-converted white LED, which is presently very common in the marketplace. A comprehensive literature search was conducted to understand what causes light output degradation in white LEDs. Past studies of GaN-based blue LEDs have shown that light output reduction over time occurs primarily due to the yellowing of the epoxy encapsulant.[1, 2] In 2000 Narendran et al. observed that 5mm-type phosphor-converted white LEDs also degraded very rapidly, and the LEDs reached the 50% light output level within 6,000 hours. In that same study, it was shown that the chromaticity values of the white LEDs shifted toward yellow over time, and it was speculated that the yellowing of the epoxy was the main cause for light output degradation.[3] In 2002, Steranka and others provided proof to the epoxy-degradation issue by replacing the epoxy surrounding the die of a white LED and demonstrating that the light was recoverable.[4] Therefore, based on past studies, the primary reason for the degradation of 5mm white LEDs is the yellowing of the epoxy due to thermal effects. The secondary reason is the degradation of the semiconductor itself.[1, 5, 6, 7] Defects within the *pn*-junction cause degradation in LED semiconductors.[5] In 1997 Sugiura reported that heat at the junction of GaN LEDs reduces quantum efficiency and enhances diffusion of impurities, as well as migration of dislocation.[6] With heat, the defects grow and cause light loss over time. Therefore, in either case (yellowing of the epoxy and degradation of the semiconductor) heat at the junction is one of the main causes for white LED degradation. Thus, the main objective of this study was to identify a method that could be used to determine the junction temperature of the white LED in a lighting system. Although there are several methods for measuring the junction temperature of LEDs, they all require access to the pins of the LEDs. Once assembled into a system, it is not easy to gain access to LED pins (lead wires) without affecting the integrity of the system. Therefore, a non-contact junction temperature method would be ideal for system evaluation.

The proposed study is analogous to the study conducted by Hong et al. in 2002,[8] except the LEDs are white, InGaN based, instead of red, AlGaInP based. Hong et al. showed that the peak wavelengths of AlGaInP LEDs shift proportionally to the junction temperature, regardless of how the temperature is created at the junction.[8] However, in the case of InGaN-type blue LEDs, the peak wavelength shift is much smaller and is therefore very difficult to measure. Figure 1 illustrates the peak wavelength shift of a sample blue LED as a function of junction temperature. While holding the ambient temperature fixed, the blue LED was driven at several constant current values (1, 10, 20, 30, 40, 50, 60 mA), and the light output was measured using a spectroradiometer at each condition. Then the ambient temperature was changed to two other values, and the procedure was repeated. As seen in Figure 1, the peak wavelength initially shifts toward shorter wavelengths with increasing current and then stabilizes for a while, and then increases. This pattern was true at all temperature conditions, and the overall shift was very small. Furthermore, the junction temperature did not show any simple correlation to wavelength shift.

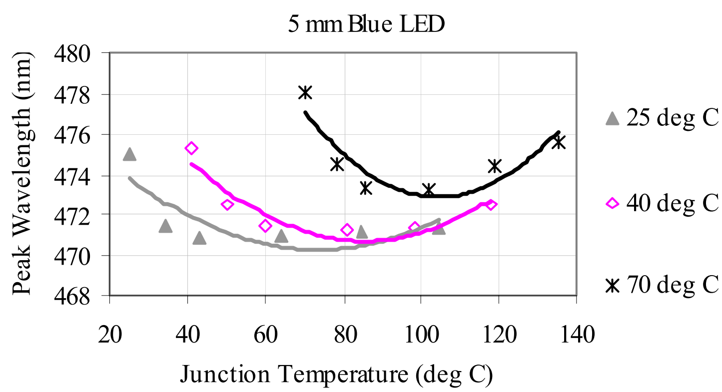


Figure 1: Peak wavelength position of a sample GaN blue LED emission as a function of junction temperature.

Tamura et al. in 2000 showed that as temperature increases, the emission intensities of the blue and yellow radiations of white light emitted by phosphor-converted white LEDs decrease at different rates.[9] The difference could be partly attributed to the fact that YAG cerium phosphor efficiency, even though small, changes with temperature, as shown in Figure 2.[10] Based on Tamura's work, it was hypothesized that the ratio of the total radiant energy of the white LED spectrum (W) to the radiant energy within the blue emission peak (B) could be used as a predictor of the junction temperature. Because this technique relies on SPD measurement, which is non-contact in nature, it is ideal for predicting LED junction temperature in a system without affecting the system's integrity.

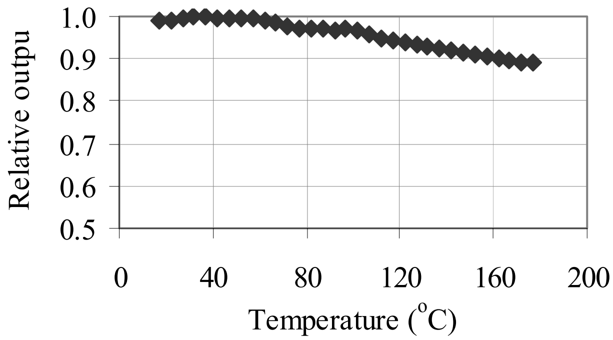


Figure 2: Relative emission of YAG:Ce Phosphor for 450 nm as a function of temperature.

2. EXPERIMENT

As stated earlier, the main objective of this study was to verify that junction temperature changes are proportional to changes in the W/B ratio in GaN+YAG Cerium phosphor white LEDs (henceforth called the "white LED"). The first step was to identify an alternative, reliable method that could be used to predict the junction temperature of the white LED. One commonly used method for estimating the junction temperature of an LED is by measuring the pin temperature and using heat transfer functions.[11, 12] To use this method, one has to rely on the thermal resistance coefficients supplied by the respective LED manufacturers. Once the thermal resistance coefficient is known, then the junction temperature, T_j, can be estimated using the equation: [11, 12]

$$T_j = T_p + P_j \times R\theta_{j\text{-}p} \quad \text{(Equation 1)}$$

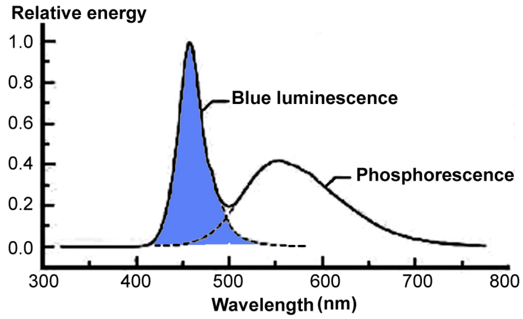
where T_p, P_j, and $R\theta_{j\text{-}p}$ are the LED pin temperature, junction power dissipation, and thermal resistance coefficient from the junction to the pin, respectively. Junction power dissipation is the product of the forward current and the forward voltage. Although estimating the LED junction temperature by measuring the pin temperature of an LED is a convenient method, the thermal resistance coefficient of the white LEDs used in this study was not available.

It has been shown in the past [13] that the LED junction temperature could be determined by measuring the change in potential drop across the LED. The junction temperature is related to the change in forward potential across the *pn*-junction by the following equation: [13, 14]

$$T_j = T_0 + \frac{V_t - V_0}{K} \quad \text{(Equation 2)}$$

where T_0 equals the reference ambient temperature; V_t is the forward potential of the LED at the reference current for the test condition; V_0 is the reference forward potential at the reference temperature and current; and K is the temperature coefficient of the forward voltage. The value of constant K can be determined by measuring the potential drop across the junction at two known temperatures.[14] By applying the known K value to Equation 2, the junction temperature can be determined for the LED by measuring the change in forward potential. Initially, this method was used simultaneously with the pin temperature measurement method to determine the thermal resistance coefficient, $R\theta_{j\text{-}p}$, for the white LEDs used in this study. The thermal resistance coefficient, $R\theta_{j\text{-}p}$, was determined to be 137°C/W for the tested white LEDs. Now that the thermal resistance coefficient is known, the pin temperature method can be used in the remainder of the experiment to estimate junction temperature.

To obtain the ratio of the total radiant energy emitted by the white LED to the radiant energy within the blue emission (W/B), the blue emission needed to be separated from the whole spectrum for assessment, as shown in Figure 3a. For simplicity, the point of lowest energy in the SPD between the peaks of blue emission and yellow emission was identified, and the SPD to the left of this point was considered as the blue emission (as illustrated in Figure 3b). The radiant energies for the blue and the white SPD were calculated by integrating the energy every two nanometers for the entire spectrum.



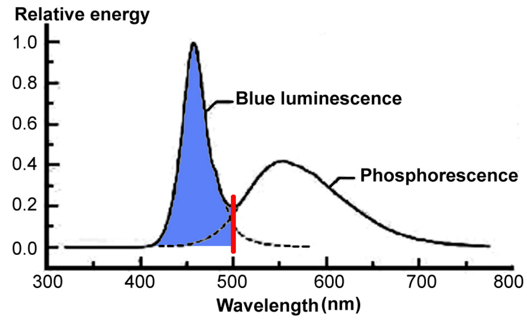
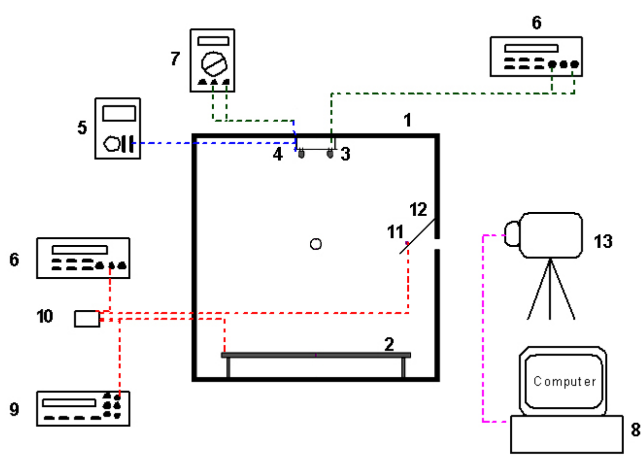


Figure 3: (a) Ideal SPD selection for blue emission. (b) Practical SPD selection for blue emission.

Figure 4 is the schematic of the experimental setup. A small thermal chamber (1) was built to keep the test LEDs at a constant temperature. The inside of this small box was painted with a white, matte finish. The temperature inside the thermal chamber (1) was controlled by a heater controller (10), which received temperature information from the resistance temperature detector (RTD) (11) and turned the heater on and off (2). The multimeter (9) displayed either the set-point temperature on the controller or the real-time temperature of the RTD. Power for the controller was supplied by the DC power supply (6). Another power supply generated stabilized DC current for the LED array (3). The tip of a J-type thermocouple (4) was soldered onto the cathode pin of an LED. The thermocouple was connected to the thermometer (5). In addition, a second multimeter (7) was used to monitor the forward voltage of the LED with the thermocouple. A white baffle (12) was used to block the direct light from entering the light detector. The spectroradiometer (13) was aimed and focused at the surface of the baffle to measure the spectral power distribution (SPD). A computer (8), which was connected with a Pico ammeter and a spectroradiometer, acquired and stored the SPDs of the LED array at different operating conditions.



1. Thermal chamber: 8”x8”x8” inside
2. Heater: 6”x6” heating pad
3. 5mm LED array: NICHIA, model NLPB-500
4. Thermocouple: OMEGA, 40-AWG, type J
5. Thermometer: OMEGA, model 872A, type J
6. Power supplies: HEWLETT PACKARD, model E3632A
7. Multimeter: FLUKE, model 87III
8. Computer: GATEWAY, model Pentium II 333
9. Multimeter: HEWLETT PACKARD, model 3478A
10. Heater controller: MINCO, model CT325
11. Resistance temperature detector (RTD)
12. Baffle
13. Spectroradiometer: PHOTO RESEARCH model PR-705

Figure 4: Experiment 1 apparatus and its descriptions. (Instruments are for illustration only. They are not to scale.)

Initially, white LEDs from the same manufacturing batch were purchased for this study. Six LEDs with the same blue peak wavelength, 466 nm, were selected and assembled into an array, all connected in series. This assembly provided sufficient light output to be measured by the optical detectors without much noise in the signals. The pin temperature and the forward voltage of only one LED in the array were measured. It was assumed that the other five LEDs had the same values since all six LEDs had similar light output characteristics. The LED array was tested at various drive currents (each LED had a constant current between 8mA and 60mA) and various ambient temperatures (25°C, 45°C, 55°C). In the experimental procedure, the pin temperature, forward voltage, forward current, and the SPD were measured at each condition. The W/B ratios were calculated from the SPDs and were compared to the junction temperatures of the LEDs (estimated from the pin temperatures) to determine the correlation of W/B ratio to junction temperature.

Figure 5 illustrates the plot of junction temperature versus W/B ratio for the LEDs tested. The solid line in Figure 5 represents a linear regression line, which shows a strong linear correlation ($R^2 = 0.99$) between junction temperature and W/B ratio. This indicates that by measuring the W/B ratio, one can estimate the junction temperature of this type of white LED.

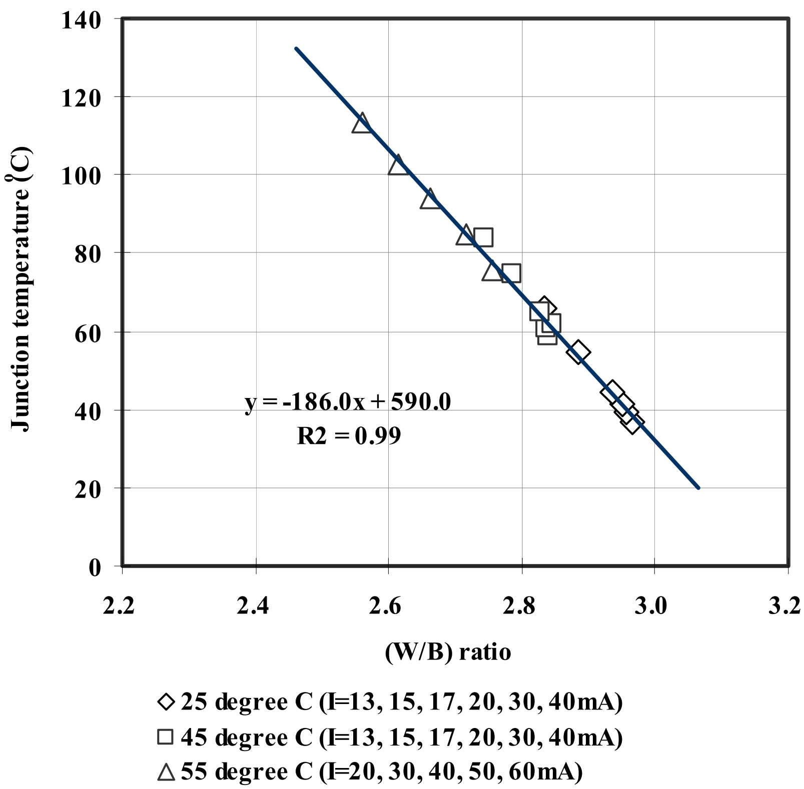


Figure 5: Junction temperature versus W/B ratio.

Usually, white LEDs, even though they are from the same manufacturing batch, have different peak wavelengths for the blue emission. Therefore, the question is: Will the linear relationship between junction temperature and W/B ratio hold, even if the peak wavelength of the blue emission is different, and will the slope be the same? To answer this question, white LEDs from two more manufacturing batches of the same manufacturer were purchased and tested in a similar manner. Once again, from each batch six LEDs with a similar blue peak wavelength were chosen, and they were assembled into an array. Each array had a different blue peak wavelength from the other two, as shown in Figure 6. The peak wavelengths of the different LED arrays correspond to 466 nm, 461 nm, and 460 nm. LED1, LED2, and LED3 are the single LEDs from the three arrays. Figure 7 illustrates the plot of junction temperature versus W/B ratio for all three LED arrays. The solid lines represent the linear regression lines, which again show a strong linear correlation (R^2 values greater than 0.97) between junction temperature and W/B ratio for all LEDs. The slope of each sample LED tested was obtained from the linear regression line, and they are 186, 186, and 200. The 95% confidence intervals for the three slopes overlap. This indicates that the linear relationship between junction temperature and W/B ratio holds for any commercial white LED of this type, even if their spectral characteristics are not identical. The slopes also are similar for white LEDs with different spectral characteristics.

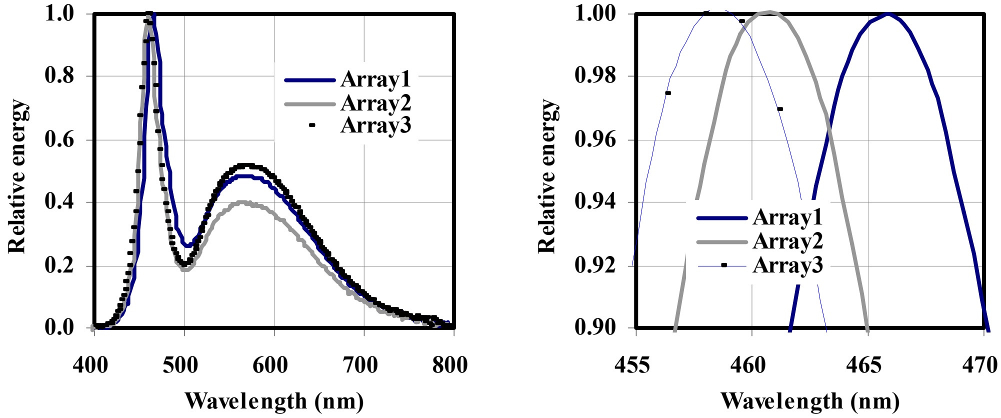


Figure 6: SPD of the different LEDs from the three arrays. The left figure is the expanded view of the right one.

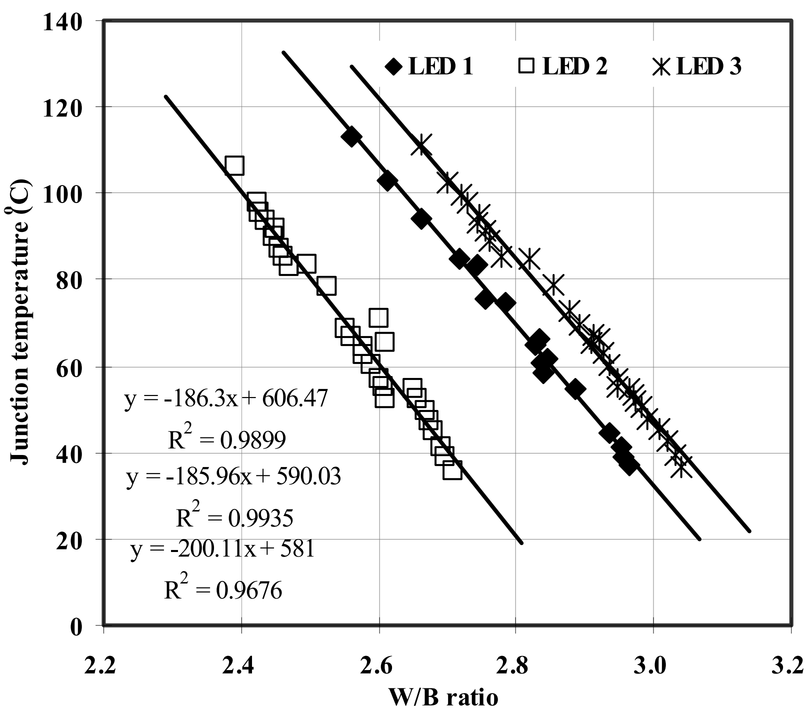


Figure 7: Effect of junction temperature on W/B ratio for three LED samples.

Therefore, the LED junction temperature can be estimated from the W/B ratio shift with the following equation:

$$T_j = T_0 + \frac{(R - R_0)}{K_r} \qquad \text{(Equation 3)}$$

Where T_0 = initial ambient temperature of the environment (also the initial junction temperature), °C
R = W/B ratio corresponding to the final equilibrium operating state (the junction temperature at this condition is T_j)
R_0 = W/B ratio at the known initial junction temperature, which corresponds to T_0
K_r = slope of the W/B versus the T_j plot, defined by $(\Delta R)/(\Delta T_j)$, $°C^{-1}$

The average K_r value for these LEDs is – 0.0052 $°C^{-1}$.

The constant value of K_r can be expressed as:

$$K_r = \frac{R_0 - R_1}{T_0 - T_1} \qquad \text{(Equation 4)}$$

where
R_0 = W/B ratio at the known initial junction temperature
R_1 = W/B ratio at the secondary known initial junction temperature
T_0 = initial ambient temperature of the environment, °C
T_1 = secondary initial ambient temperature of the environment, °C

Therefore, the average LED junction temperature can be determined non-invasively for the LED in a system by measuring (1) the initial ambient temperature and (2) the spectra instantaneously at the onset and at the final operating conditions. The system under test would be switched off and given sufficient time to cool and reach thermal equilibrium. Eventually, the initial LED junction temperature would equal the surrounding ambient temperature. The system would then be powered up, and simultaneous spectral measurements (λ_0 at T_0) would be recorded. The W/B ratio (R_0) could then be derived from the spectrum. This method would then be repeated at another ambient temperature (T_1) to obtain the W/B ratio (R_1) from λ_1 at T_1. Therefore, according to Equation 4, K could be calculated. A final spectral reading (λ at Tj) would be taken once the system was fully stabilized. The expression (Equation 3) may then be used to determine the LED junction temperature.

3. DISCUSSION

Measuring the junction temperature leads to the next step of determining the degradation rate of white LEDs. As part of ongoing research, the authors of this manuscript are presently life-testing several white LEDs at various junction temperatures.[15] The results of this follow-up study will establish the rate of degradation for this type of white LED as a function of junction temperature. Given that junction temperature can be predicted using the W/B ratio, the degradation rate also can be predicted from the W/B ratio.

The practical application of this method relies on the resolution of the W/B ratio. As an example, from Figure 7 it can be seen that for every 1°C change in junction temperature, the W/B changes 0.005. Therefore, the SPD measurement instrument and the data analysis process should yield a resolution better than 0.005 in order for the W/B ratio to estimate junction temperature changes of the order of 1°C.

This study tested only the 5mm epoxy encapsulated GaN+YAG Cerium phosphor white LED from one manufacturer. Therefore, further research is needed to test other white LED packages, including high-power packages, and to verify the applicability of this method.

4. SUMMARY

This study defined a non-contact method to estimate the junction temperature of 5mm epoxy encapsulated GaN+YAG Cerium phosphor white LEDs. This method looked at the changes in ratio of total radiant energy (W) emitted by the white LED to the radiant energy within the blue emission (B). The results show that W/B ratio change could be used as a direct measure of junction temperature. Testing white LEDs from three different manufacturing batches showed that the linear relationship between junction temperature and W/B ratio holds for any commercial white LED of this type, even if their spectral characteristics are not identical. Application of this method addresses concerns of system integrity and intended environment. By measuring the spectra and the initial ambient temperature to determine the junction temperature, an LED system can remain in stable operation. Currently, the authors are conducting life-test experiments in order to derive LED degradation rates – to then result in LED system life predictions – based on junction temperature and short wavelength amplitude. Application of this technique would mean that an LED's life in a system could be estimated without long-term testing. The data and results will be published at a later time.

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REFERENCES

1. Barton, D. et al., "Life Tests and Failure Mechanisms of GaN/AlGaN/InGaN Light Emitting Diodes," *Light-Emitting Diodes: Research, Manufacturing, and Applications II , SPIE International Symposium on Integrated Devices and Applications Optoelectronics '98, Proceedings of SPIE,* Schubert, E. F., editor, **Vol. 3279**, p. 17-27, International Society for Optical Engineering, San Jose, CA, Jan. 26-30, 1998.
2. Lee, C. et al., "Temperature Dependence of the Radiative Recombination Zone in InGaN/GaN Mulpitle Quantum Well Light-emitting diodes," J. App. Phys., **89 (11)**, pp. 6554-6556, 2001.
3. Narendran, N. et al., "What is Useful Life for White Light LEDs?" J. Illum. Eng. Soc. **Vol. 30, No. 1**, p. 57-67, 2001.
4. Steranka, F.M. et al., "High Power LEDs – Technology Status and Market Applications," phys. stat. sol. (a) **Vol. 194(2)**, p.380-388, 2002.
5. Fukuda, M., *Reliability and Degradation of Semiconductor Lasers and LEDs*, Boston: Artech House, 1991.
6. Sugiura, L., "Dislocation Motion in GaN Light-emitting Devices and its Effect on Device Lifetime," J. Appl. Phys. **81(4)**, p.1633-1638, 1997.
7. Egawa, T., Ishikawa, H., Jimbo, T. and Umeno, M., "Optical Degradation of InGaN/AlGaN Light-emitting Diode on Sapphire Substrate Grown by Metalorganic Chemical Vapor Deposition," Appl. Phys. Lett, **69 (6)**, p. 830-832, 1996.
8. Hong, E. and Narendran, N., "A Method for Projecting Useful Life of LED Lighting Systems," *Third International Conference on Solid State Lighting, Proceedings of SPIE,* Ferguson, I.T., Narendran, N., DenBaars, S.P., Carrano, JC., editors, **Vol. 5187**, International Society for Optical Engineering, San Diego, Calif., Aug. 5-7, 2003 (to be published).
9. Tamura, T., et al., "Illumination Characteristics of Lighting Array Using 10 Candela-class White LED under AC 100V Operation," J. Luminescence **87-89**, p.1180-1182, 2000.
10. Raukas, M., Private communication, OSRAM Sylvania, 2003.
11. Lumileds, Luxeon^{TM}, AB05, Thermal Design Considerations for Luxeon^{TM} Power Light Sources.
12. OSRAM Opto Semiconductors, Thermal Considerations for LEDs in Display Application, Application Notes V00-01.
13. Agilent Technologies, Application Brief A05, LED Thermal Testing.
14. Hong, E., *A Non-contact Method to Determine Junction Temperature of High-brightness (AlGaInP) Light-Emitting Diodes*, Master's thesis, Rensselaer Polytechnic Institute, 2003.
15. Gu, Y., *A Non-contact Method to Estimate Degradation Rate of Phosphor-Converted White Light-Emitting Diodes*, Master's thesis, Rensselaer Polytechnic Institute, 2003.