Physics-of-Failure-Based Prognostics and Health Management for High-Power White Light-Emitting Diode Lighting

Jiajie Fan, K. C. Yung, and Michael Pecht, *Fellow, IEEE*

***Abstract*—Recently, high-power white light-emitting diodes (LEDs) have attracted much attention due to their versatility in applications and to the increasing market demand for them. So great attention has been focused on producing highly reliable LED lighting. How to accurately predict the reliability of LED lighting is emerging as one of the key issues in this field. Physics-of-failure-based prognostics and health management (PoF-based PHM) is an approach that utilizes knowledge of a product's life cycle loading and failure mechanisms to design for and assess reliability. In this paper, after analyzing the materials and geometries for high-power white LED lighting at all levels, i.e., chips, packages and systems, failure modes, mechanisms and effects analysis (FMMEA) was used in the PoF-based PHM approach to identify and rank the potential failures emerging from the design process. The second step in this paper was to establish the appropriate PoF-based damage models for identified failure mechanisms that carry a high risk.**

***Index Terms*—Light-emitting diode (LED) lighting, physics-of-failure, prognostics and health management (PHM).**

I. Introduction

HIGH-POWER white light-emitting diodes (LEDs) have attracted increasing interest in the field of lighting systems owing to their high efficiency, environmental benefits and long lifetime in applications [1]. Therefore, how to accurately predict the remaining useful lifetime (RUL) of high-power white LED lighting in the design period is becoming a key project to popularize this novel product. However, traditional reliability prediction methods for electronic products, including Mil-HDBK-217, 217-PIUS, Telcordia, PRISM, and FIDES, are not accurate enough for predicting actual field failures (e.g., soft and intermittent faults which are the most common failures modes in today's electronics-rich systems) and provide highly misleading predictions, which can result in poor designs and poor logistics decisions [2].

Prognostics and health management (PHM) is a method for reliability assessment and prediction for products (or systems) under their actual application conditions. This is now becoming one of the critical contributors to efficient system level maintenance [3]. Physics-of-failure (PoF) is an approach that utilizes knowledge of a product's life cyclic loading and failure mechanisms to design for and assess reliability. This approach is based on the identification of potential failure modes, failure mechanisms and failure sites of the product as a function of the product's life cycle loading conditions. The stress at each failure site is obtained as a function of both the loading conditions and the product geometry and material properties. Damage models are then used to determine fault generation and propagation [4].

The purpose of this paper is to assess reliability and predict the performance of high-power white LEDs lighting (from chip level, package level to system level) by means of PoF-based PHM approach. In this approach failure modes, mechanisms and effects analysis (FMMEA) is used to identify the potential failures emerging in the high-power white LED lighting at all levels and to develop appropriate PoF-based damage models for identified failure mechanisms with high risk. The results can help quantify the reliability through evaluation of time-to-failure, or predict the likelihood of failure for a given set of geometries, material construction, environmental and operational conditions.

II. PoF-Based PHM Approach

The PoF-based PHM approach involves several steps, including FMMEA. Failure models will be identified and built for each mechanism, feature extraction, and for estimating remaining useful life [5] (see Fig. 1).

In this paper, we focus on the first step of the PoF-based PHM approach—virtual life assessment, including materials and geometries analysis, FMMEA and on the establishment of failure models for identified failure mechanisms with high risk, for high-power white LED lighting from chip level, package level to system level.

A. Materials and Geometries Analysis

To create white light, several promising strategies have been used in the applications, including di-, tri-, and tetrachromatic approaches [1]. Among them, the di-chromatic white source, combining a short-wavelength InGaN blue LED with a single yellow phosphor ($YAG{:}Ce^{3+}$), is the most commonly used

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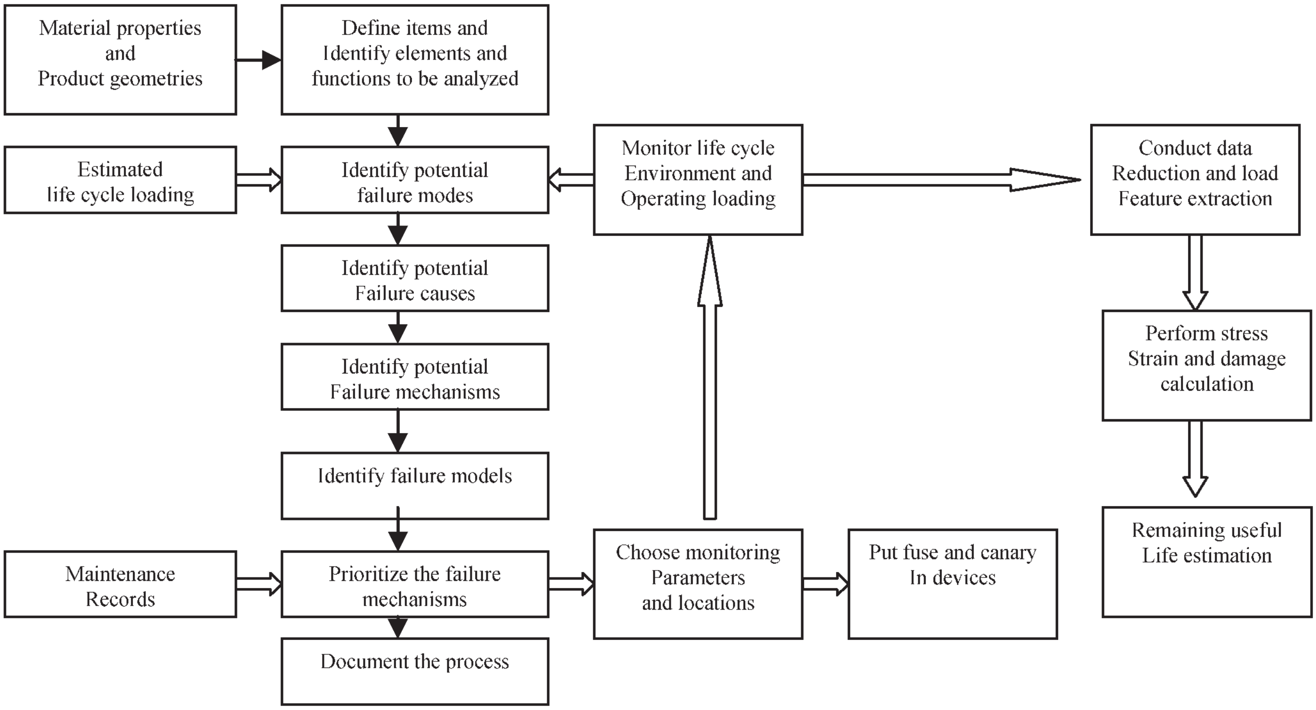

Fig. 1. PoF-based PHM approach [3].

method on the market. Fig. 2(a) shows the cross-section structure and details of the materials of a popular high-power white LED product: LUXEON_K2, PHILIPS [6]. To lower the cost and increase power efficiency, Thin Film Flip Chip (TFFC) and Wire Bonding Assembly Technology are used in this package. Meanwhile, three developments in the material selection, containing Ceramic-glass phosphor with higher thermal conductivity and more chemical and thermal stabilities replacing commonly used phosphor resin, Silicon submount taking the place of the Sapphire one, and wider copper heat sink, lower the package's thermal resistance (5.5 °C/W) largely and optimized the module's thermal management widely [7]–[9].

Fig. 2(b) illustrates a LED Lighting Lamp consisting of LUXEON_K2 LED Arrays, a cooling system and the relative power driving module. As shown, the LED packages are mounted on a Sapphire PCB using the series or parallel surface mount technology (SMT) method to improve the whole system's luminous power. To solve the accumulated heat generated from the LED Arrays, a cooling systems is introduced into this lamp systems [10]. The total system's electric power is supplied and controlled by a power driver located on the top of the cooling system and directly connected to the electrode.

Table I lists all materials used in this system from chip to lamp. Any mismatch of the materials' properties (chemical, thermal, and mechanical) at any level will degrade or damage the system's power efficiency [7]–[9]. Therefore, material selection and geometry design are the first and most critical step in the PoF-based PHM approach.

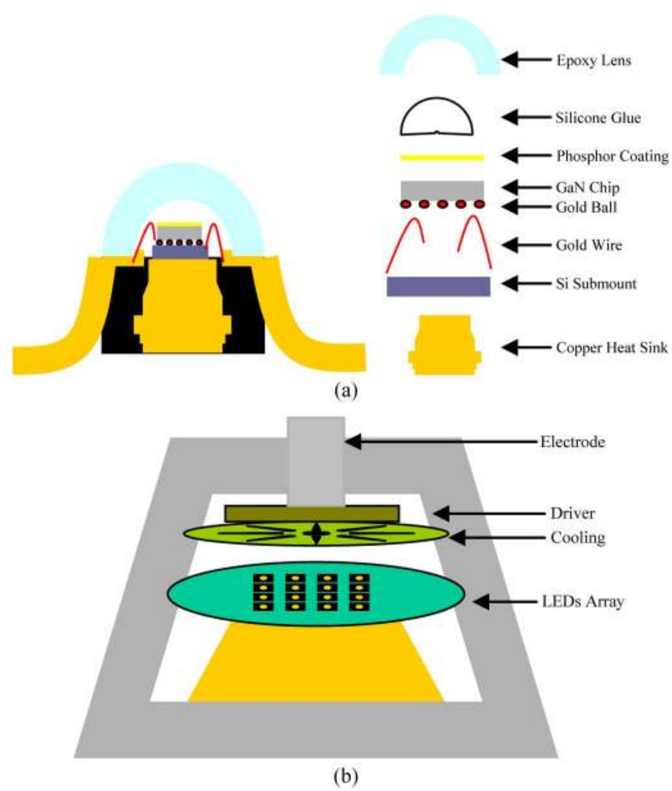

Fig. 2. Materials and structure of LED chip, (a) LEDs packages, and (b) LED lighting lamps.

B. Failure Modes, Mechanisms, and Effects Analysis

In electronics-rich systems, a failure mode is the recognizable electrical symptom by which failure is observed, i.e., circuit open or short. And each mode could be caused by one or more different failure mechanisms which could be driven by physical, chemical or mechanical means [11]. Failure mechanisms can be categorized as overstress (Catastrophic) failure or wear-out (gradual) failure mechanisms [12]. Overstress failure arises as a result of a single load (stress) condition, which exceeds the threshold of a strength property. Wear-out failure occurs as a result of cumulative damage related to

TABLE I
MATERIAL PROPERTIES OF LED CHIP, PACKAGES, AND SYSTEMS LEVELS (AT 25 °C) [7], [8]

		CTE (10^{-6}/°C)	Thermal Conductivity (W/m°C)	Elastic Modulus (Gpa)	CME (×e^{-3} cm^3/kg)	Density ρ (kg/m^3)	Specific Heat Cp (J/kg°C)	Poison's Ratio
Chip level	GaN Chip	5.59	130-140	210-295	NA	6150	490	0.31
	Epoxy Lens	45	0.17	0.5	0.21	980	1173	0.49
	Silicone Glue	300	1.8	6.1×10^{-4}	0.21	1200	92	0.34
	Ceramic Phosphor	7.8	13	NA	NA	4500	NA	0.24
	Silicon submount	3	124-148	109-190	NA	2330	702-712	0.28
	Gold Wire	14.1	318	180	NA	1930	128	0.44
Packages level	Heat Sink (Cu)	16.5	393	128	NA	8950	390	0.26
	Die Attach	30	7.5	40	0.445	2400	300	0.35
	Plastic Mould	45	0.23	5.2	0.21	1300	1256	0.35
	Lead Frame	18	401	190	NA	8300	385	0.26
Systems Level	Sapphire PCB	7.9	35~46	400	NA	3965	730	0.22

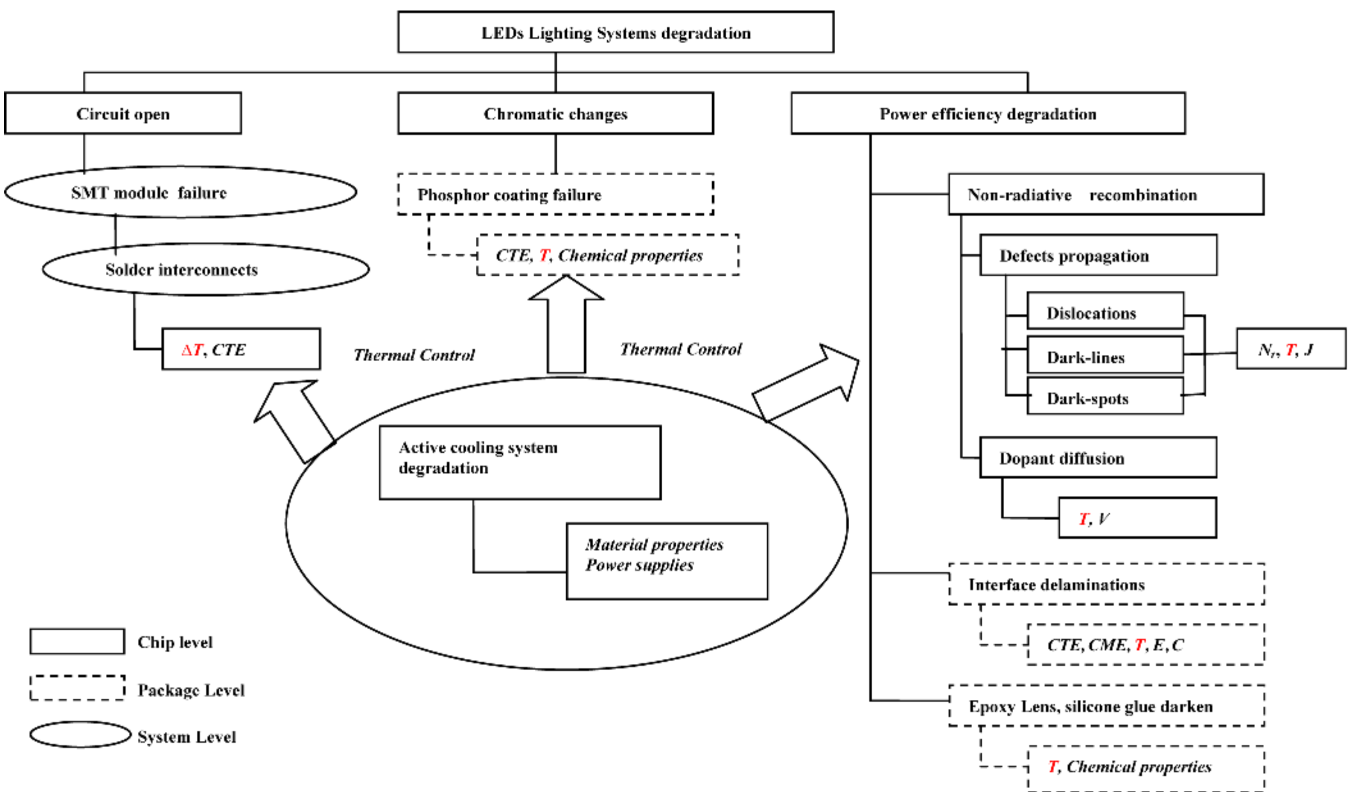

Fig. 3. FMMEA for high-power white LED lighting systems. (ΔT: Thermal Cycle; N_t: the defect density; J: Current Density; V: Voltage; E: Elastic Modulus; C: Moisture Concentration).

loads (stresses) applied over an extended period of time [5]. According to recent knowledge, PHM can be applied only in wear-out (time-dependent) failure mechanisms.

The failure modes in the mentioned LED lighting systems (i.e., Lamps) can be categorized as: 1) System circuit open (lighting off); 2) Lighting Chromatic changes; 3) Power efficiency degradation (luminous flux degradation). Like other electronics-rich systems, the failures of high-power white LED lighting also contains the above mechanisms. Following is a summary of the failure modes and the associated wear-out degradation mechanisms from chip to system in accordance with the "bottom-up" methodology (Fig. 3).

1) Chip Level Degradation: As described in the material properties analysis, the LUXEON_K2 chip used is made of GaN-based blue light-emitting diodes with a multi-quantum well (MQW) structure. In previous research results [14]–[18], the degradation of the active layer of LEDs due to increased non-radiative recombination lowers the optical output power and power efficiency. The factors responsible for this which contribute to the non-radiative recombination were proposed to [13]:

a) Defects (dislocations, dark-lines and dark-spots) propagation are some of the factors which are suspected of causing an increase in the non-radiative recombination which converts the most electron-hole recombination energy to heat [19], [20]. A Carrier-Continuity equation (1) has been widely used to show the qualitative competition among radiative, non-radiative and Auger recombination that occurs in the quantum well active region and carrier leakage out of active layer. As show in the (2) which expresses the non-radiative recombination coefficient by the Shockley–Hall–Read recombination rate, increasing defect density N_t will contribute to the non-radiative recombination and relatively reduce the light output intensity for a certain value of the forward current [19]. Normally an I/V curve can also imply chip level degradation. A qualitative relationship between I/V curve degradation and power output loss has been observed in these tests, which depends mainly on two parameters: forward bias and temperature [21]

$$\frac{dn}{dt} = \frac{J}{ed} - Bn^2(t) - An(t) - Cn^3(t) - f_{\mathrm{leak}}(n) \quad (1)$$

$$A = N_t \nu_{\mathrm{th}} \sigma \quad (2)$$

where the J/ed is the current injection rate, the $Bn^2(t)$ accounts for the spontaneous emission rate (or luminous radiative term), and the $An(t)$ represents the non-radiative carrier that accumulates at the defects. A, $BandC$ in each term are the non-radiative, radiative and Auger recombination coefficient, respectively. $f_{\mathrm{leak}}(n)$ covers the carrier leakage out of active layer. N_t is the defect density of traps, ν_{th} is the carrier thermal velocity and σ the electron capture cross section.

b) Another factor which causes an increase in non-radiative recombination emission is the diffusion of dopants or impurities in the quantum well (QW) region. During the aging process, operation at the increasing junction temperature can worsen the electrical properties of ohmic contact and semiconductor material at the p-side of diodes due to the interaction between hydrogen and magnesium [13]. As we know, in GaN-based LEDs, the GaN epilayer must be covered with a heavy layer of Mg dopant to obtain a sufficient carrier density due to the high activation energy of Mg dopant [22], but during the growth of high temperature p-type layers, Mg atoms can be easily diffused from the surface to the QW action region. Lee *et al.* [22] observed that this diffusion could be accelerated along the line of any dislocation defects and one or another of the optical gradual degradations would operate under very high temperature and voltage.

2) Package Level Degradation: Packaging is considered as a low cost method to realize mass production of LEDs and protect LED chips from damage, including electrostatic discharge (ESD), moisture, high temperature, chemical corrosion, and mechanical shock. When a GaN-based chip is packaged as a LED product, several other materials need to be used together with it. Fig. 2(a) and Table I list most of them, which are Epoxy Lens, Silicone Glue, Phosphor Coating, Die Attach Adhesive, Wire Bond, Silicon submount, Heat Sink, Lead Frame, and Plastic Mould and so on. Any degradation among those materials or interface defects will induce LED package failure and lower its reliability and lifetime. As shown in previous research results, the most common failure mechanisms are [7], [16], [23]–[25], [26]: 1) Interface delamination which could result in open circuit or heat dispersion problems; 2) Epoxy lens and Silicone glue darken which worsens the chromatic properties of white LEDs; 3) Phosphor coating degradations can cause decay of the spectral properties of white LEDs.

a) Interface delamination failures: Interface delamination, one of the common failures encountered during electronic packaging, can threaten the packages' electrical and thermal management. As shown in the structure of LUXEON_K2 series LED packages [Fig. 2(a)], there are six different parts packaged together in layers with five interfaces between adjacent ones. Hu *et al.*[7] reported on the mechanisms of delamination in LED packages and compared the two driving forces of failure (thermal-mechanical-stress and hygro-mechanical-stress) to accelerate the development of delaminations. By physical analysis, the thermal-mechanical induced stress (σ_T) between layers comes from a mismatch between the Coefficient of Thermal Expansion (CTEs) and specific heat of different materials (as shown in Table I) (3). Also the different capacities of hygroscopic swelling (CME, Coefficient of Moisture Expansion) contribute to generate the hygro-mechanical-stress (σ_M) (4). So overall, common delaminations either driven by thermal-mechanical-stress or hygro-mechanical-stress will produce voids within interface layers. This will raise the thermal resistances and finally block the thermal pass, especially for the chip-submount layer and submount-heat sink layer, the major heat dissipating route in this package

$$\sigma_T = E\alpha(T - T_{\mathrm{ref}}) \quad (3)$$

$$\sigma_M = E\beta(C - C_{\mathrm{ref}}) \quad (4)$$

$$R_{\mathrm{th}} = \frac{T_j - T_0}{Q} = \sum_{i}^{n} R_{\mathrm{th,i}} \quad (5)$$

where E is elastic modulus, α, T and T_{ref} are CTE, temperature and reference temperature, respectively, β, C and C_{ref} are CME, moisture concentration and relative moisture concentration. T_j and T_0 are the highest junction temperature and ambient temperature, respectively, and Q is the input thermal power.

To best qualify the ability of thermal management of the white LED packaging, thermal resistance (R_{th}) which is defined as the temperature difference between junction temperature and ambient environment divided by input thermal power (5) was introduced and R_{th} also can be understood as the temperature gradient between heat resource and its surroundings, which might induce thermal-mechanical-stress to shorten the life of the white LED package. Tan *et al.* [8] found that the thermal resistance of the die attachment located between the silicon submount and the copper heat sink would be enhanced greatly when voids existed within adhesives.

b) Epoxy lens and silicone glue darken failure: The chromatic properties of white LED lighting products are determined both by the stability of luminous output produced by blue GaN-based chip and by the capability of light penetration which is controlled by the quality of the lens and silicone glue coatings.

The Epoxy lenses are applied to the LEDs packages to increase the amount of light emitted to the front [28]. Because they are exposed to the air, epoxy lenses suffer thermal and moisture cycle aging during operation time and some crack or flocculent were observed in the aging test, which lower the light output from GaN-based chips. Similarly, the purpose of introducing transparent silicone glue coatings in the LED package is not only to protect and surround the LED chip, gold ball interconnects and bonding wires, but also to act as a lens through which the light beam is collimated [26]. But this polymer encapsulate is thermally unstable at high temperatures or in a high forward bias aging period, which could impact on the optical output and the wavelength shift [14], [27]. In conclusion, the aforementioned failure mechanisms are associated with the chemical degradation of materials within the product lifetime, so to increase the lifetime of lens and silicone glue coatings in the LEDs packages, choosing the thermal, mechanical, and chemical stable materials will be the most critical step during packaging design.

c) Phosphor coating degradation: The most widely used white LED on the market is a combination of blue LED chip and yellow phosphor ($YAG{:}Ce^{3+}$) powders mixed with organic resins [29], [30]. According to the previous researches [31], there are two probable reasons for this. One is that phosphor particles scatter the light emitted by the chip due to the refractive index mismatching between powders and resins. The other reason is that the thermal degradation of polymer resins, could result in the degradation of the polymer-based phosphor coating during aging. To solve this problem, a glass ceramic phosphor, with higher quantum efficiency, better hydro-stability, excellent heat-resistance, compared to the resin-based one, and with a CTE which matches with the GaN-based chip, is a promising alternative for the future.

3) System Level Degradation: To satisfy the special applications, i.e., indicators, lighting, and displays, several LEDs units are mounted together in arrays to increase the luminous flux and the chromatic types. But the accompanying problem is thermal management which is of primary importance to their reliability and efficiency [24].

A LED lighting system usually consists by LED arrays mounted on substrates, cooling systems and electrical driving modules, like a high-power white LED lamp shown in Fig. 2(b). For detail assembly technology, the LED arrays are surface mounted on a sapphire substrate with high thermal conductivity ($35 \sim 46$ W/m°C) and an active cooling system is introduced to maintain the junction temperature according to the specification requirements by the method of convection to the surroundings. Finally, to stabilize the power supply, an electrical driver is packaged between the electrode and the active cooling system. To analyze the degradation mechanisms of the whole system, a hierarchical analysis method [10] was applied to this system by separating it into three subsystems: the SMT module (LED arrays mounted on sapphire substrate) (Fig. 4), active cooling systems, and power driving circuit.

a) Degradation in SMT module: According to the optical design, several high-power white LED units are mounted on sapphire substrate by widely used soldering technology. For this subsystem, the chip level and package level failure mechanisms are summarized above, so the left failure site might be the interconnections between lead frames and sapphire substrate. As we know, the solder joint interconnects serve two important purposes [32]: 1) to form the electrical connection between the component and the substrate; and 2) to build the mechanical bond that holds the component to the substrate. But in LED packaging, they are also acting as a heat dissipation path from the heat sink to substrate (Fig. 4).

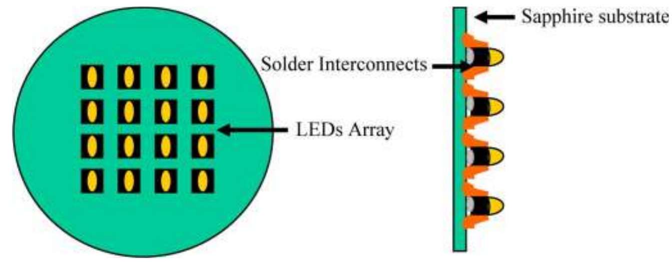

Fig. 4. Surface mount technology module.

During the product's lifetime, owing to the mismatching of the Coefficient of Thermal Expansion (CTE) between substrate and the LEDs unit, cyclic temperature changes cause cyclic displacement, which can lead to thermal fatigue failures in solder interconnects [33]. There are two major components to fatigue failures: the initiation of fatigue cracks and the propagation of these cracks under cyclic loading and both of them could cause an open circuit and light-off, suddenly. Although this seems to be a catastrophic failure for the lighting, time-dependent degradation occurs within solder interconnects under thermal and moisture cyclic aging. Therefore, one of the loads monitored to predict the lifetime in this system would be located in the solder interconnects, not just focused on the output luminous flux.

b) Degradation of active cooling systems: As mentioned in Song *et al.*'s research [10], a more practical approach to lower the junction temperature of the LEDs chip is to apply an advanced active cooling technology and potential active thermal management technologies [34] including thermoelectronics, piezoelectric fans, synthetic jets, and small form factor fans. To enhance the whole system's lifetime, the reliability of the cooling systems must be higher than the LED arrays ($> 50\,000$ h). With this principle in mind, Song *et al.* [10] chose a much more reliable cooling system (synthetic jets) which comprised two thin piezoelectric actuators separated by a compliant ring of material. The two degradation mechanisms related to the aging of the cooling system were: 1) the depolarization of the piezo-ceramic; 2) change in the elastic modulus of the compliant, rubbery tendon. And the contributions that a cooling system made to the whole lighting system were its capacity to remove the heat produced by LED modules and to lower the junction temperature. This was quantitatively expressed as an enhancement factor (EF), which could contribute to establishing the whole system's thermal induced PoF models

$$EF(P_{\text{cooling-systems}}) = \frac{Q_{\text{active}}}{Q_{\text{nc}}} \tag{6}$$

where $Q_{\text{active}}, Q_{\text{nc}}$ are the heat removed by the active cooling system and by natural convection, respectively. $P_{\text{cooling-sysrtem}}$ is the performance of the cooling system.

TABLE II
RANK PRIORITY FOR POTENTIAL FAILURE MECHANISMS

Failure Sites	Failure Modes	Failure Mechanisms	Rank Priority Rating			
			S	***O***	***D***	***RPN***
P-N Junction		Defect propagation	8	3	6	144
P-type Layer	Power efficiency degradation	Dopant diffusion	6	2	6	72
Interface		Delamination	7	3	4	84
Epoxy lens & Silicone glue		Darken	6	3	4	72
Phosphor Coating	Chromatic changes	Depolym-erization	6	3	4	72
Solder Interconnections	Circuit open	Fatigue	10	5	2	100
Cooling Systems	Heat Increase	Ageing	5	2	3	30

Note: *S*: Severity; *O*: Occurrence; *D*: Detection; *RPN*=*S*×*O*×*D*; Rank Criteria refers to [38]

But this system level degradation analysis did not take into account the package level degradation, it only correlated with the heat-induced chip level failure, because Song *et al.* [10] just supposed the chip was directly mounted on the substrate. When taking into account future maintenance and repair considerations, one should consider also the package level degradation of LED modules.

4) Rank Priority for Potential Failure Mechanisms: After classifying the failure modes and potential failure mechanisms for the whole high-power white LED lighting system, the next step is to prioritize the identified failure mechanisms with a rank priority number (RPN), which is widely used in FMMEA to determine the design risk [35], [36]. And special attention should be given to the failure mechanisms with high RPN value in the reliability design period. In the PoF-based PHM approach, damage models are established for those failure mechanisms with high RPN to evaluate the system's useful life.

Results gleaned from past experience in high-power white LED lighting systems, and RPN values are summarized in Table II. Here, it can be seen that chip level luminous degradation induced by thermal propagation and solder interconnection fatigue damage driven by thermal cycling, are the two potential failure mechanisms which carry the highest degree of risk.

C. PoF-Based Damage Modeling

After identifying the failure modes and the potential failure mechanisms and ranking the failure mechanisms, establishing the relevant PoF models could help quantify the failure through evaluation of time-to-failure or likelihood of a failure for given set of geometries, material construction, environmental and operational conditions [5]. As discussed above, the two most critical failure mechanisms with highest priority in the degradation from chip to the whole system are: 1) thermal-induced luminous degradation; and 2) thermal cycle-induced solder interconnect fatigue.

1) Thermal-Induced Luminous Degradation Modeling: Referring to the commonly used Solid State Lighting (SSL) standard, lumen depreciation or lumen maintenance is one of the most important criteria to verify the reliability of the high-power white LED lighting (Chips, Packages, or Systems). According to the laminate standard, IES LM-80-08, the lifetime of LED packages, arrays or modules can be defined as the time for 70% lumen maintenance [37].

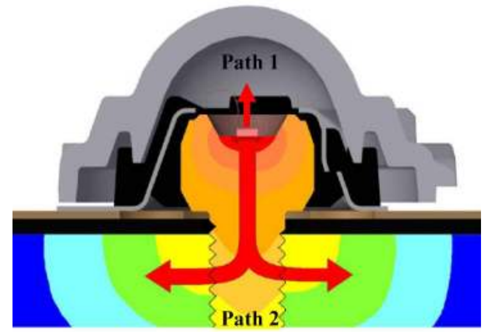

Fig. 5. Heat dissipation paths.

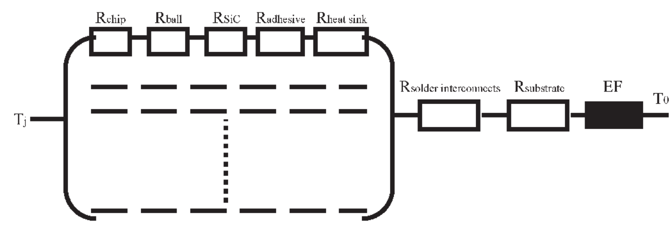

Fig. 6. Thermal resistance network of the high-power white LED lighting system (EF: Enhancement factor of cooling systems).

As mentioned already, in failure mechanisms, thermal dissipation is a serious issue in the high-power white LED lighting from chip to system and higher junction temperature accelerated by poor thermal dissipation of packages or cooling systems was responsible for deterioration in luminous efficacy and shortens the lifetime of the system. Normally, there are two paths for heat dissipation (Fig. 5): 1) by conducting heat through the upper phosphor coating and silicone glue, and the epoxy lens; 2) the other is from the materials attached to the die, the Silicon submount and through the heat sink to the substrate. But evidence showed that the first path was blocked because of the heat insulation of the polymer materials. To establish PoF-based damage models between lumen maintenance and capacity of thermal dissipation of system, a thermal resistance network was first built to evaluate the performance of heat dissipation [38] (Fig. 6).

The submodel for the lumen maintenance (L_m) of LED chips has an empirical exponential form

$$L_m = \frac{L_{\text{output}}}{L_0} = e^{-\alpha(T_j)t} \tag{7}$$

$$TTF = \frac{\ln 0.7}{-\alpha(T_j)} \tag{8}$$

$$T_j = f\{A, R_{\text{th}}, I_c, T_0\} \tag{9}$$

$$R_{\text{th}} = \sum_i^n (R_{\text{chip}} + R_{\text{ball}} + R_{\text{SiC}} + R_{\text{adhesive}} + R_{\text{heat sink}})_i + R_{\text{solder interconnects}} + R_{\text{substrate}} - EF \tag{10}$$

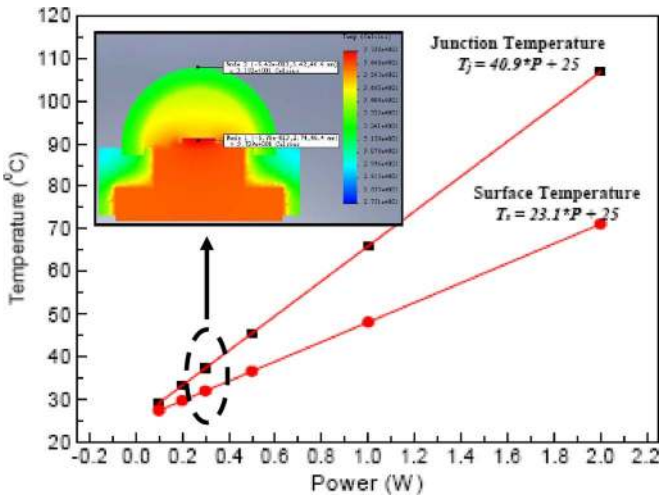

Fig. 7. Linear relationship between junction temperature and input power (Left top: FEA simulation result of temperature distribution).

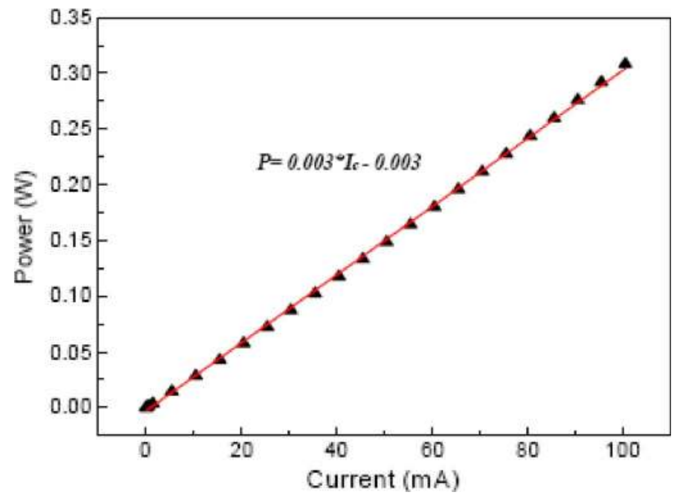

Fig. 8. Linear relationship between input current and power.

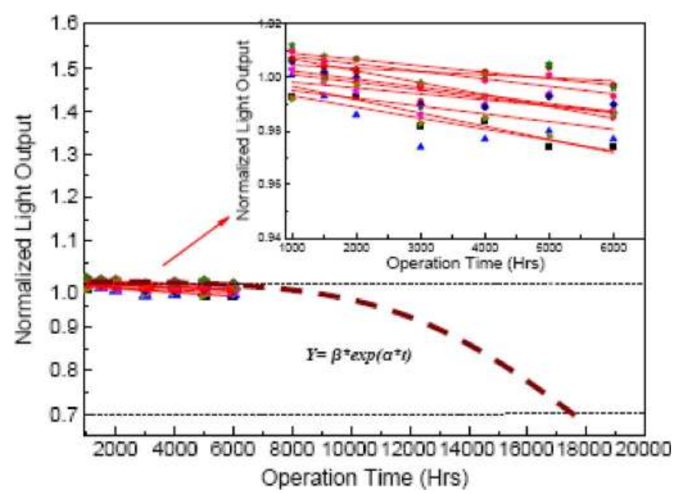

Fig. 9. Lumen maintenance plotting and prediction for LEDs under conditions (T_j = 68 °C, T_0 = 55 °C, Ic = 0.35 A, data normalized to 1 at 24 h).

where α is the junction temperature-dependent light output degradation rate, t is the operation time measured in hours and when $L_m = 0.7$, TTF is the time to failure (8). T_0 is the ambient temperature. I_c is the forward current. A represents the non-radiative coefficient which contributes to produce intrinsic heat. As shown in (5), R_{th} is the thermal resistance of the whole system (10). And the enhancement factor EF is a performance factor of the cooling system, which is defined as the ratio of the heat removed using active cooling systems to the heat removed through passive means alone [10]. The degradation of the active cooling system, including material wearout, determines the enhancement factor. As shown in Fig. 6, enhancement performance also can be combined in series into the thermal resistance network as negative thermal resistance.

Equation (9) reveals that several parameters determinate the junction temperature, and testing the junction temperature accurately is a difficult thing when GaN chip was packaged in the LED unit during aging. This paper used the finite element method based on COSMOS software to simulate the junction temperatures under different driving powers and the temperature distribution result was shown in the left top of Fig. 7 when materials properties (Table I) were put into the simulation model. Finally, the actual surface temperature of the LED unit measured by NEC MRI 9100 thermal tracer was used to verify the simulation results. Result showed the little difference between the simulation result (31.92 °C) and real test result (32.4 °C) under the same 0.3 watt driving power

$$T_j = 40.9 * P + 25 \quad (11)$$

$$T_s = 23.1 * P + 25 \quad (12)$$

$$P = 0.003 * I_c - 0.003 \quad (13)$$

$$T_j = 0.1227 * I_c + 24.877 \quad (14)$$

Figs. 7 and 8 illustrate the relationships between junction temperature, input power and input current. The linear relationship between junction temperature and input current can be inferred by inserting (13) into (11) which were calculated from fitting the simulation data. Therefore, (14) can be used to evaluate the junction temperature base on the input current for the LUXEON_K2 LED unit.

Fig. 9 showed the LM-80 test results of 10 LEDs from PHILIPS LUXEON lifetime database under the operation conditions: T_j = 68 °C, T_0 = 55 °C, Ic = 0.35 A [40]. And exponential degradation model was used to fit the lumen maintenance data from 1000 to 6000 h. Then the two parameters (α, β) were estimated for each degradation curves by least square method and the goodness of fit was determined by R^2, which was closed to 1, if the regression curve was fitted well with the data. (Table III). Based on the extrapolations of the curves, the lumen maintenance of each test samples at 10 000 h were predicted and compared with the test results, which revealed little difference between estimated and real data. With the same method, TTFs (L70 age) were calculated, but until now still no field results verified them.

2) Thermal Cycle-Induced Solder Interconnects Fatigue Modeling: Although this failure mechanism induces the catastrophic electrical power-off for LED lighting systems, time-dependent fatigue degradation of solder interconnects results in this crack failure during cyclic aging. Thus, capturing the time to failure of solder interconnects also helps to

TABLE III
LUMEN DATA (1000 TO 6000 h) AND EXPONENTIAL EXTRAPOLATIONS OF L70 AGES
($T_j = 68$ °C, $T_0 = 55$ °C, $Ic = 0.35$ A, DATA NORMALIZED TO 1 AT 24 h)

	$Y= \beta*exp(\alpha*t)$		R^2	Y (10000 hrs)	Test results (10000 hrs)	Error =(Y-Test result)/Y	Estimated TTF (L70 ages, hrs)
	β	α					
S1	1.00174	-5.2876E-06	0.82310	0.950	0.956	-0.00616	67783.8
S2	1.01149	-4.4541E-06	0.81384	0.967	0.964	0.00354	82643.4
S3	0.99726	-4.1726E-06	0.51570	0.957	0.96	-0.00365	84822.5
S4	1.00406	-2.9143E-06	0.70202	0.975	0.968	0.00740	123779.9
S5	1.00055	-2.2251E-06	0.37781	0.979	0.962	0.01690	160544.7
S6	0.99807	-2.9347E-06	0.40313	0.969	0.966	0.00331	120880.9
S7	1.00554	-3.0600E-06	0.62529	0.975	0.974	0.00127	118365.9
S8	1.00585	-1.1931E-06	0.22685	0.994	0.974	0.02004	303826.8
S9	1.01075	-2.7981E-06	0.65066	0.983	0.969	0.01410	131293.7
S10	1.01154	-2.3735E-06	0.51541	0.988	0.974	0.01398	155109.3

TABLE IV
FATIGUE FAILURE MODELS FOR SOLDER INTERCONNECTS

Failure Types	Failure models and equations	Required Parameter	Coverage
Plastic Strain Driven	1 *Coffin-Manson model* $\frac{\Delta\varepsilon_p}{2} = \varepsilon_f^{'}(2N_f)^c$	Plastic strain	Low thermal cycle fatigue
Plastic + elastic Strain Driven	2 *Coffin-Manson Basquin model* $\frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f^{'}}{E}(2N_f)^b + \varepsilon_f^{'}(2N_f)^c$	Strain range	High and low thermal cycle fatigue
Total shear strain Driven	3 *Engelmaier model* $N_f = \frac{1}{2}\left[\frac{\Delta\gamma_t}{2\varepsilon_f^{'}}\right]^{1/c}$	Total shear strain	Low thermal cycle fatigue

where, N_f = number of cycles to failure; $\Delta\varepsilon_p$ = plastic strain amplitude; ε'_f = fatigue ductility coefficient; c = fatigue ductility exponent, $\Delta\varepsilon$ = strain range; σ'_f = fatigue strength coefficient; E = elastic modulus; b = fatigue strength exponent (Basquim's exponent); T_s = mean cyclic solder joint temperature in °C; f = cyclic frequency in cycles/day;

evaluate the lifetime of LED lighting systems. Lee [32] presented the solder joint fatigue models, summarized their features and applications and classified them into five categories, including stress-based, plastic strain-based, creep strain-based, energy-based, and damaged-based. For the package type of LUXEON_K2: leaded packaging, three PoF models were fitted to identify its failure mechanisms (Table IV): *The Coffin–Manson model*, *the Coffin–Manson–Basquin model*, and the *Engelmaier model*.

Among above three models, the *Coffin–Manson fatigue model* is the best known and most widely used approach, but it assumes that fatigue failure is strictly controlled by plastic deformation and the elastic strains contribute little to fatigue. To avoid this shortcoming, *Basquin*'s equation which considers the elastic deformation's contribution is added to the *Coffin–Manson fatigue model* and the *Coffin–Manson–Basquin model* is formed. The third failure model, the *Engelmaier model*, also is an improvement on the *Coffin–Manson fatigue model* by including cyclic frequency effects, temperature effects, and elastic-plastic strain [39].

III. CONCLUSION AND PROPOSALS

In this paper, the PoF-based PHM approach, including an analysis of materials and geometries, FMMEA and failure models built for the prioritized failure mechanisms, was used to assess the reliability of high-power white LED lighting from chip level to system level. Three failure modes: 1) System open-circuit (lighting off); 2) Lighting Chromatic degradation; 3) Power efficiency degradation (luminous flux degradation), were firstly categorized to the whole system and the potential failure mechanisms and their contributing loads were presented by the "bottom-up" method. Then, the PoF-based damage models were built for the two failure mechanisms with highest priority in the degradations from chip to wholesystem.

In future work, three parts will be input into the PoF-based PHM approach systems to complete and optimize the verification and assessment process for high-power white LED lighting:

1) As one of issues with the greatest potential for failure in the lighting system, thermal management models will be optimized by multiple-modeling for all parts through the heat dissipation paths. Relation simulation models will be established for quantifying the Junction Temperature with loads including: material properties (thermal resistance, defect density etc), input currents, and ambient temperature.
2) According to the FMMEA results, appropriate sensors should be selected (i.e., I_c, V, P_{input}) for *in situ* monitoring of the load profile of high-power white LED lighting and the accelerated test based on this load profile should be designed which will lead to a more accurate prediction of the time to failure in real time.
3) Although the PoF-based damage models can be used to calculate the remaining useful life, uncertainty analysis can be added to the PHM approach to refine real life predictions.

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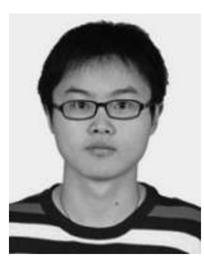

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