Enhancing Luminous Efficiency of Quantum Dot-Based Chip-on-Board Light-Emitting Diodes Using Polystyrene Fiber Mats

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Abstract*— Even though chip-on-board light-emitting diodes (COB LEDs) with quantum dots (QDs) are attracting much attention for their high optical performance, their luminous efficiency (LE) is still low owing to total internal reflection. To overcome this problem, in this study, a microfiber-silicone hybrid (MFSH) structure is proposed to enhance the LE of QD-based COB LEDs. Polystyrene (PS) fiber films were fabricated by electrospinning and subjected to planar compression modeling to precisely control their film thickness. Subsequently, these films were coated with silicone to finish packaging the COB LEDs. Their diffuse reflectance of the MFSH structures before and after silicone resin encapsulation was analyzed, witnessing a diffuse reflectance at 450 nm of 97.7% when the pure fiber-film thickness increases to 220 μm. While applying to COB LEDs, the light output power of devices with MFSH structure increases first and then decreases, causing by the balance of light extraction by the scattering fiber and absorption by the difference between chip height and fiber film thickness. Finally, to increase the light-extraction capacity of COB LEDs, the thickness of the microfiber films was optimized to 25 μm at which their LE increased by 29.7% and 31.7% for the blue LED source and QD-based COB LED source, respectively. Therefore, the MFSH structure is an effective packaging method to produce highly efficient COB LEDs.

***Index Terms*— Chip-on-board light-emitting diodes (COB LEDs), luminous efficiency (LE), polystyrene (PS) fiber mats, quantum dots (QDs).**

I. INTRODUCTION

WHITE light-emitting diodes (LEDs) are widely used in daily life due to their low cost, high lighting performance, and long life [1]. Of late, chip-on-board LEDs (COB-LEDs) are attracting great attention for high-power applications [2]. This is because COB packaging endows many advantages, including a high light output power, signal-driven power, and low manufacturing cost. Due to their narrow emission, tunable spectra, and high photoluminescence (PL) quantum yield, quantum dots (QDs) are being deployed in LEDs and considered as next-generation fluorescent materials for illumination and display applications [3]. QD-based LEDs exhibit a high color-rendering index and a wide color gamut [4]. However, they still face the problems of poor luminous efficiency (LE) and thermal stability. Numbers of studies were undertaken to solve their thermal instability problem. Hexagonal boron nitride platelets were combined with QDs to solve their heat problem [5]. And other studies focused on techniques such as a metal-based inverted packaging structure [6]. In addition, it was observed that QD-LEDs face the disadvantage of poor LE, especially for high-power COB LEDs [7].

The large difference in the refractive indices of silicone and air leads to total internal reflection (TIR), resulting in the poor light-output efficiency of COB LEDs [8]. Several, many methods have been employed to counter this drawback, including using dome-shaped lens [9] and textured surfaces [10]. However, these methods only focus on dealing with the TIR phenomenon without taking their large backscattering energy absorption into consideration. It is reported that about 60% of the luminous flux would be backscattered to the chips in conventional COB LEDs [11]. Some studies have been carried out for dealing these issues. TiO_2 nanoparticles and silicon composite were used to fabricate a thin auxiliary encapsulation to enhance the LE [7]. Roughing lead frame substrates [12] is always used to improve device light output. However, developing an efficient way to improve the LE of COB LEDs is still a big challenge.

In this study, we designed an effective and highly reflective microfiber-silicone hybrid (MFSH) structure by a combined electrospinning and planar compression process to enhance the LE of QD-based COB LEDs. To the best of our knowledge, this is the first time the effect of fiber film thickness on the diffuse reflectance of COB LEDs is evaluated.

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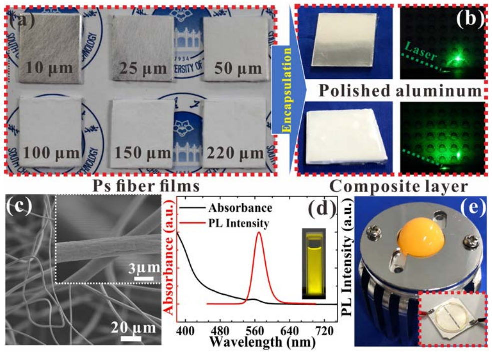

Fig. 1. (a) Photograph of PS fiber films with various thickness. (b) Samples packaged with PDMS and their optical scattering effect. (c) SEM of PS fibers. (d) Absorbance and PL intensity of CdSe/ZnS QDs. The inset shows the fluorescence of QDs in chloroform at 365 nm excitation. (e) Photograph of the QD-COB LED devices. The inset is the COB LED with MFSH structure.

II. EXPERIMENTAL SECTION

Polystyrene (PS, Mw ~ 192 000, Aladdin Company Ltd.), a common and performance-stable optical material with a reflective index of ~1.58 [13], was chosen to fabricate electrospun fiber mats. First, 1.2 g of PS pellets were dissolved in 2 mL of dimethylformamide and 2 mL of tetrahydrofuran to prepare a 0.3 g/mL electrospinning solution. Later, the solution was electrospun into fibers using a homemade electrospinning system at a voltage of 15 kV, flowing rate of 2 mL/h, and working distance of 15 cm. Then, the fiber mats were pressed at 0.42 MPa by planar compression to increase their density. Further, they were tailored into the desired shape to fit the surface of the COB substrate, as shown in the inset of Fig. 1(e). Five blue lateral LED chips with a height of 150 μm were arranged in a row at equal intervals on the COB frame. Finally, the components were packaged with polydimethylsiloxane (PDMS, reflective index of ~1.41, Dow Corning 184). Several LED modules with different fiber-film thicknesses were encapsulated, respectively. CdSe/ZnS QDs (PL quantum yield ~85%, Beida Jubang Company Ltd.) was used to fabricate the dome-shaped remote phosphor structure with a QD concentration of 0.1% to 0.7% (the ratio of QD mass to the PDMS resin) by a mold casting method [8]. The photograph of the QD-based COB modules can be seen in Fig. 1(e). Fig. 1(d) illustrates their normal absorbance and PL intensity when dissolved in chloroform. It is obvious that the QDs have a first excitonic peak at 555 nm and an emission peak at 569 nm, causing by the Stokes-shift. They perform a full width at half maximum of 32 nm.

The fiber morphology was characterized by field emission scanning electron microscopy (FE-SEM, Zeiss Merlin). The QD absorbance, PL intensity, and the diffuse reflectance of fiber films were measured by a dual-beam UV–Vis spectrophotometer (TU-1901, Beijing Persee General Instrument Company, Ltd.). The thickness of the fiber films was measured using a micrometer. The optical performance of the LED devices was tested on an LED Opto-electronic Analyzer (ATA-1000, Yuanfang Optoelectronic Information Company, Ltd.).

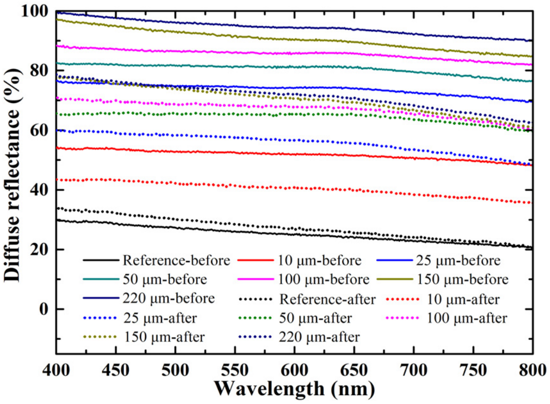

Fig. 2. Diffuse reflectance of PS fiber films before and after encapsulation.

III. RESULTS AND DISCUSSION

Fig. 1(c) shows an SEM image of the PS fibers for the diffuse layers. It can be easily seen that the fibers were randomly oriented and their diameter was ~3 μm. After compression molding, PS fiber layers with different thicknesses of 10, 25, 50, 100, 150, and 220 μm were obtained and shown in Fig. 1(a). Due to the light-scattering properties of the nonwoven structural fibers in the mat, the diffuse layers exhibited a strong white color with the increasing film thickness. As presented in Fig. 1(b), the fiber films after PDMS encapsulation still maintain a white witness, causing by the big index difference between the fibers and PDMS. When a green laser light irradiates the polished aluminum sheet, mirror reflectance takes place. However, the MFSH structure exhibits high light-scattering ability with a uniform lighting.

As presented in Fig. 2, the diffuse reflectance was measured before and after PDMS encapsulation. Before encapsulation, the greatest change was observed between the diffuse reflectance of bare polished aluminum and aluminum after depositing fibers on it. The diffuse reflectance increases with an increase in film thickness. However, the increasing rate of change reduced at thicknesses greater than 50 μm. Diffuse reflectance at 450 nm increased from 53.6% to 97.7% when fiber-film thickness increased from 10 to 220 μm. The reflectance was higher than 90% in the visible light band, contributing to improve light-extraction ability of the fiber films. After encapsulation, the diffuse reflectance of composite fiber layers is lower than that of pure fiber films. The light maybe trapped in the encapsulation resin. Obviously, fiber-film thickness is still the key parameter for controlling diffuse reflectance. As the film thickness increased, the diffuse reflectance maintains increasing because the TIR loss in the interface between PDMS and air is reduced, showing a potential application in light extraction for LEDs.

Fig. 3 shows the optical output power of blue COB LEDs with an MFSH structure in the PS fiber-film thickness range of 10 to 220 μm. Optical output power increased initially after which it reduced and gradually became constant. In fact, the reflectance of fiber films increases with an increase in their thickness, thus enhancing their light extraction. However, more light emanating from the sides of blue LED chips may be

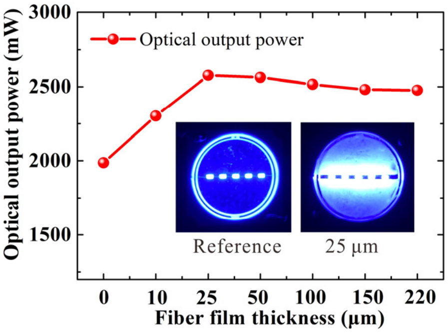

Fig. 3. Optical power output of COB LEDs with MFSH structures with different PS fiber-film thicknesses at 350 mA. The inset are the actual lighting spots.

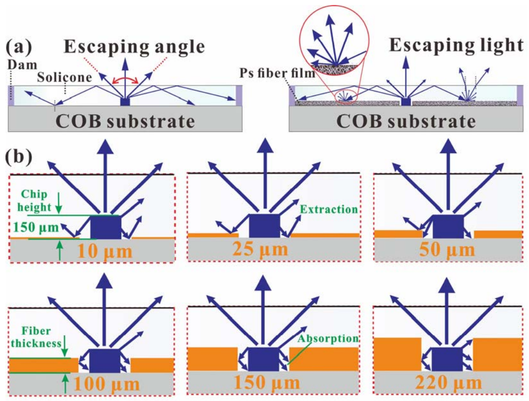

Fig. 4. (a) Schematic of light extraction. (b) Schematic of light trace with the increasing fiber layer thickness.

trapped and absorbed by the substrate owing to the height difference between the fiber film and LED chip, which brings a slight decrease in the output power. To balance the light extraction and absorbance of LED chips, fiber-film thickness was optimized to 25 μm, the maximum optical output power was 2576.8 mW at a driving current of 350 mA, which is 29.7% higher than that of the reference. Their actual lighting spots can be seen in the inset of Fig. 3. The enhanced light extraction belongs to the effect of the fiber film, which increase the light extraction and changes the light-transfer direction.

A schematic of the light-extraction process is shown in Fig. 4(a). In conventional structure, a small escaping angle occurs to light extraction because of the TIR between the encapsulation and air. Light can easily escape while the extraction angle is smaller than the escaping angle. Amount of light in large angle (lager than the escaping angle) would be tracked and absorbed by the substrate and chips. With MFSH structure at large angles, light is scattered in all directions and redirected for reextraction by the strong scattering ability of nonwoven structure fiber mat. This increases the probability of light at large angles escaping into air, thus improving their optical output power. Besides, fiber thickness may influence light extraction from the chip sidewall. There is a difference between the chip height and the fiber layer thickness, and a small gap between the fiber layer and LED chip also exists. Due to the gap and height difference, incident light is trapped and absorbed. When the fiber layer thickness is smaller than the chip, the light from side wall can be extracted and the absorption in the gap is small, otherwise, light from side wall will be trapped and absorbed in the gap. Thus, light absorption becomes more serious as fiber-film thickness increases and structure needs optimized.

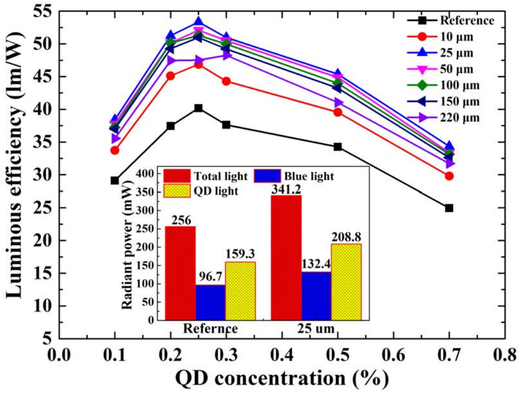

Fig. 5. LE of QD-based COB LEDs at 150 mA. The inset is the radiant power of the devices with 0.25% concentration QD film.

To investigate the effect of the MFSH structure on the performance of QD-based COB LEDs, their LE was tested in Fig. 5. As QD concentration increased from 0.1% to 0.7% for various lighting effect with different correlated color temperature, the LE of QD-based COB LEDs increases first and then decreases when the QD concentration is greater than 0.3% and further increased, causing by the aggregation and reabsorption of QDs [2]. This might also result in a high loss in blue-light absorption and a low QD light-conversion efficiency. Therefore, it is imperative to improve the blue-light extraction efficiency of the blue source. It is obvious that LE of all the devices with MFSH structure is larger than the reference devices under all QD concentration. The maximum LE of 53.4 lm/W occurs at an optimized thickness of 25 μm in 0.25% QD, which is 31.7% higher than that of the reference devices. This is because of the high blue-light extraction and QD-light excitation of the COB LEDs with MFSH structure as well as the reextraction of backscattered light. To better understand this issue, their radiant power of transmitted blue light and QD light (calculated by integrating the emission radiant spectra from 380 to 490 nm and 490 to 780 nm, respectively) and total radiant power were analyzed in the inset of Fig. 5. It can be inferred that devices with an MFSH structure exhibit an increase in total radiant power of 85.2 mW higher than the reference of 256 mW. The QD light radiant power of devices with an MFSH structure performs 208.8 mW, achieving an enhancement of 31.1% compared with the reference devices. Actually, the MFSH structure enhances blue-light extraction in blue COB LEDs under which condition more blue light excites the QDs and more QD light is produced. Besides, more blue and yellow light is backscattered to the fiber reflective surface and it is scattered to different directions to extract. Thus, it is evident that the MFSH structure greatly contributes to the LE of QD-based COB LEDs.

IV. CONCLUSION

In this study, we proposed an effective MFSH structure for light extraction from QD-based COB LEDs. PS was electrospun into fibers and then pressed to obtain dense nonwoven structure layers of different thicknesses. Subsequently, their diffuse reflectance before and after PDMS encapsulation was measured. Diffuse reflectance increased gradually with an increase in fiber thickness and the maximum diffuse reflectance was as high as 99.7% at a fiber-film thickness of 220 μm. In addition, fiber-film thickness significantly influences the light-extraction capacity of COB LEDs. Our study has demonstrated that there exists a balance between reflectance and fiber thickness. Light emitting from the chip sidewall can be trapped between the fiber film and chip sidewall. The fiber-film thickness was optimized at 25 μm to obtain the highest light extraction and it resulted in a 29.7% higher optical output power as compared to the reference. When used in QD-based COB LEDs at different QD concentrations, the MFSH structure contributes to light reextraction, resulting in more conversion from blue light into QD light. Finally, at a fiber-film thickness of 25 μm, LE increased to 31.7% at a QD concentration of 0.25% and the QD light power can be enhanced by 31.1%. Therefore, the MFSH structure significantly influences the light-extraction capacity of QD-based COB LEDs.

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