Study on the Separation Packaging Structure of Quantum Dot–Phosphor Hybrid White Light-Emitting Diodes for Backlight Display

Zong-Tao Li, Cun-Jiang Song, Qi-Liang Zhao, Jia-Sheng Li, Jia-Long Zheng, and Yong Tang

***Abstract*— The quantum dot (QD)–phosphor hybrid structure is promising for efficient white light-emitting diodes (LEDs). In this article, separation packaging structures (SPSs) having green-QD and red-phosphor configurations for backlight displays are studied. The LEDs with green-QD-down and red-phosphor-down SPSs were achieved to have the same color coordinate (0.282, 0.257) which is a typical cool white color widely used in commercial backlighting. And the optical efficiency, device cost, and thermal performances of the LEDs are comprehensively analyzed. Results indicate that the green-QD-down SPS exhibits higher backscattered loss while less conversion loss. Therefore, the green-QD-down SPS has the same optical efficiency as another structure, owing to the balance between the backscattered loss and conversion loss. The concentration differences in these two structures were discussed combining with the device cost. Moreover, the green-QD-down SPS exhibits a better heat dissipation of QDs by reducing the heat path from QDs to the lead frame, as well as less thermal power generation in conversion layers. Consequently, the maximum (39.8 °C) and minimum (31.9 °C) temperatures of its inner QD layer are 7.7% and 20.3% lower than those of the red-phosphor-down SPS at an injection current of 100 mA.**

***Index Terms*— Light-emitting diode (LED), phosphor, quantum dot (QD), separation packaging structure (SPS), thermal performance.**

I. Introduction

LIGHT-EMITTING diodes (LEDs) have become the next-generation solid-state light sources owing to their high brightness and long lifetimes [1]. The integration of blue-LED chips [2] with phosphor composites is regarded as one of the most promising techniques to generate white light for illumination [3], [4] and display applications [5]. Generally, white-LEDs with narrow red, green, and blue spectra are promising for backlighting to achieve a wide color gamut in displays [6], [7]. Quantum dots (QDs) [8], [9] attract attention owing to their tunable color and narrow spectra, particularly the green QD having a full-width at half-maximum (<20 nm) smaller than those of all current green rare-earth-based phosphors. However, the efficiency and stabilities of QDs packaged in LED devices are still considerably lower than those of conventional phosphor materials [10], owing to the host matrix effect [11], [12], lower thermal stability[13], and heavy reabsorption loss [14], limiting their practical applications. Accordingly, the QD–phosphor hybrid structure is regarded as an alternative solution to achieve higher efficiency and operation stability than those of the QD-only packaging structure [15].

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To achieve a high efficiency and thermal stability for white LEDs, the QD–phosphor hybrid structure was generally adopted a remote configuration, which separates QDs from the LED chip [16], [17]. However, when phosphor and QDs are mixed together to serve as a color-conversion layer, white LEDs still have a low optical and thermal performance. This is mainly attributed to the interabsorption effect between the QD and phosphor, the backscattered loss, as well as the low energy transfer efficiency between excitation light and color-conversion materials [18]. Considering these problems, the vertical separation packaging structure (SPS) of a remote QD–phosphor hybrid layer was investigated by Abe *et al.* [15]. Results demonstrated that the vertical SPS will often be a more cost-effective color convertor compared with the mixed structure by adjusting the exciting priority. Xie *et al.* also investigated the vertical SPS; a silica shell was coated onto the QDs surface to solve the compatibility problem between QDs and phosphor-silicone gel [19]. Moreover, Yu *et al.* [20] proposed a novel packaging scheme with horizontally layered QD–phosphor SPS to more effectively suppress the interabsorption loss, comprehensively enhancing the optical and thermal performance for white LEDs. Although the SPS, including vertical [15], [19], [21], [22] and horizontal [20] types, were extensively studied to improve the optical and thermal performances for the QD–phosphor hybrid structure, most of these studies were only focused on the configuration of green/yellow phosphors and red QDs for illumination. In recent years, green QDs have been widely applied in backlighting white-LEDs (bw-LEDs) combining with red phosphors hybrid structure [23], [24], owing to the low color

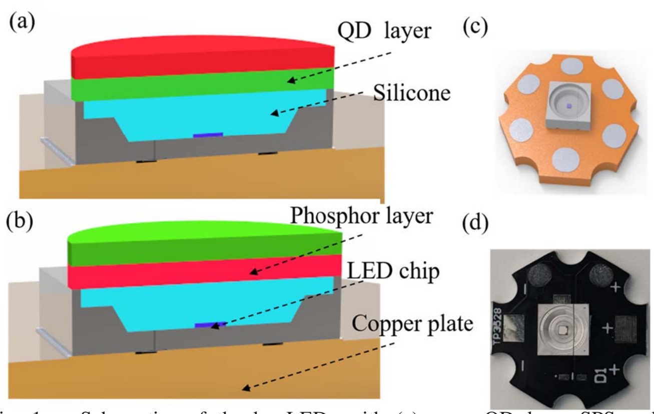

Fig. 1. Schematics of the bw-LEDs with (a) green-QD-down SPS and (b) red-phosphor-down SPSs. (c) Schematic of blank LED. (d) Real photograph of blank LED.

purity of rare-earth-based green phosphor. However, the SPS of green-QD and red-phosphor configurations [25]–[27] with different absorption characteristics have been barely studied.

In this article, bw-LEDs with green-QD-down and red-phosphor-down SPSs were achieved to have the same color coordinate (0.282, 0.257), a typical cool white color widely used in commercial backlighting, through adjusting the optical density. The optical efficiency, device cost, and thermal performances of the devices were comprehensively studied, providing a general guide for the design of SPSs for bw-LEDs.

II. Experiments

Commercial green CdSe/ZnS QDs (purchased from China Beida Jubang Company Ltd., Beijing, China) and red KSF phosphor (purchased from Shenzhen Bright phosphor Company Ltd., Shenzhen, China) are employed in our bw-LEDs owing to their high color purities and quantum yields [28], [29]. Polydimethylsiloxane (PDMS) (purchased from Dowcorning Company Ltd) is used as the dispersion matrix for the QDs and phosphor powders. The prepared QD/phosphor composites were cut into discs with diameter of 7 mm and stamped onto a blue-LED device (purchased from Nation Star Company Ltd). The gap between the blue-LED chip and conversion layer was filled with PDMS to enhance the light extraction. The sample devices and their structure diagrams are shown in Fig. 1. To achieve the same color coordinates for an effective comparison, the concentrations of QDs and phosphor powders are adjusted for both green-QD-down and red-phosphor-down SPSs. According to the process of adjusting the optical density of the layers, the obtained QD and phosphor concentrations for the green-QD-down and red-phosphor-down SPSs were fixed at 0.4%/28% and 0.7%/14%, respectively. The absorption and reflectance of the conversion layer were measured with an ultraviolet-visible spectrometer (UV-2700, Shimadzu, Kyoto, Japan). Electroluminescence (EL) spectra and luminous flux of the bw-LEDs were measured by an integrating sphere system (Otsuka LE5400). Infrared thermal images and surface temperatures were acquired by a thermal infrared camera (FLIR Therma CAM SC300).

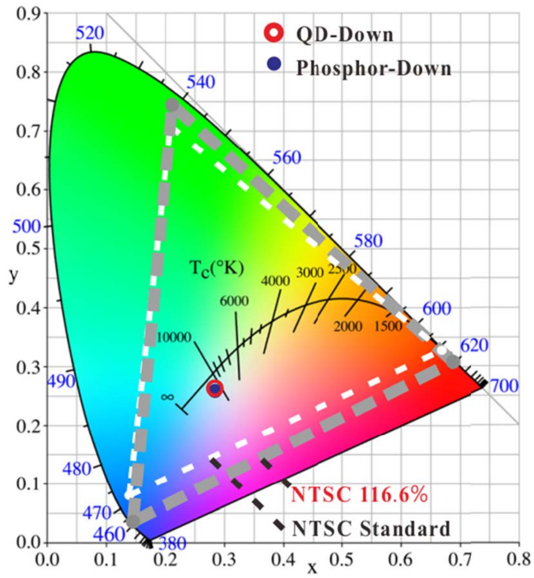

Fig. 2. CIE 1931 color coordinates of the bw-LEDs with the green-QD-down and red-phosphor-down SPSs, at a typical injection current of 100 mA.

III. Results and Discussion

For an effective comparison, the bw-LEDs based on the green-QD-down and red-phosphor-down SPSs should have the same color characteristics. Consequently, their color coordinates (0.28, 0.26) are adjusted to almost overlap as shown in Fig. 2, which have a typical cool white color used in commercial backlighting. The deviations in x- and y-coordinates are smaller than 0.005. Moreover, they have the same wide color gamut of 116.6% National Television System Committee (NTSC), and thus, in practice, can be regarded to have the same color characteristics. Accordingly, the green-QD-down and red-phosphor-down SPSs can provide the same color for bw-LEDs after adjusting the optical density, which ensures an effective comparison of the device performances. The EL emission spectra, luminous flux, and efficacy of the bw-LEDs based on the green-QD-down and red-phosphor-down SPSs are shown in Fig. 3. The EL emission peaks at 455 nm (blue light), 525 nm (green light), and 610/630/650 nm (red light) originated from the LED chips, green QDs, and red phosphors of the two structures are almost identical, respectively, as shown in Fig. 3(a). Fig. 3(b) shows the injection-current-dependent luminous flux and efficacy of the bw-LEDs with the green-QD-down and red-phosphor-down SPSs. Their luminous flux and efficacies almost coincide when the injection current is increased from 0.05 to 0.35 A. These results indicate that the optical energy losses in these devices with different SPSs can be regarded equal, which is different from the results in previous studies on green/yellow-phosphor and red-QD configurations [19]–[21].

To elucidate the underlying mechanisms responsible for the same optical energy loss of the two different structures, the impact of the upper conversion layer on the conversion light from the lower layer is investigated. Fig. 4(a) shows the EL spectra of green-QD-down SPS LEDs with and without the upper red-phosphor layer, while Fig. 4(b) shows those of red-phosphor-down SPS LEDs with and without the upper green-QD layer. After the introduction of the upper conversion

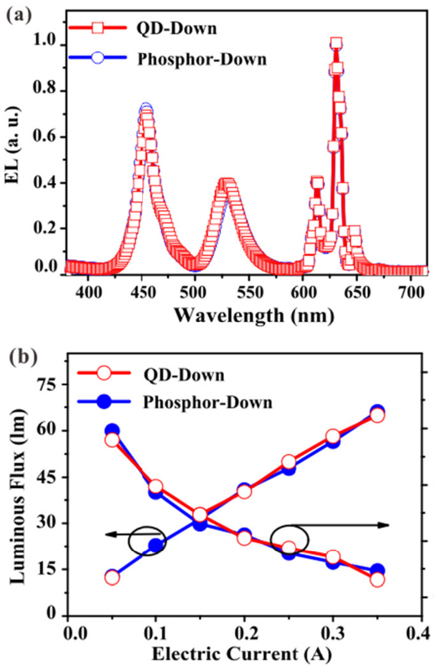

Fig. 3. (a) EL spectra of the bw-LEDs with the green-QD-down and red-phosphor-down SPSs, at a typical injection current of 100 mA. (b) Injection-current-dependent luminous flux and efficacy of the devices.

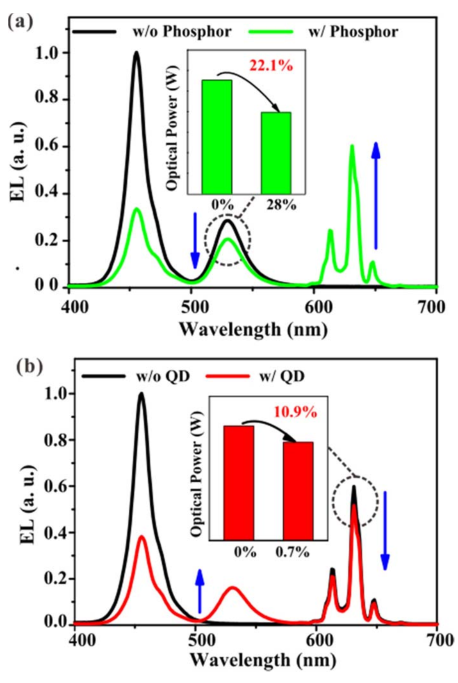

Fig. 4. EL spectra of the LED devices based on (a) green-QD-down SPS with and without the red-phosphor layer and (b) red-phosphor-down SPS with and without the green-QD layer.

layer, considerably more blue light is absorbed and converted. Therefore, a reduction in EL intensity of the blue emission peak and increase in EL intensity of the red/green light can be observed from Fig. 4(a) and (b), respectively. It is worth noting that the EL intensity of the original conversion light is also decreased after the introduction of the upper conversion layer. As shown in the inset of Fig. 4(a), the optical power originated from the green QDs is decreased by 22.1% after the introduction of the upper red-phosphor layer, while that originated from the red phosphor is decreased only by 10.9%

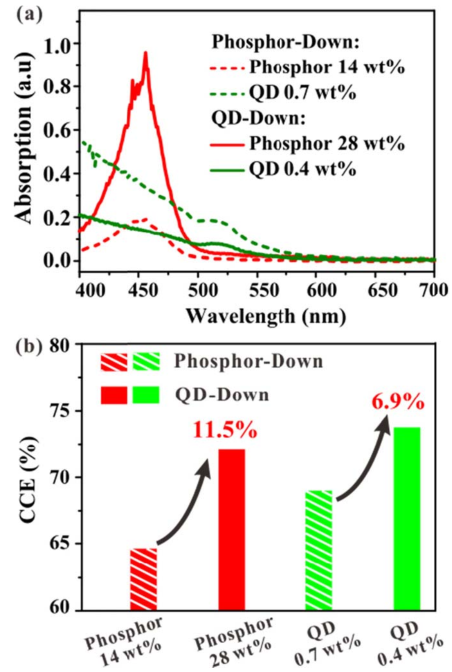

Fig. 5. (a) Absorbance spectra and (b) CCE of the conversion layers in the green-QD-down and red-phosphor-down SPSs.

after the introduction of the upper green-QD layer, as shown in the inset of Fig. 4(b). These results demonstrate that the upper red-phosphor layer leads to a considerably higher optical energy loss in the green-QD-down SPS than that of the red-phosphor-down SPS.

For better understanding, the absorption and color conversion efficiency (CCE) of the conversion layers are presented in Fig. 5(a) and (b), respectively. As shown in Fig. 5(a), the upper red-phosphor layer (28 wt% and 14 wt% of phosphor) exhibits a low absorption to the green light from green-QD layer and the green-QD layer almost does not absorb the red light form the red-phosphor layer. It is different from previous studies about the SPS which employs the red-QD and yellow-phosphor layers. The red-QD has a high absorption to the yellow light from YAG phosphor so that the optical energy loss can be introduced by the interabsorptions (QDs and phosphor). However, it should be noted that the interabsorptions in the two structures are close to 0, considerably lower than those of the red-QD and yellow-phosphor layers employed in a previous study on the SPS [19]. Therefore, the interabsorption loss is not the major factor for the optical energy loss introduced by the upper conversion layer. And the results demonstrate that the upper green-QD layer leads to a lower backscattered loss [30], as the QDs with sizes of several nanometers have a weak scattering ability [10]. Therefore, the lower backscattered loss in the red-phosphor-down SPS is the major factor for the elimination of the optical energy losses of the bw-LED compared with the green-QD-down SPS.

The efficiency of the two structures is equal despite the large differences in backscattered loss. To achieve the same color coordinates, the upper QD/phosphor layer in the phosphor/QD-down SPS must have a larger concentration than that of the lower QD/phosphor layer in the QD/phosphor-down SPS, as the lower layer is prioritized for absorption of blue light. This concentration variation can lead to different conversion losses in the two structures, which is another major factor influencing device efficiency. In this regard, the CCE is defined as the ratio of the radiant power from the QD or phosphor conversion layer $P_{\text{C\_rad}}$ to the absorption power of incident blue light $P_{\text{B\_inc}}$, which is calculated as follows:

$$\text{CCE} = \frac{P_{\text{C\_rad}}}{(P_{\text{B\_inc}} - P_{\text{B\_rad}})} \quad (1)$$

$$P_{\text{C\_rad}} = \int_{\lambda_1}^{\lambda_2} S_{\text{rad}}(\lambda) d\lambda \quad (2)$$

$$P_{\text{B\_rad}} = \int_{\lambda_3}^{\lambda_4} S_{\text{rad}}(\lambda) d\lambda \quad (3)$$

where $P_{\text{B\_rad}}$ the radiant power of blue light escaping from the conversion layer; S_{rad} (λ) corresponds to the radiant spectra, including the conversion light and the escaping blue light. As for the green-QD layer, λ_1 and λ_2 are 490 and 580 nm, respectively; while for the red-phosphor layer, λ_1 and λ_2 are 590 and 700 nm, respectively. In addition, λ_3 and λ_4 are 400 and 490 nm, respectively.

As a result, the CCE of conversion layers with different concentrations is calculated and presented in Fig. 4(b). The CCE of the lower green-QD layer (0.4 wt%) and upper red-phosphor layer (28 wt%) in the green-QD-down SPS is 6.9% and 11.5% larger than those of the red-phosphor-down SPS, respectively. The increased CCE of the lower green-QD layer with the smaller concentration (0.4 wt%) is attributed to the lower reabsorption loss, which has been explained in previous studies in detail [10]. On the other hand, the increased CCE of the upper red-phosphor layer with the larger concentration (28 wt%) is attributed to the lower total internal reflection loss, which is associated with the stronger scattering [31], [32]. Therefore, the higher conversion loss in the red-phosphor-down SPS is also a major factor for the increase in optical energy loss of the bw-LED compared with that of the green-QD-down SPS, which is opposite to the backscattered loss, thereby leading to the same efficiency of the two structures.

Although the optical efficiency is the same, the SPS can adjust the absorption priority of the conversion layer and change the QD/phosphor usage. As discussed above, the concentration of conversion layers in the green-QD-down and the red-phosphor-down SPSs shows great different, resulting in different device cost. It is assumed that the material cost ratio x is the ratio of green QD cost to red phosphor cost. The device cost ratio γ (x) is defined as the ratio of the green-QD-down SPS cost $Y_{\text{QD}-\text{down}}$ (x) to the red-phosphor-down SPS cost $Y_{\text{phosphor}-\text{down}}$ (x), which is given as follows:

$$\gamma(x) = \frac{Y_{\text{QD}-\text{down}}(x)}{Y_{\text{phosphor}-\text{down}}(x)} = \frac{x \cdot M_{1\_\text{QD}} + M_{1\_\text{phosphor}}}{x \cdot M_{2\_\text{QD}} + M_{2\_\text{phosphor}}} \quad (4)$$

where M_{1_QD} and M_{1_phosphor} are the mass of conversion materials in the QD-down SPS, which is 0.146 and 18.64 mg, respectively; while M_{2_QD} and M_{2_phosphor} are the mass of conversion materials in the phosphor-down SPS, which is 0.249 and 5.6 mg, respectively. Accordingly, the cost ratio curve is given in Fig. 6. When the cost of green QDs is less than 127 times compared with that of red phosphor, the red-phosphor-down SPS has higher cost-effectiveness.

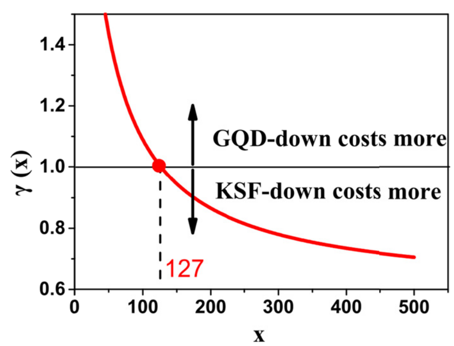

Fig. 6. Cost ratio curve of the bw-LEDs based on the green-QD-down SPS and red-phosphor-down SPS.

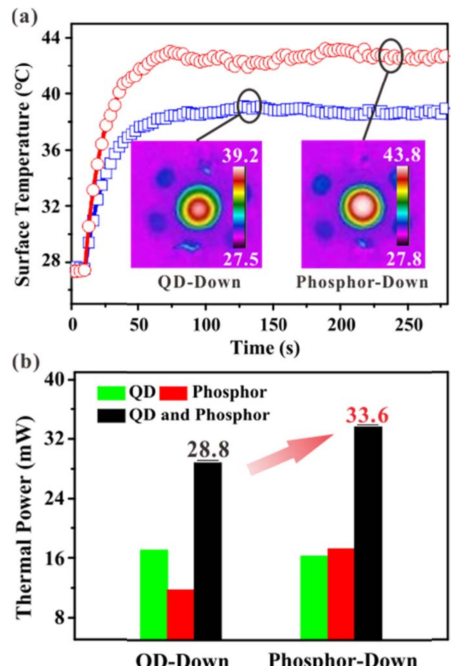

Fig. 7. (a) Time-dependent surface temperatures of the bw-LEDs based on different SPSs at the injection current of 100 mA; the insets are their steady thermal images, and the unit is degree Celsius. (b) Thermal powers generated by the conversion layers in different SPSs.

Most importantly, the SPS exhibits large influences on the thermal performances of bw-LEDs. The time-dependent surface temperatures of the green-QD-down and red-phosphor-down SPSs, at the typical injection current of 100 mA, are presented in Fig. 7(a). The steady maximum surface temperature $TS_{\max}$ achieved by the green-QD-down SPS is 10.3% lower than that achieved by the red-phosphor-down SPS. Moreover, $TS_{\max}$ is observed at the center of the conversion layer, which is confirmed by the inset infrared images. These results suggest that the green-QD-down SPS is more beneficial for heat dissipation. To have a better understanding on this issue, the thermal power of the conversion layer Q_C is calculated as follows:

$$Q_C = P_{\text{B\_abs}}(1 - \text{CCE}) = \frac{P_{\text{C\_total}}}{\text{CCE}}(1 - \text{CCE}) \quad (5)$$

$$P_{\text{C\_total}} = P_{\text{C\_rad}} + P_{\text{scat\_loss}} \quad (6)$$

where $P_{\text{C\_total}}$ is the total power of conversion light generation from the conversion layer; $P_{\text{B\_abs}}$ is the absorption power of

TABLE I

THICKNESS AND THERMAL CONDUCTIVITY OF THE PACKAGING MATERIALS IN THERMAL SIMULATION

layer	Thickness (mm)	Thermal Conductivity (W/m·K)
GaN chip	0.1	270
PCB copper	2	400
Al lead frame	1.5	200
Sn-die attach	0.05	67
silicone	1	0.3
Green QD layer	1	0.35
Red phosphor layer	1	0.3-0.55

incident blue light; and $P_{\text{scat\_loss}}$ is the backscattered loss of optical power caused by the upper conversion layer, which is obtained from Fig. 3. Actually, a part of the blue light absorbed by conversion layers converts into thermal power; therefore, Q_C can be obtained by the product of $P_{\text{B\_abs}}$ and $(1 - \text{CCE})$. In addition, a part of the conversion light generation from the lower conversion layer is lost due to the backscattering originated from the upper conversion layer; therefore, $P_{\text{C\_total}}$ is the sum of $P_{\text{C\_rad}}$ and $P_{\text{scat\_loss}}$. It is worth noting that $P_{\text{scat\_loss}}$ is 0 when calculating Q_C for the upper conversion layer. As a result, the thermal power generated by conversion layers in these two structures is given in Fig. 7(b). The thermal power generated by the QDs in the green-QD-down SPS is slightly larger than that in the red-phosphor-down SPS, though the QD conversion efficiency of the former is higher. This can be explained as the higher backscattered loss of the green light in green-QD-down SPS, which leads to considerably more conversion events in its QD layer for an enhanced QD excitation. However, the green-QD-down SPS still leads to a total thermal power, generated by conversion, 14.3% lower than that of the red-phosphor-down SPS. These results are attributed mainly to the conversion efficiency increment of the phosphor layer in the green-QD-down SPS, as discussed above. Therefore, green-QD-down SPS is beneficial to reduce the operation temperature of the bw-LED.

In the QD–phosphor hybrid structure, the operation temperature of the QD layer limits the device lifetime owing to its low thermal stability [33]. A finite-element (FE) simulation is performed to investigate the inner temperature distributions of the QD layers; the setup is based on the previous study [34]. The boundary conditions of the FE simulation were set as follows: the ambient temperature was fixed at 25 °C; forced convection occurred at the bottom surface of the PCB with a heat transfer coefficient of 30 W/(m^2·K), and other surfaces are cooled by convection with a heat transfer coefficient of 15 W/(m^2·K). And the thermal conductivity of packaging materials is shown in Table I. Herein, the thermal conductivity of green-QD layer and red-phosphor layer maybe influenced by the concentration of QD and red phosphor. The concentration of QD in green layer was only 0.4 wt% and 0.7 wt% so that their thermal conductivity is little affected. In our case, the thermal conductivity of green-QD layer was fixed at 0.35 W/m·K. As for the red-phosphor layer, the concentration increased from 14 wt% to 28 wt%, its thermal conductivity ranges from ~0.3 to 0.55 W/m·K according to the previous study [35]. And the change of thermal conductivity may be a factor affecting FE simulation and surface temperatures of bw-LED. In order to exclude this factor, the FE simulation is performed based on different thermal conductivity of red-phosphor layer as shown in Fig. 8, the green-QD-down SPS is used as an example. When the thermal conductivity of red phosphor is fixed at 0.3, 0.35, 0.45, and 0.55 W/m·K, respectively, the maximum temperature changes from 40.4 °C to 39.7 °C with a range of only 1.7%. These results indicate that the change of thermal conductivity caused by different concentrations of red phosphor is ignorable.

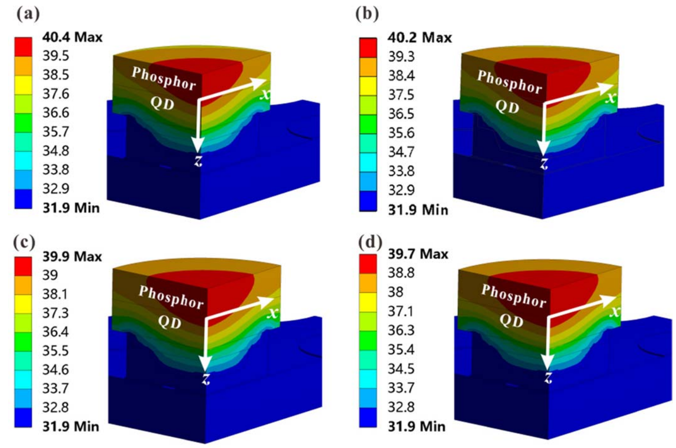

Fig. 8. Simulated temperature fields at the cross sections of the bw-LEDs based on the green-QD-down SPSs at an injection current of 100 mA with different thermal conductivities of red-phosphor layer. (a) 0.3 W/m·K. (b) 0.35 W/m·K. (c) 0.45 W/m·K. (d) 0.55 W/m·K.

Furthermore, the simulated temperature distributions of the bw-LEDs based on the green-QD-down and red-phosphor-down SPSs are presented in Fig. 9(a) and (b), respectively. Similar to the results in previous reports [18], [33], [36], the maximum temperature $T_{\max}$ is observed at the top region of the upper conversion layer owing to the low thermal conductivity of the silicone. The $T_{\max}$ values of the red-phosphor-down and green-QD-down SPSs are 43.1 °C and 40.2 °C, respectively, almost identical with the $TS_{\max}$ values obtained by the thermal measurement shown in Fig. 7. Moreover, the steady temperature distributions of the QD layers in the red-phosphor-down and green-QD-down SPSs are presented in Fig. 10(a) and (b), respectively. The comparison of the temperature distributions at the upper ($z = 0$ mm), middle ($z = 0.5$ mm), and lower ($z = 1$ mm) regions along the x-axis of the QD layers in the two structures shows that the temperature in the green-QD-down SPS is lower than that in the red-phosphor-down SPS. For example, the temperature of the red-phosphor-down SPS in the z range of 0–1 mm slightly decreases from 43.1 °C to 41.6 °C, while that in the green-QD-down SPS decreases from 39.8 °C to 35.8 °C. These results indicate that the green-QD-down SPS provides a better heat dissipation for the QDs.

In the bw-LED based on green-QD-down SPS, heat generated from the conversion layer is dissipated through

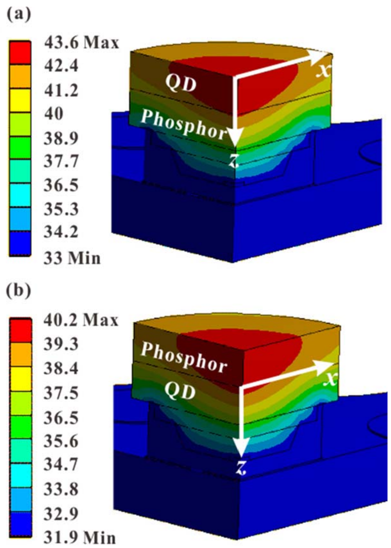

Fig. 9. Simulated temperature fields at the cross sections of the bw-LEDs based on (a) red-phosphor-down and (b) green-QD-down SPSs at an injection current of 100 mA.

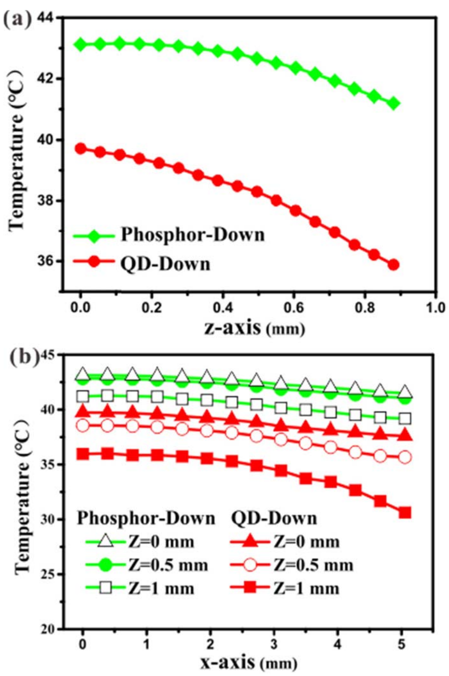

Fig. 10. Simulated temperature distributions of the QD layer along (a) z-axis and (b) x-axis.

two paths. Part of the heat generated from these layers will take the upper path to dissipate through the conversion layer; the rest of the heat is dissipated through the lower path, which comprises the silicone, lead-frame, and substrate. Since these layers are made of silicone with low thermal conductivity of ~0.2 W/(m·K), thermal resistance at the upper path is quite large. Therefore, most of heat is dissipated through the lower path [37]. On the other hand, it is well recognized that the thermal conductivity of the phosphor layer shows little difference when the phosphor concentration is kept lower 50 wt% [35]. In our cases, the concentration of phosphor was changed in a small range from 14 wt% to 28 wt%. It is reasonable that the enhancement in the heat dissipation is

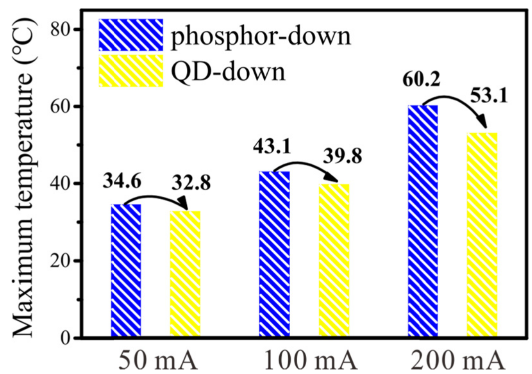

Fig. 11. Simulated current-dependent maximum temperatures of QD layer in bw-LEDs based on different SPSs at the injection current of 50, 100, and 200 mA.

mainly caused by the lower path, where the lead-frame is as an effective heat sink for QDs. Therefore, a minimum temperature $T_{\min}$ of 31.9 °C is achieved in the green-QD-down SPS, which is 20.3% smaller than that in the red-phosphor-down SPS (40 °C). Furthermore, the current-dependent maximum temperature of QD layers in bw-LEDs with different SPSs was measured by the simulated temperature fields (as shown in Fig. 11). For simplification, it is assumed that the heat power is linearly increased with the injection current. The maximum temperature of QD layer in the red-phosphor-down SPS (34.6 °C) was 1.8 °C higher than that of the green-QD-down SPS at an injection current of 50 mA. When the injection current increases to 200 mA, the maximum temperature of QD layer in the red-phosphor-down SPS was 7.1 °C higher than green-QD-down SPS. These results further demonstrate that the green-QD-down SPS is beneficial to increase the thermal performance of the bw-LED especially with larger injection current.

IV. Conclusion

In this article, we investigated the effects of the SPSs on the optical efficiency, device cost, and thermal performances of the bw-LEDs. The bw-LEDs with different SPSs exhibit the same color coordinates (0.28, 0.26) by adjusting the optical density, which is a typical cool white color widely used in commercial backlighting. Results indicate that their optical efficiency is equal owing to the priority absorption of blue light in the lower conversion layer, the green-QD-down SPS has a larger and smaller phosphor and QD concentrations compared with those of the red-phosphor-down SPS, respectively. Therefore, the green-QD-down SPS exhibits higher backscattered loss while less conversion loss according to the spectra analysis and CCE measurement. We believe that the balance of these two factors is critical for their same optical efficiency, which may be adjusted in the future by improving the backscattering or conversion efficiency. Much more studies considering different kinds of phosphor and QDs are still necessary. As the concentration is different in these devices, it is found that when the cost of green QDs is 127 times higher than that of red phosphor, the green-QD-down SPS has higher cost-effectiveness. Furthermore, thermal performances of these devices are investigated by combing experiments and simulations. The thermal measurement and FE simulation confirm that T_{max} and T_{min} of the QD layer in the green-QD-down SPS are 39.8 °C and 31.9 °C, which are 7.7% and 20.3% lower than those of the red-phosphor-down SPS, respectively. These results can be explained as the green-QD-down SPS exhibits a lower conversion loss and better heat dissipation for the QD layers closer to the heat sink. Consequently, this article can provide a better understanding to design SPS for bw-LEDs.

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