IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 10, Number 5, September 2018

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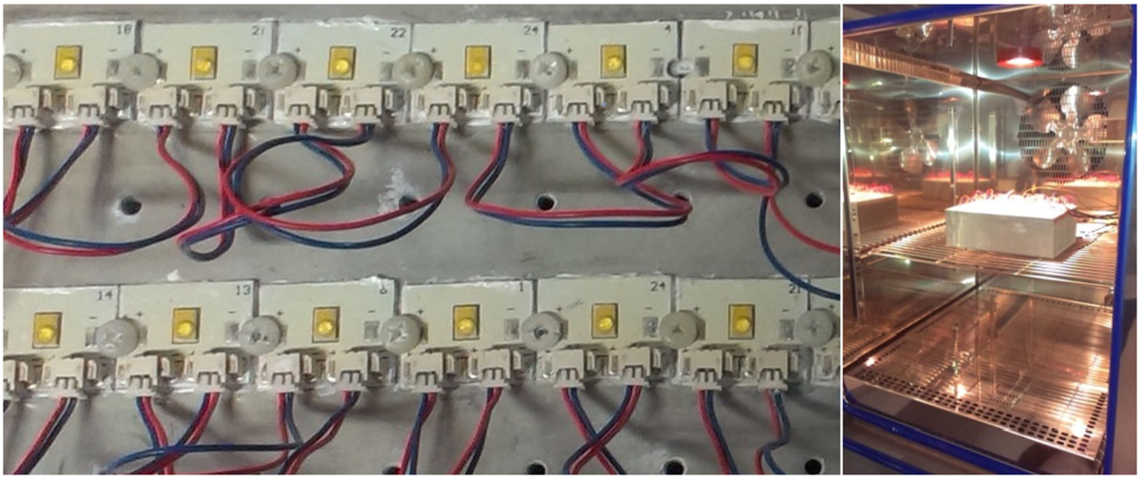

DOI: 10.1109/JPHOT.2018.2869726
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A Practical Degradation Based Method to Predict Long-Term Moisture Incursion and Color Change in High Power LEDs

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DOI:10.1109/JPHOT.2018.2869726
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Manuscript received August 2, 2018; revised September 2, 2018; accepted September 6, 2018. Date of publication September 26, 2018; date of current version October 4, 2018. Corresponding author: Thong Kok Law (e-mail: LAW_Thong_Kok@nyp.edu.sg).

Abstract: The effect of relative humidity on LEDs and how the moisture incursion is associated to the color shift is studied. This paper proposes a different approach to describe the lumen degradation of LEDs due to the long-term effects of humidity. Using the lumen degradation data of different types of LEDs under varying conditions of relative humidity, a humidity based degradation model (HBDM) is developed. A practical estimation method from the degradation behaviour is proposed to quantitatively gauge the effect of moisture incursion by means of a humidity index. This index demonstrates a high correlation with the color shift indicated by the LED's yellow to blue output intensity ratio. Physical analyses of the LEDs provide a qualitative validation of the model, which provides good accuracy with longer periods of moisture exposure. The results demonstrate that the HBDM is an effective indicator to predict the extent of the long-term impact of humidity and associated relative color shift.

Index Terms: High power light emitting diodes, relative humidity, lumen degradation, color shift, moisture incursion, yellow-blue ratio, data driven model, humidity index.

1. Introduction

High power LEDs are widely used today in many applications due to their high efficiency and long lifetime. Although the degradation of the LED is of great interest as this is a limiting factor to its widespread adoption, there is comparatively little research in this area [1]. Despite LED lumen depreciation and color shift being two critical modes of degradation of the LED which should be analysed in tandem, most literature treat these two as independent phenomena [2].

Data driven (DD) methods are currently the most widespread methods used for LED prognostics. DD studies of LED degradation are commonly analyzed by linear or nonlinear statistical regression methods. An example of a linear regression technique is the Euclidean distance technique [3] used to measure the degradation of an LED's light output based on its junction temperature and the operating current, from which linear extrapolation is then used to predict the remaining useful life of LEDs. For nonlinear regression, commonly used approaches include the exponential function, the inverse power law model, and the Arrhenius model. For example, the IES-TM-21 standard [4] uses the exponential regression model and least-squares regression (LSR) approach to project the long-term luminous flux maintenance under different operational conditions. However, in actual practice, the IES-TM-21 generates large errors caused by different types of uncertainties, such as discontinuous measurement, operating environment, and future load [5]. This methodology also does not provide statistical or detailed reliability information on its own.

There are also many variants or combinations of the regression methods such as the two-stage method, approximation methods, analytical methods, the Wiener process, the Gaussian process, and the gamma process, the use of each dependent upon specific requirements. For example, the general degradation path model by Lu and Meeker [6] describes a statistical method in which degradation measures were used to estimate a time-to-failure distribution. Based on this general degradation path model, Fan *et al*. [7], [8] proposed a model combining several regression methods (approximation approach, analytical approach, and two-stage method) and statistical models (Weibull, lognormal, and normal) optimized to predict LED lifetime.

While Wiener processes are useful for many degradation modelling applications, it is appropriate when the degradation process varies bidirectionally over time with Gaussian noise. For example, Huang *et al*. [9] used an efficient likelihood function employing a modified Wiener process to produce results matching IES-TM-21 lifetime predictions, following previous research on the Wiener diffusion process by Tsai *et al*. [10]. However, for one-directional processes like LED light output degradation, the gamma process is a more appropriate model where the degradation over time may be split up into sequential steps and modelled by the gamma distribution [11]. However, because this approach is inherently complicated and difficult to analyze, other algorithms (for example Markov chain Monte Carlo) are likely to be necessary to obtain the unknown parameters. Other data-driven methods not primarily involving statistical regression include Bayesian networks, Kalman filters and Particle filter methods. While Bayesian methods are simple to build and modify even with incomplete data, the method is only suitable for time independent data, besides needing structural historical information regarding the cause and effects of failures [12]. For example, Lall *et al.* use Bayesian probabilistic models [13] to analyze LED degradation with a statistical approach which establishes the failure threshold decay rate using the Arrhenius model as a basis, but omitting the effects of current or humidity. Alternatively, the Kalman Filtering method is an effective technique for state estimation for linear systems, but may not be as suitable for non-linear systems. Accordingly, variants such as the unscented Kalman Filter developed by Fan *et al.* [14] to predict the future LED chromaticity state alleviate this problem by using a deterministic sampling approach. This approach is however still encumbered by the complexity of the state estimation model. On the other hand, the Particle Filtering method is better suited for highly non-linear processes. Fan *et al*. depict a particle filter-based approach [15] based on both Sequential Monte Carlo and Bayesian techniques to predict the lumen maintenance life. This method is reported as having a higher accuracy in predicting the long-term lumen maintenance life. However, the prediction accuracy of the Particle Filtering method is highly dependent on parametric initialization and thus limits the suitability for new LED products.

While other studies investigate lumen degradation from primarily qualitative approach [16]–[18], the scarcity of research taking into account the impact of relative humidity specifically and its corresponding association with color degradation is notable. In spite of the fact that the requirement for color consistency has become more important than lumen maintenance in many applications, prediction models involving color shift are limited [19]. The Spectral Power Distribution (SPD) is the quantitative inference of an LED's color shift process and both the lumen depreciation and color shift are related to the SPD since photometric and colorimetric parameters such as luminous flux, correlated color temperature (CCT), and yellow-to-blue spectral ratio (YBR) can be computed from the SPD. Based on the SPD analysis, Qian *et al*. [19], predicted both lumen depreciation and color shift by using the prediction of the evolutionary degradation process of the SPD to predict the lumen and associated color drift curves based on the CIE 1976 chromaticity coordinate system. The YBR is another indicator of color shift which has the advantage of also being a means to indicate the LED failure mechanism. Greater degradation of the blue intensity over yellow is likely related to chip failure while the reverse is suggested to be due to phosphor degradation [20], [21]. Under high stress conditions which incur higher degradation rates and color change, a method to predict YBR color shift would be particularly practical as an indication of the likely failure mechanism due to more pronounced symptoms.

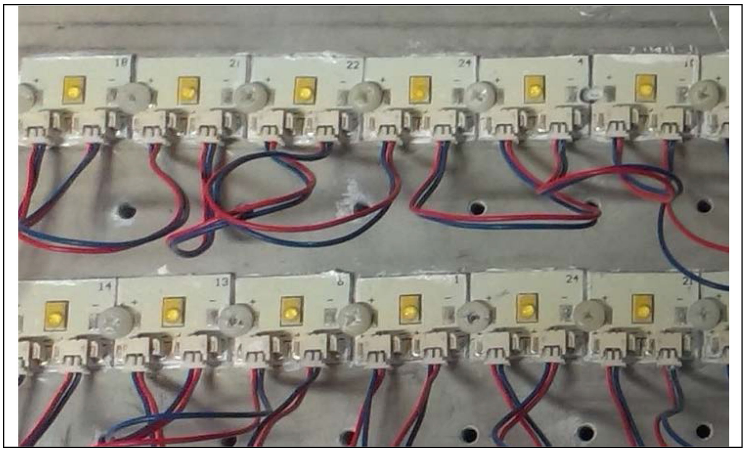

Fig. 1. Individual LEDs on metal core PCBs (MCPCB) mounted on aluminum heat sink.

Based on degradation data of different types of LEDs under humidity stress, this paper proposes a degradation based data driven model using the lumen depreciation data to predict the time-dependent effect of humidity on the LED. The humidity index, derived using Hallberg-Peck's model and the IES TM-21 approach is developed to provide a practical indication of the impact of moisture incursion according to the lumen decay under varying humidity levels. Subsequently, the YBR shift is analyzed from experimental data and the association of this humidity index with the magnitude of the change in yellow-to-blue spectral ratio (YBR) is investigated and analyzed. Finally, the YBR shift predicted by the proposed model is validated qualitatively by means of physical study of the failure mechanism.

2. Experimental Setup and Procedures

The 3 types of LEDs used for the experiments are all commercial GaN LEDs rated at either 1W (P1W and S1W) or 0.3W (S03W). The P1W LEDs have a flip-chip configuration while both S1W and S03W LEDs have conventional die-bonding configurations. For the conventionally bonded packages, GaN LED is grown onto sapphire and subsequently bonded onto a heat spreading substrate. The flip-chip die-bonded P1W GaN LED device is directly bonded onto heat spreading substrate via Au bumps. A sample size of 20 is used for each of the 3 LED packages at each humidity level (10% or 85% relative humidity).

The LED packages are soldered on metal core PCBs (MCPCB) and mounted onto heatsinks (Fig. 1) before being placed into environmental test chambers preset at 10% or 85% relative humidity (RH) at a constant operational temperature of 55 °C. A bias current of 350 mA is applied to the 1W LEDs and 100 mA to the 0.3W LED. Optical and electrical measurements of the LEDs are conducted at 1000 h intervals up to 8000 h. An integrated LED measurement system is used to evaluate the electrical-optical properties of the LED packages. The system consists of a Labsphere 20" integrating hemi-sphere system, a Keithley 2602A Source Meter and a Peltier-based temperature controller (TEC). The LED is placed onto a temperature-controlled cold plate with a temperature tolerance of $+/-0.1$ °C. The photometric properties of the emitted light output are measured using a spectro-radiometer. To ensure traceable optical measurements, reference lamp calibration and absorption correction are conducted prior to each measurement. An electrical I-V measurement is conducted before and after the optical-thermal measurements to ensure that the LED device did not degrade after each measurement. On completion of the 8000 hour tests on all the LED packages, capacitance-voltage measurements were conducted using a Keysight E4990A Impedance Analyzer at room temperature with the LEDs biased from -7 V to 2 V. In-depth failure analyses of the samples were done by means of Scanning Electron Microscopy with Energy Dispersive X-ray Spectrometry (SEM–EDX).

3. Results and Discussion

3.1 Moisture Incursion Based on Lumen Decay

As the degradation of the lumen performance follows an exponential trend [22], the exponential regression model could be used to fit the averaged degradation data by using the nonlinear least squares (NLS) method. From IES-TM-21 [4], the degradation equation can be expressed as:

$$\varphi(t) = B \exp(-\alpha t) \tag{1}$$

where t is the operating time, φ(t) the averaged normalized luminous flux output at time t, B the projected initial constant and α the decay rate both from the least squares curve-fit. To incorporate the effect of both temperature and humidity on LED life, the Hallberg-Peck model [23] is typically used and the acceleration factor due to this model can be described as follows:

$$A_H = \left(\frac{R_{\text{use}}}{R_{\text{stress}}}\right)^n \exp\left(K\left[\frac{1}{\Delta T}\right]\right) \tag{2}$$

where A_H is a humidity acceleration factor, R_{stress} and R_{use} the testing and reference relative humidity respectively, K and n constants and ΔT the change in operating temperature. For the purpose of providing information on the sole effects of humidity stress, equation (2) is treated as having one independent variable (relative humidity) with stress conditions at constant temperature, leading to the factoring out of the exponential term. Under such conditions then, A_H reduces to $[\frac{R_{stress}}{R_{use}}]^n$ and the time t_{stress} to reach a specified lumen level in terms of the reference t_{use} is described as:

$$t_{\text{stress}} = \left[\frac{R_{\text{use}}}{R_{\text{stress}}}\right]^n t_{\text{use}} \tag{3}$$

For the same specified lumen output level φ reached at use and stress conditions, the expression in (1) under the reference and stress conditions can then be equated giving:

$$\alpha_{\text{stress}} t_{\text{stress}} = \alpha_{\text{use}} t_{\text{use}} \tag{4}$$

where α_{use} is the lumens degradation rate under stated initial humidity conditions and α_{stress} the degradation rate under the stress conditions. On assumption that during the stress tests, the failures induced by temperature and humidity are independent, a functional form describing the light degradation can be developed to account for the exponential loss in luminous flux under conditions of increasing relative humidity. From equations (3) and (4), a degradation model developed as a function of some base degradation rate α_{use} that caters to both these factors would fundamentally be described as:

$$\alpha_{\text{stress}} = H\alpha_{\text{use}} \tag{5}$$

where H is a humidity expression. From both experimental observation and parameter fitting, this humidity expression derived from the Hallberg-Peck's model may be described as:

$$H = \left[\frac{R_{\text{stress}}}{R_{\text{use}}}\right]^{H} \tag{6}$$

where ψ_H is described as a humidity constant which represents the level of moisture related degradation in the LED. The expression is incorporated into the original exponential curve-fit equation (1) to give the following combined model:

$$\varphi(t) = B \exp\left(-\left[\frac{R_{\text{stress}}}{R_{\text{use}}}\right]^{H} \alpha_{\text{use}} t\right) \tag{7}$$

The combined expression (7) can be described as a humidity-based degradation model (HBDM) which can be fitted to the lumen maintenance data for the 3 LED types. Using degradation data, the HBDM describes the effect of assumed moisture ingress in an LED at an operational RH level compared to a specified base RH level. Using the procedure prescribed in IES TM-21 for 20 units of each of the 3 types of LED, the nonlinear least squares method was utilised for the

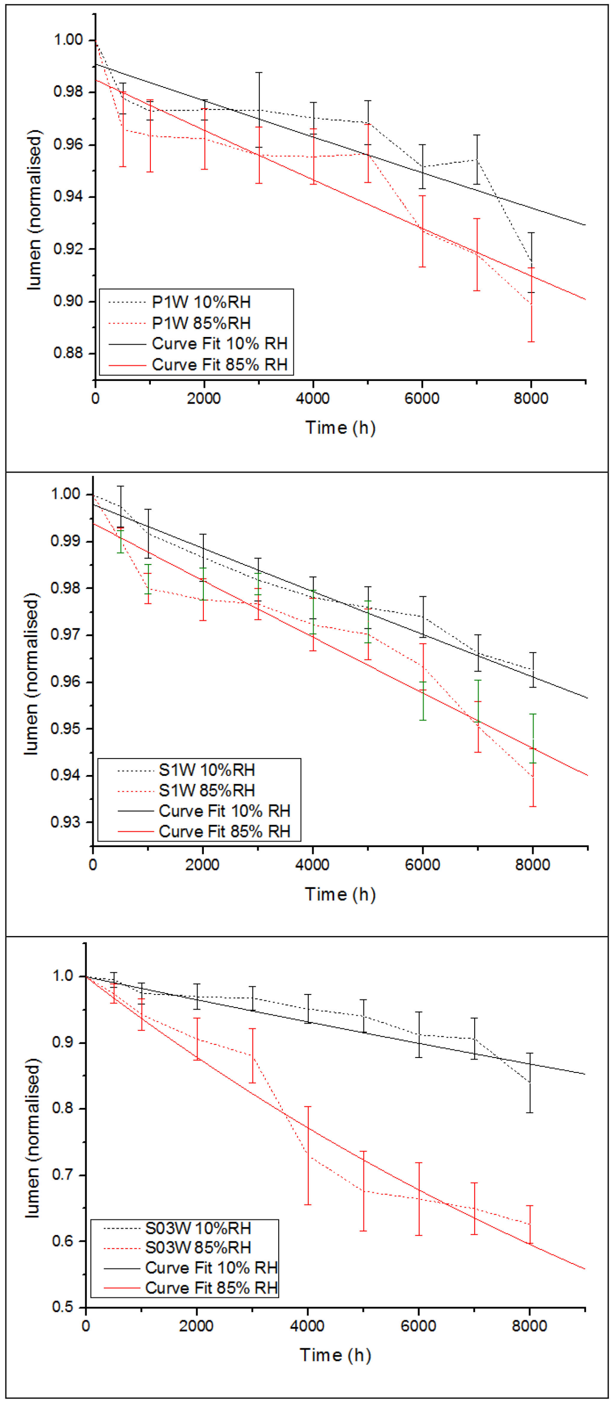

Fig. 2. Exponential curve fit with normalized lumen data for P1W (top), S1W and S03W (bottom) at 10% RH and 85% RH.

degradation curve-fit. The extracted parameters are used to extrapolate the lumen maintenance value to where the luminous flux output decreases to L70 (70% of initial luminous flux). Fig. 2 shows the exponential curve-fit based on equation (1) for the 3 types of LEDs used at both 10% RH and 85% RH. Superimposed with the curve-fit are the normalised lumen data which was used in the computations.

TABLE 1
Computations of ψ_H for Various LEDs at Differing RH Levels

LED power rating	LED	%RH	Degradation rate α	ψ_H
1W	P1W	10	7.145E-06	0
		85	9.917E-06	0.153
1W	S1W	10	4.702E-06	0
		85	6.197E-06	0.129
0.3W	S03W	10	1.765E-05	0
		85	6.473E-05	0.607

Using 10% RH as the baseline for all tests, ψ_H is assigned an initial value of 0 at α_{use} at this humidity level. Accordingly, rearranging equations (5) and (6) above, ψ_H can be derived as:

$$_H = \frac{\log(\alpha_{stress}/\alpha_{use})}{\log(R_{stress}/R_{use})} \quad (8)$$

For the validity of ψ_H, the baseline values α_{use} and R_{use} are set below that of α_{stress} and R_{stress} respectively. The results for ψ_H for the experimental data is as shown in Table 1. As RH increases with corresponding increase of the degradation rate α, ψ_H increases in proportion to the degradation rate. This indicates the relative level of moisture incursion in the LED associated to the lumen decay. At 85% RH, it is observed that $\psi_H = 0.607$ for the lower powered S03W compared to $\psi_H = 0.129$ and 0.153 for the higher powered S1W and P1W respectively corresponding to a higher ψ_H at higher degradation rates α.

Assuming the normalised expression for lifetime L_P based on TM-21 where:

$$L_P = \frac{\ln\left(100\frac{1}{P}\right)}{\alpha_{stress}} \quad (9)$$

where L_P is the lumen maintenance life and P is the percentage of the initial lumen output that is maintained. By substituting in equation (9), ψ_H may then be used to predict the lifetime at a particular RH level. The lumen degradation mechanisms of the experimental data were explored using statistical methodology. The lifetime data of each individual sample at 10% RH and 85% RH was collected for probability distribution analysis and plotted in Fig. 3. The degradation mechanisms for both humidity stress conditions for P1W are similar as the shape parameters of the lognormal distributions are close to each other as shown in Table 2. Similarly, the degradation mechanisms for S1W at both 10% and 85% RH are noted to be similar. However, because of the comparatively larger difference in the scale factor and shape parameter for S03W between 2 RH levels, the degradation mechanism is expected to be different [16], [21].

3.2 Color Change Based on HBDM

Color output is evaluated from the LED spectral power distribution (SPD). Based on the two decomposed peaks, the ratio of the phosphor converted yellow light to blue light emitted from the LED or yellow-to-blue ratio (YBR) could be calculated from [24]:

$$YBR = \frac{\int SPD^P(\lambda)d\lambda}{\int SPD^B(\lambda)d\lambda} \quad (10)$$

where the SPD^P and SPD^B are derived from the radiant flux as a function of the wavelength λ. In the case of S03W (Fig. 4) for example, the yellow intensity at 85% RH has a significantly higher deterioration compared to 10% RH. Computed over the whole test period of 8000 hours, the trend of YBR change may be demonstrated for all 3 LEDs for 10% and 85% RH as shown in Fig. 5.

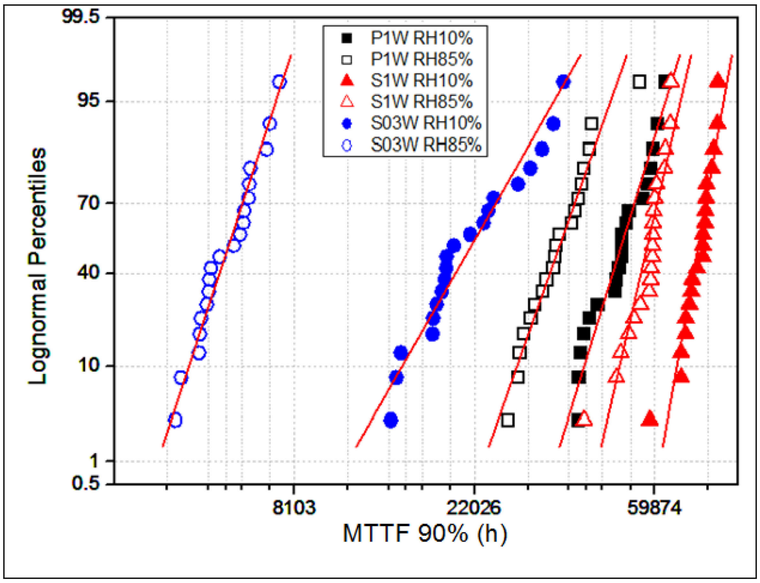

Fig. 3. Lognormal distribution of P1W, S1W and S03W individual samples at 10% RH and 85% RH.

TABLE 2
Lognormal Distribution Shape and Scale Parameters

	P1W		S1W		S03W	
Lognormal Distribution Parameters	**10% RH**	**85% RH**	**10% RH**	**85% RH**	**10% RH**	**85% RH**
Shape	10.804	10.461	11.234	10.951	9.965	8.626
Scale	0.154	0.177	0.089	0.115	0.287	0.165

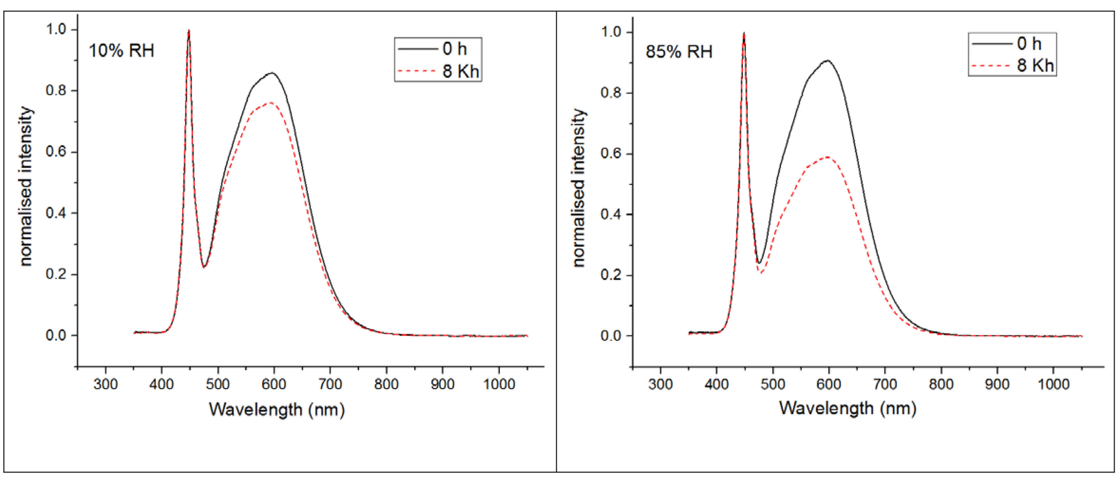

Fig. 4. Spectral power distribution for S03W at 10% RH (left) and at 85% RH (right).

It is observed from Fig. 5 that at all RH levels, the P1W and S1W both exhibit increasing trends while the S03W conversely has a decreasing yellow-blue light output ratio. Table 3 summarises this YBR change over the test period for each RH level as well as the difference in YBR change $\Delta(YBR)_{RH}$ between the stress condition R_{stress} and the base condition R_{use}. S03W has a significantly larger YBR change over the test period at both RH levels and between the RH levels, the negative

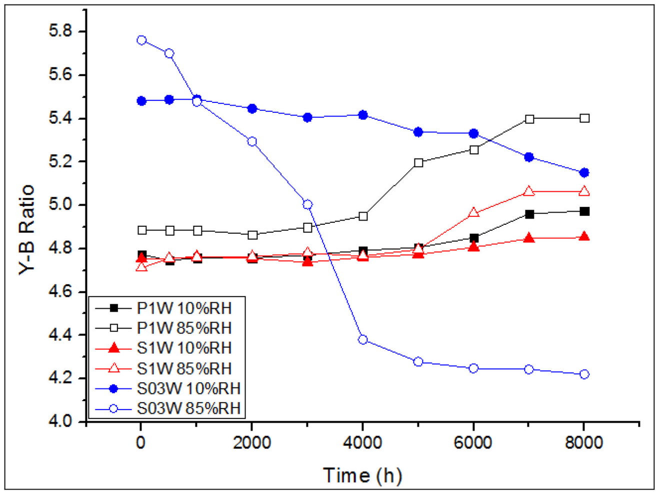

Fig. 5. YBR shift at different RH levels over test period.

TABLE 3
Summary of YBR Changes Over Time and RH Levels

LED	YBR Change over test period @base condition		YBR Change over test period @stress condition		Difference between RH $\Delta(YBR)_{RH}$ $=\Delta(YBR)_{RH}$ (a) - $\Delta(YBR)_{RH}$ (b)	Calculated ψ_H
	R_{use}	$\Delta(YBR)_{RH}$ (a)	R_{stress}	$\Delta(YBR)_{RH}$ (b)		
P1W	10% RH	0.204	85% RH	0.502	0.298	0.153
S1W	10% RH	0.102	85% RH	0.351	0.249	0.129
S03W	10% RH	-0.331	85% RH	-1.547	-1.219	0.607

sign for S03W denoting the decreasing YBR. The results correlate with the larger difference in scale parameter computed for S03W (Table 2) in relation to the other LEDs, indicating a different degradation mechanism for this LED. It is observed for all the LEDs that ψ_H is positively associated to the absolute value of $\Delta(\mathrm{YBR})_{RH}$ in that an increase in $|\Delta(YBR)_{RH}|$ is reflected by a corresponding increase in ψ_H. The correlation of color shift to lumen depreciation has been corroborated in several studies [19]–[21] and since ψ_H is based on the degradation curves of lumen depreciation, it is proposed that ψ_H serves as an degradation based index to estimate the color shift in the LED related to the relative humidity. As a means of statistically measuring the strength of the relationship between ψ_H and $\Delta(YBR)_{RH}$, the correlation coefficient value r is computed based on:

$$r = \frac{N\sum xy - (\sum x)(\sum y)}{\sqrt{\left[N\sum x^2 - (\sum x)^2\right]\left[\left[N\sum y^2 - (\sum y)^2\right]\right]}} \tag{11}$$

where x and y represent the ψ_H and $\Delta(YBR)_{RH}$ variables respectively, and N is the number of pairings of the two respective variables. The correlation coefficient r is computed to be greater than 0.99 indicating a high positive association in that as ψ_H increases, the value of $\Delta(YBR)_{RH}$ increases correspondingly. The t-test for the data gives $t = 9.92$, which at $P < 0.001$ implies that the correlation coefficient may be regarded as significant. Fig. 6 shows the correlation scatter matrix which shows good association between the two variables, with all the data points falling within close proximity in the confidence ellipse. The proposed HBDM thus serves to provide an indication of the impact of humidity correlating the value of ψ_H with the absolute value of the change of YBR caused by this moisture incursion.

As a means of validation of the link between the lumen degradation and the change in color, the photopic eye sensitivity function relationship with lumen output $\varphi(t)$ as prescribed by the International

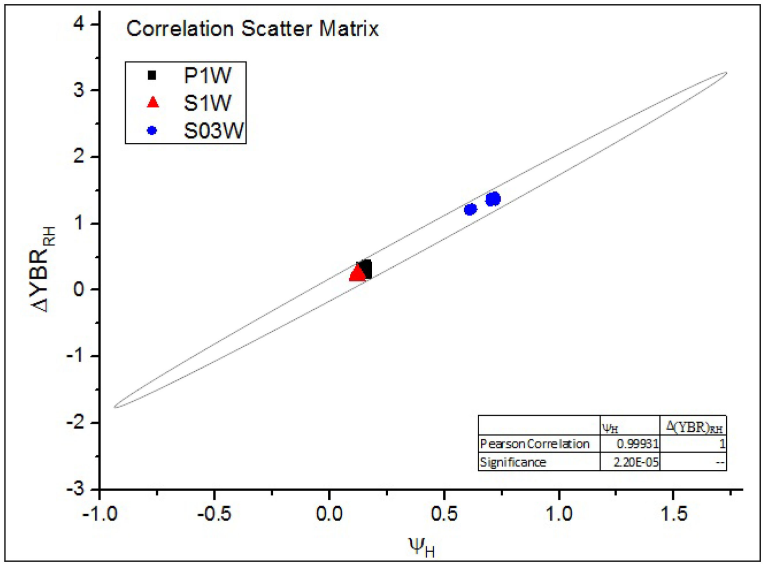

Fig. 6. Scatter matrix with confidence ellipse of ψ_H and $\Delta(YBR)_{RH}$.

Commission on Illumination (CIE) [25] given by the base equation is used:

$$\varphi(t) = K_m \int_{380}^{780} \varphi_e(\lambda) . V(\lambda) . d\lambda \tag{12}$$

where the maximum spectral luminous efficacy normalization factor $K_m = 683$ lb/W, φ_e the radiant flux derived from the SPD from wavelength 380 nm to 780 nm, and V(λ) the spectral luminous efficiency function for photopic vision. Inserting the HBDM expression for φ(t) from equation (7) into equation (12) gives:

$$\mathrm{B}\exp\left(-\left[\frac{R_{\text{stress}}}{R_{\text{use}}}\right]^{H}\alpha_{\text{use}}\mathrm{t}\right) = K_m \int_{380}^{780} \varphi_e(\lambda) . V(\lambda) . d\lambda \tag{13}$$

Using the degradation values at the corresponding humidity levels from Table 1, then the value of ψ_H applying the human eye sensitivity function aspect may be computed from the radiant flux. It is observed from the experimental data that the minima or separation point between the yellow and blue spectra may be approximated at about 470 nm. To establish the relationship between the ψ_H in equation (13) and the YBR, equation (12) may be separated into two components representing the blue and yellow SPD peaks respectively:

$$\varphi(t) = K_m \int_{380}^{470} \varphi_e(\lambda) . V(\lambda) . d\lambda + K_m \int_{470}^{780} \varphi_e(\lambda) . V(\lambda) . d\lambda \tag{14}$$

So as to allow for the input of the discreet experimental values, equation (14) is approximated by numerical summation which may be described as:

$$\varphi(t) = K_m \sum_{i=380}^{i=470} \varphi_e(\lambda_i) V(\lambda_i) \delta(\lambda_i) + K_m \sum_{i=470}^{i=780} \varphi_e(\lambda_i) V(\lambda_i) \delta(\lambda_i) \tag{15}$$

As the YBR is derived from the deconvoluted SPD of the LED, the expression for YBR in equation (10) may be thus written as: umidity levels

$$YBR = \frac{\sum_{i=380}^{i=470} \varphi_e(\lambda_i) \delta(\lambda_i)}{\sum_{i=470}^{i=780} \varphi_e(\lambda_i) \delta(\lambda_i)} \tag{16}$$

By substituting the radiant flux and spectral luminous efficiency function values for photopic vision at the respective relative humidity levels into equation (16), the change in YBR based on the photopic eye sensitivity function had shown to yield similar values for the different LED samples as in Table 3 with a variation of less than 6% for ψ_H and $\Delta(YBR)_{RH}$. Although the universal applicability of the HBDM method can only be verified by applying the method to the field or experimental data at all scenarios, this approach has certain advantages over other data driven methodologies. The index ψ_H is simple to calculate and use and allows for both the prediction of relative moisture incursion and color shift under specified humidity conditions.

3.3 Degradation Investigation by Physical Analyses

For further validation of the HBDM, physical analysis of the degraded LEDs is conducted. An investigation of the physical mechanisms due to the degradation of LEDs is first conducted using capacitance-voltage (C-V) tests. C-V measurements provide a tool to detect any modification of the heterostructure of GaN based LEDs. An increase in capacitance may indicate an increase in the charge concentration in the active region of the LEDs due to either a rise in the concentration of defects or a redistribution of the charge in the space-charge region, because of a doping or impurity diffusion process [26], [27]. In Fig. 7, it is observed that the capacitance-voltage curves change for both P1W and S1W. At the P1W reverse bias region between −1 and −3 V, the distinct step-like change in capacitance at 85% RH suggests a doping increase attributable to a charge concentration increase within the quantum well. The decreasing slope at this region implies that the net fixed charge concentration in the depletion region is not uniform and the small increase of capacitance with voltage implies a high net fixed charge concentration as a greater amount of bias voltage increase is required to achieve the same increment of depletion layer width [28], [29].

The increased capacitance at the S1W reverse bias region at 85% RH demonstrates 2 distinct gradient changes more pronounced than at 10% RH. From 0 to −0.5 V, similar to P1W the gentler gradient indicates the highly charged area while the steeper gradient between −1.5 to −2 V implies the lowly charged region. The resulting carrier concentrations have been attributed to the accumulation of carriers within the quantum wells resulting in the movement of charged defects towards the active layer of the LEDs. The rate of non-radiative recombination is directly correlated to the density of defects located within the active region and an increase in charged defect density can lead to a decrease in the optical efficiency of the LED [30]. On the other hand, the C-V measurements for S03W do not display any discernible changes from 10% to 85% RH, which preliminarily may indicate little modifications to the LED itself. These C-V results are in line with Fig. 5 which indicate a different physical degradation mechanism for S03W compared to the two 1W LEDs. Although the S03W has a greater degradation rate, the C-V measurements indicate that chip deterioration is more likely to be a factor for P1W and S1W.

From the current-voltage electrical measurements done on the LEDs, the series resistance R_S is computed. Compared to S03W, the series resistance of both P1W and S1W both showed less change over the test time and between the two RH levels (Table 4), suggesting less deterioration of the ohmic contacts of the LED. The significantly larger increase of the series resistance for S03W would indicate greater reduction of the emission efficiency of the chip, explaining the higher lumen degradation. This increase in series resistance could possibly be due to metal–metal and metal–semiconductor inter-diffusion [27], [31], [32]. The larger shift in the S03W series resistance could possibly be due to the interaction between hydrogen and magnesium, which causes a reduction of the active acceptor concentration. This leads to the deterioration of the properties of the anode contact, thereby changing the resistivity and p-layer injection properties [33].

As S03W exhibited both greater lumen degradation rates and color change over the test period for both humidity levels compared to the other LED types, further investigation was conducted to understand the failure mechanism as it relates to the HBDM. A close examination of the degraded S03W (Fig. 8) reveals that there was delamination at the interface of the LED chip and the lead frame at 85% RH. A possible reason is cited as von Mises stress at the interface due to hygroscopic stress caused by moisture ingression over time [34]. It is postulated that higher relative humidity

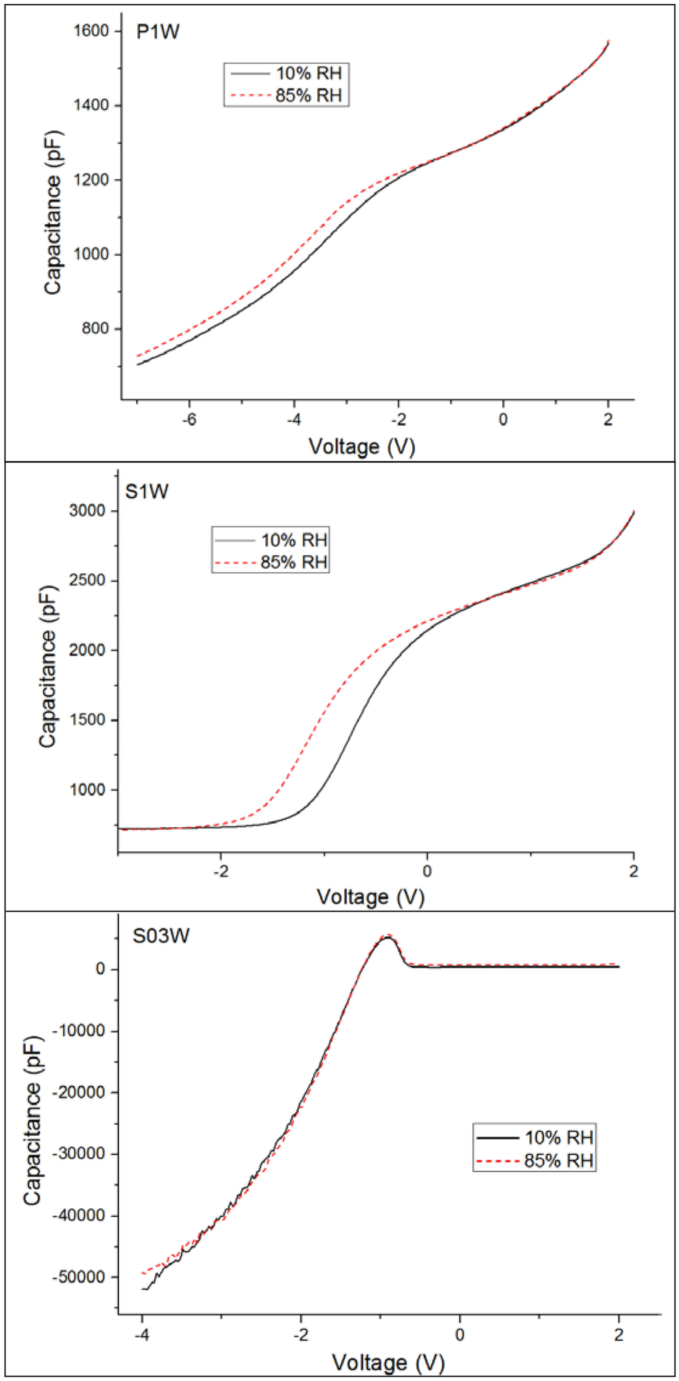

Fig. 7. Capacitance-voltage (C-V) measurements for P1W (top), S1W and S03W (bottom) at 10% RH and 85% RH.

levels cause further moisture inception leading to greater degrees of delamination which has been shown to be a mechanism for white LED light degradation [35].

In addition, SEM–EDX analysis of the LED (Fig. 9) indicates an increase of elemental oxygen at 85% RH compared to 10% RH at the interface of the chip and the lead frame, which is coated with silver to enhance light reflectivity. As shown in Table 5, there is a significant increase in the

TABLE 4
Change in Series Resistance R_S Over Time and RH Levels

LED	R_S change over 8Kh @10% RH (a)	R_S change over 8Kh @85% RH (b)	Ratio of R_S change between RH [(b)/(a)]
P1W	0.325	0.589	1.812
S1W	0.261	0.362	1.387
S03W	0.485	1.091	2.249

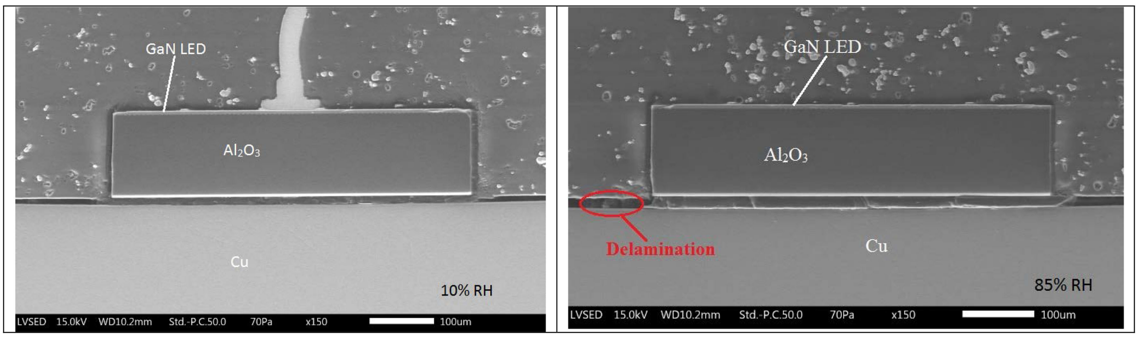

Fig. 8. Micrographs of S03W at 10% RH (left) and 85% RH (right).

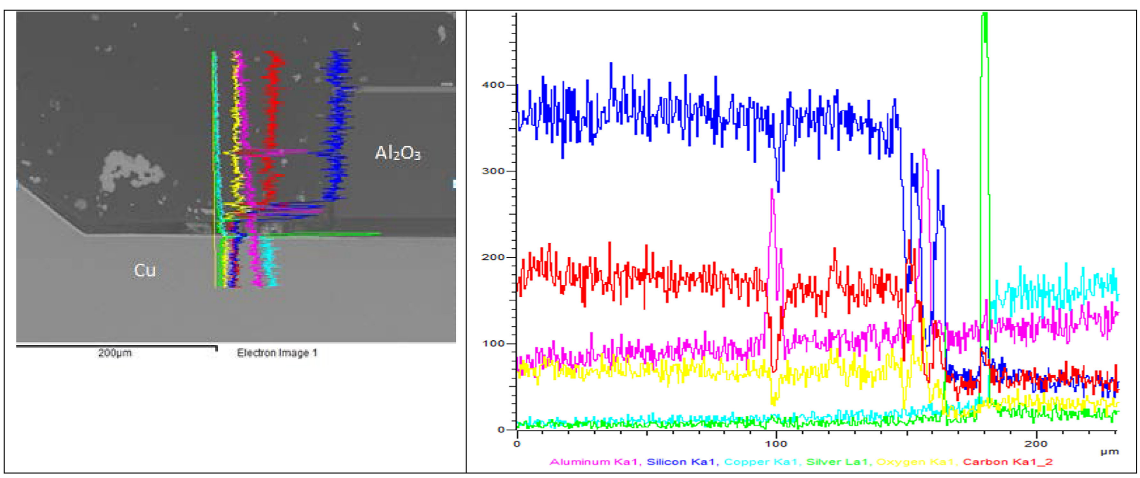

Fig. 9. SEM micrograph (left) and EDX analysis (right) of die after 85% RH aging.

TABLE 5
S03W Elemental Weight by Percentage at 10% RH and 85% RH

Element	Element weight percentage @ 10% RH	Element weight percentage @85% RH
Carbon C	2.41	2.25
Oxygen O	7.76	13.04
Magnesium Mg	0.4	0.58
Silicon Si	0.51	0.76
Titanium Ti	0.86	0.78
Zinc Zn	1.38	1.42
Silver Ag	86.68	84.38

weight percentage of oxygen and this observation is consistent for all the samples subjected to failure analysis. It had been reported by Chen *et al.* [36] that in the presence of humidity, atomic oxygen will react with the absorbed water to form a hydroxyl (OH) radical, which reacts with Ag to form Ag_2O which is the cause of silver corrosion on the surface of the lead frame. This oxidation leads to darkening of the silver layer which impairs its light reflectivity and affects the color output of the LED.

In addition, it is postulated that at higher humidity levels, the water vapour reaches the die, causing phosphor degradation. Light scattering due to the water layer and internal reflection of the light from the die occurs due to the change in the refractive index of the water layer, leading to a reduction in the phosphor conversion efficiency, which corresponds to the YBR reduction. In terms of phosphor deposition, the S03W LEDs apply dispersed phosphor coating method whilst the P1W and S1W adopt the conformal phosphor coating method. It is postulated that the method of phosphor application plays a key role in the YBR deterioration under long term moisture incursion.

4. Conclusions

This paper proposes a new approach to indicate the lumen degradation of LEDs due to the effects of humidity. A practical predictive method from the degradation behaviour is developed to gauge the long-term moisture incursion by means of a humidity index ψ_H. This index shows good agreement with the absolute change in YBR with a positive association although a limitation of the model is that the direction of this change is not directly discernible. The results demonstrate that the HBDM is effective in indicating the extent of the impact of humidity and the relative YBR color shift associated with this impact. It was found that the HBDM showed good accuracy with longer periods of moisture exposure. To validate the HBDM, both non-destructive and destructive testing were conducted to investigate the reasons and extent of both the light and color degradation. The physical analyses indicate that P1W and S1W may exhibit chip deterioration while S03W exhibits phosphor or package decay by delamination and silver layer corrosion. The results are in line with the HBDM in terms of lumen and YBR predictions. The next step of this work is to link the degree or levels of physical deterioration numerically to the HBDM based on experimental study.

Acknowledgment

The authors would like to thank Dr. Ronnie Teo (A*STAR SimTech) not only for the C-V and SEM/EDX results, but also for his invaluable advice.

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