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Using SiO_2 nano-particles for better color uniformity and lumen output in 8500 K conformal and in-cup white LEDs

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ABSTRACT

In the effort of improving the performance of white light LEDs devices (WLEDs), the SiO_2 nano-particles were applied and have shown a significant impact on the optical properties. Specifically, the light output of the lighting devices is enhanced when a mixture of SiO_2 particles and silicone gel is diffused on the encapsulation layer surface. This enhancement is the result of light scattering from SiO_2 that strengthens the emitted blue light at further angles and reduces the color discrepancy. The evidence is that CCT deviation in SiO_2-doped structure decline from 1000 K to 420 K in -70° to 70°. In addition, the SiO_2 with refractive index in between the phosphor material and outside environment allows light to be emitted outward more effectively. This lighting enhancement of SiO_2-doped structure increases the lumen output by 2.25% at 120 mA power source in comparison to structure without SiO_2. These experimental outcomes suggest that SiO_2 is an effective material to add in WLEDs structure for better lighting efficiency.

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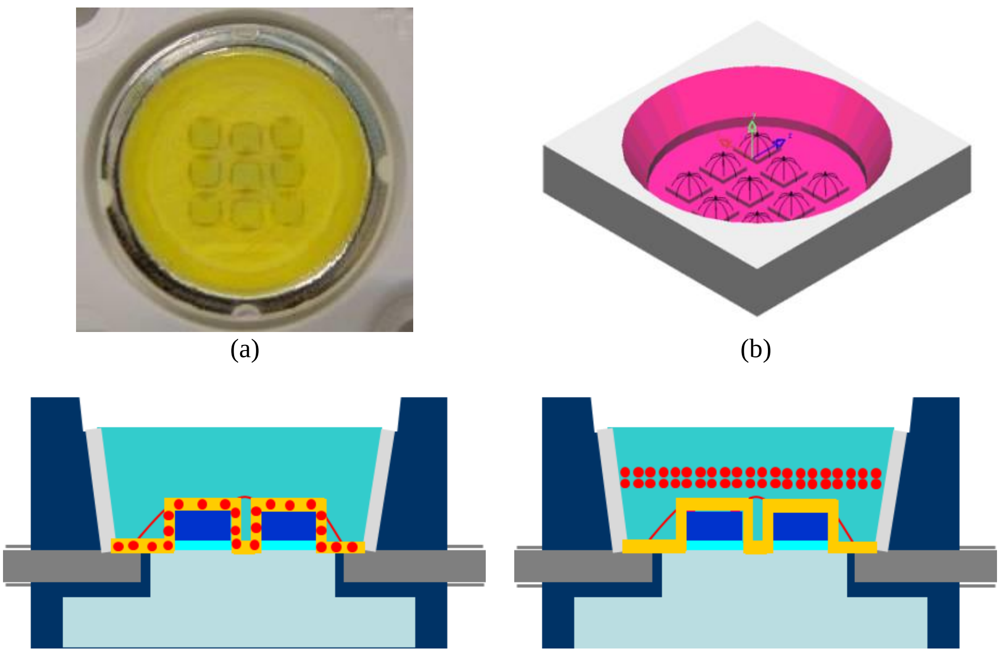
1. INTRODUCTION

In the recent decade, white light-emitting diodes (WLEDs) have been emerged as an indispensable part of Solid-state lighting (SSL) due to their significantly improved structure, and thus, it is easy to understand the popular of WLEDs in applications for high-power light devices [1], [2]. Generally, a WLED is created by using blue LED chip and yellow-light emitting phosphor material such as $Y_3Al_5O_{12}$ (YAG) to mix the blue lights and yellow lights to generated white light. However, this method was unable to fabricate the adequate devices that meet all the requirements of advanced applications [3]-[5]. The high lumen output and ideal manufacturing expense are the advantages of this phosphor-converted light, although the chromatic distribution and lighting efficiency need to be improved if this structure to be employed in high demand lighting [6]-[8]. Many methods were suggested including using the half-spherical encapsulation [9], [10] and ELiXIR pcLEDs structure with the interior light reflection for higher emitted light [11]-[15]. The scattered light can be enhanced through structure modifications, however, the light loss because the emitted light cannot escape and then absorbed by the materials of the structure would need other methods to correct [16]. One solution that stands out is to place a gap between the phosphor layer and the light-emitting chip so that the light loss can be lessened. As a result, different structures that employed this solution were introduced including the structure with remote ring and scattered photon extraction (SPE) [17]-[19]. The remote phosphor structure is an excellent method to prevent light loss, which has been proven through superior light output to the traditional WLEDs structure. On the other hand, the chromatic uniformity in remote phosphor structure is not ideal due to the shape of the encapsulation layer is hollow at the center. This leads to the uneven density of phosphor at different angles resulting in a yellow border around the emitted light of the device [20]. To enhance the overall performance of WLEDs, we applied the SiO_2 particles which have shown positive results in our experiments regarding the color temperature consistency and light output. Because the SiO_2 particles have distinct scattering properties and suitable refractive that can lead to better color quality and extracted light, it is confirmed that this type of diffusor can be used to create higher quality WLEDs.

2. RESEARCH METHOD

We used LightTools software to model the WLEDs structure applied in our experiments, as shown in Figure 1(a). The model of lighting configuration with remote structure is created through this process with the following components: 1) blue LED chips that are 24 mils square and peak wavelength at 450 nm, are embedded to plastic lead-frame at the bottom as shown in Figure 1(b). The light output of these lighting emitting chips is 95 mW under the energy source of 120 mA; 2) The transparent silicone is integrated into the lead frame by dispensing and cured at 150 °C for 1 h; 3) the phosphor materials are mixed with silicone binder and alkyl-based solvent to create a mixture of phosphor-suspension. The pulse spray coating with interval control is applied to ensure the consistency of the phosphor mixture, as conducted in previous research [21]-[23]. The $Y_3Al_5O_{12}$ (YAG) phosphor with a particle size of about 12 µm is the source for yellow radiation in the structure. After that, the phosphorus mixture is distributed on the silicon's surface to fabricate the original remote phosphor structure of a WLED as shown in Figure 1(a). The SiO_2 nano-particles are then merged in the remote phosphor structure in the final step. 5% SiO_2 nano-particles, which are integrated into the phosphor layer, are first processed by mixing with silicone binder and an alkyl-based solvent. The LED is maintained at the same color temperature and coordinate for comparison at a driving current of 120 mA. The configurations of conformal phosphor structure and in-cup phosphor structure with SiO_2 are then fabricated and used for experiments, as demonstrated in Figure 1(c) and Figure 1(d), respectively. In addition, the cross-sectional scanning electron microscopic (SEM) was utilized for examining the size of SiO_2 particles and the result is approximate 300 nm. Besides, we used an energy dispersive spectrometer (EDS) to analyze the properties of SiO_2 nanoparticles with silicone gel.



(a) (b) (c) (d)

Figure 1. WLEDs structure; (a) photograph of WLEDs sample, (b) the simulated WLEDs model, (c) conformal phosphor structure, and (d) In-cup phosphor structure

3. RESULTS AND DISCUSSION

The color uniformity of WLEDs at different angles can be defined by deducting from the highest CCT an amount equal to the lowest CCT. The SiO_2 concentration is modified repeatedly to study its influence on optical properties and color temperature discrepancy at different amounts. The results of CCT deviation in Figure 2 confirmed that 10 mg/cm^2 of SiO_2 is the best for chromatic uniformity that results in a 58% enhancement compared to other lighting configurations. In Figure 3, the conventional structure and SiO_2 nano-particles remote phosphor structures in a far-field pattern are presented. The color uniformity in WLEDs is excellent with 10 mg/cm^2 SiO_2, however, adding more SiO_2 particles into the configuration is still capable of stimulating better chromatic performance than the traditional structure although CCT deviation might be impacted. This evidence proved that WLEDs structure with 10 mg/cm^2 of SiO_2 can enhance both color homogeneity at different angles and boost lumen output.

The angular correlated color temperature (CCT) of conventional configuration and SiO_2-doped WLEDs with 10 mg/cm^2 were studied and demonstrated in Figure 2. The conventional structure from -70° to 70° has 1000 K color deviation, this index is reduced to 420 K in SiO_2-doped WLEDs. The emitted blue light in conventional structure usually become less and less at far angles due to light being confined and re-absorbed, which worsen the color uniformity. The WLEDs structure using SiO_2, on the other hand, with scattering events enhanced by SiO_2 particles can easily modify the amount of blue light at farther angles, which leads to higher overall angular color distribution and color quality. The light output of conventional structure and WLEDs infused with 10 mg/cm^2 are expressed in Figure 3. At 120 mA power current, the correlated color temperatures in two structures are 5010 K and 5097 K, which is not much discrepancy. However, the SiO_2 particles with lower refractive index, which can fit between the indices of inner structure and outer atmosphere, allow emitted light to pass more freely among layers, which leads to a 2.25% lumen output enhancement at 120 mA power current. The index of refraction in SiO_2 particles with silicone is 1.5, which is in the middle of air (n=1) and phosphor material (n=1.8), so it is effective in boosting gradient efficiency between the layers.

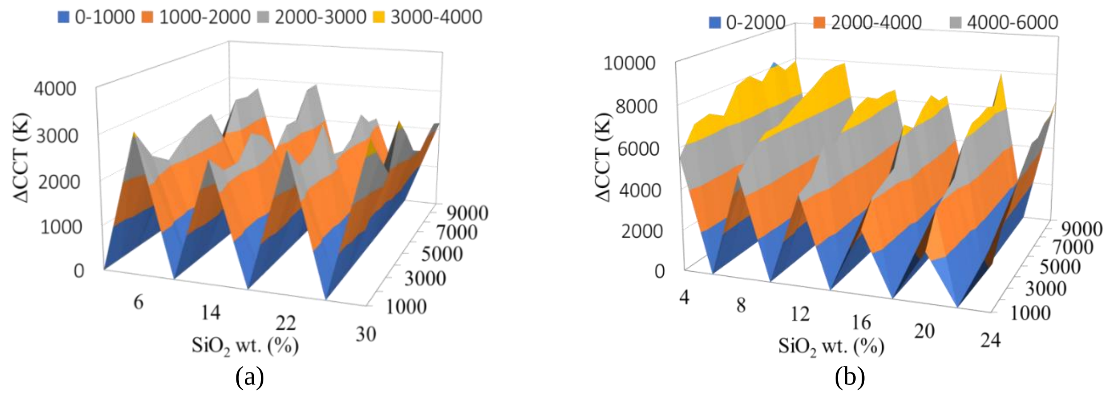


Figure 2. CCT deviations of SiO_2 particles with different diameters: (a) conformal structure, (b) in-cup geometry

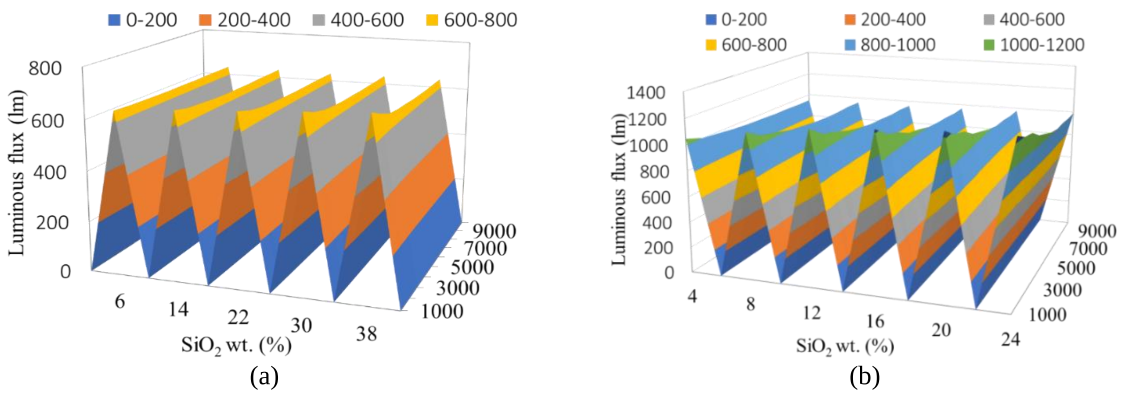


Figure 3. Luminous fluxes of SiO_2 particles with different diameters: (a) conformal structure, (b) in-cup geometry

The influence of the scattering effect on the optical performance of WLEDs are measured by investigating the angle-dependent CCTs of LED packages with varied SiO_2 nanoparticles concentration, the results are expressed in Figure 4. The uniformity of the angle-dependent CCTs was positively impacted by SiO_2 nanoparticles. This content of Figure 4 indicates that the higher SiO_2 nanoparticle concentration is the stronger yielded scattering effect. In general, the uniformity of CCTs is defined by taking the maximum CCT and deduct to the minimum CCT. Without SiO_2 nanoparticles in the structure, the reference CCT was located at a high level (approximately 5319 K). In the case of SiO_2-doped configuration, the CCT variation presented at 0° and 70° was eradicated. This leads to the conclusion that SiO_2 with silicone gel is an effective enhancer for lighting devices. The optical properties of SiO_2-doped devices, however, are yet to be discovered. To advance further into the usage of SiO_2, we conducted experiments including transmission–absorption and haze to identify the traits of this SiO_2 phosphor–silicone mixture. Compared to the conventional dispensing structure, the absorption percentage in the SiO_2 nanoparticle dispensing structure is higher from approximately 32% to nearly 42% at the wavelength of 460 nm. This incident is the reason for the greater emitted yellow light in SiO_2-doped samples, which leads to an increase in luminous flux.

After integrating the SiO_2 nanoparticle in the phosphor layer, the reflective index will be changed with different SiO_2 nanoparticle concentrations. Moreover, the refractive indices (RI) of silicone, phosphor, SiO_2 nanoparticle are 1.4, 1.8 and 2.23. Thus, the RI of the phosphor layer with SiO_2 nanoparticle is computed using (1) [24], [25].

$$RI = V_1RI_1 + V_2RI_2 + V_3RI_3 \quad (1)$$

In which V_1, V_2 and V_3 are the materials' concentrations, which are expressed by the percentage of each material in the compound. For the SiO_2 nanoparticle lighting configuration, the percentages of the SiO_2 nanoparticles mixed into the phosphor layer in the dispensing structure were 1 wt% and 3 wt%, respectively. Therefore, the RIs of the phosphor layer in each case were 1.428 and 1.445. The influence of different refractive index layers is defined with TFCalc32 simulation. Comparing the light extraction of the conventional configuration to the SiO_2-doped one, we can see that the values are similar due to the refractive indices being the same. Thus, the light output improvement for SiO_2 nanoparticle dispensing structure mostly from the support of SiO_2 nanoparticle scattering properties. To demonstrate the scattering effect of the SiO_2 nanoparticles in detail, Mie-scattering simulation was applied for scattering events of the SiO_2 particles at different concentrations. The stimulated model for this experiment employed no phosphors and contained only SiO_2 nanoparticles to ensure the accuracy of the result. The RI of the SiO_2 nanoparticle with silicone was 2.23 at the wavelength of 460 nm. The size of SiO_2 particle was approximately 300 nm, and the concentrations of SiO_2 nanoparticles were approximately 1% and 3%. Besides, the structure using 1% wt. SiO_2 showed the haze intensity of almost 100% in the wavelength range below 500 nm. However, when the wavelength is higher than 500 nm, this haze intensity started to decrease. The simulated results and the scattering effect of SiO_2 are similar to our measured results, which confirmed that these scattering properties of SiO_2 are accurate. When adding more SiO_2 particles, the haze intensity almost reached a value similar to that in the wavelength ranging from 300 to 700 nm.

The changes in blue and yellow scattering intensity corresponding to SiO_2 sizes are estimated by the full-field finite-difference time-domain (FDTD) simulation. The SiO_2 particles are kept stable at 5% concentration and 1.5 refractive index throughout experiments to measure the influences of SiO_2 particle sizes on the color quality and light output. The analysis of results shows that 400 nm SiO_2 is the optimal wavelength for scattering intensity of both blue and yellow emission, which is 450 nm for blue light and 560 nm for yellow light. The addition of SiO_2 particles in lighting configuration is good for color quality development, however, excessive SiO_2 particles can be detrimental to extracted light. Therefore, the optical properties of a phosphor layer with only SiO_2 and silicone were measured, which shows that the absorption ability rises as the SiO_2 component increase. This absorption ability from SiO_2/silicone layer is the equivalent of 5%-15% at 300 nm and is expected to expand if the particle size is large. This result, as in Figure 5, proved that absorption capacity is related to particle size and can be employed to evaluate the lighting efficiency and confirmed that the expansion of particles does not harm the scattering events.

The effects of SiO_2 nano-particles on the scattering events in remote phosphor structure were studied from the relative intensity of blue and yellow light. The remote structure with SiO_2 stabilized the distribution of blue light at different angles of the regions illuminated by the emitted light. This effect proved that scattering effects from SiO_2 changed the scattering path of the blue ray, an effect that is confirmed by development in chromatic consistency. The emitted yellow light, on the other hand, did not change as much as the blue light with or without SiO_2 particles in WLEDs structure. The evidence being the haze intensity of blue light reaches 35% at 450 nm while yellow light only achieved 30% at 600 nm with the same amount of particles 10 mg/cm^2. This discrepancy in haze intensity between yellow light and blue light shows that emitted yellow light is lower than blue light, which lessens the color temperature deviation in WLEDs with SiO_2. The result that shows haze intensity in yellow light at 600 nm only equal 50% of blue light haze intensity at the same wavelength is another point for this conclusion. Therefore, the correlated color deviation caused by the discrepancy of blue light at different scatting angles can be settled by changing blue light distribution in the remote phosphor structure. Besides the color deviation, the blue light at 70° is also affected by SiO_2, which suggests the use of SiO_2 particles in optimizing blue light at far angles with 10 mg/cm^2.

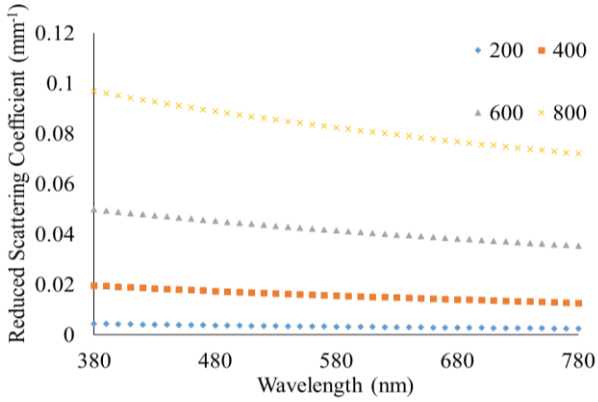


Figure 4. The reduced scattering coefficient of SiO_2 particles at different sizes and wavelength

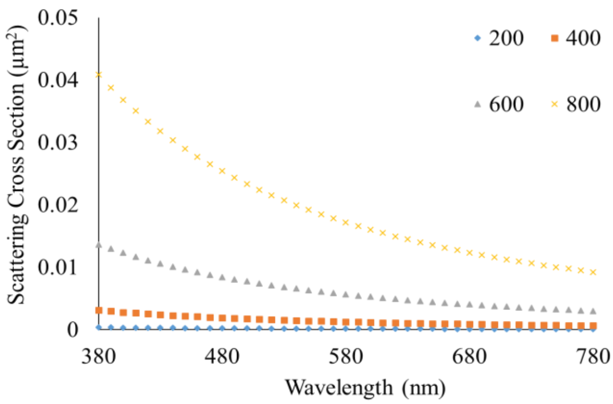


Figure 5. The scattering cross-section of SiO_2 particles at different sizes and wavelength

4. CONCLUSION

The angular-dependent CCT uniformity and emitted light measured from the structures with SiO_2 particles verified that this type of nano-particle is effective in enhancing the lighting efficiency of remote phosphor WLEDs. In particular, compared to the structure without SiO_2, the WLED configuration with SiO_2 particles has the color temperature variation reduced by 58%. In terms of lumen output, the yielded light when there are SiO_2 particles is 2.25% higher with the same energy source of 120 mA. The scattering properties of SiO_2 have been analyzed with haze intensity to find the optimal amount of SiO_2 for WLEDs development, which leads to a conclusion that 10 mg/cm^2 is the best setting for color quality. In addition, SiO_2 particles can eradicate the yellow ring that damages the chromatic performance of WLEDs while avoiding light loss in the process proved that SiO_2 remote phosphor WLEDs can potentially be the next lighting solution.

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