Optical Performance Enhancement for Chip-on-Board Packaging LEDs by Adding TiO_2/Silicone Encapsulation Layer

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***Abstract*— Owing to the strong light scattering effect of TiO_2 nanoparticle and silicone composite, a method for improving optical performances of chip-on-board (COB) packaging LEDs was proposed through introducing a thin auxiliary encapsulation layer with high-concentration TiO_2 nanoparticle and silicone composite below the main encapsulation layer. Its optical performance enhancement effect was examined by experiments. Results show that for the main encapsulation layer only consisting silicone, the proposed packaging method enhances the light extraction efficiency (LEE) up to 65%. However, for another case in which the main encapsulation layer is phosphor and silicone composite, the LEE enhancement effect is correlated to the phosphor concentration. When the phosphor concentration reduces from 0.12 to 0.035 g/cm^3, the LEE enhancement effect increases from 6% to 24%. Meanwhile, the angular correlated color temperature (CCT) deviation is reduced from 900 to 470K between viewing angles from $-90°$ to $90°$, when the average CCT is ~5500K.**

***Index Terms*— Light-emitting diodes (LEDs), chip-on-board (COB) packaging, optical performance enhancement, TiO_2 nanoparticle/silicone composite.**

I. Introduction

POPSHOR-CONVERTED white light-emitting diodes (LEDs) have obtained very wide applications in general illumination in recent years, such as street lighting, museum illumination and residential illumination, owing to their high light efficiency, low power consumption, environmental friendliness and high reliability [1]–[3]. Nowadays, white LEDs are penetrating into some special illumination markets, for example, the vehicle forward lamp, gymnasium lighting, projector lighting and so on [4]. But these new applications usually bring higher technical challenges such as lower thermal resistance, higher light efficiency, larger input power, better white light quality and durability.

Chip-on-board (COB) packaging in which multiple chips are directly integrated on packaging substrates are becoming a main packaging technology for LED devices with the input power larger than 10W or more. This is attributed to its many advantages over the traditional single-chip LED integration, including simple packaging process, low manufacturing cost and compact size [5]. However, the light efficiency of present COB packaging LED devices generally stays a low level, because of the total internal reflection (TIR) effect loss at the flat interface between the air and the encapsulation layer. Meanwhile, the angular color uniformity (ACU) of white LEDs packaged by the COB technology presents the bad performance [6].

Few technologies are being devoted to enhance the light extraction efficiency (LEE) of LED COB devices by diminishing the interface TIR effect, which include patterned substrates [5], roughened encapsulation layer interfaces [7] and domed-shaped encapsulation lenses [8]. So far, it is reported that the best normalized LEEs of patterned substrate with optimized structure interfaces are about 0.85. And the roughened encapsulation layer can gain the LEE improvement of 12.13% as the maximum value. However, their LEEs can't compete with traditional single-chip LED packaging component yet [9]. Although the domed-shaped encapsulation lens method presents higher LEE enhancement effect, it must be at the cost of the vast encapsulation material consumption and not compact packaging structure. In addition, most of previous studies only focused on the case of encapsulation material with the pure silicone. Their LEE and ACU performances have not been examined for dominant LED COB packaging structures whose encapsulation layer material are the phosphor silicone composite. Therefore, seeking new LED COB packaging methods with high LEE and good ACU is still an interesting and challenging issue.

Herein, we presented a packaging method for enhancing optical performances of LED COB packaging devices. Compared with the traditional packaging method, the proposed method introduces a thin auxiliary encapsulation layer made up of the high concentration TiO_2 nanoparticle and silicone composite on packaging substrates and below the main encapsulation layer. Measurement results show that the proposed packaging method can significantly improve the LEE for both of main encapsulation layer materials, pure silicone and phosphor silicone composite. Meanwhile, for packaging cases with

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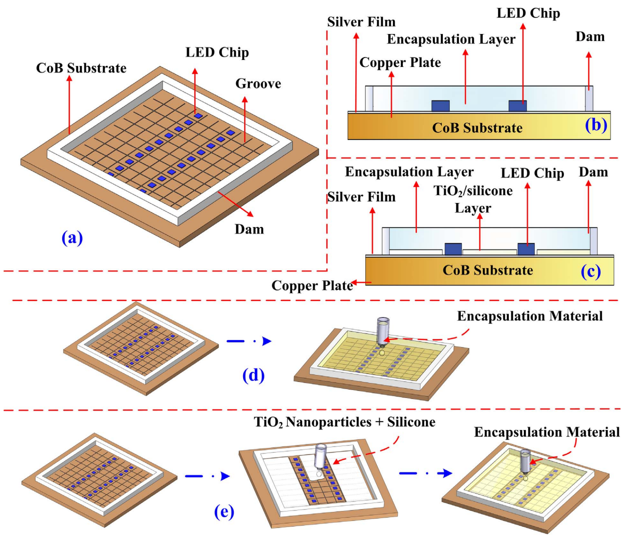

Fig. 1. Schematic representation of LED COB packaging modules and packaging method. (a) Packaging substrate with bonded LED chips. (b) Traditional LED COB packaging structure with single encapsulation layer. (c) Proposed LED COB packaging structure with dual encapsulation layers. (d) Traditional packaging process. (e) Proposed packaging process.

the phosphor silicone composite as the main encapsulation layer material, the ACU performance can also be enhanced by the proposed packaging method.

II. Experiments

Fig. 1(a) shows a LED COB packaging substrate with the size of 40mm × 40mm. The COB substrate consists of the copper substrate and a square dam with the height of 1.8mm for encapsulation material coating. The thermal conductivity of copper substrate is about 340 W/(m·K). On the upper interface of the substrate, shallow grooves were fabricated and a thin silver film was deposited for light reflection. The size of the area surrounded by the dam is 20mm × 20mm. And, within this area, 20 pieces of conventional blue LED chips with the size of 1mm × 1mm × 0.15mm were bonded in two columns. The distances between two chip columns, chip column and boundary are 6mm and 7mm, respectively. Each column chips are electronically connected by gold wire bonding process in series. Two columns were in parallel.

TiO_2 nanopaticles have been adopted in LED packaging due to its very high refractive index (=2.7) [10]. They were usually mixed into the encapsulation material and coated above LED chips to enhance LEE. In this research, as a difference we used the strong scattering ability of the high concentration TiO_2 nanopaticle to lessen TIR effect at the interface between air and encapsulation layers [11]. Figs. 1(b) and (c) show the traditional and proposed LED COB packaging structures, respectively. Different with the traditional method in Fig. (b), there are dual encapsulation layers in Fig. 1(c). The high concentration TiO_2 nanoparticle and silicone composite was coated on substrates to form an auxiliary encapsulation layer with small thickness. In our experiment, it is about 40micro. It is noted that the auxiliary encapsulation layer is just beside LED chips and does not cover the LED chips to avoid scattering the light from the LED chips.

The detail encapsulation layer packaging processes are presented in Figs. 1(d) and (e). Compared with the traditional

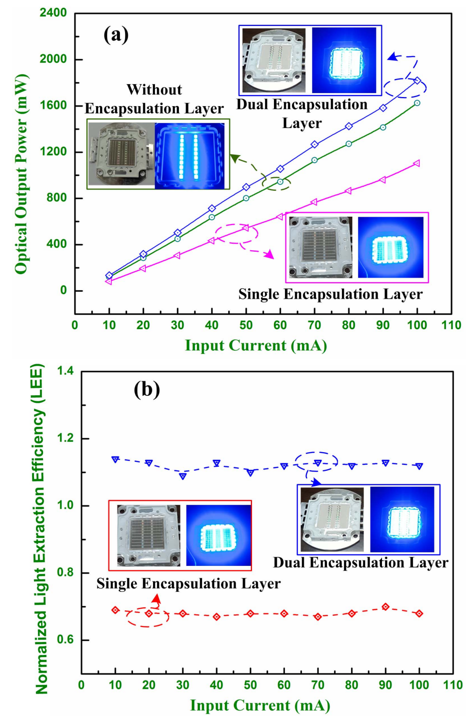

Fig. 2. Light efficiency comparison between dual and single encapsulation layer structure. (a) Optical output power. (b) Normalized light extraction efficiency (LEE).

packaging processes, the nanoparticle and silicone composite was dispensed on the packaging substrate before dispensing the main encapsulation layer. The thickness of TiO_2/silicone composite layer controlled by the dispensed composite volume. Here, TiO_2 nanopaticles with the size of 50nm were applied, and they have no absorption for visible light in LED range. The TiO_2 nanoparticle concentration was 1.0g/cm^3. The refractive index of TiO_2/silicone composite is in direct proportion to the TiO_2 nanopaticle concentration or volume fraction in composite [11]. In our experiments, it is about 1.799. Two kinds of main encapsulation layer materials, the pure silicone and phosphor silicone composite were studied. For the phosphor silicone composite, the phosphor concentration ranged from 0.035 g/cm^3 to 0.12 g/cm^3.

After finished packaging processes, the LED modules were fixed on a large heat sink for thermal dissipation. The LEE was measured by the integrating sphere at the room temperature. And, the ACU is measured by the method same as that in Ref. 3.

III. Results and Discussion

Fig. 2(a) shows optical output powers with the input current ranging from 10mA to 100mA. Three curves represent LED modules without the encapsulation layer, with the pure silicone encapsulation layer, and with the dual encapsulation layers, respectively. From this figure, it can be seen that the dual encapsulation layer structure presents the highest light output in the whole measured current range. While the pure silicone encapsulation layer leads to the smallest light output. The normalized LEE results were presented in Fig. 2(b). It was defined by the ratio of optical output power of module with encapsulation layer to that without encapsulation layer at the same current input. All normalized LEEs follow this definition.

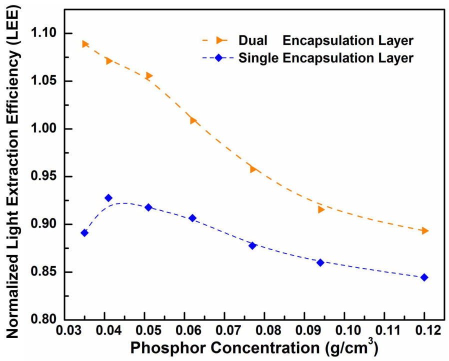

Fig. 3. Normalized LEE variations with phosphor concentration.

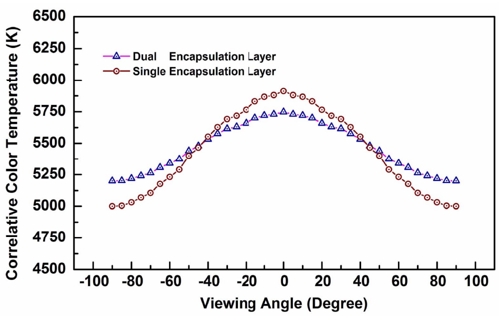

Fig. 4. Angular CCT deviations at average CCT of 5500K.

It can be found that normalized LEEs of both packaging structures keep nearly the same when the input current range is within 100mA. The normalized LEE of dual encapsulation keeps 1.12, while that of single encapsulation layer is 0.68. Therefore, the dual encapsulation layer structure gains the 64.7% LEE enhancement. The different LEE performances can be explained as follows. In the traditional single encapsulation layer packaging, due to the TIR effect, a mass of light is reflected at the interface between air and the encapsulation layer, and propagates toward the packaging substrate. Then it is specularly reflected by the smooth substrate with the silver film again. So such light is still in the TIR region and circularly propagates in LED modules. Finally, the part of light is absorbed by the packaging materials. In the dual encapsulation packaging structure, most of reflected light from the upper interface is backward scattered by the TiO_2/silicone encapsulation layer. Scattered light would be redirected, and can escape from LED modules. Thus its LEE presents a large enhancement.

Fig. 3 shows the variation of normalized LEE with phosphor concentration for both structures. From this figure, it can be seen that the dual encapsulation layer structure have higher normalized LEE. And more specifically, with the phosphor concentration increasing from 0.035g/cm^3 to 0.12g/cm^3, the LEE improvement reduces from 24% to 6%. It results from the phosphor particle scattering effect. Larger phosphor concentration has higher light scattering ability. Therefore, the attribution of TiO_2/silicone composite scattering effect gets less. The luminous efficiencies (LE) were also obtained. For LED modules with CCT of 5500K, the LE of dual and single encapsulation layers are 110 lm/W and 98lm/W, respectively. So the LE enhancement by dual encapsulation layer also reaches 12.2%.

The ACU performances of both structures were examined. For comparison, both average CCTs of single and dual encapsulation layer structures keep the same value of 5500K. Their angular CCT distributions are shown in Fig. 4. The angular CCT deviations of dual encapsulation layer structure and single encapsulation layer structure are about 470K and 900K between viewing angles from -90° to 90°, respectively. Thus, dual encapsulation layer structure shows 49% ACU improvement. This enhancement is attributed to the mixing effect of the TiO_2/silicone encapsulation layer with very strong scattering ability on blue and yellow light reflected by the main encapsulation layer upper interface. The escaped blue light and yellow light patterns from LED modules get the better match.

IV. Conclusions

In this letter, we introduced a packaging structure with dual encapsulation layers for LED COB packaging devices, in which a TiO_2 nanopaticle thin and auxiliary encapsulation layer is added. The detail packaging processes realizing the new encapsulation layer structure were described. Experimental results show that the proposed packaging method can result in the large LEE enhancement compared with the traditional packaging method. The maximum enhancement reaches up to 65% for packaging structure with the pure silicone encapsulation layer. Besides, the new packaging structure displays the ACU improvement of 49% for LED modules with average CCT of 5500K.

This study is still a start for improving LED COB packaging. For wide application of such packaging method, parameter optimization and reliability research are necessary.

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