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A statistical study to identify the effects of packaging structures on lumen reliability of LEDs

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ABSTRACT

The development of high-power light-emitting diode (LED) devices has been bedeviled by the reliability problems. And most reliability issues are caused by the packaging materials rather than the chips. However, which packaging material is the most influential remains unrevealed. To answer this question, a statistical method was introduced in this paper. Optical simulations were conducted to calculate the optical output power of LED package according to the orthogonal experimental design. Range and variance analyses were carried out to determine the significance of the relevant factors on the LED's light output. The results showed that the dome lens among the non-luminescent packaging materials had the most significance in affecting the light output. It is concluded that this method is useful in detecting the most significant part of LED packaging materials during the development of new packaging structures and is beneficial for enhancing the whole reliability of LED package effectively.

1. Introduction

White light-emitting diode has been attracting interests due to its extraordinary characteristics over conventional light sources such as high efficiency, low consumption, environmental protection and long life, etc. [1–5]. However, reliability issues have become a critical bottleneck for its further development. For an LED package, it was widely acknowledged [6–8] that the chip reliability is better compared to the packaging materials. Kang et al. [6,7] used a metal package to estimate the LED chip's reliability so that other degradation factors in packages (such as paste, resin, etc.) were excluded. Three kinds of chips mounted on metal packages and conventional plastic packages were subjected to aging temperatures of 70 °C–140 °C. After 5000 h, only one kind of chip with metal package showed <10% degradation. However, all three conventional plastic packages showed 20%–40% degradation to their initial values. Chen et al. [8] prepared four types of LED modules with different package components and subjected them to accelerated life tests under temperature of 125 °C and current of 350 mA. The results showed that the module without silicone and phosphor layer exhibited no depreciation while the other three types (with silicone and/or phosphor layer) degraded to failure. This implies that reliability issues tend to arise more from the package components rather than the LED chip.

So far, the most common white LEDs are based on phosphor-converting scheme on blue LED chips. The phosphor particles absorb part of the blue light emitted from the LED chip, then down-convert part of the blue light into yellow emission. The mixture of the transmitted blue light and yellow light gives a white visual sense. Such a white LED module consists of many packaging materials, including phosphor gel, silicone gel, optical lens, molding compound, lead frame, cupper slug and so on. During the aging process, most of the materials would degrade to certain extents and thus can affect the LED's optical performance and worsen the reliability [5,9].

Ever since LED was invented, researches have been carried out to study and improve its reliability. The experimental methods have been undergoing a series of evolutions. At the beginning, the whole LED samples were subjected to high temperature oven for thermal storage test and aged to failure. The relative parameters (optical, electrical, thermal parameters, and also sample appearance) were measured and analyzed to see what change the aging process could bring [10,11]. Then researchers focused more on the aging conditions. Due to LED's long lifetime, accelerated stress tests are always utilized for its reliability estimation. The mostly used accelerated stress conditions are temperature, current, and humidity. And the single or combination stresses are used for aging condition [12–14]. The analysis method is as same as the aforementioned. Later, it is noticed that the parameter changes during the aging process in terms of shorter time intervals would probably reflect the change of material properties. In this context, various kinds of online testing method are developed to detect LED's parameter change in real time during the aging process [15,16]. At the same time, some researchers focused on reliability problems related with the packaging components. The influences of packaging types and packaging materials were studied to exhibit their relations with LED's reliability. Chen et al. [8] prepared four types of LED package samples with different

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components and subjected them to accelerated aging tests. By comparison results, it was found that flaws and voids were induced in the silicone encapsulant and the phosphor layer led to a fast light energy loss during the initial aging test. Mehr et al. [17] carried out thermal degradation tests to investigate the thermal stability and lifetime of remote phosphor encapsulant plates. Apart from lumen degradation, a significant change both in the correlated color temperature (CCT) and in the chromaticity coordinates (CIE x, y) was observed. And the decrease of CCT took place with almost the same kinetics as the lumen depreciation. Singh et al. [18] proposed a moisture-electrical-temperature (MET) test to evaluate the phosphor-related reliability of high power LEDs. They found that different degradation mechanisms were resulted from the difference in the thermal expansion coefficient between the molding and lens materials. To this stage, the whole experiment is like a mixture hotchpotch that all the packaging materials were aged as a whole and the analysis on each individual packaging material would be perplexed by the coupling effect of different materials. Therefore, experiments were conducted to decouple the influence of individual packaging material on the LED's reliability. Meneghini et al. [19] studied the thermal aging of remote phosphor plate to explore its degradation mechanism. In the experiments, only phosphor plate was exposed to long-term high temperature stress test. They found the phosphor degradation mainly leads to problems like decrease of conversion efficiency and worsening of chromatic properties. Huang et al. [20] carried out aging tests on the individual packaging material and investigated LED's spectral power degradation correspondingly by using optical simulation method. The degradation kinetics were investigated and it was found that silicone degradation induces only initial lumen degradation of the LED packages. Despite all the above efforts to studying the influences of packaging materials on the light output, which material has the greatest impact still remains unrevealed.

In this paper, a statistical method was introduced to decouple the reliability analysis and determine the most influential packaging material on LED's lumen output. The experimental scheme was determined based on orthogonal experimental design. Packaging materials which degrade to various extents are needed according to the experimental scheme. It is not easy to study the optical degradation of LED packages with different material combinations by experiments. Thus, optical simulations were conducted to calculate the optical output power under different degrees of attenuation instead. Analysis of variance (ANOVA) was carried out to determine the significance of each packaging material's influence. By this means, the most influential packaging material on LED's light output was finally determined.

2. Simulations

2.1. Monte Carlo Ray-tracing simulation setup

The GaN-based blue LED chip model was firstly created. The structure and thickness of different layers were illustrated in Fig. 1. The luminescent multi-quantum well (MQWs) was sandwiched by an n-GaN layer and a heterostructure of p-GaN layer and p-AlGaN layer. A sapphire substrate and a current spreading layer made by indium tin oxide (ITO) were also considered. The top and bottom faces of the MQW were set as luminescent sources with Lambertian light intensity distribution. The output power was set to 1 W in total. The absorption coefficients and refractive indices of p-GaN, p-AlGaN, MQW, and n-GaN are 2, 2, 8, and 2 mm^{-1} and 2.43, 2.43, 2.51, and 2.43, respectively [21,22]. The absorption coefficients of ITO and sapphire are set as 0 and their refractive indices are 2 and 1.77, respectively. The reflection coefficient of the reflecting layer is set as 0.95. By setting the absorption coefficients and refractive indices of the materials, the optical model of the conventional GaN-based blue LED emitter can be successfully established.

As shown in Fig. 2, a conventional phosphor-converted LED package is built by using a 3D modeling software. The LED module is mounted on

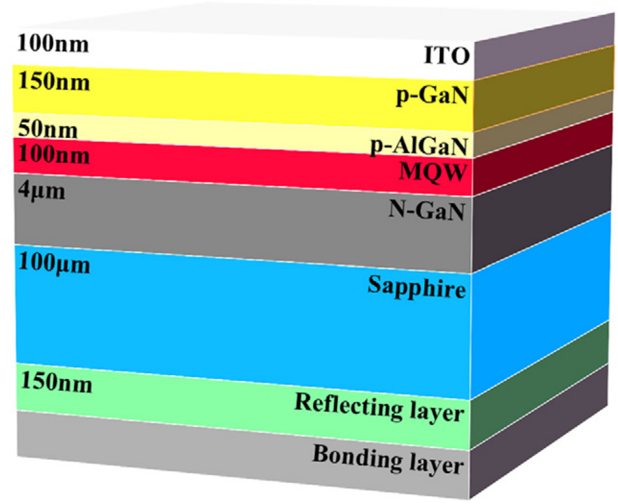

Fig. 1. Structure of conventional blue LED chip.

a metal core printed circuit board (PCB) for heat dissipation and electrical connection. A 1 mm × 1 mm × 0.1 mm blue LED chip is mounted on the heat slug via die attach adhesive. The copper slug is embedded in a polyphthalamide reflector cup (PPA cup) and bonded onto the PCB via solder. The inner diameters of the PPA cup are 4 mm and 5.6 mm respectively. A hemi-spherical dome lens with a diameter of 5.6 mm is modeled and the space inside the module is filled with silicone encapsulant. The effect of gold wire bonding is considered to be ignorable, so the gold wires are not created in the simulation model.

The refractive indices of the silicone encapsulant and dome lens are 1.53 and 1.586 respectively. The information of the phosphor used in the simulation is based on the actual phosphor material. More specifically, the type is yttrium aluminum garnet (YAG): Ce and the concentration is 1.65 g/cm^3. The mean diameter of the phosphor particles is kept as 6 μm. The refractive index of the phosphor gel is kept as 1.53. The absorption and scattering coefficient are 7.756 and 4.533 mm^{-1} for blue light and 0.03 and 5.943 for yellow light [21]. The specific wavelengths of 445 nm and 570 nm are used in the calculation to represent the excitation and emission spectra for simplification. Even though the refractive indices of materials vary along with the wavelength, the change

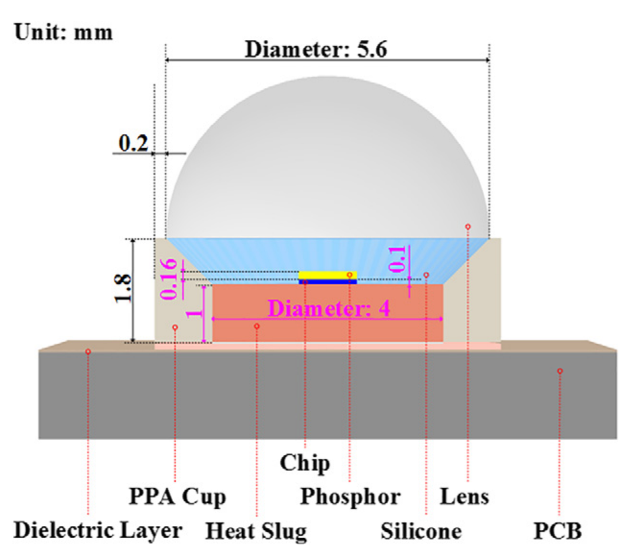

Fig. 2. Schematic of the white LED package for optical simulations.

range is very small under the wavelengths of interests. Thus, the variation is neglected in the parameter setting. As for the blue light, the specific wavelength of 445 nm is used to represent the emission spectrum of the LED chip. The optical models have been validated by previous studies [21–23]. Through the simulation, the light output power of LED package under various conditions can be obtained.

2.2. Orthogonal experimental design

The quantitative evaluation and statistical analysis of the effects of packaging materials' degradation were investigated on the light output power through orthogonal experimental design [24]. For simplification, only non-luminescent packaging materials were considered as relevant factors. In other words, the degradation of LED chip and phosphor layer were not considered in this simulation. Under high temperature (with/without current loading) based aging conditions, the transmissivity of some packaging materials and surface reflectivity of some packaging structures would degrade over aging time. And they can both affect the lumen output of the LED package. Thus, there were four relevant factors in the optical simulation: the reflectivity of the top surface of the heat slug (Factor A), the reflectivity of the inner surface of the PPA cup (Factor B), the absorption coefficient of the silicone encapsulant (Factor C), and the absorption coefficient of the dome lens (Factor D). The transmissivity/reflectivity of the packaging components would degrade inconsistently across the wavelengths of interest during the aging experiments. In other words, the transmittance degradation of blue and yellow light would not always keep consistent along with aging. In the optical simulations, the variation is neglected and the parameter changes are considered to be constant across the wavelengths of interest for simplification. The orthogonal table $L_{16}(4)^5$ was designed, in which a blank column was designated for the error evaluation. Four levels were set for each factor, and the boundary values for the levels were determined according to the experimental results in references [20,25]. More specifically, four levels of 0.95, 0.90, 0.85, and 0.80 were set for the reflectivity of heat slug and PPA cup. And four levels of 0, 0.05, 0.10, and 0.15 were used in the absorption coefficient of silicone encapsulant and dome lens. By setting different parameter combinations, the light output power can be obtained via the optical simulations. Based on the investigation factors, the corresponding levels, and the designated boundary values, the orthogonal experimental table is shown in Table 1.

3. Results and discussion

3.1. Simulation results

By the optical simulations, the light output powers are calculated. For case 1, the light output power and correlated color temperature (CCT) are calculated to be 381.35 mW and 6531 K respectively. The simulated spectral power distribution (SPD) of LED package is presented in Fig. 3. The SPD is with a peak wavelength of 445 nm for the blue light and a peak wavelength of 570 nm for the down-converted light. As for other cases, the results of output power are listed in Table 1. Although it is better to use lumen maintenance to assess LED package's reliability, it cannot be obtained directly by the optical simulation. In IES LM-80-08 standard [26], lumen maintenance is defined as the luminous flux output at any selected elapsed operating time. It is noticed that light output vs aging time can reflect lumen maintenance. The simulated light output power is related to material property change (transmissivity, reflectivity), and the latter one is closely related to aging time. Thus, we used the light output power under different material properties to indirectly estimate LED's reliability with aging time. It can be seen that as the packaging components degrade (reflected in the parameter setting), the light outputs of LED module decrease. Detailed statistical analyses were carried out in the following sessions.

3.2. Range analysis

The goal of range analysis is aimed to clarify the significance levels of different influencing factors on the lumen output of LED package. Based on the range analysis, the most significant factor in this case could be disclosed. The statistics of the range analysis of the effect of different factors on the LED's light output power was summarized in Table 2. The K value for each level of a parameter was the average of four values shown in Table 1, and the range value (R) for each factor was the difference between the maximal and minimal value of the four levels. And the square of deviation (S) of four levels for each factor was also obtained accordingly. Based on the results of range analysis and the square of deviation, the significance sequence of all the investigated influencing factors was lined as follows: Factors D, A, C, and B.

Therefore, it could be concluded that the absorption coefficient of the dome lens (Factor D) had the most significant influence on the lumen output of LED package in this case. The reason may be attributed to the large volume of the dome lens. According to the Bouguer-Lambert-Beer law [20], the intensity of lights propagating through

Table 1
Design of orthogonal table $L_{16}(4)^5$ and lumen output of the optical simulations.

Simul. no.	Reflectivity of the top surface of the heat slug	Reflectivity of the inner surface of the PPA cup	Absorption coefficient of the silicone encapsulant	Absorption coefficient of the dome lens	Light output power (mW)
	Factor A	Factor B	Factor C	Factor D	
1	0.95	0.95	0	0	381.35
2	0.95	0.90	0.05	0.05	285.57
3	0.95	0.85	0.10	0.10	234.72
4	0.95	0.80	0.15	0.15	202.95
5	0.90	0.95	0.05	0.10	244.88
6	0.90	0.90	0	0.15	236.19
7	0.90	0.85	0.15	0	257.61
8	0.90	0.80	0.10	0.05	243.14
9	0.85	0.95	0.10	0.15	184.72
10	0.85	0.90	0.15	0.10	190.73
11	0.85	0.85	0	0.05	274.51
12	0.85	0.80	0.05	0	278.25
13	0.80	0.95	0.15	0.05	200.06
14	0.80	0.90	0.10	0	244.73
15	0.80	0.85	0.05	0.15	183.92
16	0.80	0.80	0	0.10	226.05

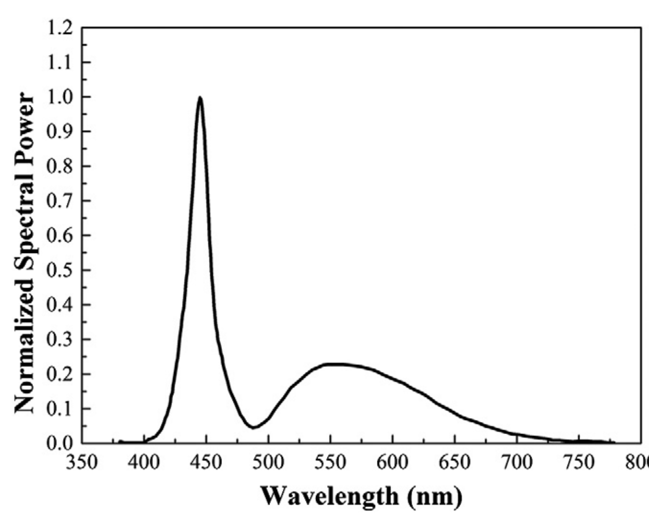

Fig. 3. Spectral power distribution of the LED package.

Table 2
Range analysis for the light output power of the LED package.

Statistics	Factor A	Factor B	Factor C	Factor D
K_1	1104.59	1011.01	1118.1	1161.94
K_2	981.82	957.22	992.62	1003.27
K_3	928.21	950.76	907.31	896.38
K_4	854.76	950.39	851.35	807.78
R	249.83	60.61	266.74	354.15
S	8313.13	642.88	10,105.98	17,413.49

medium can be expressed as

$$\frac{I}{I_0} = e^{-\alpha \cdot L}, \tag{1}$$

where I_0 and I are the intensity of the incident light and emergent light, L is the distance of transmission path, and α is an exponential constant, which is related to material properties, such as transmittance of lens, reflectivity of package inner surface and so forth. When the transmittance of lens degrades, the constant α increases and thus the lumen output I decreases. Besides, the volume of lens in this case is so large that the effect is dominate compared with other packaging materials.

3.3. Analysis of variance

From the range analysis, it was concluded that the absorption coefficient of dome lens had the most significant influence on LED's light output power compared with other factors. However, the objective effect of these factors on the lumen output of LED package was not investigated. Thus, analysis of variance (ANOVA) was carried out. In the experimental scheme, a blank column was set in the orthogonal table for error estimation. The sum of squares of deviation (SS), degree of freedom (DF), and mean squared deviation (MS) of LED's output power were calculated and summarized in Table 3. The F value of a factor is the ratio of the MS value of the factor to that of error line. By comparing the obtained F value with the theoretical one of specific level and DF, the significance level can be determined for each factor. As shown in Table 3, factors A and C showed significance ($P < 0.05$) in affecting the lumen output of LED package and factor D showed great significance ($P < 0.01$). The influence of factor B was not significant and it was because relatively small account of light arrived at the inner surface of the PPA cup.

Based on the statistical analysis above, the dome lens among the non-luminescent packaging materials was found to have the most significance in affecting the lumen output of LED package during degradation process. This case gives an example that the proposed statistical method can be successfully used in detecting the most influential packaging material in LED module. Through the ANOVA, the significance of each factor can be determined. During the developing and manufacturing process of LED packages, more efforts need to be dedicated to improving the reliability of the most influential packaging material so that the performance and reliability of the whole LED package can be enhanced effectively.

Table 3
Analysis of variance for the light output power of the LED package.

Statistics	SS	DF	MS	F[a]
Factor A	8313.13	3	2771.04	21.89[b]
Factor B	642.88	3	214.29	1.69
Factor C	10,105.98	3	3368.66	26.61[b]
Factor D	17,413.49	3	5804.50	45.85[c]
error	379.82	3	126.61	

[a] $F_{0.05}(3,3) = 9.28$, $F_{0.01}(3,3) = 29.5$.
[b] $P < 0.05$.
[c] $P < 0.01$.

4. Conclusion

In this paper, a statistical method was proposed for experimental design to analyze the importance of packaging materials on LED's reliability. A case was used as an example to demonstrate the method. Optical simulations were carried out to obtain the light output power of LED package according to the orthogonal experimental design. Four factors which influence LED's light output were investigated. Range analysis and analysis of variance were conducted to determine the significance of the factors on the LED's light output. The results showed that the dome lens had the most significance in affecting the light output of LED package in this case. This method can be used to detect the most significant part of LED packaging materials during the development of new packaging structures and patterns so that the materials can be selected pointedly to enhance the whole reliability effectively.

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