Electronic Supplementary Material (ESI) for Nanoscale.


# Supplementary information

## Co-Doping of Tellurium with Bismuth Enhances Stability and Photoluminescence Quantum Yield of $Cs_2AgInCl_6$ Double Perovskite Nanocrystals

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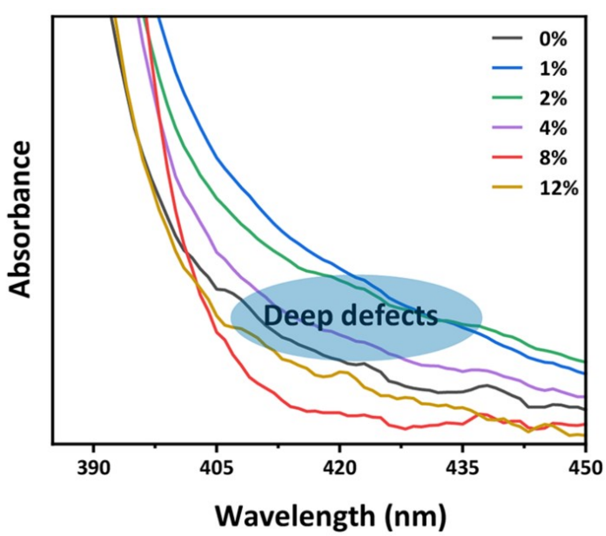


**Figure S1**. Absorption spectra (enlarged tail region) of $Cs_2AgInCl_6$:0% Te, 1% Bi and Te/Bi-co-doped ($Cs_2AgInCl_6$:x% Te, 1% Bi) NCs

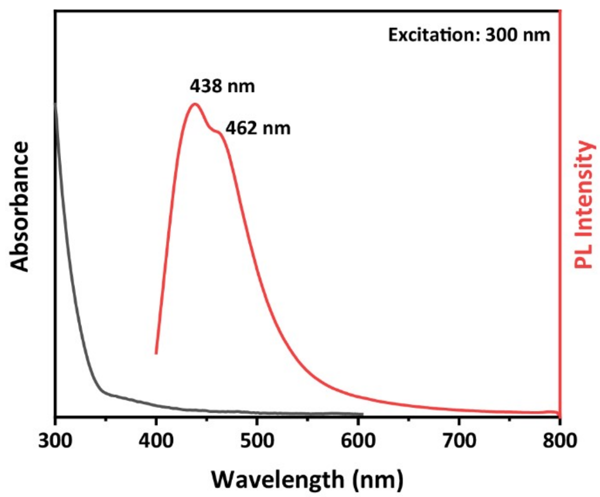


**Figure S2**. Absorption and PL spectra of $Cs_2AgInCl_6$ NCs solely doped by 8% tellurium precursors (without any Bi co-dopant).

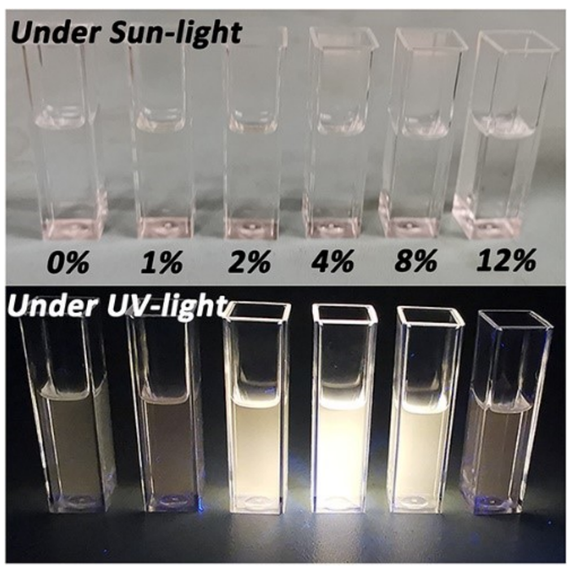


**Figure S3**. Photographs of $Cs_2AgInCl_6$:x% Te, 1% Bi NCs (x=0, 1, 2, 4, 8, and 12) under sun-light and UV-light. Note that in the bottom row the camera lens was focusing on the middle sample ($Cs_2AgInCl_6$:4% Te, 1% Bi NCs), otherwise the emission of samples with low PL QYs could hardly be observed.

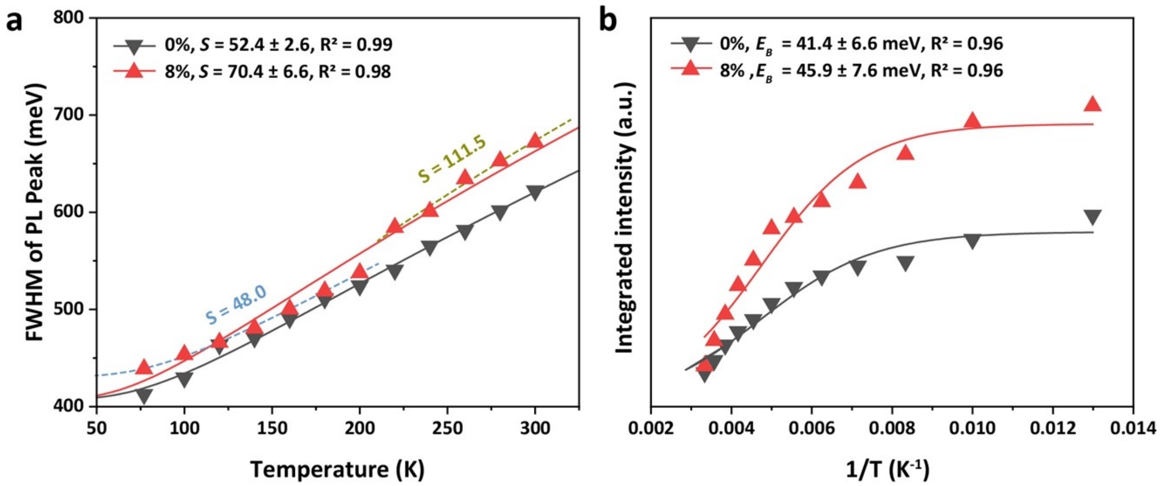


**Figure S4**. (a) Thermal evolution of the PL FWHM and (b) temperature-dependent integrated PL intensity of $Cs_2AgInCl_6$:0% Te, 1% Bi and $Cs_2AgInCl_6$:8% Te, 1% Bi NCs.

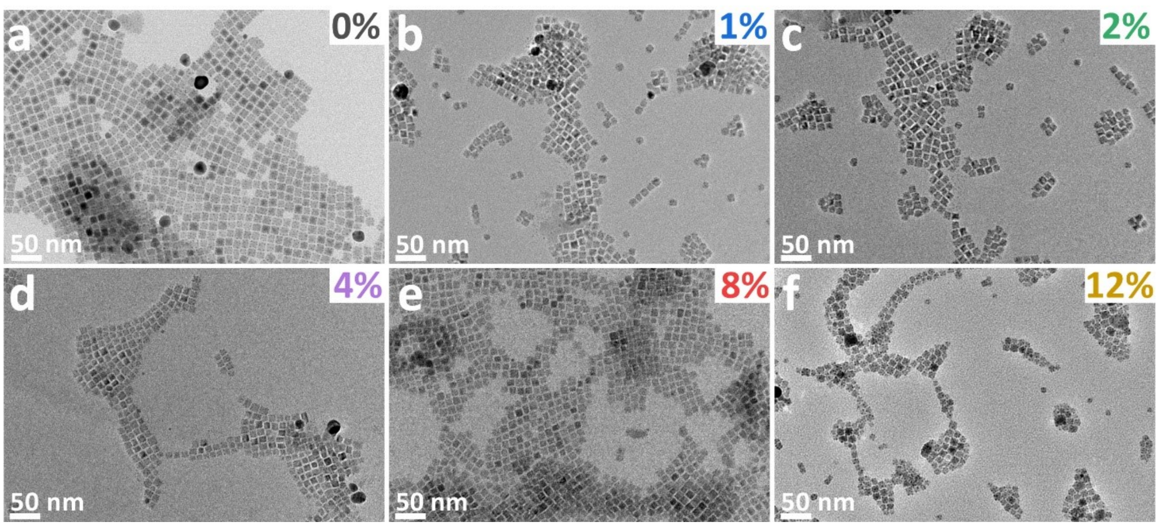


**Figure S5**. Wide-view TEM images of $Cs_2AgInCl_6$:x% Te, 1% Bi NCs (x=0, 1, 2, 4, 8, 12).

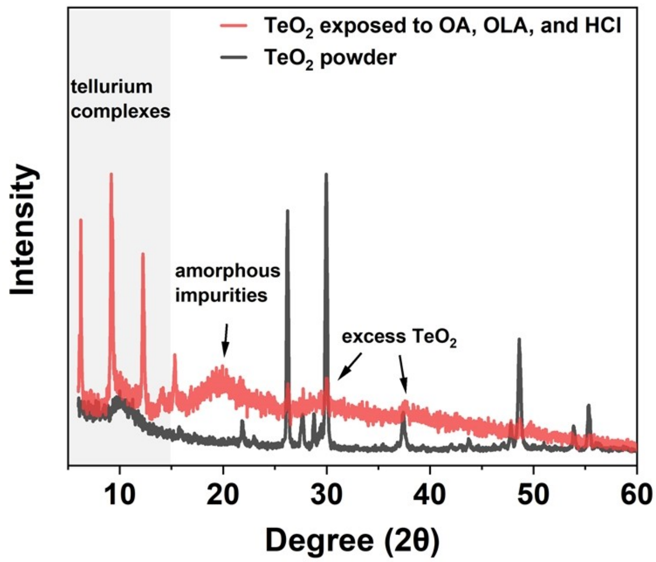


**Figure S6.** XRD pattern of $TeO_2$ precursor in the original form and exposed to OA, OLA, and hydrogen chloride. Emerging diffraction peaks below 15$^{o}$ could belong to tellurium complexes such as $R_2TeO$ and/or $Te_2O_3Cl_2$.

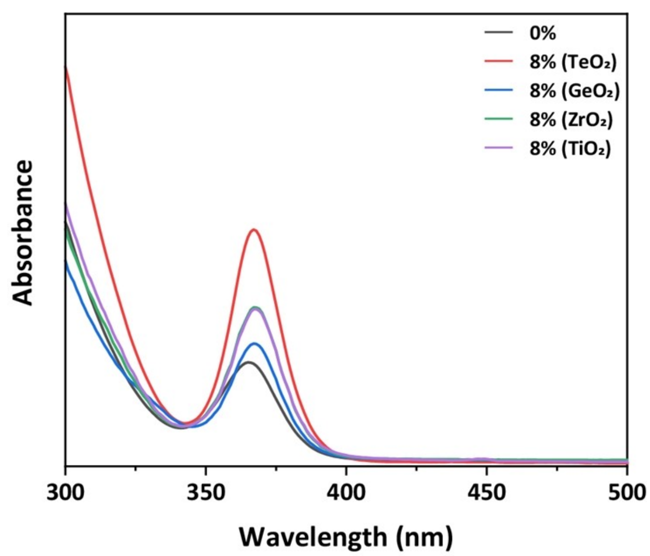


**Figure S7**. Absorption spectra of $Cs_2AgInCl_6$:0% Te, 1% Bi NCs, $Cs_2AgInCl_6$:8% Te, 1% Bi NCs (fed by 8% $TeO_2$), and NCs fed by 1% Bi and 8% of inert dioxides $GeO_2$, $ZrO_2$, and $TiO_2$.

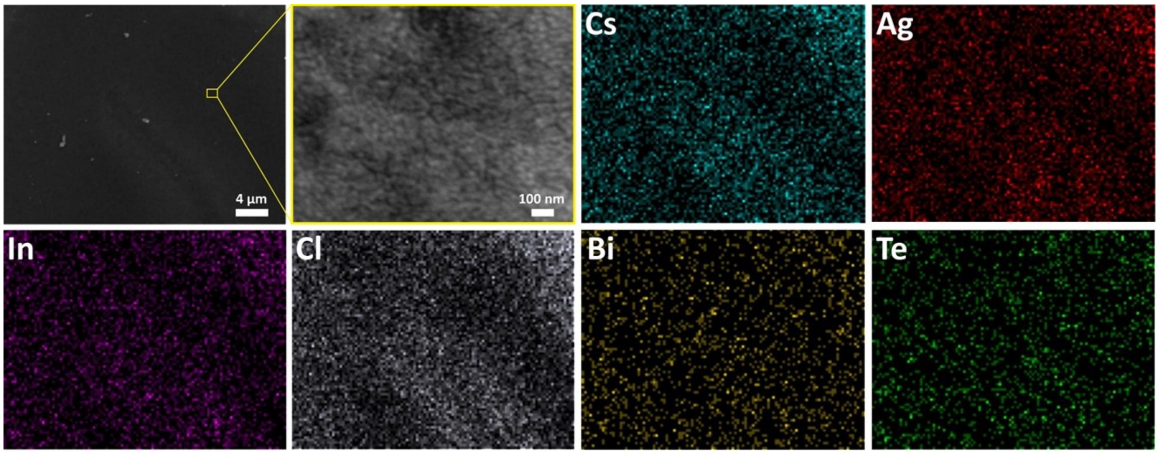


**Figure S8**. SEM image, and corresponding elemental mapping images for Cs, Ag, In, Cl, Bi and Te elements of thin films based on $Cs_2AgInCl_6$:8% Te, 1% Bi NCs that were stored in the refrigerator for around one month.

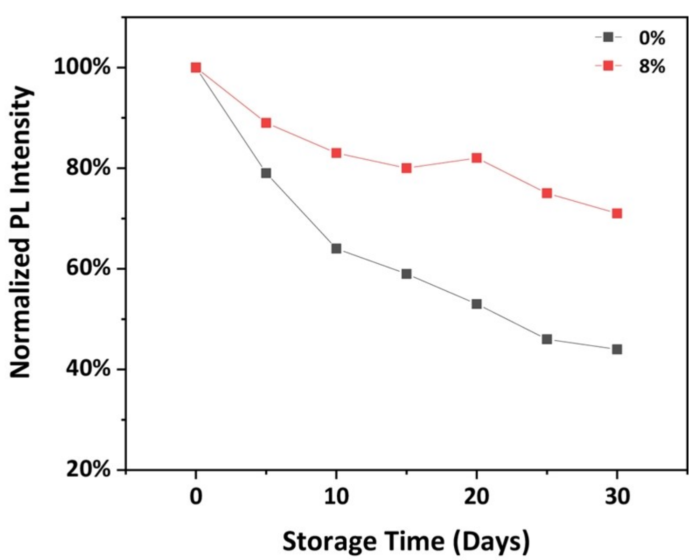


**Figure S9**. Normalized PL intensity of $Cs_2AgInCl_6$:0% Te, 1% Bi and $Cs_2AgInCl_6$:8% Te, 1% Bi NCs after storing in the refrigerator for around one month.

**Table S1**. Comparison of the PL characteristics of the $B^{III}$ site doped $Cs_2AgInCl_6$ NCs. RT: room temperature.

| Composition (NCs) | Reaction temperature | Excitation | PL peak | PL QY | Year | Refs |
|---|---|---|---|---|---|---|
| $Cs_2AgInCl_6$ | 105 °C | 300 nm | 560 nm | 1.6% | 2018 | 1 |
| $Cs_2AgInCl_6$:1.6% Mn | 105 °C | 290 nm | 620 nm | 16% | 2018 | 1 |
| $Cs_2AgIn_{0.9}Bi_{0.1}Cl_6$ | RT | - | 570 nm | 2% | 2018 | 2 |
| $Cs_2AgInCl_6$ | 100 °C | 300 nm | > 550 nm | 0.6% | 2019 | 3 |
| $Cs_2AgInCl_6$:1% Bi | 260 °C | 368 nm | 580 nm | 11.4% | 2019 | 4 |
| $Cs_2AgInCl_6$: $Cu^{2+}$ | 220 °C | 350 nm | 460 nm | - | 2020 | 5 |
| $Cs_2AgInCl_6$: 1% Bi-2% Ce | 260 °C | 375 nm | 580 nm | 26% | 2021 | 6 |
| **$Cs_2AgInCl_6$:8% Te, 1% Bi** | 280 °C | 370 nm | 591 nm | 34% | **This work** | |

**Table S2**. Optical parameters of $Cs_2AgInCl_6$:x% Te, 1% Bi NCs (x=0, 1, 2, 4, 8, 12), including PL QY, average lifetime of excitons $\tau_{avg}$ and the radiative recombination rate $K_r$.

| Samples | PL QY (%) | $\tau_{avg}$ (μs) | $K_r$ ($\times 10^5$ $s^{-1}$) |
|---|---|---|---|
| $Cs_2AgInCl_6$: 0% Te, 1% Bi | 12 | 1.06 | 1.13 |
| $Cs_2AgInCl_6$: 1% Te, 1% Bi | 5 | 0.63 | 0.79 |
| $Cs_2AgInCl_6$: 2% Te, 1% Bi | 13 | 0.94 | 1.38 |
| $Cs_2AgInCl_6$: 4% Te, 1% Bi | 22 | 1.11 | 1.98 |
| $Cs_2AgInCl_6$: 8% Te, 1% Bi | 34 | 0.96 | 3.54 |
| $Cs_2AgInCl_6$: 12% Te, 1% Bi | 10 | 1.05 | 0.95 |

**Table S3**. XPS analysis of elemental ratios in $Cs_2AgInCl_6$ NCs doped by 1% Bi and different amounts of Te.

| Samples | Cl:In | In:Ag | Cl:Ag |
|---|---|---|---|
| $Cs_2AgInCl_6$:0% Te, 1% Bi | 6.4 | 1.2 | 7.5 |
| $Cs_2AgInCl_6$:1% Te, 1% Bi | 6.5 | 1.2 | 7.7 |
| $Cs_2AgInCl_6$:8% Te, 1% Bi | 5.9 | 1.1 | 6.7 |
| $Cs_2AgInCl_6$:12% Te, 1% Bi | 6.5 | 1.2 | 7.5 |

**References**


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