Warm white light generating nanocrystal hybridized LEDs with high color rendering index

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Today lighting consumes 20% of the world electricity production [1]. Solid state lighting (SSL) is predicted to save 50% of the electricity consumption for lighting and consequently reduce carbon emission by 300 million tons per year [2]. Recently in SSL, nanocrystal (NC) based light emitting devices have made great progress [3-7]. Nanocrystals are particularly advantageous for use in white light sources because they feature tunable and relatively narrow emission across the visible spectral range. They further exhibit small overlap between their emission and absorption spectra, and also provide the ability to be easily and uniformly deposited in solid films using common techniques (spin casting, dip coating, etc.). However, despite their recent progress to date, such nanocrystal integrated white LEDs have not been demonstrated to exhibit warm correlated color temperatures (CCT) simultaneously with high color rendering indices (CRI) [3-7], though this is required for indoor lighting [1-3]. As a matter of fact, such high-CRI, warm-white LEDs have previously not been achieved using phosphors, which are the most commonly used luminophors, either [3].

In this talk to meet this demand, we will present our proposal, development, and demonstration of high-CRI, warm-white LEDs using custom-design nanocrystal luminophors. In our hybrid devices we used green and red emitting CdSe/ZnS core-shell nanocrystals (with photoluminescence peak at λ_{PL}=555 and 613 nm, respectively) integrated on our blue InGaN/GaN light emitting diodes (with electroluminescence peak at λ_{EL}=452 nm) [8]. Using red and green NCs on blue LED was important for efficient pumping of NCs and obtaining high CRI. In our designs using our nanocrystal emitters, the red emission above 650 nm was significantly avoided, unlike using phosphors that exhibit strong emission tail in the red above 650 nm. As a result, in the case of using phosphors, the luminous efficacy (LE) of optical radiation (i.e., the ratio of the emitted luminous flux to the radiant flux) substantially drops (because the eye sensitivity function decreases quickly above 650 nm). On the other hand, in our case, the use of these nanocrystal luminophors enabled to achieve white light generation with high LE in the warm-white region, while maintaining high CRI. Based on our careful designs and hybridization of the nanocrystal emitters, we developed and demonstrated three sets of proof-of-concept warm-white LEDs with high-quality white light properties as follows: 1.) (x, y)=(0.37, 0.30), LE=307 lm/W of optical radiation, CRI=82.4, CCT=3228 K; 2.) (x, y)=(0.38, 0.31), LE=323 lm/W of optical radiation, CRI=81.0, CCT=3190 K; and 3.) (x, y)=(0.37, 0.30), LE=303 lm/W of optical radiation, CRI=79.6, CCT=1982 K, shown on CIE chromaticity diagram in Fig. 1 [8].

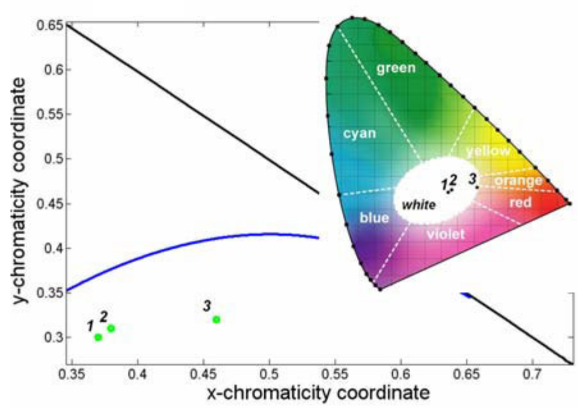

Figure 1. Tristimulus coordinates of our nanocrystal-hybridized warm-white LEDs (Samples 1, 2 and 3 shown in green points 1, 2 and 3) along with the planckian locus (shown in blue line). The inset shows these tristimulus coordinates on a CIE 1931 chromaticity diagram.

For the first warm-white LED sample, we hybridized 0.22 mg (0.578 nmol) of red-emitting CdSe/ZnS core-shell NCs and subsequently 0.26 mg (2.166 nmol) of green-emitting NCs on blue LED (λ_{EL}=452 nm). These nanocrystals were designed to have diameters of 9.6 nm and 7.7 nm (with a size distribution of ±5%) to emit at the peak wavelengths of 613 nm and 555 nm, respectively. Red emitting nanocrystals increased the color temperature of the resulting hybrid device; but, at the same time they may have undesirably reduced the luminous efficacy by contributing to emission above 650 nm. Therefore, it was necessary to carefully set the

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emission wavelength and amount of the red NCs. In addition, the green emitting nanocrystals balanced out the red emission at 555 nm along with the blue LED emission at 452 nm by holding the tristimulus coordinates in the white region and the color rendering index sufficiently high. We obtained the luminescence of this hybrid LED at various current injection levels at room temperature as shown in Fig. 2 (bottom), leading to the photometric properties of (x, y)=(0.37, 0.30), LE=307 lm/W of optical radiation, CRI=82.4, and CCT=3228 K. Such a hybrid white LED satisfied the future SSL criterion of CRI ~ 80 with a warm CCT.

For the second warm-white LED sample, we integrated 0.13 mg (1.083 nmol) CdSe/ZnS core-shell NCs emitting at 555 nm in green region and then 0.44 mg (1.156 nmol) of NCs emitting at 613 nm in red region on blue LED (λ_{EL}=452 nm). The luminescence of this hybrid LED at various current injection levels is depicted in Fig. 2 (middle). This implementation experimentally led to (x, y)=(0.38, 0.31), LE=323 lm/W of optical radiation, CRI=81.0, and CCT=3190 K. In this case, the correlated color temperature became warmer and decreased to 3190 K because of the increased relative intensity of the red-emitting nanocrystals. Therefore, this light source generated warmer white light, while keeping its chromaticity operating point in the white at the same time. Also, the luminous efficacy of its emitted spectrum reached a relatively high level of 323 lm/W. Though its color rendering index decreased to 81.0, this light source still satisfied the criterion for the future indoor SSL sources.

As the last demonstration of our hybrid warm-white LEDs, we designed to hybridize 0.13 mg (1.083 nmol) of green-emitting NCs (λ_{PL}=555 nm) and 0.66 mg (1.734 nmol) of red-emitting NCs (λ_{PL} =613 nm) on blue LED (λ_{EL} =452 nm). The resulting spectra of hybrid LED at various levels of current injection are presented in Fig. 2 (top), corresponding to (x, y)=(0.37, 0.30), LE=303 lm/W of optical radiation, CRI=79.6, and CCT=1982 K. In this design, the operating point was located approximately on the boundary of white region near to the red-color end as shown in Fig. 1. Therefore, this hybrid white LED generated highly warm-white light at an extra-low correlated color temperature of 1982 K.

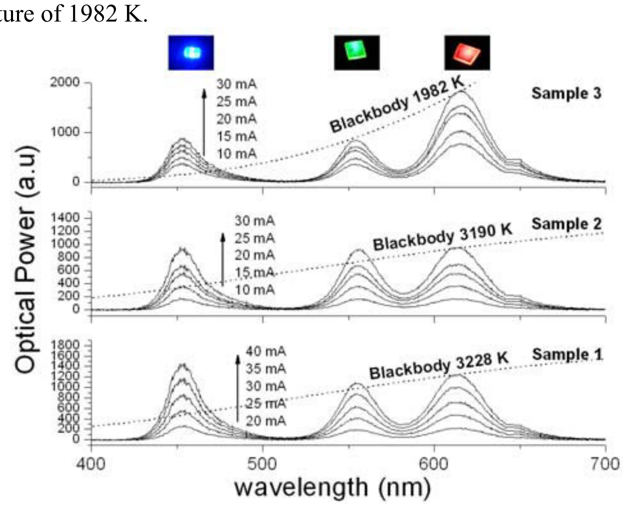

Figure 2. Luminescence spectra of our nanocrystal hybridized warm-white LEDs (Samples 1-3) when electrically driven at room temperature.

In conclusion, hybridizing custom-design CdSe/ZnS core–shell NC emitters on InGaN/GaN based blue LEDs, we demonstrated three warm-white light sources with desirably low CCT ranging from 3227 K to 1982 K as is required for SSL indoor applications. In these proof-of-concept demonstrations, high color rendering indices (82.4) and high luminous efficacies of emitted spectra (327 lm/W) were achieved, while the color temperature was simultaneously kept low as desired. Our proof-of-concept demonstrations indicated that such nanocrystal luminophor based warm-white LEDs with high-quality photometric properties hold great promise especially for future indoor lighting applications.

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