Supplementary Information

Colour-Encoded Electroluminescent White Light-emitting Diode Enabled by Perovskite-Cu-In-S Quantum Composites

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Supplementary Information

1. X-ray diffraction results of the perovskite and Cu-In-S (CIS) quantum composites

We measured X-ray diffraction to investigate the structural properties of the $CsPbBr_3$ perovskite and CIS quantum composites (XRD). Figure S1 shows the XRD results of the $CsPbBr_3$ perovskite and CIS quantum composites, which were fabricated by a spin-coating on the glass substrate. The XRD results showed the diffraction patterns corresponding to each quantum dots (QDs) even after mixing them. The pristine perovskite QDs showed the cubic crystal structure and retained a cubic structure. Also, the CIS QDs showed the diffraction peak corresponding to the (220) plane. These results indicate that there were no physical and chemical reactions between two different QD materials.

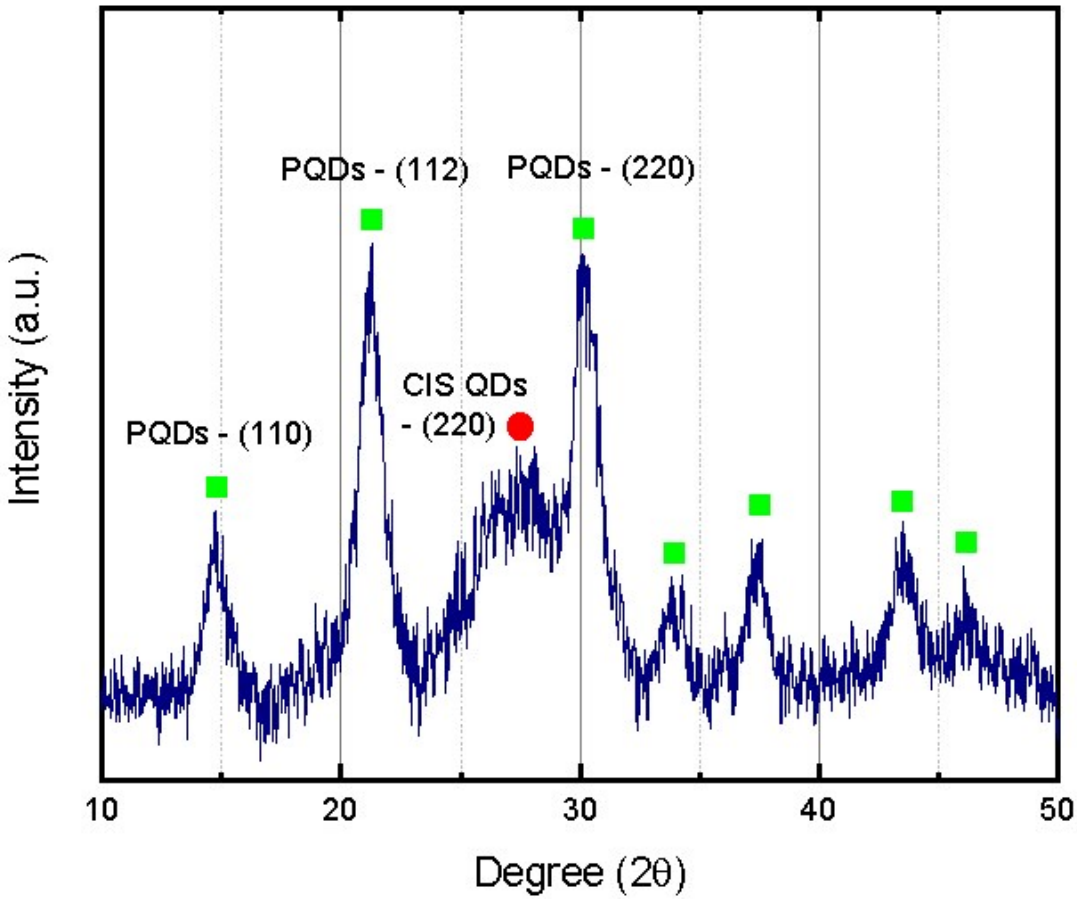

Figure S1. XRD pattern of the mixture of $CsPbBr_3$ perovskite and CIS quantum composites.

2. X-ray photoelectron spectroscopy results of the perovskite and CIS quantum composites

An X-ray photoelectron spectroscopy (XPS) was measured for the composite samples to investigate the element configuration of the perovskite and CIS quantum composites. Figure S2 shows the XPS survey spectra of the perovskite and CIS quantum composites. The constituting elements of perovskite and CIS QDs are found at each corresponding peak positions. The In *3d* and Br *3d* peaks are clearly seen, which are from CIS and perovskite $CsPb(Br_{1-x}Cl_x)_3$ QDs, respectively.

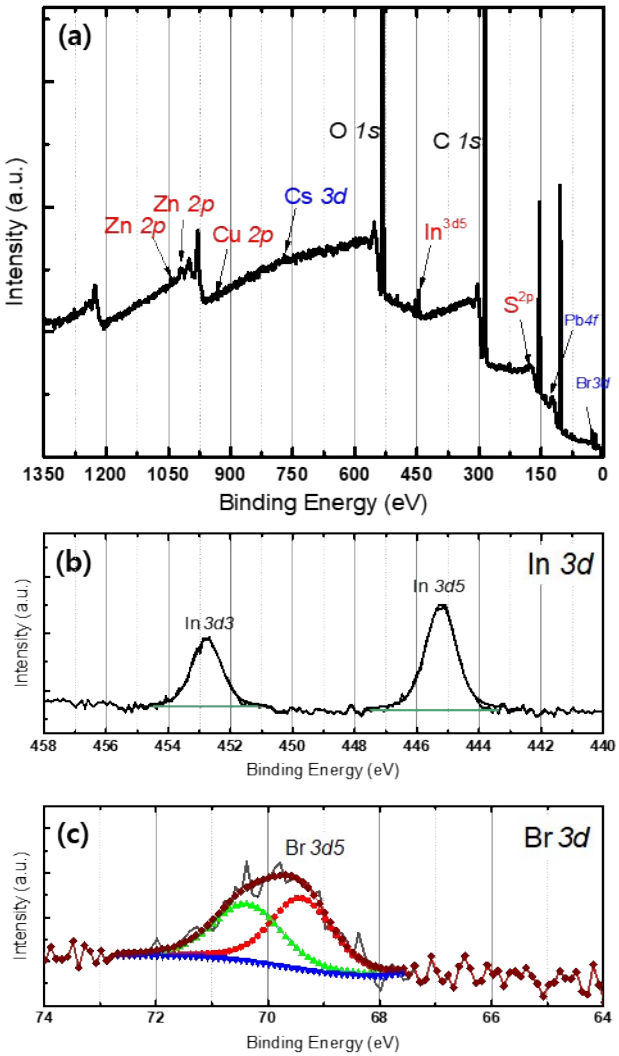

Figure S2. (a) Survey XPS spectra, (b) In *3d* peak, and (c) Br *3d* peak of the $CsPbBr_3$ perovskite and CIS quantum composites.

3. Transmission electron microscope images of the perovskite and CIS quantum composites

To investigate the physical shape and structural property of the perovskite and CIS quantum composites, we measured them through Cs-corrected-Scanning-Transmission-Electron-Microscope (TEM, NEO ARM/JEOL). Figure S3 shows the TEM images of the perovskite and CIS quantum composites with a volume ratio of 1:1:1 of the blue, green, and red-emitting QDs. The blended solutions were dropped onto the copper TEM grid. In the TEM image, the perovskite and CIS QDs showed cube-shaped crystal and spherical shaped crystal, respectively. Therefore, the perovskite and CIS QDs preserved their own structure without modification or agglomeration.

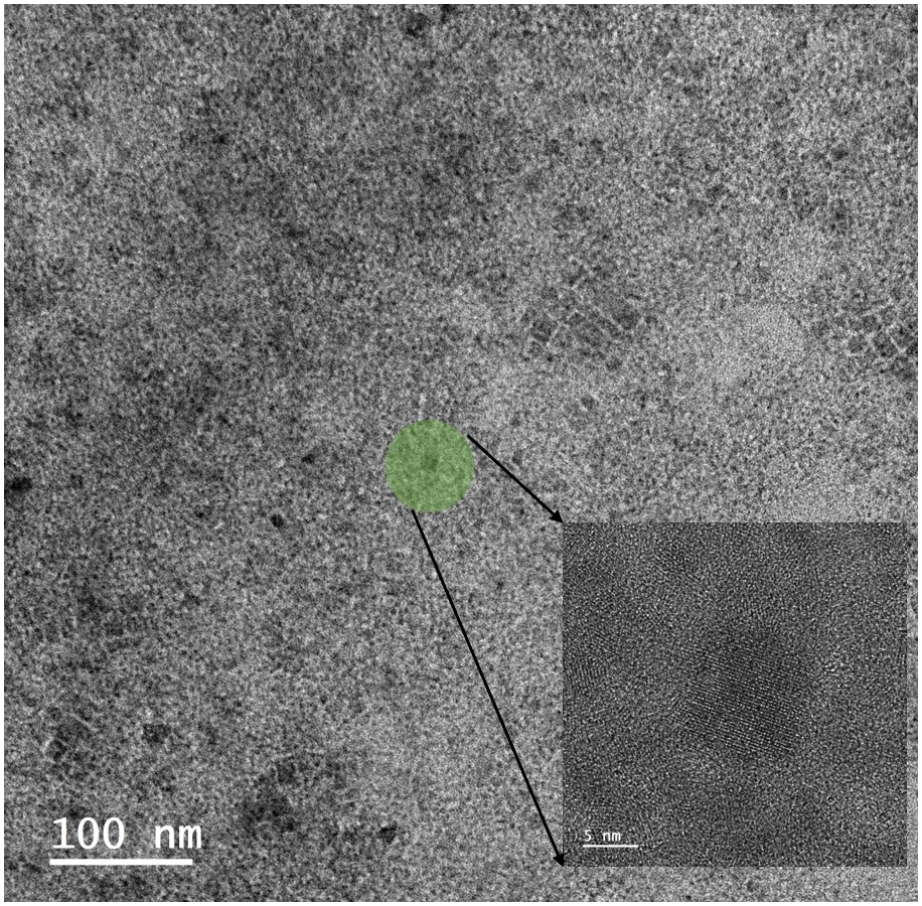

Figure S3. TEM images of the mixture of perovskite and CIS QDs.

4. UV-visible absorption spectra of the perovskite and CIS quantum composites

To investigate the optical property of the individual perovskite and CIS QDs, UV-visible absorption spectra were measured for the solution state. The photoluminescence (PL) spectra were obtained using a 405 nm laser and MAYA 2000 spectrophotometer. The absorption spectra were obtained on a UV-visible spectrometer (Agilent 8453). The absorption spectra were obtained for the QD films, which were fabricated by a spin-coating on the sapphire substrate. The perovskite and CIS quantum composites showed distinct absorption spectra corresponding to orange, green, and blue-emitting QDs.

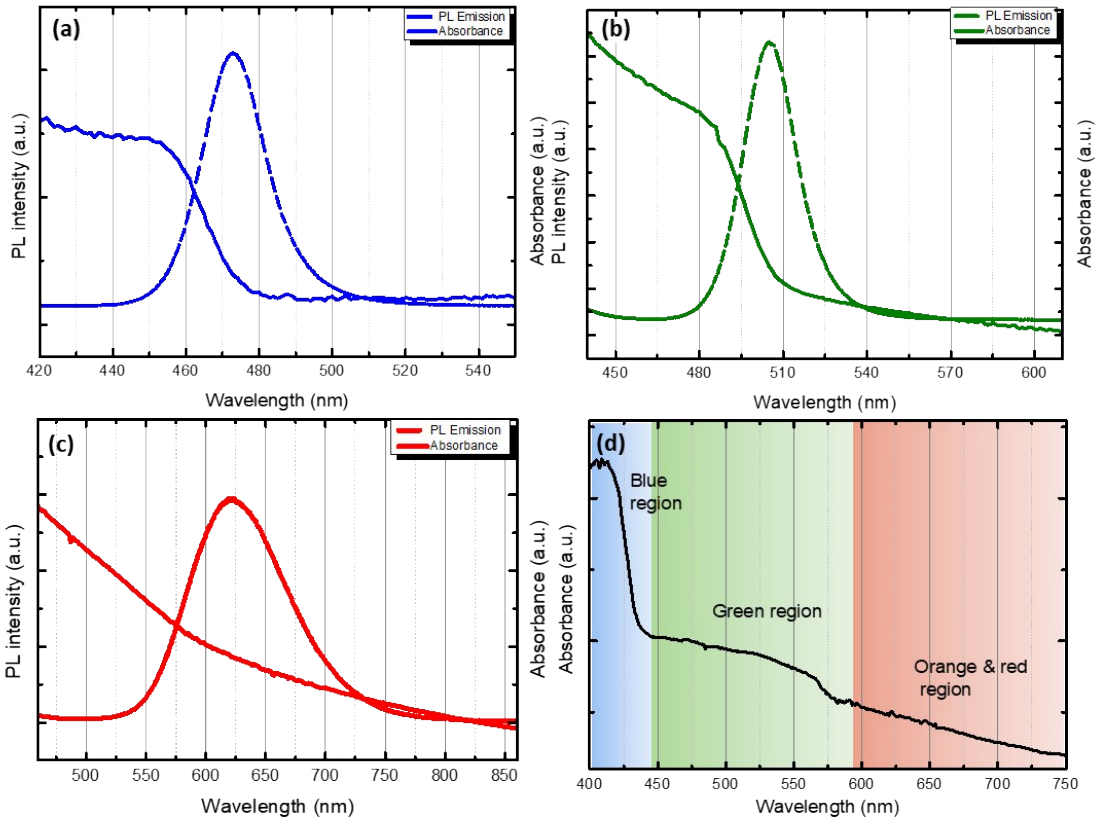

Figure S4. Photoluminescence spectra and UV-vis absorption spectra of (a) blue-emitting, (b) green-emitting perovskite $CsPb(Br_{1-x}Cl_x)_3$ QDs, and (c) orange-emitting CIS-QDs. (d) UV-vis absorption spectra of property of the perovskite and CIS quantum composites.

5. Current density-voltage (J-V) curves of the blue, green, and orange LEDs

To investigate the electrical characteristic of the LED devices consisting of individual perovskite and CIS QDs, J-V curves were measured for the blue, green, and orange LEDs. Figure S5 show the J-V curves of the blue and green perovskite QD-based LEDs and CIS QD-based orange LED. The devices consist of ITO/PEDOT:PSS/PVK/QDs layer/ZnO/Al structure, which is the same as the white LED. The relatively lower current density of the orange colour-emitting CIS QD-based LED would be due to the insulating behaviour of the longer ligands on the CIS QD. We washed off the excess ligands on the perovskite and CIS quantum composites with acetonitrile solvent after spin coating to solve these problems for the white LED.

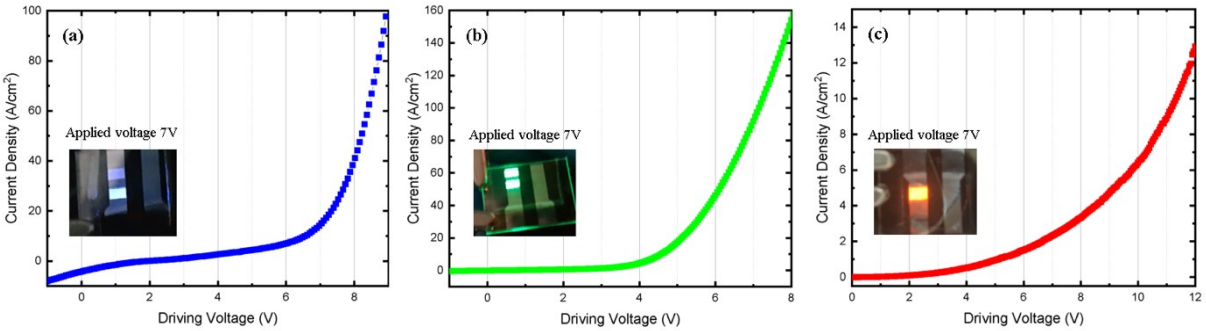

Figure S5. (a) J-V curves of blue-emitting perovskite $CsPb(Br_{1-x}Cl_x)_3$ QD and (b) green-emitting perovskite $CsPbBr_3$ QD, and (c) orange-emitting CIS-QDs based LEDs. All emission images of the LED devices were taken at a driving voltage of 7 V.

6. Summary table of the emission colour coordinates as a function of mixing ratio between blue and green emitting perovskite and red emitting CIS QDs

Table S1. Summary table of the emission colour coordinates as a function of mixing ratio between blue and green emitting perovskite and red emitting CIS QDs

Mixing ratio (R:G:B)	PL peak positions	CIE coordinates	Emission colour
0.25:1:1	**479/517/680 nm**	**(0.21, 0.34)**	**Sky bluish white**
0.5:1:1	**479/517/680 nm**	**(0.22, 0.33)**	**Sky bluish white**
1:1:1	**477/517/680 nm**	**(0.25, 0.35)**	**White**
1:1:2	**479/517/680 nm**	**(0.49, 0.36)**	**Reddish white**
1:1:4	**475/517/680 nm**	**(0.52, 0.36)**	**Reddish white**