Using SiO\textsubscript{2} nano-particles for better color uniformity and lumen output in 8500 K conformal and in-cup white LEDs

My Hanh Nguyen Thi\textsuperscript{1}, Nguyen Thi Phuong Loan\textsuperscript{2}, Thuc Minh Bui\textsuperscript{3}, Tri-Vien Vu\textsuperscript{4}

\textsuperscript{1}Faculty of Mechanical Engineering, Industrial University of Ho Chi Minh City, Viet Nam
\textsuperscript{2}Faculty of Fundamental 2, Posts and Telecommunications Institute of Technology, Vietnam
\textsuperscript{3}Faculty of Electrical and Electronics Engineering, Nha Trang University, Vietnam
\textsuperscript{4}Modeling Evolutionary Algorithms Simulation and Artificial Intelligence, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Vietnam

ABSTRACT

In the effort of improving the performance of white light LEDs devices (WLEDs), the SiO\textsubscript{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\textsubscript{2} particles and silicone gel is diffused on the encapsulation layer surface. This enhancement is the result of light scattering from SiO\textsubscript{2} that strengthens the emitted blue light at further angles and reduces the color discrepancy. The evidence is that CCT deviation in SiO\textsubscript{2}-doped structure decline from 1000 K to 420 K in -70° to 70°. In addition, the SiO\textsubscript{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\textsubscript{2}-doped structure increases the lumen output by 2.25% at 120 mA power source in comparison to structure without SiO\textsubscript{2}. These experimental outcomes suggest that SiO\textsubscript{2} is an effective material to add in WLEDs structure for better lighting efficiency.

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 \cite{1,2}. Generally, a WLED is created by using blue LED chip and yellow-light emitting phosphor material such as Y\textsubscript{3}Al\textsubscript{5}O\textsubscript{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 \cite{3}-\cite{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 \cite{6}-\cite{8}. Many methods were suggested including using the half-spherical encapsulation \cite{9}, \cite{10} and ELiXIR pcLEDs structure with the interior light reflection for higher emitted light \cite{11}-\cite{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 \cite{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 SiO₂ particles which have shown positive results in our experiments regarding the color temperature consistency and light output. Because the SiO₂ 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 Y₃Al₅O₁₂ (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 SiO₂ nanoparticles are then merged in the remote phosphor structure in the final step, 5% SiO₂ 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 SiO₂ 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 SiO₂ particles and the result is approximate 300 nm. Besides, we used an energy dispersive spectrometer (EDS) to analyze the properties of SiO₂ nanoparticles with silicone gel.

![Figure 1. WLEDs structure: (a) photograph of WLEDs sample, (b) the simulated WLEDs model, (c) conformal phosphor structure, and (d) In-cup phosphor structure](image-url)
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 SiO₂ 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/cm² of SiO₂ is the best for chromatic uniformity that results in a 58% enhancement compared to other lighting configurations. In Figure 3, the conventional structure and SiO₂ nano-particles remote phosphor structures in a far-field pattern are presented. The color uniformity in WLEDs is excellent with 10 mg/cm² SiO₂, however, adding more SiO₂ 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/cm² of SiO₂ can enhance both color homogeneity at different angles and boost lumen output.

The angular correlated color temperature (CCT) of conventional configuration and SiO₂-doped WLEDs with 10 mg/cm² 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 SiO₂-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 SiO₂, on the other hand, with scattering events enhanced by SiO₂ 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/cm² 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 SiO₂ 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 SiO₂ 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 SiO₂ particles with different diameters: (a) conformal structure, (b) in-cup geometry](image1)

![Figure 3. Luminous fluxes of SiO₂ particles with different diameters: (a) conformal structure, (b) in-cup geometry](image2)
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° 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].

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RI = V_1RI_1 + V_2RI_2 + V_3RI_3
\]

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 scattering 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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