

## Supplementary Materials

### Room temperature synthesis of perovskite for stable light-emitting diodes by tin doping and organic ligand

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## EXPERIMENTAL

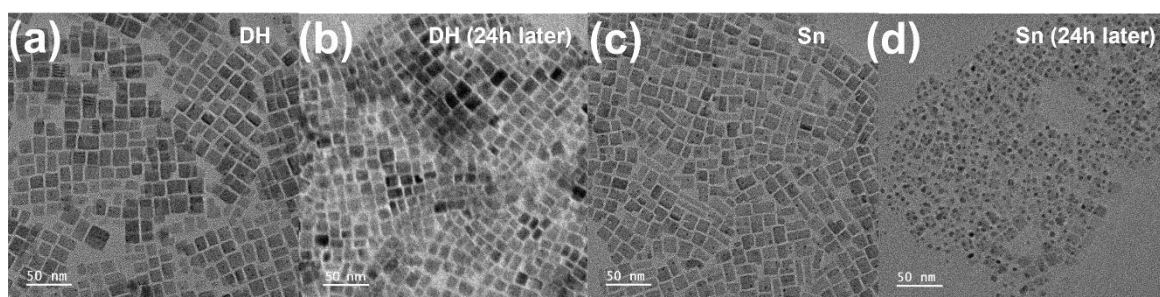
### Materials

[2-(9H-Carbazol-9-yl)ethyl]phosphonic Acid (2PACz, TCI), 2,2',2''-(1,3,5-Benzinetriyl)-tris(1-phenyl-1-H-benzimidazole) (TPBi, ITSCO), Lithium fluoride (LiF, ITSCO), Aluminum (Al, ITSCO), Dopamine hydrochloride (Sigma-Aldrich), N,N-dimethylformamide (DMF, Sigma-Aldrich, 99.8%), Dimethyl sulfoxide (DMSO, Sigma-Aldrich, 99.9%), chlorobenzene (CB, Sigma-Aldrich, 99.8%), CsBr, PbBr<sub>2</sub>, SnBr<sub>2</sub>, Oleic acid (OA, 90%, Sigma-Aldrich) and Oleylamine (OLA, 70%, Sigma-Aldrich) were used as received without further purification.

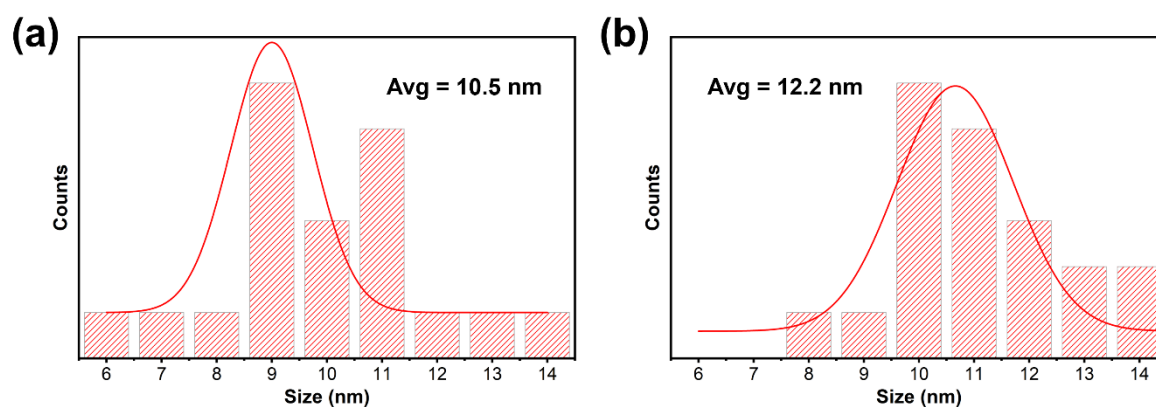
### Characterization

The size, morphology, and crystallinity of the nanoparticles were characterized by field-emission transmission electron microscopy (FE-TEM, JEOL, JEM-F200, Japan) in EDS. TEM images were obtained using high-resolution transmission electron microscopy (HR-TEM, FEI, USA). The lattice constant was determined from the HR-TEM images using GATAN software. The absorption spectra were obtained using a UV-vis spectrophotometer (Varian, Cary 50, USA). PL excitation and emission spectra were measured using a steady-state spectrofluorometer (PTI, QuantaMaster, Japan) with an excitation wavelength of 375 nm. XRD patterns were collected on a powder diffractometer (Bruker New D8-Advance, USA) with monochromatized Cu K $\alpha$  radiation ( $\lambda = 1.5418 \text{ \AA}$ ). XPS was performed using a

ULVAC- PHI X-TOOL instrument. PLQY was measured using a spectrofluorometer (JASCO, FP- 8500, Japan) with an integrating sphere. TRPL was measured with time-resolved fluorescent spectrophotometer (Edinburgh Instruments, FLS1000-DD-stm, UK). Device data of the PeLED were recorded using the M761 OLED IVL-test system (MC Science, Republic of Korea), CS150 (MC Science, Republic of Korea), and Keithley 2614B (I.V solution).

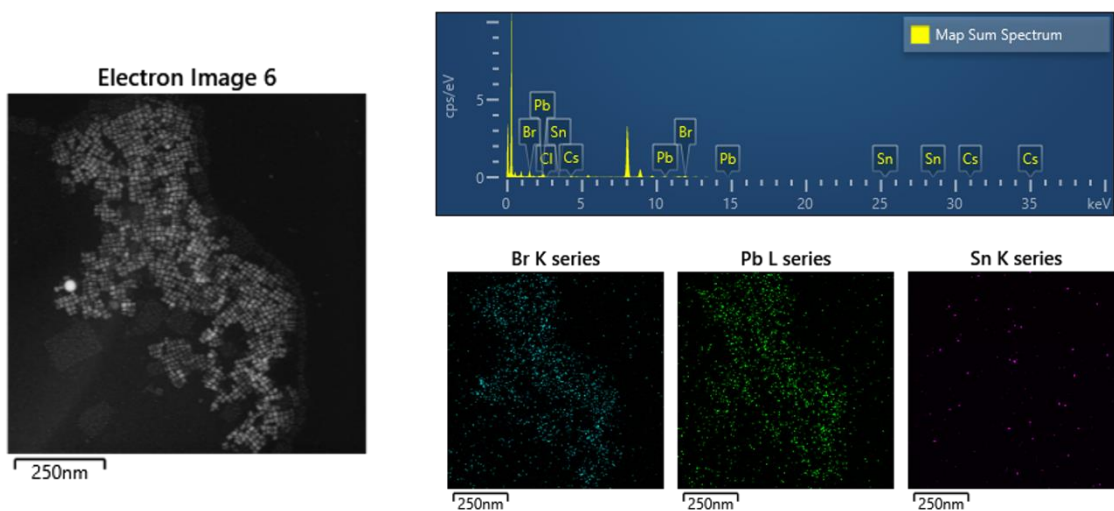


**Supplementary Figure 1.** TEM images of DH, Sn treated perovskite a, c as-prepared and b, d after 24 hours

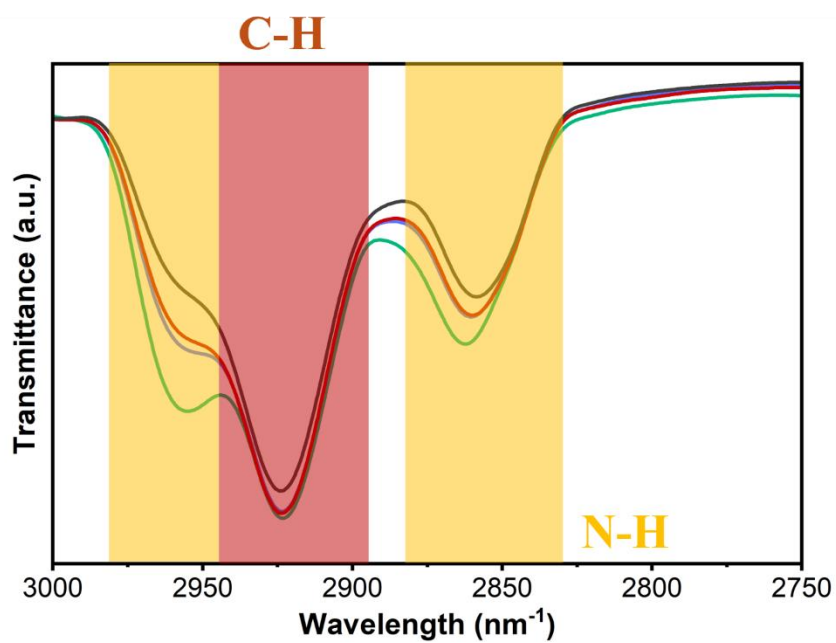


**Supplementary Figure 2.** Size distribution of as-prepared a pristine and b Sn:DH.

## Energy Materials

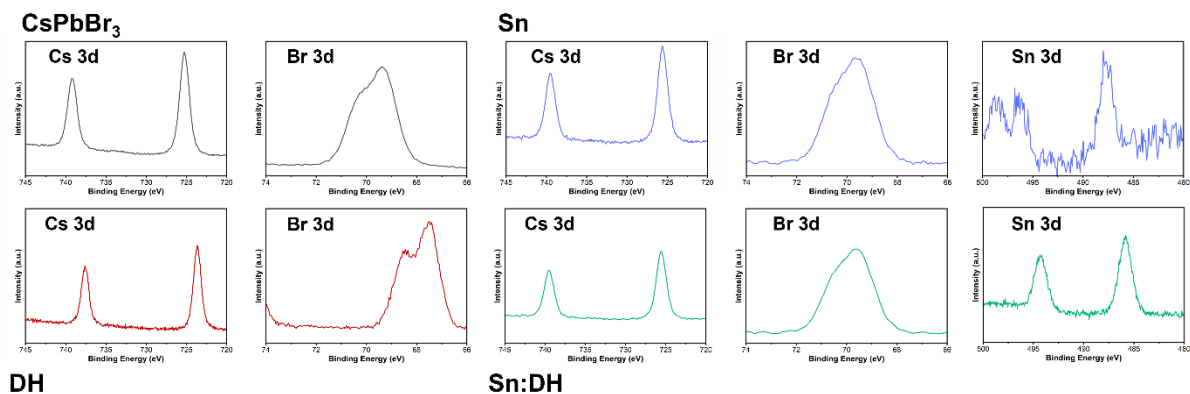


**Supplementary Figure 3.** The TEM-EDS image of Sn:DH.

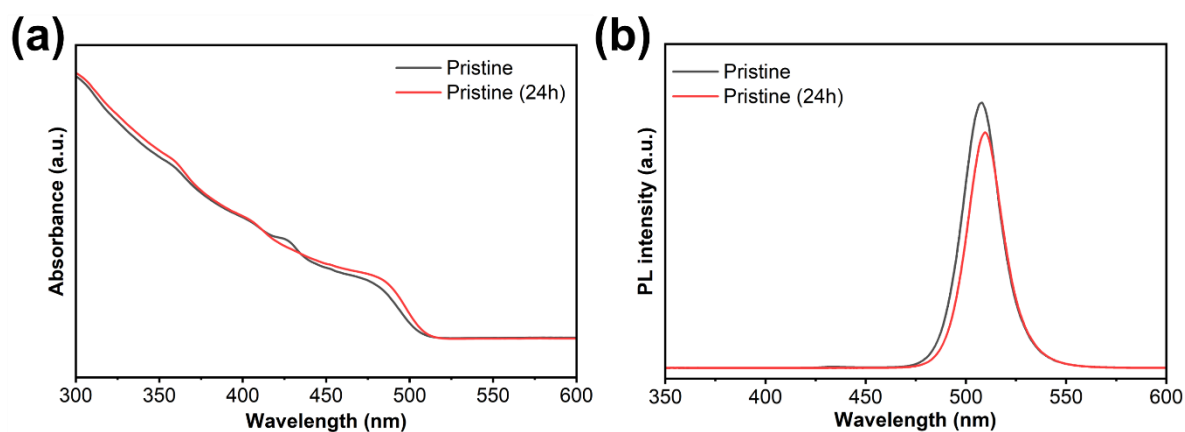


**Supplementary Figure 4.** Chemical analysis depending on doping of Sn and injecting DH. Magnified FT-IR spectra related to C-H, N-H stretching vibrations.

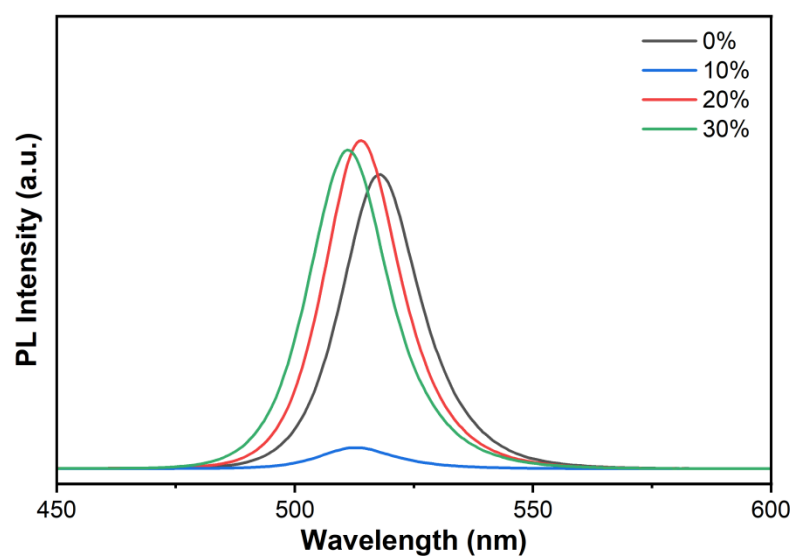
## Energy Materials



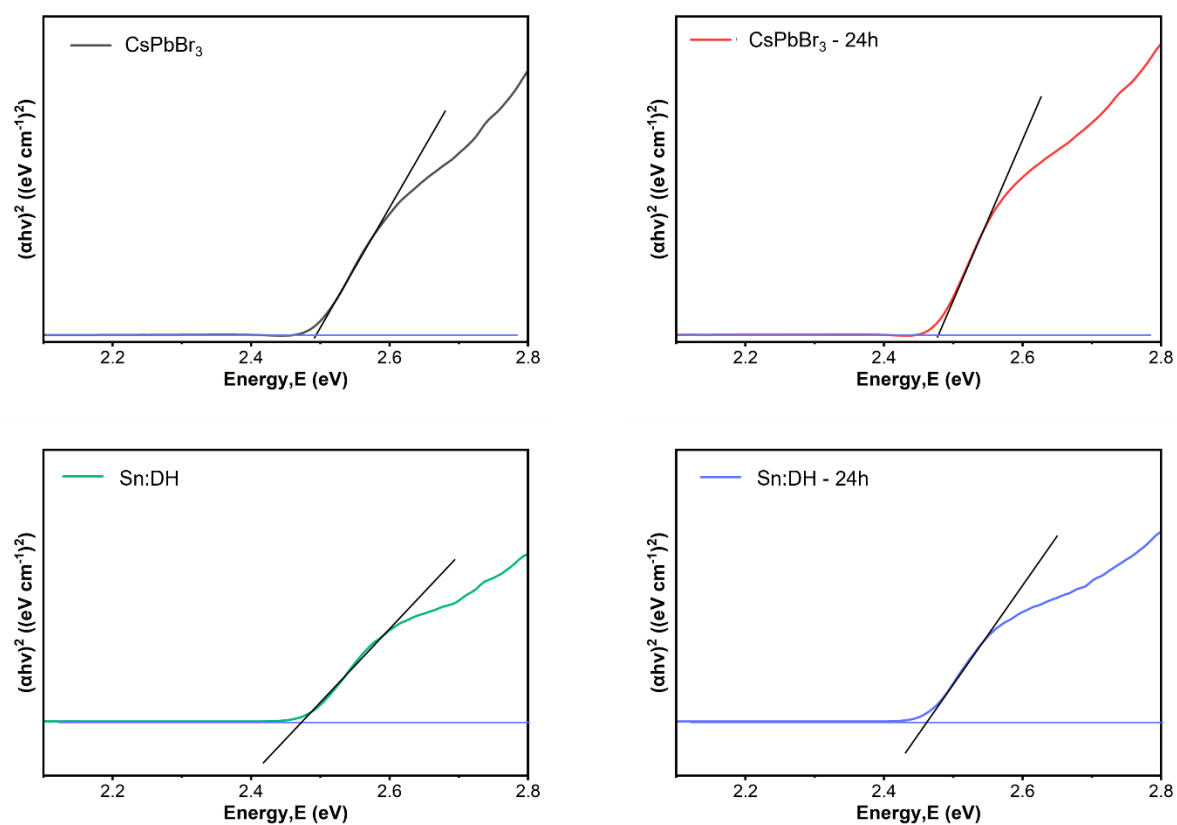
**Supplementary Figure 5.** XPS spectra of perovskites depending on the doping of Sn, and injection of DH.



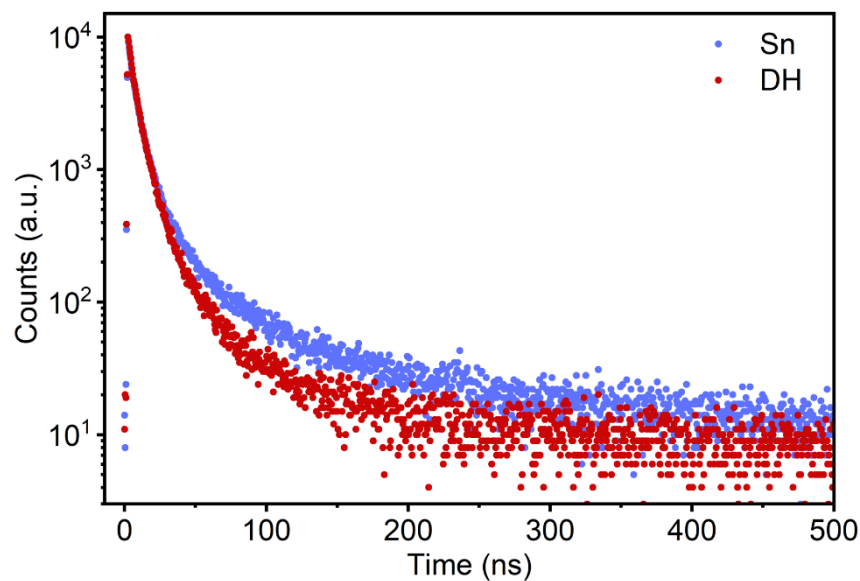
**Supplementary Figure 6.** (a) UV-vis absorbance spectra and (b) PL spectra of pristine perovskite



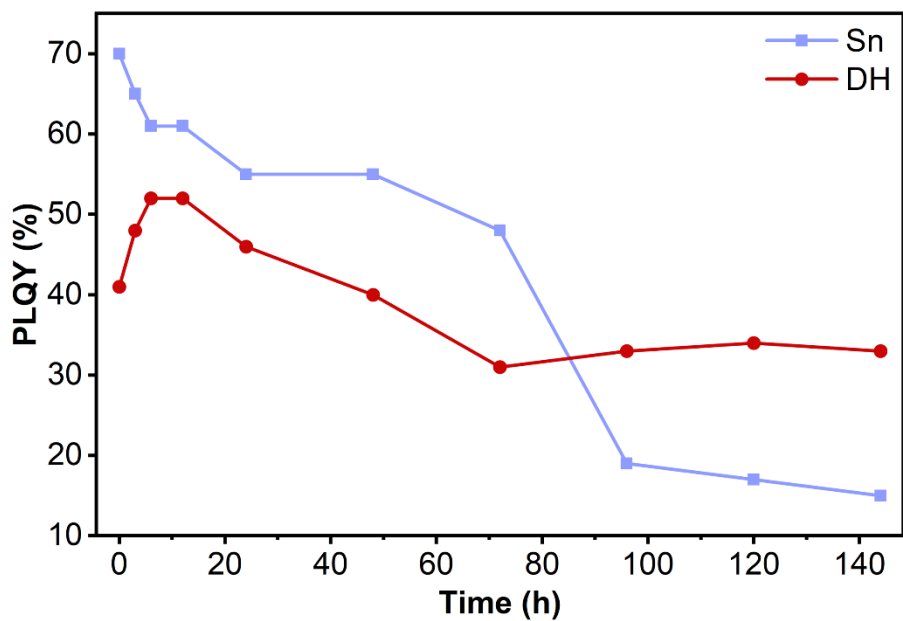
**Supplementary Figure 7.** PL spectra of CsPbBr<sub>3</sub> depending on doping concentration of Tin.



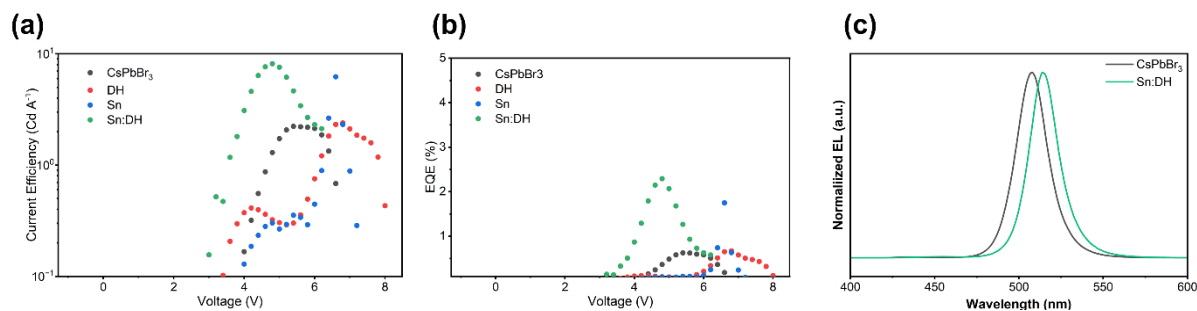
**Supplementary Figure 8.** Tauc plots of perovskite depending on Sn,DH treatment and aging for 24 hour



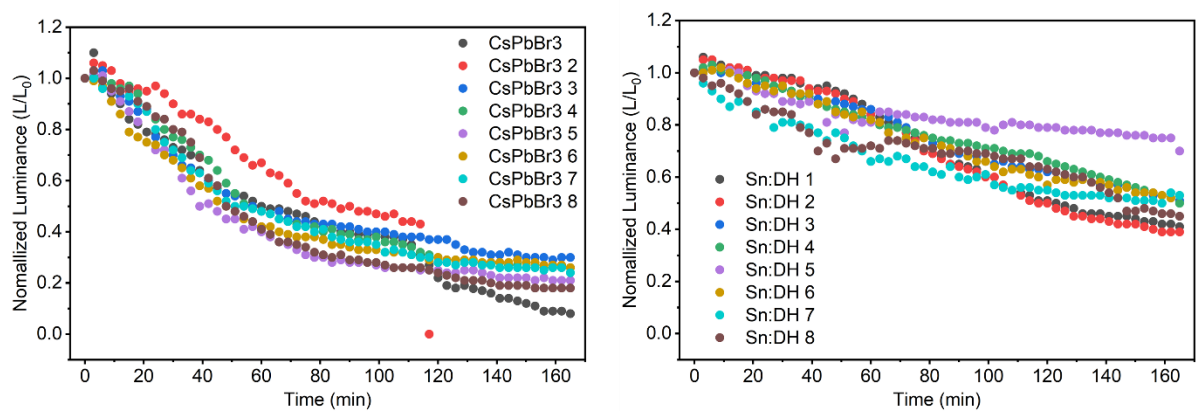
Supplementary Figure 9. TRPL decay curves of Sn, DH treated perovskites



Supplementary Figure 10. Time-dependent PLQY of Sn, DH-treated perovskites until 144 hours



**Supplementary Figure 11.** Electrical properties of PeLEDs. (a) Current efficiency, and (b) EQE of PeLEDs. (c) EL spectra of pristine CsPbBr<sub>3</sub> and Sn:DH measured at 4V.



**Supplementary Figure 12.** Operational stability of CsPbBr<sub>3</sub>-devices, and Sn:DH-devices.

**Supplementary Table 1. Wt% and atomic % of Sn:DH from TEM-EDS**

|       | Line     | k factor | K factor    | Absorption | Wt%    | Wt%   | Atomic % |
|-------|----------|----------|-------------|------------|--------|-------|----------|
|       | type     |          | type        | Correction |        | sigma |          |
| Br    | K series | 2.454    | Theoretical | 1.00       | 34.11  | 6.92  | 51.80    |
| Sn    | K series | 33.898   | Theoretical | 1.00       | 1.98   | 7.82  | 2.02     |
| Cs    | K series | 85.414   | Theoretical | 1.00       | 26.69  | 13.63 | 24.37    |
| Pb    | L series | 3.107    | Theoretical | 1.00       | 37.23  | 7.58  | 21.80    |
| Total |          |          |             |            | 100.00 |       | 100.00   |

**Supplementary Table 2. XRD peak values of CsPbBr<sub>3</sub> and Sn:DH with crystallite size calculated by Scherrer equation**

|                             | <b>2θ</b><br>(deg) | <b>FWHM</b><br>(deg) | <b>D-spacing</b><br>(Å) | <b>Crystallite<br/>size</b><br>(nm) | <b>Lattice strain</b><br>(ε) |
|-----------------------------|--------------------|----------------------|-------------------------|-------------------------------------|------------------------------|
| CsPbBr <sub>3</sub>         | 15.3               | 1.02                 | 5.80                    | 7.86                                | 0.033                        |
| 24h-<br>CsPbBr <sub>3</sub> | 15.23              | 1.13                 | 5.81                    | 7.08                                | 0.037                        |
| Sn:DH                       | 15.1               | 1.21                 | 5.87                    | 6.64                                | 0.040                        |
| 24h-Sn:DH                   | 15.19              | 1.13                 | 5.82                    | 7.08                                | 0.037                        |

**Supplementary Table 3. The stoichiometric composition of CsPbBr<sub>3</sub> and Sn:DH calculated from XPS spectra**

|                     | <b>Cs 3d</b> | <b>Pb 4f</b> | <b>Br 3d</b> | <b>Sn 3d</b> |
|---------------------|--------------|--------------|--------------|--------------|
| CsPbBr <sub>3</sub> | 1.15         | 0.68         | 3.29         | 0            |
| Sn:DH               | 0.67         | 0.35         | 2.28         | 0.09         |

**Supplementary Table 4. Optical properties of pristine and Sn:DH perovskite both as-prepared and after 24 hours**

|              | <b>Pristine</b> | <b>Pristine 24h</b> | <b>Sn:DH</b> | <b>Sn:DH 24h</b> |
|--------------|-----------------|---------------------|--------------|------------------|
| PL peak (nm) | 508             | 509.5               | 514          | 514              |
| FWHM (nm)    | 21              | 21                  | 21           | 20               |
| PLQY (%)     | 67              | 57                  | 65           | 73               |

**Supplementary Table 5. Summary of the parameters from fitting four TRPL decay curves**

|                       | <b>Sn:DH</b> | <b>DH</b> | <b>Sn</b> | <b>Pristine</b> |
|-----------------------|--------------|-----------|-----------|-----------------|
| τ <sub>1</sub> (ns)   | 4.38         | 2.29      | 3.9       | 2.38            |
| τ <sub>2</sub> (ns)   | 18.99        | 10.16     | 12.83     | 8.94            |
| τ <sub>avg</sub> (ns) | 10.75        | 5.61      | 8.41      | 5.74            |

Supplementary Table 6. Electrical properties of pristine and Sn:DH perovskite-based PeLEDs

|                                          | Pristine     | Sn:DH        |
|------------------------------------------|--------------|--------------|
| Turn-on voltage (V)                      | 3.6          | 3.2          |
| Luminance (cd m <sup>-2</sup> )          | 4032         | 9522         |
| CIE coordination                         | (0.12, 0.77) | (0.11, 0.78) |
| Operational stability (min)              | 57           | 123          |
| Turn-on voltage at 10 cd m <sup>-2</sup> |              |              |