# Efficiency and Droop Improvement in Hybrid Warm White LEDs Using InGaN and AlGaInP High-Voltage LEDs

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***Abstract*—This study investigates the optical and electrical characteristics in hybrid warm white high-voltage light-emitting diodes (HV-LEDs). The luminous efficiency of the hybrid warm white LED in this study improved by 11% and 51%, compared to conventional cool and warm LEDs, respectively, solving the warm white gap in white LEDs. The efficiency droop of the hybrid warm white LED was reduced to 21.8% from 26.8% for the conventional cool white LED, and from 26.3% in the conventional warm white LED at 40 mA (35 A/cm$^2$) the operated current. Furthermore, the color rendering index (CRI) and angular correlated color temperature (CCT) were analyzed, indicating a significant improvement in hybrid warm white HV-LEDs.**

***Index Terms*—High voltage, light-emitting diodes (LEDs), phosphor, warm white.**

## I. Introduction

WHITE light-emitting diodes (WLEDs) are regarded as the next generation of environmentally friendly lighting sources, and are particularly useful in solid-state lighting (SSL) [1]–[3]. Therefore, because they are an energy-saving lighting source, it is imperative to increase the quantum or the lumen efficiency in WLEDs. As mentioned in our previous study, high-voltage LEDs (HV-LEDs) achieve higher lumen efficiency by embedding multiple series-connected micro-diodes in one large chip [4]. The chief advantage of HV-LEDs is that they focus on the reduction of the operation driving current, which efficiently eases current crowding and the efficiency droop, compared to conventional large chip DC-LEDs with the same amount of power. Furthermore, the high voltage operation can also reduce the voltage conversion losses from wall plug to SSL devices.

To date, phosphor-converted WLEDs have been the critical technology used in SSL devices. SSLs generally comprise two types, such as cool and warm WLEDs, which are combined with blue chips and various phosphor materials [5], [6]. For cool WLEDs, yellow phosphor, such as $\mathrm{Y_3A_5O_{12}:Ce^{3+}}$, is commonly used. Conversely, regarding warm WLEDs, the addition of red phosphor, such as nitride-based phosphor, is required to obtain warm white. However, the differences in luminous efficiencies of cool WLEDs and warm WLEDs are a serious issue, and are known as the warm white efficiency gap [7]. This could be attributed to several reasons: First, red phosphor has lower conversion efficiency because of larger stokes shift losses. Second, the reabsorption phenomenon in yellow light in the mixture of yellow and red phosphor used in warm WLEDs causes the cascade excitation process [8]. Furthermore, the difference in luminous efficiency is approximately 25%–40% between cool WLEDs and warm WLEDs [7]. Therefore, how to improve the efficiency gap between two types of WLEDs becomes the urgent issue in SSL.

In this study, the hybrid warm white HV-LEDs—including blue chips, red chips, and yellow phosphor—were shown to theoretically and experimentally improve the efficiency gaps in WLEDs. In addition, the efficiency droop was significantly improved by the hybrid warm white HV-LED package. Furthermore, the CRI value achieved 90 in warm white HV-LED LEDs.

## II. Device Fabrication

In the experiment, the LEDs were grown on c-plane sapphire substrate by metal-organic chemical vapor deposition (MOCVD) system including n-GaN layer, an $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{N}$/GaN multiple-quantum wells, a p-AlGaN electron blocking layer, and a p-GaN layer. After that, the inductively coupled plasma (ICP) etcher method was used to form the isolation trenches between microchips. To prevent short circuit between each microchip, the passivation $\mathrm{SiO_2}$ layer was deposited by plasma-enhanced chemical vapor deposition (PECVD). Finally, the bridged Cr/Au were simultaneously evaporated by e-beam evaporator to serve as cathodes. Each chip process were referred as [9]. Fig. 1 shows the schematic diagram of the hybrid warm white LED, conventional cool white LED, and conventional warm white LED. The hybrid warm white LED was prepared with four 45 mil×45 mil InGaN HV-LEDs with domain wavelengths of 452.5 nm, two 50 mil× 25 mil AlGaInP HV-LEDs with domain wavelengths of 617 nm, and yellow YAG phosphor. The forward voltages of InGaN and

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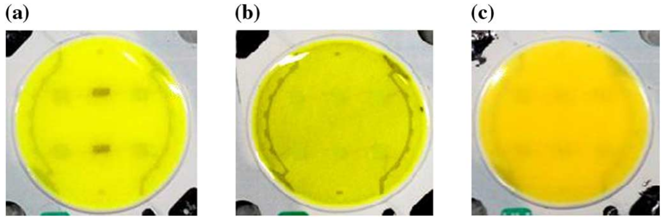

Fig. 1. Schematic diagram of: (a) the hybrid warm white LED, (b) conventional cool white LED, and (c) conventional warm white LED.

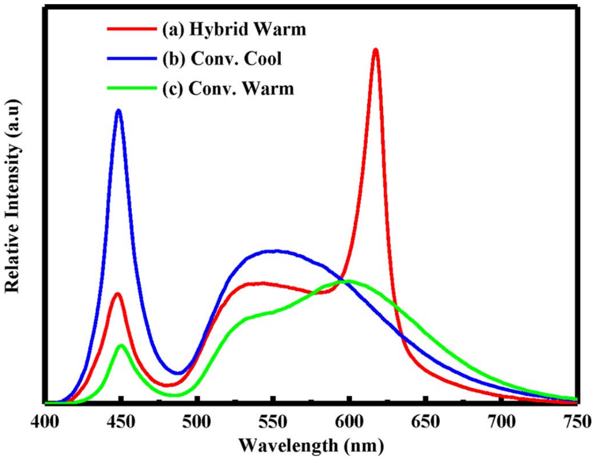

Fig. 2. EL spectra of the hybrid warm white LED, conventional cool white LED, and conventional warm white LED.

AlGaInP HV-LEDs under a 40 mA driving current were 53 and 21 V, respectively. For the reference, the samples were prepared with six 45 mil×45 mil InGaN HV-LEDs, and the phosphor component of the cool white and warm white LEDs were yellow YAG phosphor and a mixture of yellow YAG phosphor and red Nitride phosphor with wavelength of 610 nm, separately. It is worth to notice the cost of this hybrid white LED. In the hybrid white LED, we used the two red AlGaInP HV-LEDs to replace the two blue InGaN HV-LEDs. Since the price of a red AlGaInP LED is close to the price of a blue InGaN LED, the cost of the hybrid white LED is comparable to the conventional cool/warm white LEDs.

The electroluminescence (EL) spectra are shown in Fig. 2, and were measured at a forward current of 40 mA (approximately 35 A/cm$^2$) for the hybrid warm LED, the conventional cool white LED, and the conventional warm white system. Fig. 2(a) shows the EL spectrum of the hybrid warm LED, including the blue LED, red LED, and yellow phosphor $(\mathrm{Y_3Al_5O_{12}:Ce^{3+}})$. The full width at half maximum (FWHM) of the blue LED and red LED were 21 and 25 nm, respectively. The luminous efficiency and CRI in the hybrid warm white LED were approximately 130 lm/W and 90 under 3000 K, respectively. As shown in Fig. 2(b), the emission peak wavelength of the yellow phosphor $(\mathrm{Y_3Al_5O_{12}:Ce^{3+}})$ occurred at 550 nm with a FWHM of 121 nm in the conventional cool white LED. Fig. 2(c) was composed of blue, yellow, and red emission bands located at 452.5 nm, 540 nm, and 600 nm, respectively, which were attributed to the blue LED, yellow phosphor, and red phosphor white LED achieved a luminous efficiency 118 lm/W and CRI 70 under 6000 K, whereas the conventional warm white LED ranks were 86 lm/W and CRI 80 under 3000 K.

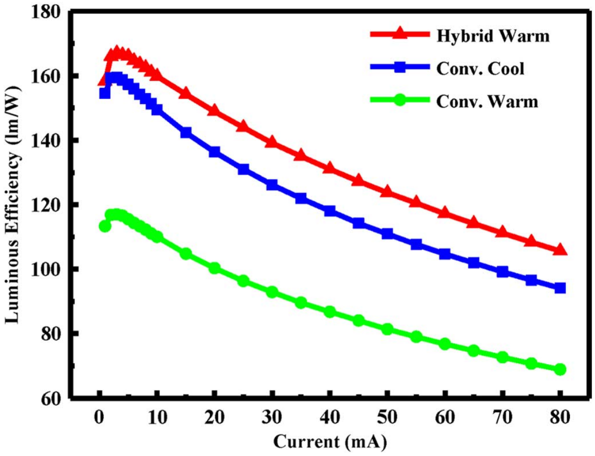

Fig. 3. Lumen efficiency of hybrid warm white LED, conventional cool white LED and conventional warm white LED.

## III. Results and Discussion

Fig. 3 shows the luminous efficiency of the conventional cool and warm white and the proposed hybrid warm white LED as a function of a pulsed current at room temperature. There were significant efficiency differences among the conventional cool and warm white LEDs, which were calculated as being approximately 27%. The main reason for the large gap was the warm white gap, as mentioned. At this point, the luminous efficiency of the warm white LED increased from approximately 11% and 51% compared with the conventional cool and conventional warm LED.

For an explanation for the improvement in the hybrid warm LED, the chromaticity coordinates are shown in Fig. 4. Points A and C represent the cool white light with 6000 K on (0.324, 0.335) and the warm white light with 3000 K on (0.439, 0.409), respectively. To achieve the warm white light on Point C, red phosphor is generally added to the cool white light LED on Point A, which is called the conventional method. However, red phosphor suffers from the larger Stokes shift losses and the reabsorption of yellow light by the red phosphor, resulting in reduced luminous efficiency. Therefore, to solve this problem, this study demonstrated a different method to achieve high-efficiency warm white light. The proposed method comprises two steps for creating warm white light: 1) more yellow phosphor was added into the cool white light on Point A to create the yellowish white light on Point B with 5000 K, resulting in an approximate 10% enhancement of luminous efficiency, compared with Point A, and 2) the red chip with a domain wavelength of 617 nm on (0.627, 0.327) was mixed with the former yellowish white light on Point B to obtain the warm white light on Point C. Incorporating the red chip to replace the red phosphor solved the warm white gap problem and increased the luminous efficiency, compared with the reference.

Furthermore, the normalized luminous efficiency droop was investigated in three types of samples, as shown in Fig. 5. The efficiency droop of the hybrid warm white LED was improved from 26.8% in conventional cool white and 26.3% in conventional warm white to 21.8%. These improvements in efficiency

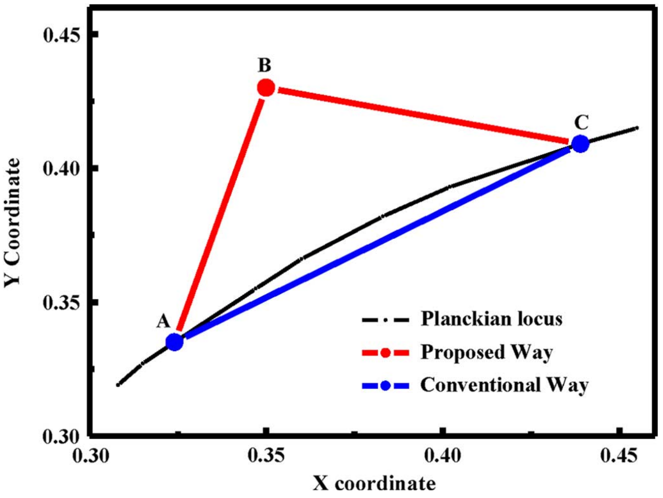

Fig. 4. Comparison of the conventional and proposed method to fabricate the warm white.

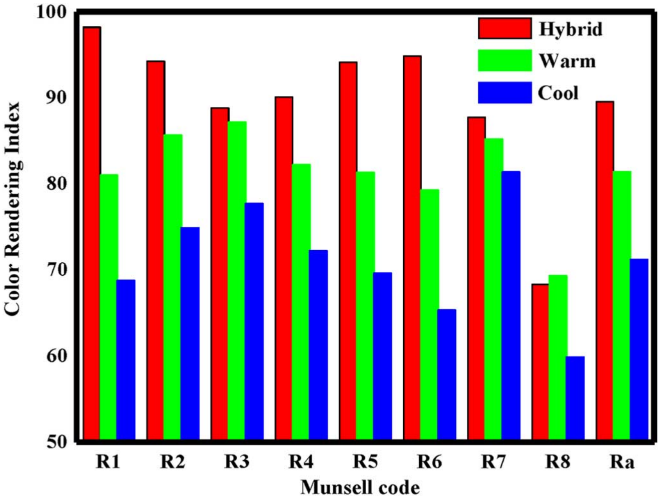

Fig. 6. CRI of hybrid warm white LED, conventional cool white LED, and conventional warm white LED analyzed at various Munsell codes.

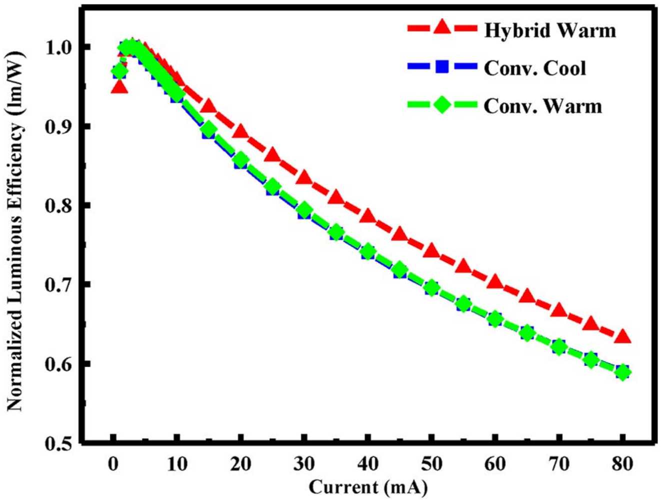

Fig. 5. Normalized luminous efficiency of hybrid warm white LED, conventional cool white LED, and conventional warm white LED.

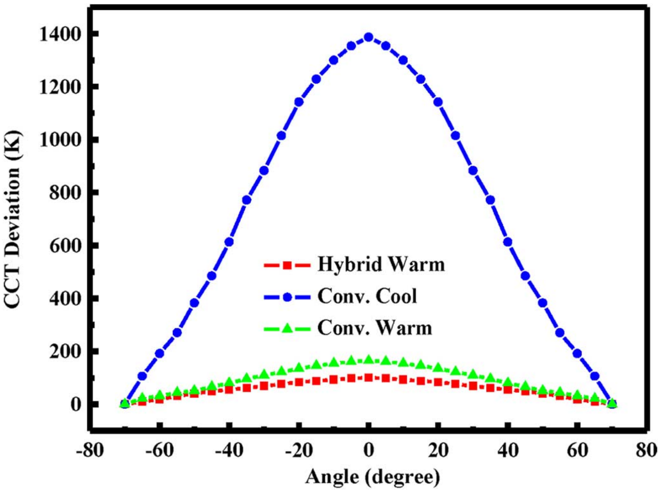

Fig. 7. CCT deviation of the hybrid warm white LED, conventional cool white LED, and conventional warm white LED.

were attributed to the additional AlGaInP HV-LEDs. Some studies have indicated that the major reason for the efficiency drop in III-V nitrides has been caused by the carrier overflow [10], as well as the Auger scattering [11] and charge separation issues in leading to reduction in efficiency in InGaN QW LEDs. The LEDs with novel barrier designs had been studied for efficiency-droop suppression [12], [13], and novel active region with optimized optical matrix elements had also been used to suppress charge separation in InGaN QWs [14]–[16]. For the AlGaInP heterostructures, the lower piezoelectric polarization electric fields caused the alleviation of the efficiency droop [17]. Therefore, in this experiment, when the AlGaInP HV-LED was employed to the InGaN HV-LED, the normalized efficiency droop improved as the reference. The warm white LED not only raised the luminous efficiency, but also reduced the efficiency droop, compared with the conversional warm and cool LEDs.

In addition to luminosity, the CRI is a quantitative measure of the ability of a light source to faithfully reproduce the colors of various objects compared to an ideal or natural light source, and is important for general lighting [18]. As shown in Fig. 6, R1 to R8 are the color rendering properties of the light source tested by eight test color samples (TCSs) distributed over the complete range of hues. Results indicated that the proposed hybrid warm white achieved the highest value among the eight TCSs. Especially, the best CRI value was observed from R1, which was tested by the light grayish red sample. Furthermore, the general CRI Ra represents the average value among these eight TCSs, and the highest Ra ranked at 90 was achieved by the proposed hybrid warm white LED.

To analyze the light quality of the WLEDs, we measured angular correlated color temperature (CCT) deviation for the three types of LEDs. The angular CCT deviation curves from −70 to 70 deg are shown in Fig. 7.The CCT deviations were 1387 K, 164 K, and 100 K for the conventional cool white, warm white, and the hybrid warm white LEDs, respectively. Moreover, a superior uniformity of angular-dependent CCT was obtained in the hybrid warm white LED, compared with the reference. This could be attributed not only to the excellent light quality in the warm white region, but also to the proper arrangement of the chips in the package. The red LED chips were bonded in the middle of the package, helping lower the CCT deviation caused by the Lambertian emission of blue LEDs and the isotropic emission of phosphor.

## IV. Conclusion

In conclusion, hybrid warm white HV-LEDs were investigated—including InGaN HV-LEDs, AlGaInP HV-LEDs, and yellow YAG phosphor. The results indicated that the luminous efficiency of the hybrid warm white HV-LEDs increased 11% and 51% at 40 mA (35 A/cm$^2$), compared with the conventional cool white and warm white LEDs, respectively. In addition, the efficiency droop of the hybrid warm white LEDs improved from 26.8% in conventional cool white and 26.3% in conventional warm white to 21.8%. Replacing red phosphor with red LEDs was the chief reason for the improvements. Furthermore, the CRI was ranked at 90, and the uniform angular CCT within a 100 K deviation was achieved by the hybrid warm white LED.

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