White Light Generation with CdSe/ZnS Core-Shell Nanocrystals and InGaN/GaN Light Emitting Diodes 

Sedat Nizamoglu†, Tuncay Ozel†, Emre Sari *, and Hilmi Volkan Demir*†

†Department of Physics, ‡Department of Electrical and Electronics Engineering, and * Nanotechnology Research Center

Bilkent University, Ankara, Turkey TR-06800

Email: volkan@bilkent.edu.tr, Telephone: [+90] (312) 290-1021, Fax: [+90] (312) 290-1015

Abstract—We present hybrid white light sources that integrate CdSe/ZnS core-shell nanocrystals on blue InGaN/GaN light emitting diodes (LED). We report on the demonstrations of white light generation using yellow nanocrystals (λ_{EL}=580 nm) hybridized on a blue LED (λ_{EL}=440 nm) with tristimulus coordinates of x=0.37 and y=0.25, correlated color temperature of T_{c}=2692 K, and color rendering index of Ra=14.6. Sample 2 contains cyan and red nanocrystals (λ_{EL}=500 nm and 620 nm) on a blue LED (λ_{EL}=440 nm) with x=0.37, y=0.28, T_{c}=3246 K, and Ra=19.6. Sample 3 is composed of green, yellow, and red nanocrystals (λ_{EL}=540 nm, 580 nm, and 620 nm) coated on a blue LED (λ_{EL}=452 nm) and achieves x=0.30, y=0.28, T_{c}=7521 K, and Ra=40.9.

II. CHARACTERIZATION AND RESULTS

A. Characterization of LEDs and nanocrystals

After we grow our LED epitaxial wafers on sapphire using MOCVD at Bilkent Nanotechnology Research Center, we use standard lithography, mesa reactive ion etching and metalization steps to fabricate our LEDs. The electroluminescence characteristics of the fabricated LEDs are shown in Fig. 2.

Figure 1: Photograph of white light generation with our LEDs coated with nanocrystals.

In this work, we present different single, dual and trio combinations of CdSe/ZnS core-shell nanocrystals coated on blue InGaN/GaN LEDs for white light generation. Sample 1 consists of yellow nanocrystals (λ_{PL}=580 nm) hybridized on a blue LED (λ_{EL}=440 nm) and exhibits tristimulus coordinates of x=0.37 and y=0.25, correlated color temperature of T_{c}=2692 K, and color rendering index of Ra=14.6. Sample 2 contains cyan and red nanocrystals (λ_{PL}=500 nm and 620 nm) integrated on a blue LED (λ_{EL}=440 nm) and features x=0.37, y=0.28, T_{c}=3246 K, and Ra=19.6. Sample 3 is composed of green, yellow, and red nanocrystals (λ_{PL}=540 nm, 580 nm, and 620 nm) coated on a blue LED (λ_{PL}=452 nm) and achieves x=0.30, y=0.28, T_{c}=7521 K, and Ra=40.9.

Figure 2: Electroluminescence spectra of our LEDs at various current injection levels with the peak emission wavelengths of (a) 440 nm and (b) 452 nm.
To functionalize the LED top surface, we hybrid-integrate our LEDs with our CdSe/ZnS core-shell nanocrystals via surface treatment, spin-casting and curing. The photoluminescence characteristics of our nanocrystals are shown in Fig. 3.

![Graph showing photoluminescence characteristics](image)

**Figure 3.** Photoluminescence characteristics of our cyan, green, yellow, and red CdSe/ZnS core-shell nanocrystals.

**B. Characterization of white hybrid nanocrystal LEDs**

In operation, the LED that is electrically driven optically pumps the integrated nanocrystal films and, consequently, the nanocrystal photoluminescence and the LED electroluminescence contribute together to the white light generation. To satisfy the white light condition on C.I.E. chromaticity diagram, the relative optical power of the emitted light at the chosen wavelengths can be tuned using the hybrid device parameters including the type and density of nanocrystals and the thickness and order of the nanocrystal films.

The relative optical emission spectra of Sample 1 that consists of yellow nanocrystals ($\lambda_{PL}=580$ nm) hybridized on a blue LED ($\lambda_{EL}=440$ nm) are shown at various current injection levels in Fig. 4. These spectra correspond to the tristimulus coordinates of $x=0.37$ and $y=0.25$ on C.I.E. (1931) chromaticity diagram, the correlated color temperature of $T_c=2692$ K, and the color rendering index of $R_a=14.6$. This falls in the white region in chromaticity diagram as shown in Fig. 7. However, the color rendering index is low due to the dichromatic characteristics of this white hybrid LED.

For Sample 2, we integrate dual cyan and red nanocrystals ($\lambda_{PL}=500$ nm and 620 nm) on a blue LED ($\lambda_{EL}=440$ nm). The relative optical emission spectra of Sample 2 are shown at various current injection levels in Fig. 5. These spectra correspond to $x=0.37$, $y=0.28$, $T_c=3246$ K, and $R_a=19.6$, which is also in the white region as shown in Fig. 7. In this case, the color rendering index is improved with respect to the dichromatic source of Sample 2.

For Sample 3, we use a combination of green, yellow, and red nanocrystals ($\lambda_{PL}=540$ nm, 580 nm, and 620 nm) integrated on a blue LED ($\lambda_{EL}=452$ nm). The emission spectra of Sample 3 are shown at various current injection levels in Fig. 6. These spectra correspond to $x=0.30$, $y=0.28$, $T_c=7521$ K, and $R_a=40.9$. This operating point mathematically falls into the white region in chromaticity diagram as shown in Fig. 7. Because of trichromaticity of this hybrid LED, the color rendering index is the highest in this case, compared to Samples 1 and 2.

![Emission spectra of yellow nanocrystals](image)

**Figure 4.** Emission spectra of yellow nanocrystals ($\lambda_{PL}=580$ nm) hybridized with blue LED ($\lambda_{EL}=440$ nm) at various current injection levels (Sample 1).

![Emission spectra of dual cyan and red nanocrystals](image)

**Figure 5.** Emission spectra of dual cyan and red nanocrystals ($\lambda_{PL}=500$ nm and 620 nm) hybridized with blue LED ($\lambda_{EL}=440$ nm) at various current injection levels (Sample 2).

![Emission spectra of green, yellow, and red nanocrystals](image)

**Figure 6.** Emission spectra of green, yellow, and red nanocrystals ($\lambda_{PL}=540$ nm, 580 nm, and 620 nm) hybridized on blue LED ($\lambda_{EL}=452$ nm) at various current injection levels.

Figure 3 shows the operating points of Samples 1, 2, and 3 on C.I.E. (1931) chromaticity diagram. All of these samples accomplish white light generation.
III. CONCLUSION

In this paper we present hybrid white light sources that integrate CdSe/ZnS core-shell nanocrystal films on blue InGaN/GaN LEDs. These hybrid white light sources hold promise for future lighting and display applications.

ACKNOWLEDGMENT

This work is supported by a Marie Curie European Reintegration Grant MOON 021391 and EU-PHOREMOST Network of Excellence 511616 within the 6th European Community Framework Program and TUBITAK under the Project Nos. 104E114, 106E020, 105E065, and 105E066. H.V.D. and S.N. also acknowledge additional support from Turkish Academy of Sciences and TUBITAK.

REFERENCES