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Comparison of silicone and spin-on glass packaging materials for light-emitting diode encapsulation

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ABSTRACT

Traditional white light light-emitting diode (LED) encapsulation is performed by mixed phosphors and silicone coating on LED die. However, this encapsulation with silicone coating incurs overheated temperatures and yellowing problem. Therefore, this work attempts to replace silicone paste by using spin-on-glass (SOG) materials. Experimental results indicate that although initial brightness of SOG-based packaging is lower than that of silicone packaging, its light attenuation is significantly lower than that of silicone for a long lighting time. After the LED power is turned on for 12 h, the brightness of LED with silicone and SOG material packaging decreases from 84 to 48 lm and 73 to 59 lm, respectively. Therefore, SOG material provides an alternative packaging solution for high power LED lighting applications.

1. Introduction

High power gallium-nitride (GaN) based light-emitting diodes (LEDs) have received considerable attention recently, owing to their wide applications in solid-state lighting illuminations. To satisfy the demands of general lighting applications, the reliability of high-power LED and the luminous efficiency of white LEDs have been extensively studied. However, high-power LED encapsulation incurs problems, such as silicone yellowing and phosphor with a hot recession effect [1–5]. Traditional white light LED encapsulation is mixed by phosphors and silicone coating on LED die. However, this encapsulation also suffers from an insufficient color rendering index (CRI) of a white light. Therefore, by adding red phosphors (Nitrides258) to phosphors, one can complement the red light and increase the CRI [5]. Additionally, the silicone in traditional packaging directly contacts to LEDs, which apparently incur yellowing problems. The heating effects are reduced using the remote phosphor coating. As well-known, remote and an addition of red phosphor coatings reduce the brightness, yet substantially increase CRI and lifetime [6–9]. Moreover, for a situation in which the traditional silicone coating encounters an overheated temperature and ultraviolet light, the polymer molecular bond configuration is broken and undesirable free radicals are produce, ultimately incurring yellowing problem. To overcome this problem, this work attempts to replace silicone paste by using spin-on-glass (SOG). Previous works demonstrated that phosphor-converted white light-emitting diodes using Ce:YAG-doped glass exhibit a better thermal stability than those using Ce:YAG-doped silicone [10,11]. Additionally, other works have developed a remote phosphor layer to improve LED reliability [12,13]. Therefore, this work investigates two coating materials of silicone and SOG as well as two structures with and without remote coating for LED reliability.

Taguchi method [14–18] is a process optimization technique that investigates how multi-parameters affect the performance of a process. This method can minimize the variation in a process through robust design of experiments. By using orthogonal arrays [15], the Taguchi method organizes the parameters affecting the process and the levels at which they should be varied. This method allows the determination of factors that affect the characteristic performance of a process the most with a minimum amount of experiments. Generally, the variation is quantified using a generic signal-to-noise (S/N) ratio. These S/N ratios are a measure of the effect of noise factors on performance characteristics. Several S/N ratio types of characteristics are available, e.g., larger is better, nominal is best and smaller is better [14,16]. The S/N ratio is calculated by the S/N analysis.

Larger-is-better;

$$S/N_{LB} = -10\,\mathrm{Log}\,\frac{\sum_{i=1}^{n}\frac{1}{(y_i)^2}}{n}$$

nominal is best;

$$S/N_{NB} = -10\,\mathrm{Log}\,\frac{\bar{y}}{\sigma_y}$$

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smaller is better;

$$S/N_{SB} = -10\,\mathrm{Log}\,\frac{\sum_{i=1}^{n} y_i^2}{n}$$

where S/N denotes the signal-to-noise ratio; y_i represents the individually measured brightness ratio and CRI, n denotes the number of samples measured; $\bar{y}$ is the mean of y_i and σ_y is the variance of y_i. A higher brightness ratio implies a better performance. Taguchi method is used to find the optimal parameters for the white-light LED packaging. Therefore, larger-is-better criterion is selected for the brightness and the CRI to obtain the optimal performance. While focusing on brightness and CRI optimization, this work compares silicone paste and SOG for LED reliability.

2. Experiments

An epitaxial growth was deposited using a metal organic chemical vapor deposition system. Its structure consisted of an undoped GaN buffer layer, a 2 μm thick highly conductive n-type GaN:Si layer, an $In_{0.2}Ga_{0.8}N$/GaN multi-quantum well layer (which consisted of five periods of a 7 nm thick GaN barrier and a 3 nm thick InGaN well) and a 0.4 μm thick Mg-doped GaN layer. Carrier concentrations in the p-GaN and n-GaN layers were 5×10^{17} cm^{-3} and 1×10^{18} cm^{-3}, respectively. A mesa area was formed by using an inductively coupled plasma etcher for current isolation. A thin Ni/Au (1.5 nm/3.5 nm) transparent contact layer was deposited by electron-beam evaporation on the GaN top layer, and then thermally annealed in oxygen for 10 min. Additionally, the Ti/Al/Ti/Au metals for the p-GaN and n-GaN contact pads were deposited to form electrodes. The LED die was fixed on the chip on plane by silver paste and then was placed on the heat plate to heat at 110 °C for 90 min.

For white light LED encapsulation, four packaging parameters, such as SOG and silicone coatings, with and without remote phosphor, adding red phosphor and adding protective layer, were investigated. The remote phosphor coating can reduce the heating effects; adding red phosphor can increase CRI as well. Additionally, the top protective layer can reduce the high refractive index difference. In this work, these packaging factors were optimized using Taguchi method. Table 1 lists those four factors and two levels used in our experiment, based on the Taguchi method. If two levels are assigned to each of these factors, then the conventional method requires 2^4 or 16 experiments to identify the optimal condition. Notably, the number of experiments can be reduced to eight by using the Taguchi method. It can save a half of experimental time. The orthogonal array of L8 type is used, as shown in Table 1. This design requires eight experiments with four parameters at two levels of each parameter. In this work, the interactions of these four parameters were neglected. The LED brightness and CRI were measured at an injection current of 350 mA by using a SLM-20T 50 cm integrating sphere lumens measurement system manufactured by OP Mount Instrument Inc., Taiwan.

Next, the long time reliability was examined by injecting the LED samples with a current of 700 mA for 12 h to accelerate the worse test. The brightness of LED was measured by integrating sphere lumens measurement system every minute during long time lighting. Additionally, the silicone and SOG coating films were annealed by a hot plate at 120 °C for 12 h in air to observe how heating affects the optical transmittance of these two coating films.

3. Results and discussions

Four packaging factors of SOG/silicone coatings, remote phosphor, adding red phosphor and adding protective layer in LED encapsulation were optimized by Taguchi method. Eight packaging experiments were performed using the design parameter combinations listed in Table 1. Four specimens were fabricated for each parameter combinations. Table 1 lists the S/N ratio on the brightness ratio of white light (lumens/W) to blue light (lumens/W) and CRI for each experiment. A higher brightness ratio implies a better white light conversion performance. Therefore, in this work, the larger-is-better criterion was selected for the brightness ratio to obtain the optimal packaging performance. Fig. 1(a) shows the S/N ratio on the white to blue light brightness ratio. The larger difference implies that the factor significantly affects the white light conversion efficiency. This finding suggests that packaging material selection (factor B) most significantly affects the brightness ratio. The addition of red phosphor (factor C) is the next most significant factor. The objective attempts to maximize the brightness ratio. This implies that high brightness can be achieved by using a factor with a higher brightness ratio. Fig. 1(a) clearly indicates that the highest S/N ratio values in each factor are 13.17, 13.82, 13.64 and 13.13, which correspond to the factor A1, B1, C1 and D2, respectively. Therefore, the best packaging parameters of the white light brightness are as follows: (A1) no remote phosphor, (B1) silicone used as a paste with a phosphor, (C1) no red phosphor added, and (D2) no protective layer added. Notably, the visible light transmittance of silicone (99.4%) is higher than that of SOG (90.4%). Thus, the white light brightness in silicone is stronger than that in SOG.

Additionally, the added red phosphor results in bilayered formation, owing to different particle sizes between red and yellow phosphors [19–22], ultimately lowering the white light conversion. Fig. 1(b) shows the S/N ratio of the CRI. The highest S/N ratio of CRI in each factor are 37.86, 37.58, 37.87 and 37.59, which correspond to the factor A2, B1, C2 and D2, respectively. This finding suggests that the added red phosphor (factor C) more significantly affects CRI, subsequently increasing the CRI. The remote phosphor (factor A) is the next most significant factor. The best packaging parameters of the CRI are as follows: (A2) the remote phosphor, (B1) silicone used as a paste with a phosphor, (C1) a red phosphor added, and (D2) no protective layer added.

Many materials and techniques with mixing phosphor have been proposed to solve the yellowing problem in silicone coating with phosphor. In literature, as is well-known, the thermal tolerance of glass is better than silicone [10–13,23]. The SOG materials to replace silicone paste are studied. Fig. 2 shows four LED packaging structures,

Table 1
The S/N ratio on the brightness ratio and color rendering index.

Factor				Brightness ratio (white/blue light intensity)	S/N ratio on the brightness ratio	Color rendering index (CRI)	S/N ratio on the CRI
A Remote phosphor	B Silicone or SOG	C Adding red phosphor	D Adding protective layer				
No	Silicone	No	Yes	5.369	14.60	68.05	36.67
No	Silicone	Yes	No	4.504	13.07	78.05	37.85
No	SOG	No	No	5.319	14.52	69.30	36.81
No	SOG	Yes	Yes	3.340	10.47	74.03	37.39
Yes	Silicone	No	No	4.900	13.80	76.10	37.63
Yes	Silicone	Yes	Yes	4.825	13.66	80.90	38.16
Yes	SOG	No	Yes	3.824	11.65	75.60	37.57
Yes	SOG	Yes	No	3.602	11.13	80.10	38.07