

Highly efficient white electroluminescent devices with hybrid double emitting layers of quantum dots and phosphorescent molecules

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Synthesis of blue and green QDs

In a synthesis of blue-emitting CdZnS/ZnS core/shell QDs, S-OA solution (8 mmol of S in 5 mL of oleic acid (OA)) was prepared at 200°C before beginning the synthesis. A mixture including 1 mmol of CdO and 10 mmol of ZnO was placed in a three-neck flask with 7 mL of OA, followed by heating to 150°C with N₂ flowing. After adding 15 mL of 1-octadecene to the mixture, its temperature was quickly elevated. When the temperature of the solution was reached at 310°C, S-ODE solution (1.6 mmol of S in 2.4 mL of ODE) was injected into the hot reactor. The reaction of CdZnS core was maintained at 310°C for 12 min. Then, the previously prepared S-OA solution was slowly added into above reactor for the overcoating of thick ZnS shell, and the reaction was held at 310°C for 8 hr. In a typical synthesis of green-emitting CdZnSeS/ZnS core/shell QDs, a clear solution comprised of 2.2 mmol of Se and 2.2 mmol of S in 2.2 mL of trioctylphosphine (TOP) was made in advance. A mixture (0.14 mmol of Cd acetate and 3.41 mmol of Zn oxide with 7 mL of OA) was placed in a three-neck flask. With

increasing the temperature of the mixture to 150°C, 15 mL of ODE was added to the flask. For forming CdZnSeS core, pre-prepared (Se+S)-TOP solution was swiftly injected into the reactor at 310°C, and the reaction was maintained for 10 min. Subsequently, S-ODE (1.6 mmol of S dissolved in 2.4 mL of ODE) was introduced into the mixture, followed by the successive ZnS shelling. A Zn stock solution (2.86 mmol of Zn acetate dehydrate in 4 mL of OA and 1 mL of ODE) was added, and S-TOP (9.65 mmol of S in 5 mL of TOP) was put into the flask. The procedure of ZnS shelling was held at 270°C for 10 min and 20 min for each step, respectively. A purification process had to be gone through before as-synthesized QDs were applied to a device. The process repeatedly proceeded with adding excess non-solvent and using centrifugation. Then, purified QDs were redispersed in hexane for a deposition of EML. Before fabricating a QDs-mixed EML, the optical densities of QDs were adjusted to 2.5 at 440 nm and 2 at 520 nm for blue and green ones, respectively. The solutions of blue and green QDs were blended in a ratio of 3:1, and the mixed solution was employed to form a QDs-mixed EML.

Synthesis of ZnO NPs

Colloidal ZnO NPs dispersed in ethanol were synthesized according to previously reported method [Ref. 11]. In a typical reaction of colloidal ZnO NPs, 5 mmol of Zn acetate dehydrate was dissolved in 30 mL of dimethyl sulfoxide (DMSO). A mixture (5 mmol of tetramethylammonium hydroxide (TMAH) in 10 mL of ethanol) was drop-wised into above clear solution, and the reaction continued for 1 hr at room temperature. Then, by introducing an excess acetone, as-synthesized ZnO NPs were precipitated and finally redispersed in ethanol.

Fabrication of hybrid QLEDs with double EMLs

The hybrid QLEDs were fabricated on indium-tin-oxide (ITO) coated glass substrates. The substrates were sequentially cleaned with isopropyl alcohol and then rinsed with deionized water. After the patterned ITO substrates were treated in ultraviolet-ozone for 15 minutes. ZnO nanoparticles (NPs) were deposited on ITO substrates by spin-casting ZnO NPs dispersion at a spin-rate of 3000 rpm for 60 seconds. For the fabrication of hybrid EML, mixed QDs (CdZnS/ZnS for blue and CdZnSeS/ZnS for green) dispersion was spin-cast on top of ITO/ZnO NPs substrates at a spin-rate of 2000 rpm for 5 seconds. The organic materials and metals were deposited in continuance by thermal evaporation without breaking vacuum. 4,4'-bis (carbazol-9-yl) biphenyl (CBP) + Tris [1-phenylisoquinoline-C2, N] iridium(III) [Ir(piq)3] (red phosphorescent materials), CBP for hole transport layer (HTL), MoO₃, and Al were thermally evaporated with a deposition rate of $\sim 2 \text{ \AA /s}$ for CBP + Ir(piq)₃, $\sim 2 \text{ \AA /s}$ for CBP, $\sim 0.5 \text{ \AA /s}$ for MoO₃, and, $\sim 5 \text{ \AA /s}$ for Al electrode.

Characterization

The current density-voltage-luminance (J-V-L) characteristics of the devices were measured by using a spectroradiometer (Minolta CS2000) with Keithley 2400 source meter under ambient conditions. From these J-V-L measurements, the changes in the luminance and current efficiency of the devices as a function of the applied voltage were studied systematically.

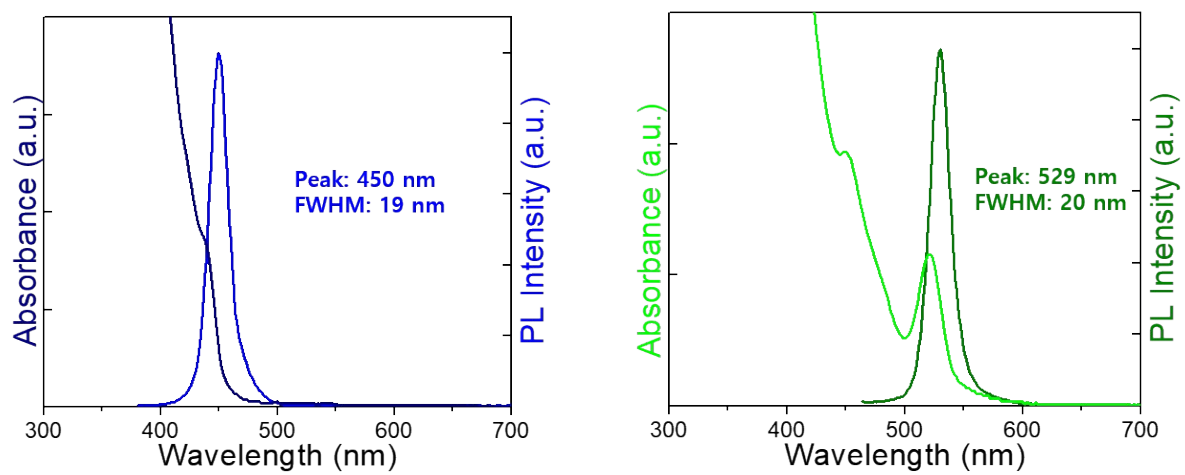


Fig. S1 Absorption/PL spectra with (a) blue and (b) green QDs.

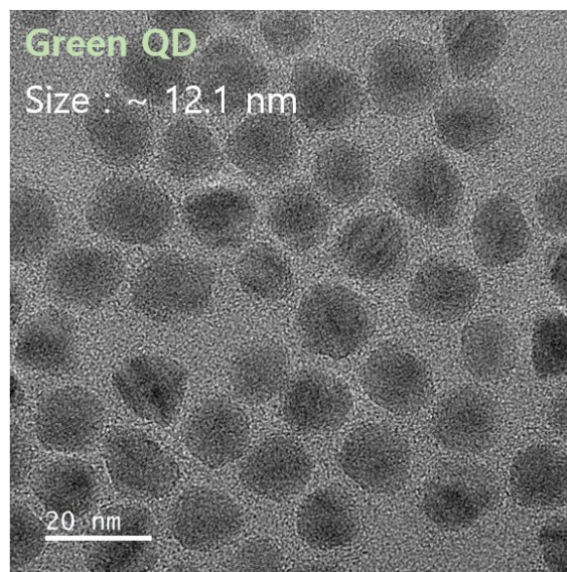
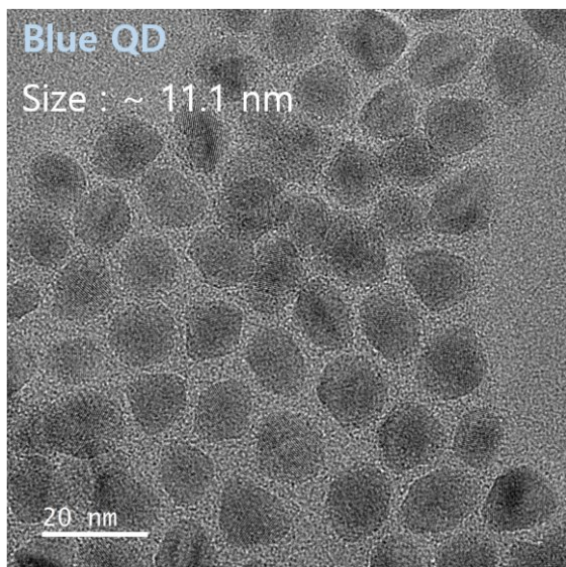


Fig. S2 TEM images of blue and green QDs.

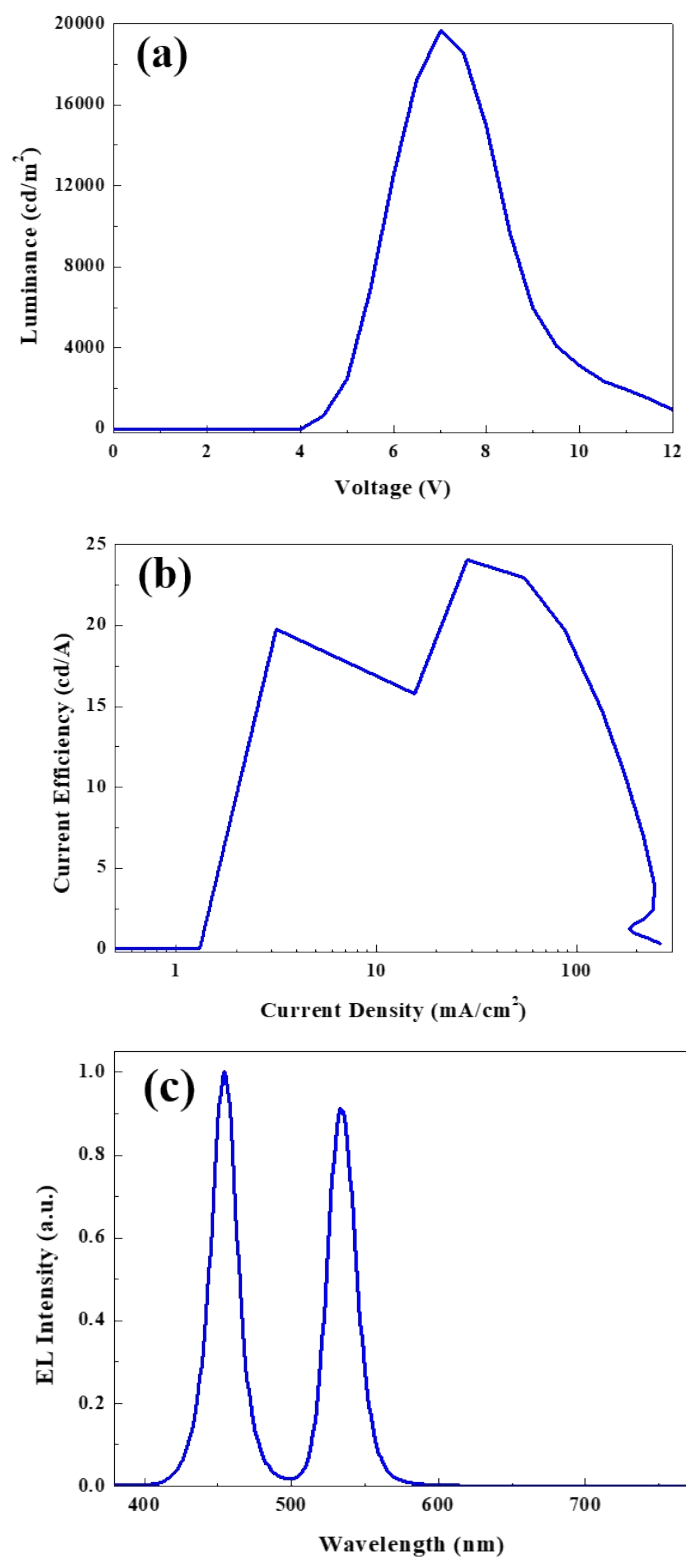


Fig. S3 Device characteristics of QLEDs with mixed QDs as an EML: (a) Luminance-voltage, (b) current efficiency, and (c) EL spectrum.

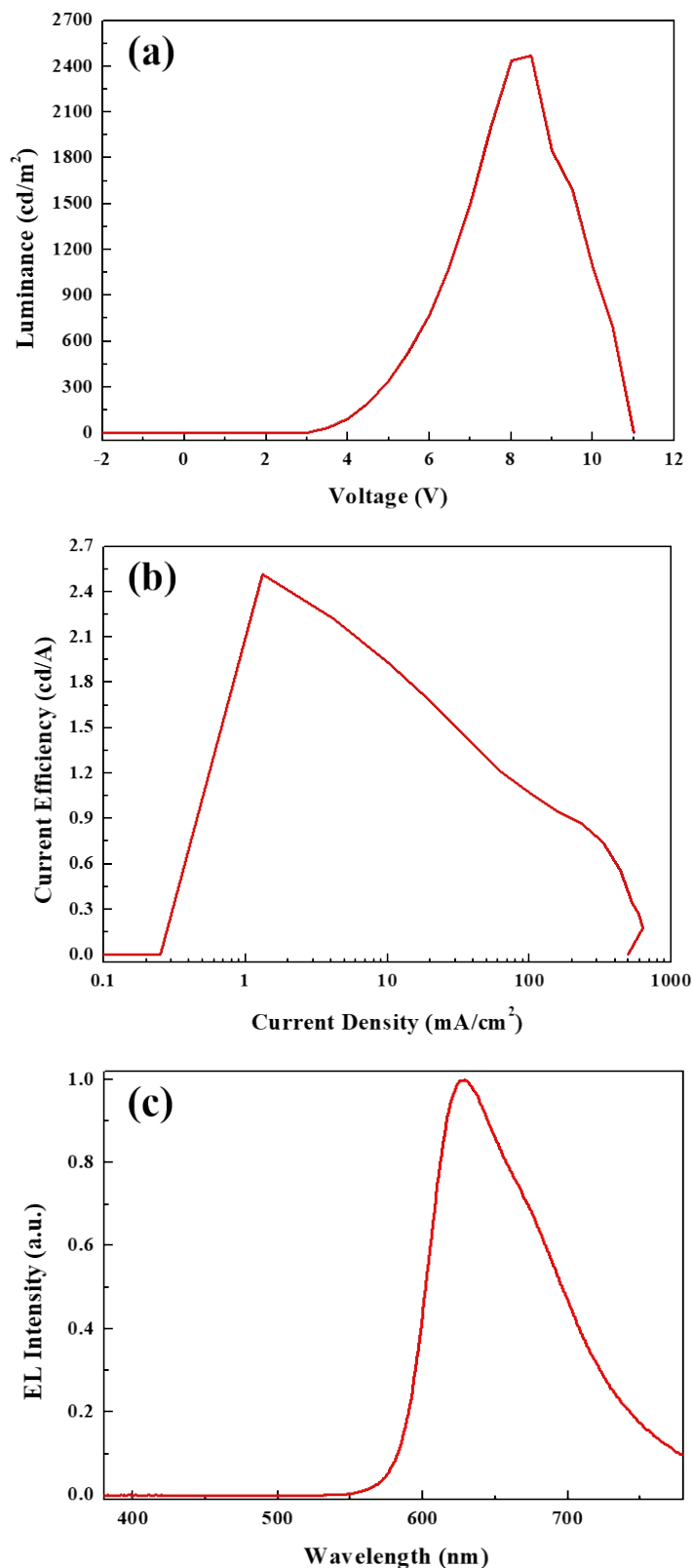


Fig. S4 Device characteristics of OLEDs with CBP:Ir(piq)₃ as an EML: (a) Luminance-voltage, (b) current efficiency, and (c) EL spectrum.

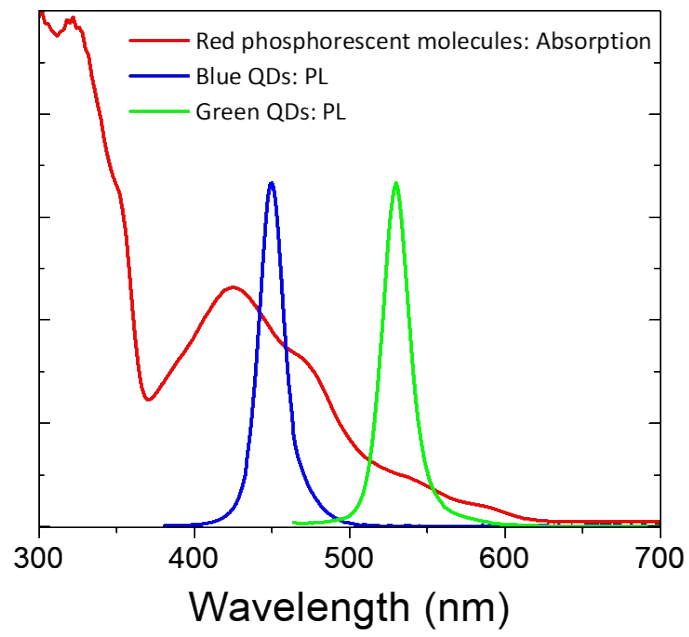


Fig. S5 Spectral comparison of absorption of CBP:Ir(piq)₃ and PL of blue and green QDs.

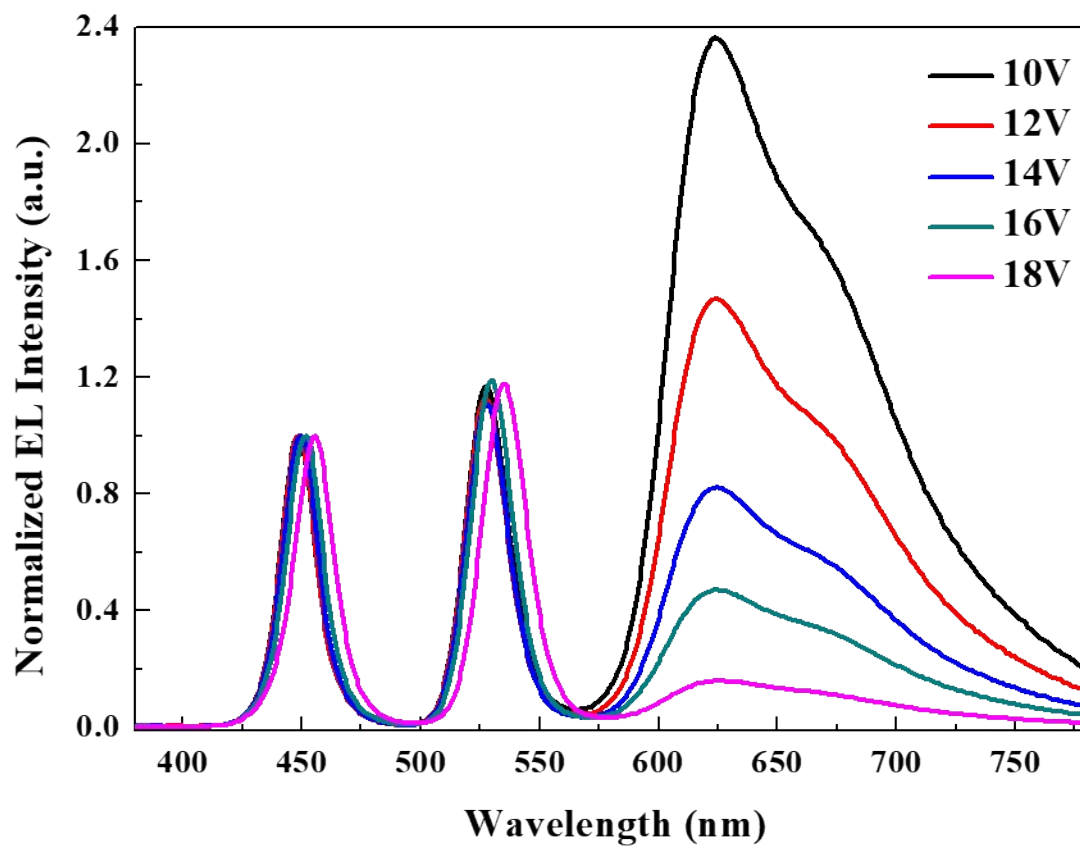


Fig. S6 Voltage-dependent normalized EL spectra for trichromatic hybrid QLEDs.

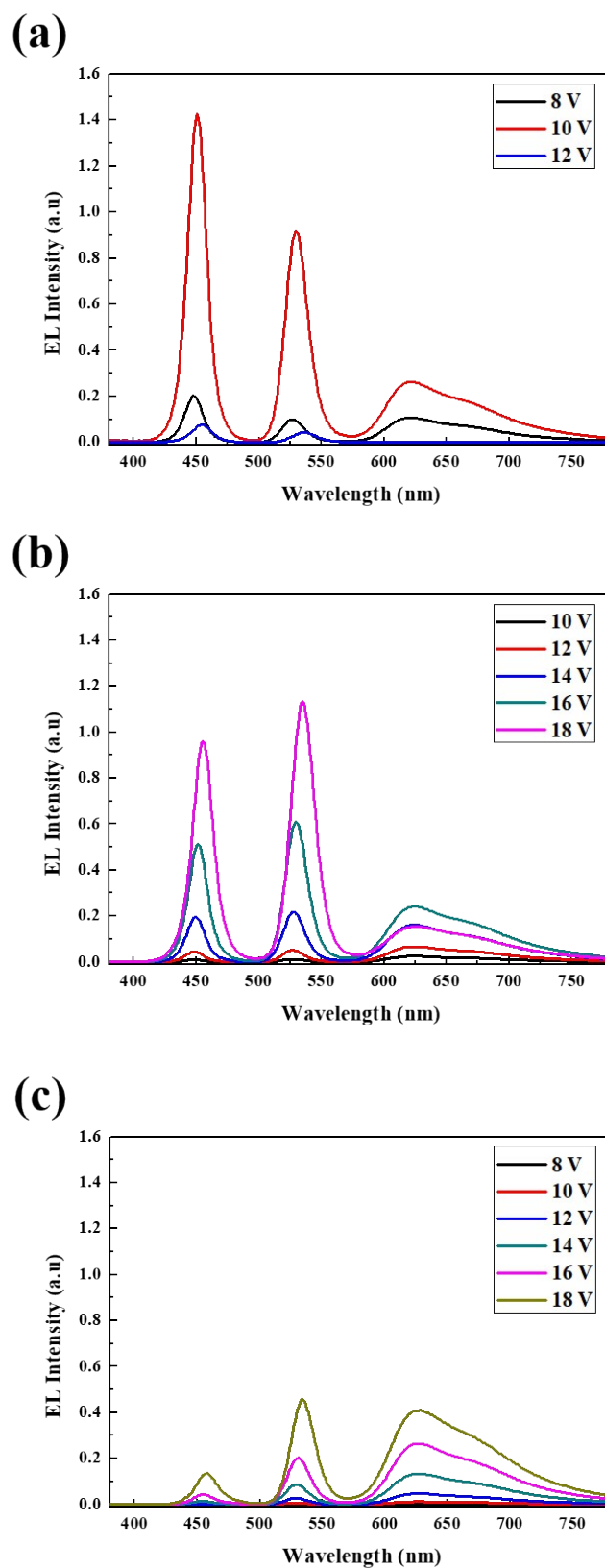


Fig. S7 Voltage-dependent EL spectra of hybrid QLEDs with different thicknesses of EML2
 (a) 20 nm, (b) 30nm and (c) 40 nm.