Development of RGB-LEDs Using RGB Phosphors

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Abstract

RGB-LEDs are widely used for indirect lighting in vehicle interiors. However, conventional methods that directly utilize the emission from RGB chips suffer from significant color variation in both primary and mixed colors. In this study, we addressed this issue by applying phosphors corresponding to each RGB color to suppress color variation. Additionally, we improved temperature characteristics and brightness degradation under high current conditions, enabling the development of high-power RGB-LEDs. This paper introduces the details of the development.

1. Introduction

Light Emitting Diodes (LEDs) have become widely used in various applications such as lighting and displays, and it is now rare to go a day without encountering LED light in daily life. In recent years, RGB-LEDs have been increasingly adopted for automotive interior lighting. While primarily used for ambient lighting, the need for RGB-LEDs is expected to grow in both interior and exterior applications as autonomous driving technology advances. Figure 1 shows an example of RGB lighting using a light guide.

White LEDs typically emit white light by combining a blue InGaN chip with yellow and red phosphors. In contrast, conventional RGB-LEDs mainly use a red AlGaInP chip and blue and green InGaN chips, a method referred to as the "chip method." Although amber and red LEDs using phosphor conversion (PC) have already been commercialized[(1)(2)], there are no examples of LEDs that emit RGB light using only phosphor emissions within a single package.

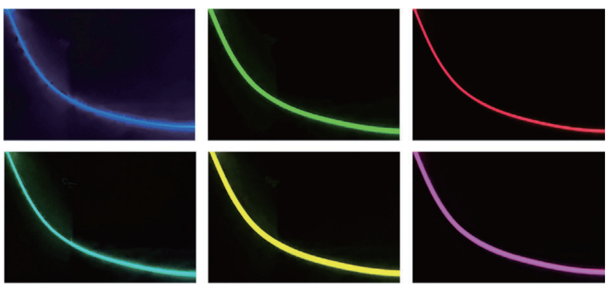

Figure 1. Example of RGB Lighting Using a Light Guide

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In this study, we developed an RGB-LED design that uses phosphors for all RGB colors (referred to as the phosphor method) and addressed the following three challenges:

1. Significant color variation in RGB chips, which currently requires fine software-based adjustments.
2. Large color shifts due to temperature changes, also corrected via software.
3. Increasing demand for high brightness that is visible even during daytime.

2. Wavelength Variation in Chips and Phosphors

LED chips are fabricated through wafer processes, but variations in elemental composition ratios and film thickness lead to inconsistencies in electrical characteristics, light output, and emission wavelength. Therefore, each diced chip is individually measured and categorized into wavelength ranks.

Figure 2(a) illustrates a conceptual diagram of wavelength variation among chips across the wafer, categorized into wavelength ranks.

Example distributions of wavelength variation in blue chips are shown in Figure 3(a). Typical blue LEDs exhibit a wavelength variation exceeding 10 nm and are ranked in 2.5 nm increments.

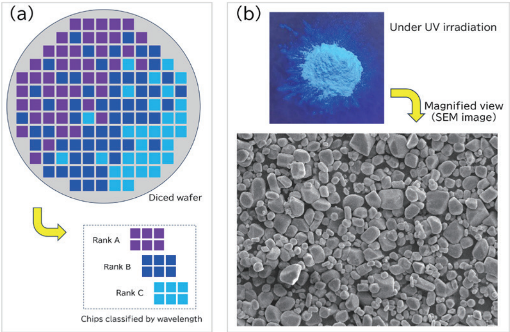

Figure 2. (a) Conceptual Diagram of Wavelength Ranking for Chips and (b) Photograph and SEM image of Phosphors

In contrast, as shown in **Figure 2(b)**, phosphors consist of powders with particle sizes ranging from 5 to 20 μm. Several hundred grams of raw material are placed in crucibles and fired. After firing, the phosphors are processed through crushing, washing, adjusting particle size, and mixing to produce the final product. The mixing process helps to homogenize powders with slightly different properties, resulting in minimal wavelength variation across the entire batch.

As an example, **Figure 3(b)** shows the wavelength distribution of the blue phosphor $BaMgAl_{10}O_{17}:Eu^{2+}$, which was used in cold cathode fluorescent lamps (CCFL) for LCD backlights. Compared to blue LED chips, which typically have a wavelength variation exceeding 10 nm and are ranked in 2.5 nm increments, the phosphor's distribution is confined to a narrow 0.5 nm range (467.0 to 467.5 nm), demonstrating its superior consistency.

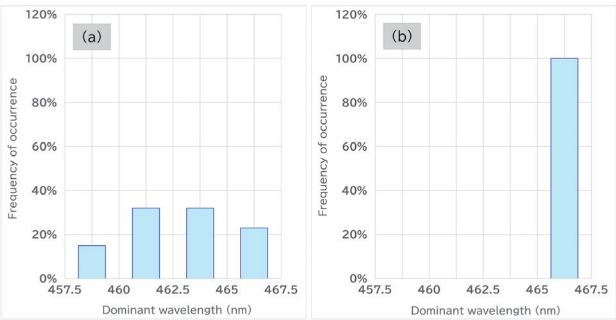

Figure 3. (a) Wavelength Variation in Blue Chips and (b) Wavelength Variation in Blue Phosphors

3. Reduction of Chromaticity Variation in Primary Colors

In the chip method, phosphors are not required, and chips are simply encapsulated with silicone resin. In contrast, the phosphor method requires three phosphors for RGB color. While the chip method cannot adjust chromaticity variation through encapsulation, the phosphor method allows control of chromaticity by adjusting the amount of phosphor.

The following sections describe the chromaticity variation reduction for each RGB color using the phosphor method.

3.1 Red (PC-Red) LED

A blue chip was combined with a phosphor resin made by mixing silicone resin and red phosphor $(Sr,Ca)AlSiN_3:Eu^{2+}$. **Figure 4** shows the emission spectra when varying the amount of phosphor.

The following phenomena were observed:

1. Increasing the phosphor amount decreases blue emission.
2. The phosphor absorbs blue light and converts it to red, increasing red emission.
3. Beyond a certain threshold, red emission decreases due to concentration quenching.
4. Excess phosphor leads to reabsorption and re-emission at longer wavelengths, shifting the emission spectrum (This process is known as the reabsorption-and-excitation process).

These effects cause the chromaticity to shift from blue toward red on the CIE chromaticity diagram. As the chromaticity approaches the boundary of the reproducible color range, it moves along the edge (**Figure 5(a)**). By

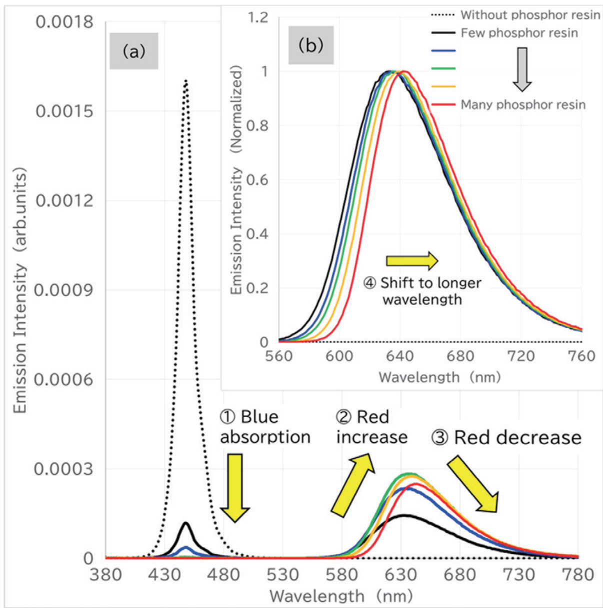

Figure 4. (a) Emission Spectrum of a Blue Chip Combined with Red Phosphor and (b) Emission Spectrum Normalized to the Red Emission Peak

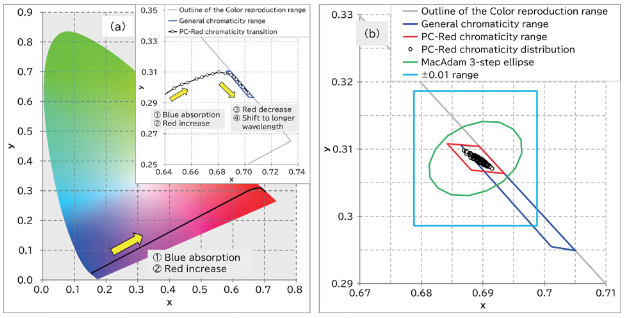

Figure 5. (a) Chromaticity Shift of PC-Red with Varying Phosphor Amount and (b) Chromaticity Distribution

maintaining a uniform phosphor amount, chromaticity variation can be suppressed.

Figure 5(b) shows the target chromaticity range of ±0.01, the MacAdam 3-step ellipse, and the chromaticity distribution of PC-Red LEDs. The distribution falls within the MacAdam ellipse, confirming the effectiveness of this method.

The chromaticity range (red line) was defined accordingly. Compared to the conventional 9 nm wavelength range of red LEDs, PC-Red achieves a narrower 3 nm range, reducing variation to one-third.

3.2 Green (PC-Green) LED

A blue chip was combined with a phosphor resin made by mixing silicone resin and green phosphor

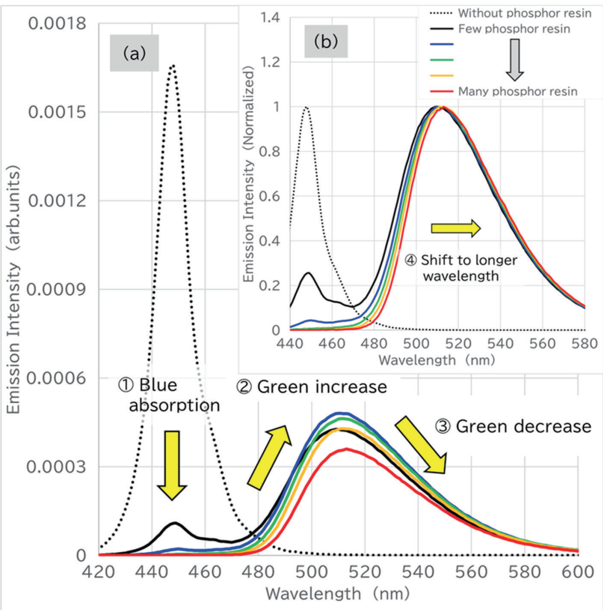

Figure 6. (a) Emission Spectrum of a Blue Chip Combined with Green Phosphor and (b) Emission Spectrum Normalized to the Green Emission Peak Intensity

$Ca_8Mg(SiO_4)_4Cl_2:Eu^{2+}$, and the resulting emission spectrum is shown in Figure 6.

Similar phenomena to PC-Red were observed:

1. Increasing the phosphor amount decreases blue emission.
2. The phosphor absorbs blue light and converts it to green, increasing green emission.
3. Beyond a certain threshold, green emission decreases due to concentration quenching.
4. Excess phosphor leads to reabsorption and re-emission at longer wavelengths, shifting the emission spectrum.

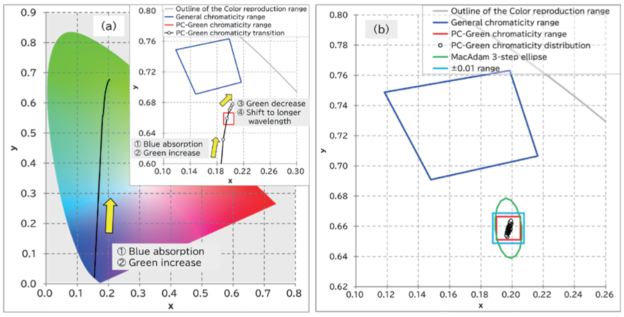

Figure 7. (a) Chromaticity Shift of PC-Green with Varying Phosphor Amount and (b) Chromaticity Distribution

As shown in Figure 7(a), chromaticity shifts from blue toward green. The green phosphor used has a broad emission bandwidth, so the chromaticity does not reach the outer edge of the reproducible color range. Increasing the phosphor amount decreases chromaticity shifts, and uniform phosphor application suppresses variation (Figure 7(b)).

The chromaticity distribution of PC-Green also falls within the ±0.01 range and the MacAdam 3-step ellipse. The chromaticity range (red line) was defined accordingly. Compared to the conventional 15 nm wavelength range of green LEDs, PC-Green achieves a narrower 3 nm range, reducing variation to one-fifth.

3.3 Blue (PC-Blue) LED

Examples of combining blue chips with blue phosphors are rare due to the perception that chromaticity variation in blue chips is difficult to control. However, techniques using blue phosphors to suppress such variation are known[(3)].

A blue chip was combined with a phosphor resin made by mixing silicone resin and blue phosphor $Sr_3MgSi_2O_8:Eu^{2+}$, and the resulting emission spectrum is shown in Figure 8.

Although the emission spectra of the chip and phosphor overlap, the following phenomena were observed:

1. Increasing the phosphor amount decreases chip-originated blue emission.
2. Increasing the phosphor amount increases blue emission from phosphor.
3. Excess phosphor causes a decrease in blue emission from phosphor.
4. Excess phosphor leads to reabsorption and re-emission at longer wavelengths, shifting the emission spectrum.

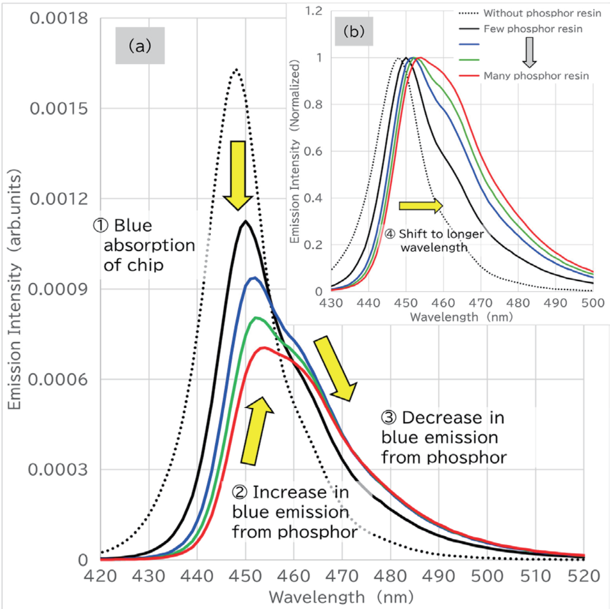

Figure 8. (a) Emission Spectrum of a Blue Chip Combined with Blue Phosphor and (b) Emission Spectrum Normalized to the Blue Emission Peak Intensity

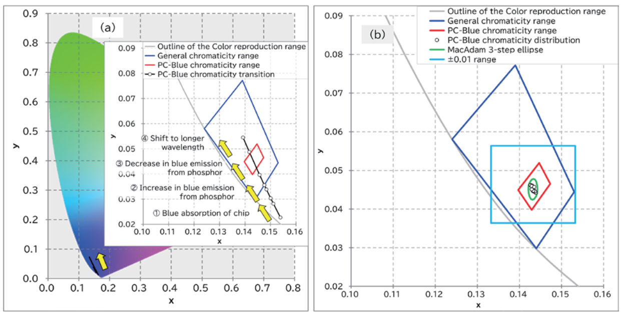

Figure 9. (a) Chromaticity Shift of PC-Blue with Varying Phosphor Amount and (b) Chromaticity Distribution

Table 1. Chromaticity Width of PC RGB-LEDs within MacAdam Ellipse (3-Step)

Region	x	y
Red Region	0.015	0.011
Green Region	0.017	0.04
Blue Region	0.002	0.005

As shown in Figure 9(a), chromaticity moves linearly within the blue region. Uniform phosphor application suppresses chromaticity variation.

The chromaticity distribution of PC-Blue falls within the ±0.01 range and the MacAdam ellipse (3-step), but the blue region's ellipse is smaller than those for red and green (Table 1). Therefore, the chromaticity range (red line) for PC-Blue was set slightly larger than the ellipse. Compared to the conventional 10 nm range of blue LEDs, PC-Blue achieves a 2 nm range, reducing variation to one-fifth.

4. Expansion of Color Reproduction Range

To suppress chromaticity variation in RGB LEDs, conventional methods generate the reference color points within the emission distribution of the chips[4].

Specifically, the triangle formed by the upper and lower chromaticity limits of RGB colors is used as the color reproduction range, with its vertices serving as reference points. For example, green is reproduced by weakly emitting blue and red LEDs.

In chip methods, RGB chips are ranked in 4 to 5 nm increments, requiring different emission ratios for each rank combination. This necessitates software-based adjustments for each rank, posing a challenge.

In contrast, the phosphor method achieves chromaticity distributions within the ±0.01 range and the MacAdam 3-step ellipse for each RGB color. Therefore, each color can be used as a single rank reference point.

The area of the resulting triangle was compared with the NTSC standard commonly used in displays. The chip method achieved 83.4% of NTSC, while the phosphor method reached 95.1%, demonstrating a wider color reproduction range (Figure 10).

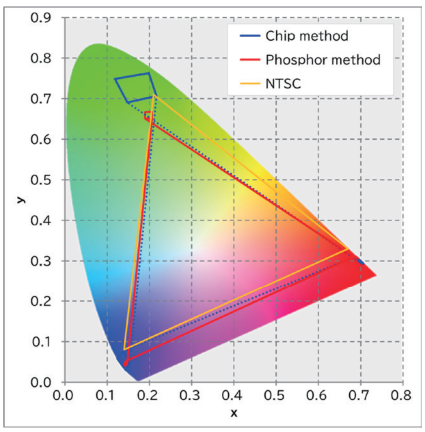

Figure 10. Comparison of Color Reproduction Range

5. Reduction of Chromaticity Variation in White Light

RGB-LEDs can produce mixed colors such as white, cyan, yellow, and amber by adjusting the emission intensity of each RGB component. In conventional chip methods, if chromaticity variation in RGB chips is not corrected via software, the output ratio of RGB remains fixed, resulting in noticeable variation in mixed colors.

Figure 11 presents a simulation of how chromaticity variation in RGB primary colors affects the chromaticity of white light when output ratios are fixed.

Figure 11 (a) shows the chip method, where 64 chromaticity coordinates are generated from combinations of four points within the chromaticity ranges of RGB chips (blue lines in Figures 5 (b), 7 (b), and 9 (b)).

Figure 11 (b) shows the phosphor method, where 64 chromaticity coordinates are generated similarly using the chromaticity ranges of phosphor-based RGB LEDs (red lines in Figures 5 (b), 7 (b), and 9 (b)).

The phosphor method clearly demonstrates smaller chromaticity variation in white light, with all coordinates falling within the ±0.01 target range. Although some combinations slightly exceed the MacAdam 3-step ellipse, this is attributed to the PC-Blue chromaticity range (red line in Figure 9 (b)) being set slightly larger than the MacAdam 3-step ellipse. If the PC-Blue range is adjusted to fit within the MacAdam 3-step ellipse, mixed color variation can also be suppressed accordingly.

To reduce the PC-Blue chromaticity range, improvements are needed in both material design (e.g., phosphor composition and particle size distribution) and manufacturing techniques (e.g., uniform application of phosphor resin). Both areas offer sufficient room for enhancement.

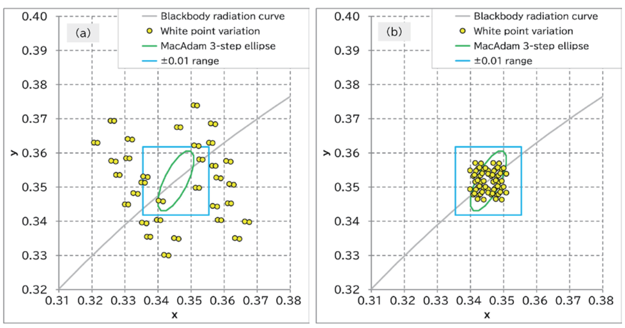

Figure 11. Chromaticity Variation in White Light: (a) Chip Method and (b) Phosphor Method

6. Chromaticity Shift Due to Temperature Change

The temperature characteristics of LED chips are largely determined by their material composition. Red chips, in particular, exhibit poor temperature stability, with emission intensity decreasing as temperature rises. Additionally, the emission wavelength shifts toward longer wavelengths, resulting in deeper red light with lower visual brightness[5].

In contrast, PC-Red uses a blue chip with good temperature characteristics and a red phosphor, resulting in less brightness degradation compared to red chips (Figure 12).

Phosphor temperature characteristics can be improved by reducing the concentration of activators[6]. However, this also reduces blue light absorption, making it difficult to achieve high color purity in PC-Green and PC-Red emissions. Therefore, sharing the blue light absorption function with pigments or color filters (e.g., color resist materials) may offer a solution for improving temperature stability.

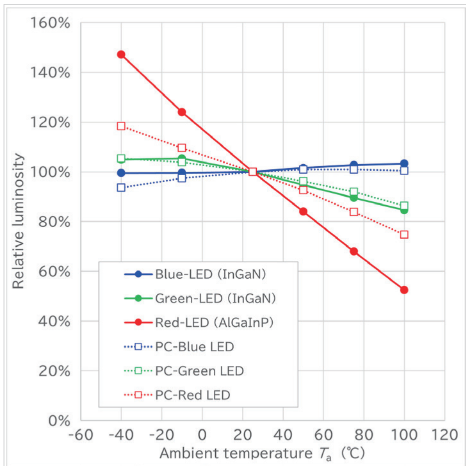

Figure 12. Temperature Characteristics of Chip Method and Phosphor Method

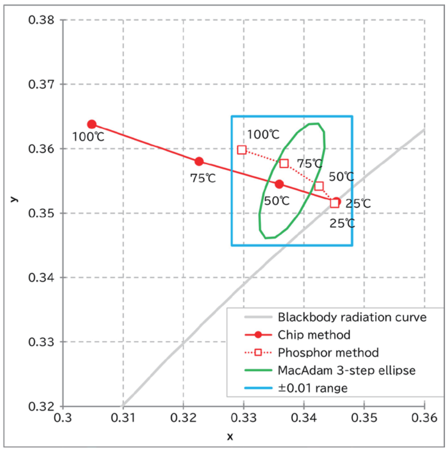

Figure 13. Chromaticity Shift Due to Temperature Increase

Figure 13 shows the chromaticity shift of white light due to temperature changes in both chip methods and phosphor methods. The phosphor method maintains chromaticity within the ±0.01 range even when the temperature increases from 25°C to 100°C. In contrast, the chip method exhibits more than twice the chromaticity shift, which is visually noticeable (**Figure 14**).

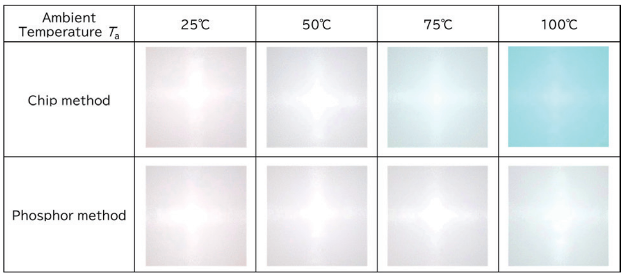

Figure 14. Appearance of RGB-LED Emission Color Change with Temperature Increase (Photographed Through a Diffuser Plate)

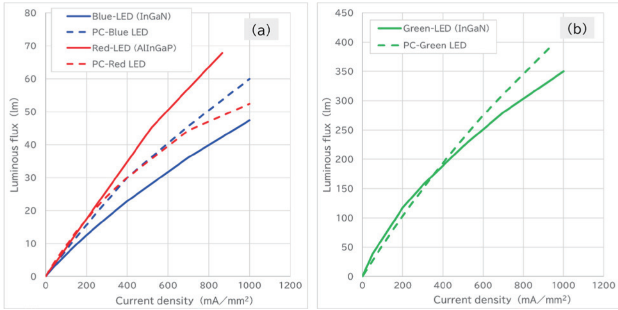

Figure 15. Relationship Between Current Density and Luminous Flux: (a) Blue and Red, (b) Green (Current Application Time: 10 ms to Suppress Heat Effects)

Table 2. Brightness of Red LED with Temperature Increase (Current Application Time: 10 ms)

Ambient Temperature (Ta)	25 °C	100 °C
Red LED (AlGaInP)	64 lm	33 lm
PC-Red LED	47 lm	35 lm

7. Adaptation to High-Power Operation

While indirect lighting in vehicle interiors provides attractive effects at night, visibility during daytime is limited. In Europe, daytime running lights (DRLs) are mandatory to improve vehicle visibility. Although not yet required in Japan, visibility will become increasingly important with the spread of autonomous driving.

Therefore, high-power RGB-LEDs are expected to be necessary in the future, and this study examined their feasibility.

The simplest approach to high-power LED design is to increase chip size to accommodate higher current. **Figure 15** shows the change in brightness with increasing current.

Blue chips tend to shift their emission toward shorter wavelengths under high current, resulting in darker blue light due to lower visual sensitivity. However, the RGB phosphors used in this study exhibit increased emission intensity when excited by shorter wavelengths.

As a result, PC-Blue and PC-Green show less brightness degradation compared to blue chips, making them suitable for high-power applications.

PC-Red, while less bright than red chips at 25°C, maintains brightness better at elevated temperatures. At 100°C, PC-Red is brighter than the red chip (**Table 2**). Since high-power LEDs generate significant heat and must operate at high temperatures, the phosphor method offers advantages in maintaining brightness under such conditions.

8. Product Concept

The phosphor method requires separate phosphor resin layers for each RGB color. To prevent unintended emission from non-target phosphors (e.g., PC-Green or PC-Blue when PC-Red is activated), shielding between phosphor layers is necessary.

Two LED packaging types are considered:

- Surface Mount Device (SMD) type, with three compartments in a single package
- Chip on Board (COB) type, where chips are mounted directly on the substrate (**Figure 16**)

To realize high-power RGB-LEDs, the COB type is preferable due to its superior heat dissipation. COB also allows adjustment of chip quantity based on required brightness and supports integration of electrical circuits for modularization.

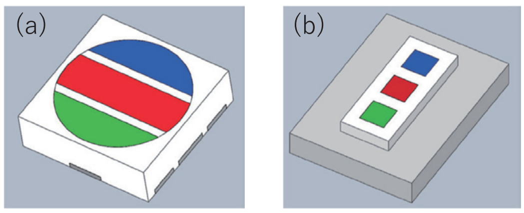

Figure 16. (a) SMD Type and (b) COB Type

9. Conclusion

We developed RGB-LEDs using phosphors for each RGB color. Compared to the conventional chip method, chromaticity variation in primary colors was significantly reduced, and mixed color variation such as white was also suppressed.

Temperature-induced chromaticity shifts were minimized, eliminating the need for software-based color correction. These features make the phosphor-based RGB-LEDs highly promising for practical applications.

Although this report focused on specific phosphors, changing the phosphor type allows customization of chromaticity variation, temperature characteristics, and emission wavelength, enabling tailored RGB-LEDs to meet customer requirements.

Furthermore, the phosphor method is well-suited for high-power applications, maintaining brightness under high current and high temperature conditions. Combined with COB customization, this approach aligns with our commitment to delivering products for niche markets, addressing detailed customer needs.

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