Japanese Journal of Applied Physics
Vol. 44, No. 21, 2005, pp. L 649–L 651

**JJAP Express Letter**

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# Strongly Enhanced Phosphor Efficiency in GaInN White Light-Emitting Diodes Using Remote Phosphor Configuration and Diffuse Reflector Cup

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(Received April 1, 2005; accepted April 21, 2005; published May 11, 2005)

Enhancement of phosphor efficiency is reported for GaInN-based white light-emitting diodes (LEDs) employing a large separation between the primary LED emitter and the wavelength converter, and a diffuse reflector cup. Ray-tracing simulations show that extraction efficiency of wavelength-converted light is enhanced by 75%. The experimental improvement in phosphor efficiency of blue-pumped yellow phosphor is 15.4% compared with conventional phosphor-based white LEDs. The improvement is attributed to reduced re-absorption of wavelength-converted light by the LED chip.

[DOI: 10.1143/JJAP.44.L649]

KEYWORDS: light-emitting diodes, GaN, diffuse reflector, encapsulant, phosphor

Short-wavelength emitting primary light sources such as GaInN-based ultraviolet and blue light-emitting diodes (LEDs) can be used as efficient excitation sources for organic and inorganic luminescent materials for down-converting photon energies.[1–3] For example, a blue-emitting GaInN chip pumping a yellow YAG:Ce phosphor results in dichromatic white light by means of mixing the two complementary colors. Typical structures of the phosphor arrangement in dichromatic white LEDs are shown in Figs. 1(a) and 1(b). Figure 1(a) shows a *conformal* phosphor distribution, i.e., a phosphor layer replicating the contour of the LED chip.[4] Figure 1(b) shows a uniform distribution of phosphor within the reflector cup, which we refer to as "*phosphor-in-cup*". Next, we show that both distributions limit the light-extraction efficiency in LEDs.

The placement and arrangement of phosphors is critical for the efficiency of white LEDs. The *conformal* and *phosphor-in-cup* distribution limit the efficiency of white LEDs for the following reason: Since the phosphor re-emits light isotropically, a large portion of light emitted by the phosphor directly impinges on the LED chip where the light can be re-absorbed. This issue is severe in the conformal phosphor configuration due to the close proximity of the phosphor and the LED chip. If the phosphor is placed at a sufficiently large distance from the LED chip, we refer to this configuration as *remote phosphor*, the probability of a light ray emanating from the phosphor and directly hitting the low reflectivity LED chip is small, thereby improving the phosphor efficiency. In addition, this *remote phosphor* configuration reduces the operating temperature of the phosphor, which is expected to improve the reliability of white LEDs. Fig. 1(c) shows a *remote phosphor* configuration, in which phosphor layer of uniform thickness is distributed over the reflector cup. However, there is still a large probability of a light ray being reflected by the reflector cup and being re-absorbed by the LED chip, as shown by Ray 1 and Ray 3 of Fig. 1(c). This is due to the specular surface of the reflector cup and its particular geometry which can result in trapped optical modes.

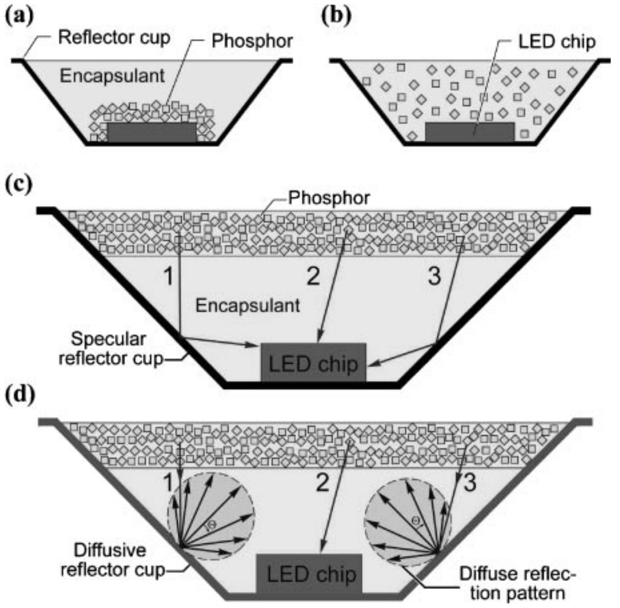

Fig. 1. Arrangements of phosphor in white LED: (a) *Conformal* distribution directly on LED chip. (b) Uniform distribution in reflector cup (*phosphor-in-cup*). (c) Uniform distribution thin layer above LED chip (*remote phosphor*). (d) *Remote phosphor* distribution in diffuse reflector cup.

In this letter, a new method of packaging of white LEDs that employs a diffuse reflector cup as well as a *remote phosphor* configuration, as illustrated in Fig. 1(d), is presented. Diffuse reflectors have an angular distribution of the reflected intensity $I$ given by $I \propto \cos\theta$, where $\theta$ is the angle of reflection irrespective of the angle of incidence. Therefore, the light Ray 1 and Ray 3 in Fig. 1(d), are directed upward thereby not impinging on the LED chip.

Ray-tracing simulations have been performed to confirm the benefits of optically decoupling the phosphor from the primary emitter. Using *Light Tools* software, we have simulated four types of white LEDs with different phosphor arrangements, *phosphor-in-cup* and *remote phosphor*, for *specular* and *diffuse* reflector cups. In the ray-tracing simulation, we assume that refractive index $n_{\text{epoxy}} = 1.6$, $n_{\text{phosphor}} = 1.82$, $n_{\text{free space}} = 1.0$ (above cup) and cup reflectance $R_{\text{Ag reflector}} = 95\%$, LED chip reflectance $R_{\text{LED chip}} = 50\%$,[5] LED chip thickness of $100\,\mu\text{m}$, $a = 300\,\mu\text{m}$, $b = 150\,\mu\text{m}$, and $\theta = 45°$, where $a$, $b$, and $\theta$ is shown in Fig. 2.

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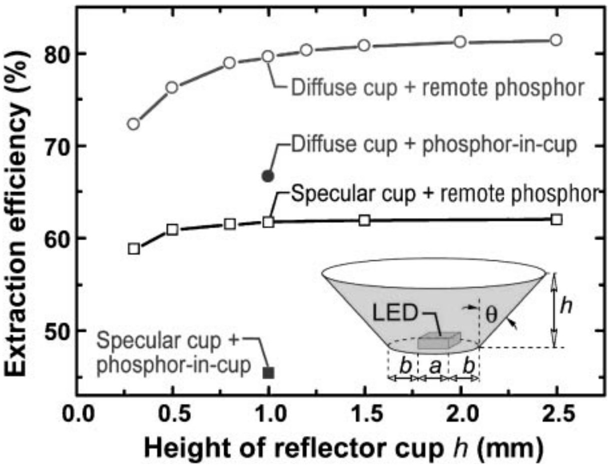

Fig. 2. Calculated light extraction efficiency as a function the height of reflector cup, obtained from ray-tracing simulations.

We also assume that the phosphor emitting at $\lambda = 550$ nm is a uniformly distributed cylindrical source with thickness of 100 μm and no absorption at 550 nm. Figure 2 shows the light extraction efficiency as a function of the height of reflector cup *h*, obtained from ray-tracing simulations for different configurations. The improvement of light extraction efficiency by using the *remote phosphor* arrangement is 36% for a specular reflector cup, and 75% for a diffuse reflector cup, compared with the *phosphor-in-cup* arrangement for a specular reflector cup. For the *phosphor-in-cup* arrangement, the use of a diffuse reflector cup results in a 47% improvement over the specular reflector cup. We also have simulated the light extraction efficiency of the LED chip emitting at $\lambda = 470$ nm with different reflector cups. The light extraction efficiency of the LED chip on the diffuse reflector cup is 3.6% lower than that on the specular reflector cup. This minor decrease is caused by the small probability that light reflected by the diffuse cup is reflected towards the LED chip. Note that the decrease in light extraction of the primary emitter by using a diffuse reflector cup is negligibly small compared to the increase in phosphorescence efficiency.

White LED lamps comprising a blue GaInN chip emitting at ~470 nm and YAG:Ce phosphor with different phosphor arrangements and reflector cups were fabricated. The surface of diffuse reflector cup was roughened by bead blasting. Figures 3(a) and 3(b) show a specular and a diffuse reflector cup, respectively. The roughened Ag reflector shows a more than two orders of magnitude higher diffusely reflected power compared with the specular Ag reflector. GaInN blue LED chips were die-bonded to the bottom of reflector cups followed by wire bonding. For a *phosphor-in-cup* arrangement, the reflector cups were filled with an epoxy resin containing yellow phosphor. For a *remote phosphor* arrangement, the reflector cup was partially filled with a transparent epoxy resin (without phosphor) followed by curing, and then further filled with an epoxy resin containing yellow phosphor. After curing at 150°C for 3 h, the reflector cups were encapsulated by standard LED technology in transparent epoxy resin. Figure 3(c) shows the cross-sectional view of the *remote phosphor* arrangement.

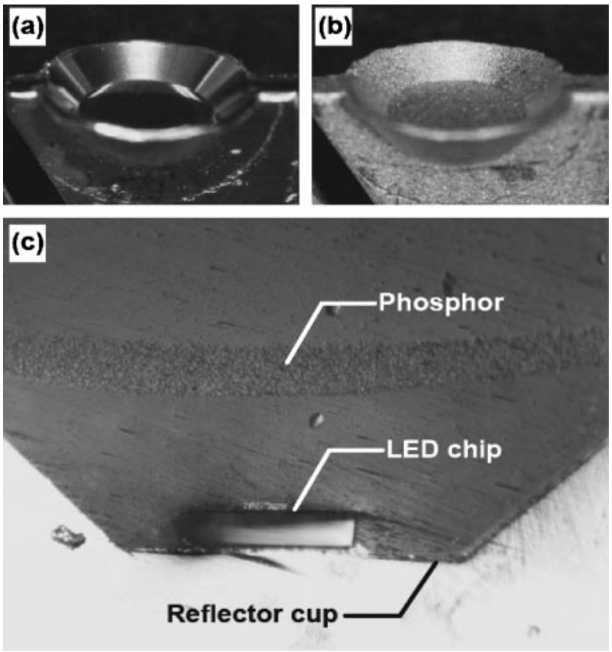

Fig. 3. Optical micrographs of (a) a specular reflector cup, (b) a diffuse reflector cup and (c) cross-sectional view of remote phosphor arrangement.

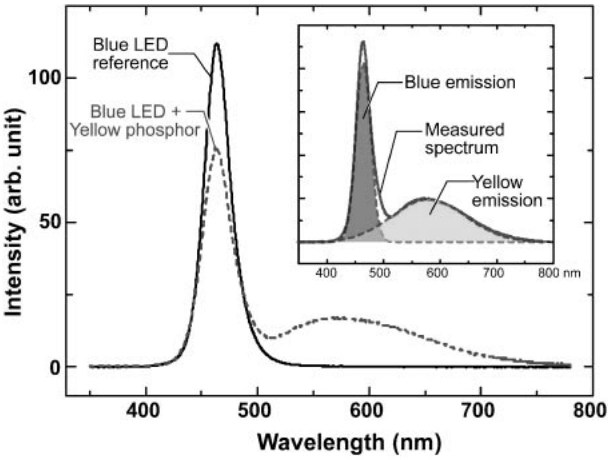

Fig. 4. Emission spectra of reference blue LED, and blue-pumped white LED with yellow phosphor. Deconvolution into blue emission from LED chip and yellow emission from phosphor is shown in the inset.

The emission spectra of the reference blue LED, and blue-pumped white LED with yellow phosphor are shown in Fig. 4. The measured emission spectra can be deconvoluted into blue emission from LED chip and yellow emission from phosphor, as shown in the inset of Fig. 4. The optical output power of each of the components can be determined by integrating the measured spectra over wavelength. The power conversion efficiencies of phosphor were calculated from the ratio of output power of yellow component to the difference in output power between blue LED reference emission (without phosphor) and the blue component of the white LED, as summarized in Table I. The improvement of power conversion efficiency by using the *remote phosphor* arrangement is 7.8% for specular reflector cup, and 15.4% for diffuse reflector cup, compared with the *phosphor-in-cup* arrangement in specular reflector cup. For the *phosphor-in-cup* arrangement, the use of a diffuse reflector cup results in

Table I. Light output power and power conversion efficiency of the four samples.

| | Blue reference (mW) | Blue emission (mW) | Yellow emission (mW) | Conversion efficiency (Improvement) |
|---|---|---|---|---|
| Specular phosphor-in-cup | 3.96 | 1.29 | 1.60 | 59.9%<br>(—) |
| Specular remote phosphor | 3.96 | 1.90 | 1.33 | 64.6%<br>(7.8%) |
| Diffuse phosphor-in-cup | 3.84 | 1.37 | 1.62 | 66.7%<br>(11.4%) |
| Diffuse remote phosphor | 3.84 | 2.02 | 1.23 | 69.1%<br>(15.4%) |

a 11.4% improvement over the specular reflector cup. Although the experimental results show a trend consistent with ray-tracing simulations, the improvements are smaller than expected. This could be due to the presence of a relatively large encapsulant dome outside the reflector cup in the experiments, which results in the decrease of the difference in light extraction between a diffuse and a specular reflector cup.

In conclusion, results are presented that show that the reflector cup surface roughness, geometric dimensions and phosphor placement strongly influence the phosphor efficiency in white LEDs. The improvement of light extraction efficiency by using the *remote phosphor* arrangement and a diffuse reflector cup is 75% in a ray-tracing simulation, and is 15.4% in experiments compared with the conventional phosphor-in-a specular reflector cup arrangements. This improvement is attributed to a reduced re-absorption probability of wavelength-converted light by the LED chip.

RPI gratefully acknowledges support by the Samsung Advanced Institute of Technology (SAIT), the National Science Foundation (NSF), the Defense Advanced Research Projects Agency (DARPA), and the US Army Research Offices (ARO).

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