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Cell refinement of CsPbBr₃ perovskite nanoparticles and thin films

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In this work, we performed a detailed study of the phase transformations and structural unit cell parameters of CsPbBr₃ nanoparticles (NPs) and thin films. *In situ* X-ray diffraction patterns were acquired as a function of temperature, where the positions and widths of the diffraction peaks were systematically tracked upon heating and cooling down to room temperature (RT). Scanning electron microscopy provides physical insight on the CsPbBr₃ thin films upon annealing and transmission electron microscopy gives physical and crystallographic information for the CsPbBr₃ NPs using electron diffraction. The secondary phase(s) CsPb₂Br₅ (and CsPb₄Br₆) are clearly observed in the XRD patterns of both nanoparticles and thin films upon heating to 500 K, whilst from 500 K to 595 K, these phases remain in small amounts and are kept like this upon cooling down to RT. However, in the case of thin films, the CsPb₂Br₅ secondary phase disappears completely above 580 K and pure cubic CsPbBr₃ is observed up to 623 K. The CsPbBr₃ phase is then kept upon cooling down to RT, achieving pure CsPbBr₃ phase. This study provides detailed understanding of the phase behavior vs. temperature of CsPbBr₃ NPs and thin films, which opens the way to pure CsPbBr₃ phase, an interesting material for optoelectronic applications.

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Introduction

Organic–inorganic halide perovskites have become very popular in the photovoltaic field during the last six years owing to their attractive structural and physical properties, achieving a photovoltaic power conversion efficiency today of more than 22%.¹ Organic–inorganic perovskites usually contain three-dimensional arrays of inorganic PbX₆ anions surrounded by organic ammonium counter ions or by inorganic counter ions, most commonly Cs⁺. In 1958, CsPbX₃ (where X = Cl, Br or I) was reported for the first time,² where the use of an inorganic cation in the form of Cs⁺ makes it a completely inorganic perovskite with the potential for better stability. Since then, there has been growing interest in thin films of CsPbX₃ and, more recently, in CsPbX₃ nanoparticles (NPs). The complexity of the preparation of CsPbX₃ thin films depends on the halide being used. CsPbI₃ films are more challenging in terms of stability while CsPbBr₃ are more stable (mainly for optoelectronic activity) after their deposition on the substrate. On the other hand, recent reports^{3,4} on colloidal synthesis of CsPbX₃ show that CsPbI₃, CsPbBr₃ or CsPbCl₃ NPs are much more stable than their corresponding thin films. CsPbBr₃ and CsPbI₃ (thin films and NPs) have a preferred orthorhombic structure with *Pnma* space group at room temperature.^{5–7}

In the case of CsPbBr₃, there are several reports that also present a secondary phase of CsPb₂Br₅,⁸ some relating the CsPb₂Br₅ to be tetragonal with an indirect band gap,⁹ while others successfully synthesized an all-inorganic composite of CsPbBr₃–CsPb₂Br₅ that works as the emitting layer in a light emitting diode (LED) exhibiting high external quantum efficiency (EQE).¹⁰ Recently, Dursun *et al.* synthesized single crystals of CsPb₂Br₅ revealing its structure to be two-dimensional with Cs⁺ in between Pb₂Br₅[−] layers having an approximately 3.1 eV indirect band gap and inactive photoluminescence (PL).¹¹

In this study, we performed X-ray diffraction (XRD) measurements at various temperatures for CsPbBr₃ NPs and films (bulk) up to a maximum temperature of 623 K. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used to support the XRD measurements. The XRD patterns were taken every 10–15 K (see Experimental section) upon heating and also during cooling back to room temperature (RT). We carefully followed the structural phase transformations with temperature in air. We successfully recognized the secondary phase CsPb₂Br₅ in both thin films and NPs; interestingly, this phase appears in a very small quantity upon annealing to 573 K and importantly it disappears completely above 580 K in the case of thin films and also stays like this when cooling down back to RT. This paves the way to synthetically avoiding the parasitic CsPb₂Br₅ phase, which seems to be insulating and optically inactive, in the case of CsPbBr₃ thin film.

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Results and discussion

In this work, *in situ* XRD was performed at different temperatures for CsPbBr₃ NPs and thin films. The samples were heated from RT to 573 K and 623 K for thin films and NPs, respectively, then cooled back down to RT.

A main structural change is observed by *in situ* powder XRD measurements upon heating (and cooling) for CsPbBr₃ at ~ 390 K corresponding to the orthorhombic/cubic phase transition (Fig. 1). For the NPs, a pure orthorhombic CsPbBr₃ phase is observed at RT before heating, while thin films show tetragonal CsPb₂Br₅ and orthorhombic CsPbBr₃ phases. The CsPb₂Br₅ presence is attributed to the perovskite-based crystallization process that occurs during the preparation of the homogenous perovskite thin film on the substrate. The peak width is wider in the case of the NPs, indicating smaller crystallites than for thin films. The extended Debye–Scherrer method developed by Williamson–Hall was used on the XRD data in order to try to determine the crystal size based on the peak shapes and FWHM. However, the method also depends on the morphology and shape of particles and is strongly related to the X-ray beam orientation over the film to be analyzed. In addition, when peaks become too sharp it is usually impossible to determine crystal sizes this way. Small angle X-ray scattering (SAXS) could be a useful method to determine the crystallite size, although it is rather complicated to use *versus* temperature. The insets in Fig. 1 show the peak deviations and phase transformations that occur upon heating with the general disappearance of the double peaks related to the distorted orthorhombic phase

observed at low temperature to a single peak (with $K\alpha_1$ and $K\alpha_2$) related to the cubic phase. For instance, (002) and (101) transform into (100) Miller indices at $2\theta \sim 15^\circ$, (040) and (202) into (200) at $\sim 30^\circ$, and (240) and (321) into (211) at $\sim 37.5^\circ$.

Profile matching refinements using the Rietveld method and the FULLPROF program were performed on all the XRD data as a function of temperature in order to verify the phase symmetries and precisely determine the unit cell variations. Cell parameters, zero shift and peak shape factors (U, V and W from Caglioti's formula) were refined for each pattern. Fig. 2 shows the refined data at RT before and after *in situ* XRD thermal treatment, as well as at the highest temperature for both NPs and thin films. A very good match was found between the observed and calculated data (all reliability factors are $2.2 < \chi^2 < 4.7$ and $0.12 < R_{wp} < 0.26$, after Rietveld refinements), confirming the theoretical models, and refinements can be used for precisely determining the crystal unit cell at different temperatures. Note that peak shapes are sharper at RT after annealing owing to crystal size growth after the heating process.

Fig. 3b shows the unit cell parameters changes with temperature. In the case of the NPs, the orthorhombic structure is described with the *Pnma* space group (also mentioned in the literature as *Pbnm* with a different origin choice),^{6,12} and cell parameters are $a = 8.240(2)$ Å, $b = 11.755(2)$ Å and $c = 8.210(2)$ Å. The peak shifts observed with the temperature increase correspond to a thermal cell expansion and for the cubic phase the cell parameter is equal to $5.9061(4)$ Å (*Pm $\bar{3}m$*) at 623 K. When cooling down to RT, the orthorhombic CsPbBr₃ phase exhibits $a = 8.2638(5)$ Å, $b = 11.6107(7)$ Å and $c = 8.1959(6)$ Å unit cell

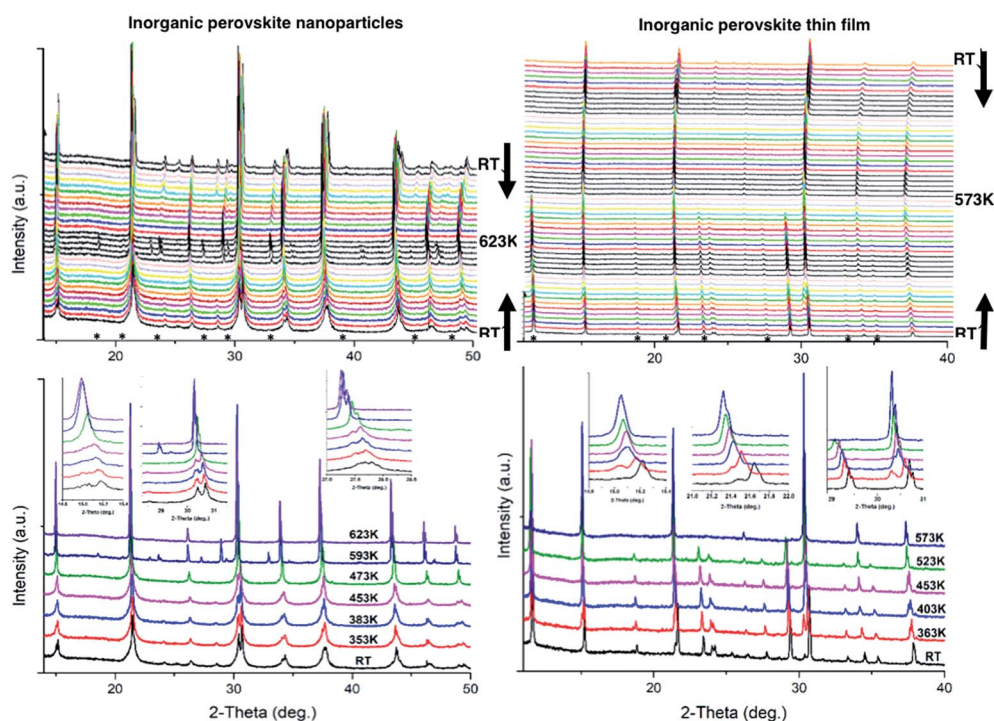


Fig. 1 X-ray diffraction patterns recorded *in situ* at different temperatures for (left) CsPbBr₃-based nanoparticles and (right) thin films. Scan step is every 15 K from 308 K to 623 K (top left) and every 10 K in the 303–573 K temperature range (top right) upon cooling and heating. Selected XRD patterns are shown with particular areas in insets. Asterisk symbolizes the CsPb₂Br₅ phase.



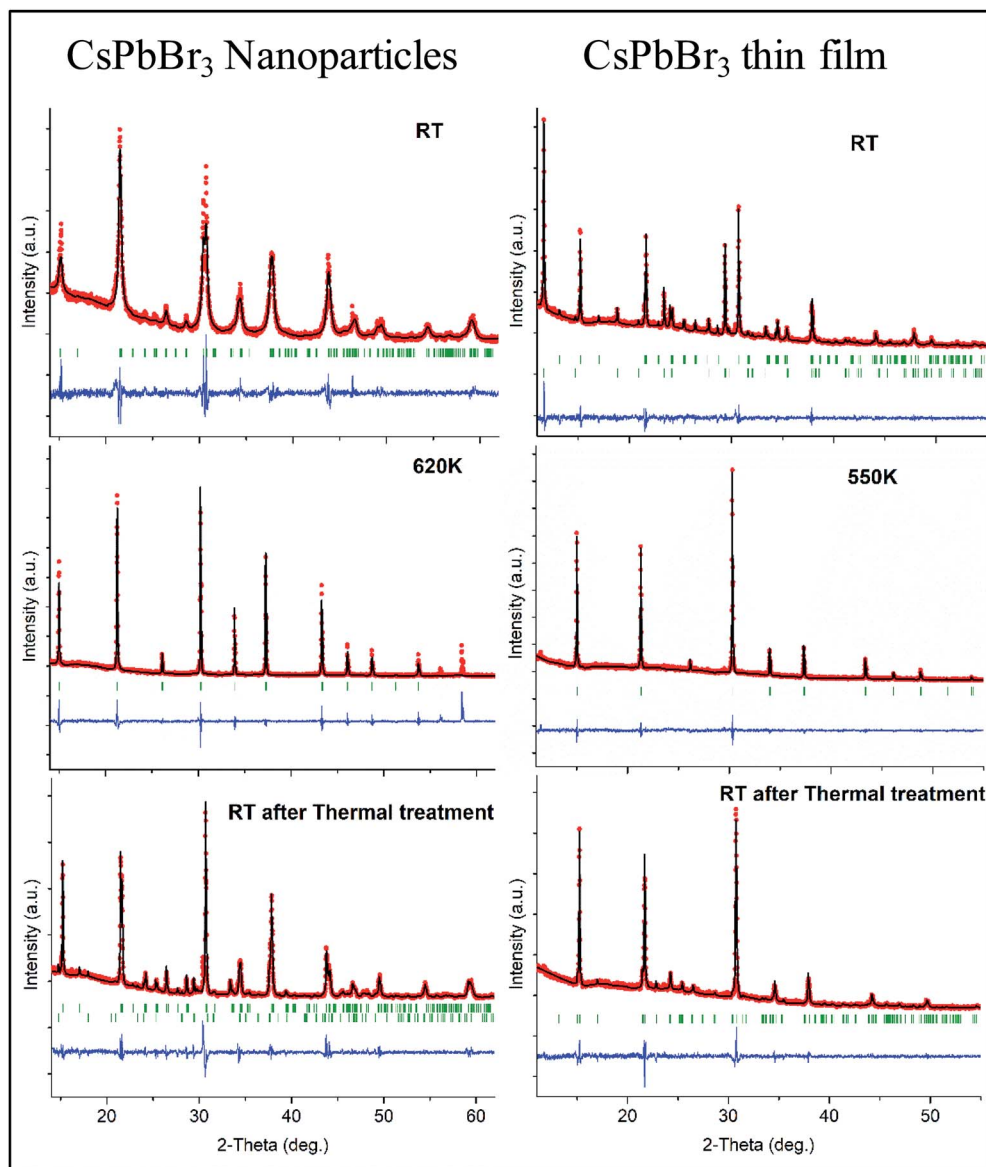


Fig. 2 Profile matching of the XRD patterns for (left) CsPbBr₃-based NPs and (right) thin films. At RT before *in situ* XRD heating measurements (top), highest temperature (middle) and back to RT (bottom). Symbols correspond to the observed (red dots), calculated (black line), difference (blue line below) XRD patterns and Bragg peaks (green vertical lines).

parameters. The peak full width at half maximum (FWHM or H_w) is then on average half the value (for instance, $H_w = 0.13$ at $2\text{-theta} = 15.1^\circ$) of the one measured before heat treatment ($H_w = 0.28$), characterizing a wider crystallite size. A bigger change in the 'c' unit cell parameter is observed for the NPs compared to the thin film between heating and cooling, which indicates that there might be a preferred orientation or stronger distortion along the c-axis during the synthesis process. The distorted octahedral environments of Pb²⁺ and unit cell differences are attenuated owing to structural rearrangement after heating. The minority phase CsPb₂Br₅ left at RT after thermal treatment, presents $a = b = 8.484(1)$ Å and $c = 17.362(2)$ Å cell parameters with *I4/mcm* space group. The temperature and excess Pb²⁺ are two key factors for the formation of CsPbBr₃/CsPb₂Br₅ mixtures. During the synthesis processes, the evolution between CsPb₂Br₅

and CsPbBr₃ is reversible in a solution of superfluous Pb²⁺ and Br[−]. In our case, pure nanocrystals of cube-like shape were obtained at RT and upon heating in air these nanoparticles drive to the appearance of a small quantity of CsPb₂Br₅ dispersed with the main CsPbBr₃ phase. Li *et al.*⁹ showed that tetragonal CsPb₂Br₅ nanosheets are obtained by an oriented attachment of orthorhombic CsPbBr₃ nanocubes by varying the ligands, involving a lateral shape evolution from octagonal to square. The shape and phase evolution from CsPbBr₃ to CsPb₂Br₅ demonstrated that the reaction could take place at 397 K (in the solvent with a negative Gibbs variation). CsPb₂Br₅ prefers growing horizontally at two crystal facets (100) and (110) and forms 2D layer structures with Pb and Br elements while Cs is between the two layers. As the nanocrystals grew, the evolution between CsPbBr₃ and CsPb₂Br₅ persisted. However,



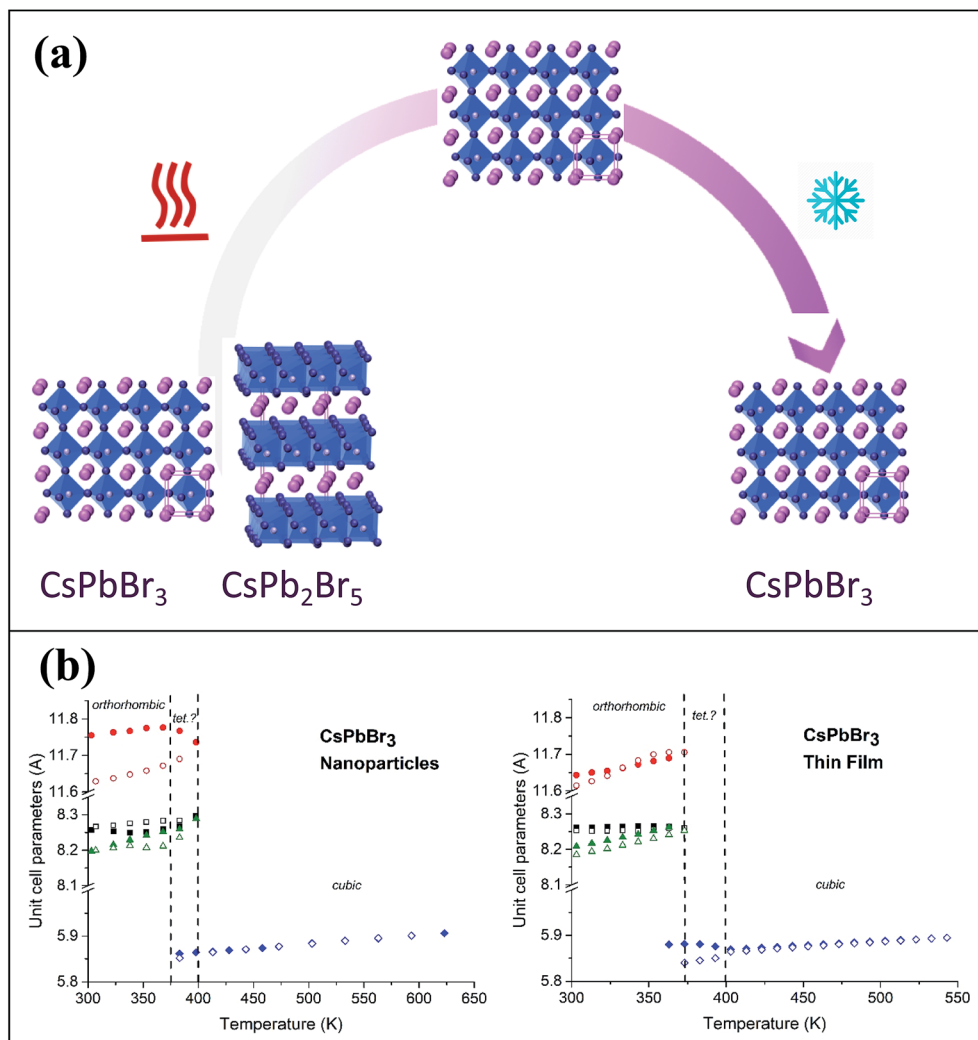


Fig. 3 (a) Schematic illustration of the process described in this work. On heating the CsPbBr₃ thin films to 623 K, the CsPb₂Br₅ disappears and pure CsPbBr₃ remains when cooling down to room temperature. (b) Cell parameters as a function of temperature for (left) NPs and (right) thin films. Triangles, squares and circles correspond to the *a*, *b* and *c* unit cell parameters, respectively. Closed and open symbols correspond to the heating and cooling sequence, respectively. The uncertainty of the cell value is contained within each symbol. 'tet' corresponds to tetragonal.

CsPb₂Br₅ changes back to CsPbBr₃ if sufficient Cs⁺ remains (in solution) at a relatively high temperature of 463 K. In the case of thin films, both CsPb₂Br₅ and CsPbBr₃ phases coexist at RT. The orthorhombic CsPbBr₃ phase shows cell values of *a* = 8.583(6) Å, *b* = 11.648(7) Å and *c* = 8.2081(4) Å, while for the majority phase CsPb₂Br₅, *a* = *b* = 8.4923(4) Å and *c* = 15.194(1) Å. At 573 K, *a* = 5.8972(3) Å for the cubic CsPbBr₃. Once cooled down to RT, orthorhombic CsPbBr₃ presents *a* = 8.2506(6) Å, *b* = 11.773(2) Å and *c* = 8.1878(5) Å cell parameters. Note that the intermediate phase of tetragonal symmetry ('tet' corresponds to 'tetragonal' in Fig. 3b), usually described in the literature^{6,13} from 360–400 K in the case of CsPbBr₃, cannot be clearly distinguished here on the XRD patterns (Fig. 1). Indeed, the peaks observed at $2\theta \sim 24^\circ$ and 29° in the XRD patterns corresponding to the orthorhombic phase remain up to 390 K while the peak splitting observed at $2\theta \sim 15^\circ$ and 30.5° can still be attributed to the low temperature orthorhombic (*Pnma*) structure. In addition, profile matching refinements performed

with either orthorhombic or tetragonal (*P4/mbm*) symmetry at 370 K show good pattern matching in both cases, with a reliability factor actually slightly improved for the former one ($\chi^2 = 2.4$ and 3.7, respectively), corresponding to a more distorted structure. Additional peaks corresponding to the CsPb₂Br₅ (and possibly CsPb₄Br₆) are observed in the XRD patterns of both nanoparticles and thin films from 500 to 595 K, which remain in small amounts upon cooling down to RT. For thin films, the main CsPb₂Br₅ phase starts to disappear upon heating above 500 K and is at a very low quantity above 570 K, while the cubic CsPbBr₃ is the main phase at the highest temperatures (see Fig. 1). Our thin films were then re-heated to 623 K in order to check their behavior and stability. The CsPb₂Br₅ secondary phase disappears completely above 580 K and pure cubic CsPbBr₃ is observed up to 623 K. This phase is then kept upon cooling down to RT with the usual symmetry distortion observed at $T \sim 390$ K (Fig. 3a).



Annealing films made of CsPbBr₃ nanoparticles can lead to morphological transformations (sintering) and chemical transformations (transformation and vanishing of tetragonal CsPb₂Br₅ phase) that could be linked to the desorption of different organic species from the film at different temperatures.¹⁴ Post-synthesis transformation of insulating Cs₄PbBr₆ into bright perovskite CsPbBr₃ can also be performed through thermal annealing by physical extraction of CsBr.¹⁵ The extracted Cs⁺ and Br[−] ions would be complexed by residual organics or form very small clusters hardly detectable by XRD. CsPb₂Br₅ could recombine with CsBr by the following reaction: CsPb₂Br₅ + CsBr = 2CsPbBr₃. Similarly, during the annealing process of our thin films initially containing a mixture of CsPb₂Br₅ and CsPbBr₃, CsPb₂Br₅ can transform into CsPbBr₃ releasing ions of Pb₂⁺ and 2Br[−] (PbBr₂), which can spontaneously react with Cs₄PbBr₆ in order to form pure CsPbBr₃ (Cs₄PbBr₆ + 3PbBr₂ = 4CsPbBr₃). Therefore, small quantities or clusters of CsBr and PbBr₂ extracted during the annealing process will contribute to the phase transformations and, if in appropriate proportions, to the formation of pure CsPbBr₃ that can remain down to RT.

Top view scanning electron microscopy (SEM) images of the CsPbBr₃ thin film can be observed in Fig. 4. The CsPbBr₃ thin films were annealed to 338 K, 368 K, 398 K, 428 K, 458 K, 503 K, 563 K and 623 K in order to get some observations on the film morphology while heating. Upon increasing the temperature, the perovskite grains melt together, losing their shape, while the XRD measurements show that their crystallinity is maintained.

The case of the CsPbBr₃ NPs is different. Transmission electron microscopy (TEM) images at three annealing temperatures are shown in Fig. 5.

The NPs were synthesized using the metathesis reaction, which involves the injection of Cs-oleate precursor into a hot mixture of PbBr₂, octadecene, and ligand (oleic-acid and oleyl-amine). After the Cs-oleate injection, the mixture was cooled down with an ice bath. At this point, before the purification process, a thermal treatment was performed. The NPs crude mixture were heated slowly to 430 K and 563 K, for comparison.

In the case of the NPs without thermal treatment (*i.e.* “no thermal treatment”) a typical size of 6 ± 1 nm and cubic-like shape are observed. The *d*-spacing values, calculated from the electron diffraction patterns, are *d* = 4.2 Å which is related to the most intense peaks and close to each other in XRD, *i.e.* (112) and (020); *d* = 2.9 Å related to the second most intense peak (220) in the XRD and *d* = 2.0 Å related to (224) and (040) crystallographic planes. Based on these *d*-spacing, the NPs are in the orthorhombic phase at RT.

TEM images of the NPs after annealing to 430 K can be seen in the middle of Fig. 5. Two different sizes of NPs were observed. A set of small NPs with size distribution of 6 ± 1 nm, and large NPs in the size of 28 ± 4 nm. The *d*-spacing determined after measuring the distances from the center of electron diffraction pattern to the diffracted lines are *d* = 3.0 Å and *d* = 2.1 Å for the small NPs close to the (220), (224) and (040) planes of the orthorhombic symmetry of CsPbBr₃ while for the large NPs the

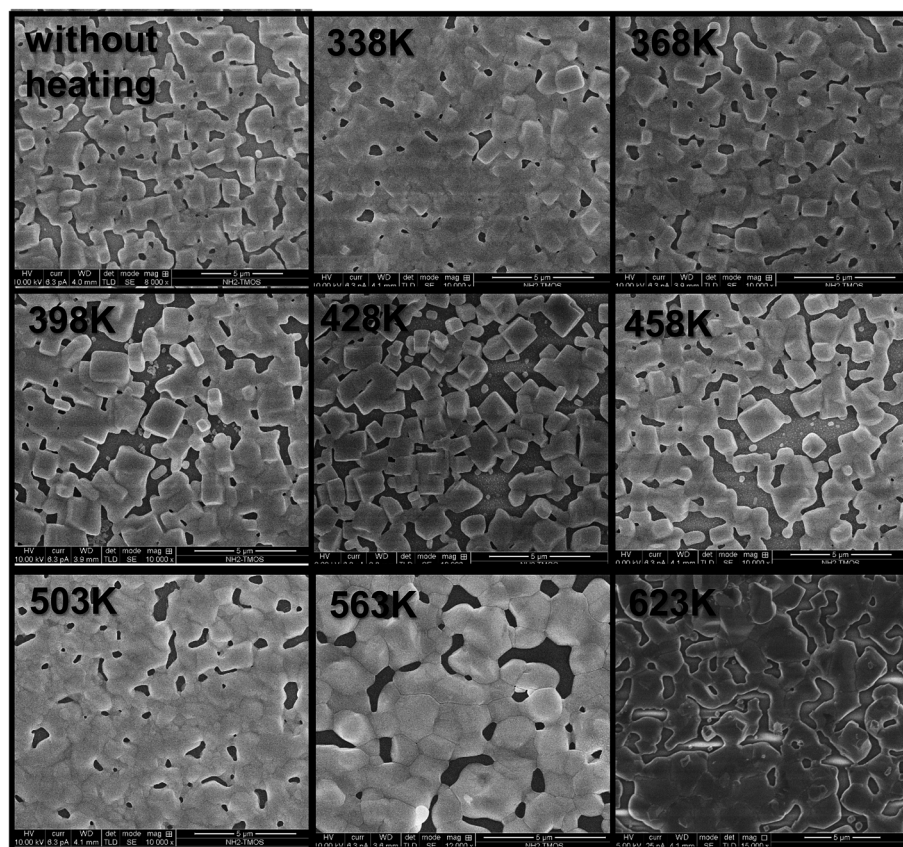


Fig. 4 SEM top view images of CsPbBr₃ thin films at different annealing temperatures. Scale bar is 5 μm.



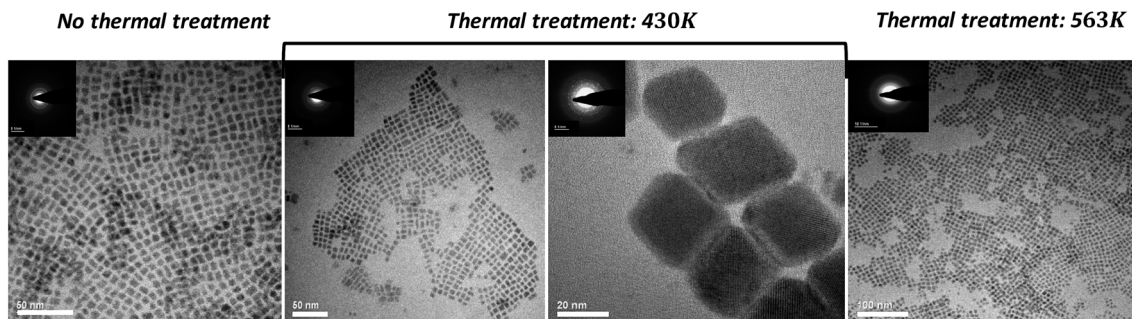


Fig. 5 TEM micrographs of CsPbBr₃ and CsPb₂Br₅ NPs after different annealing temperatures. Insets correspond to the electron diffraction patterns taken from these NPs.

d -spacing are $d = 2.6$ Å, $d = 2.3$ Å and $d = 1.60$ Å, which can be attributed to the (310), (313) and (504) planes also observed by XRD for the tetragonal phase of CsPb₂Br₅. This further confirms the presence of the CsPb₂Br₅ phase in the NPs.

In the case of the annealing treatment up to 563 K, a change to the color of the crude solution was observed during the annealing process owing to the precipitation of large NPs (larger than in the case of 430 K). It can be assumed that the large NPs contain the CsPb₂Br₅ phase as predicted in the case of 430 K annealing and while heating further to 563 K these NPs keep on growing, making them too large to be analyzed by TEM. As mentioned earlier, the XRD measurements above 500 K recognized the CsPb₂Br₅ phase in the NPs samples, which further supports our assumption. Fig. 5 shows the small NPs that were observed in parallel to the very large NPs after the annealing treatment to 563 K. Analyzing their electron diffraction patterns once back at RT provides the corresponding d -spacing: $d = 2.5$ Å and $d = 2.1$ Å; these values match with the orthorhombic phase of CsPbBr₃, the regular stable phase at room temperature.

Conclusions

This work describes a detailed structural study on CsPbBr₃ thin films and NPs. *In situ* XRD as a function of the temperature was acquired systematically each 10–15 K, where the lattice parameters and the phases of cesium lead bromide perovskite were tracked upon heating above RT. Both thin films and NPs exhibit the orthorhombic phase at RT while their cubic phase was revealed upon heating to 623 K. In both cases the parasitic CsPb₂Br₅ phase is observed at 500 K, where from 500 K to 595 K, this phase remains in small amounts and kept like this upon cooling down to RT. Interestingly in the case of thin films, further heating to 623 K results in complete elimination of the CsPb₂Br₅ phase, which remains like this when cooled down back to RT. In addition, a bigger change in the ‘ c ’ unit cell parameter is observed for NPs compared to thin films between heating and cooling, which indicates that there might be a preferred orientation or stronger distortion along the c -axis during the synthesis process. The distorted octahedral environments of Pb²⁺ and the unit cell differences are attenuated owing to structural rearrangement after heating. SEM and TEM characterization support the different morphologies and phases

observed by the XRD. This study shows the importance of understanding the structural changes in all-inorganic perovskites and provides a route to achieve pure CsPbBr₃ phase.

Experimental

XRD measurements

In situ X-ray diffraction (XRD) measurements were performed in air with a Bruker AXS D8-ADVANCE instrument in the Bragg–Brentano configuration (with copper radiation CuK α 1 = 1.5405 Å and CuK α 2 = 1.5445 Å) equipped with an Anton-Paar HTK1200N heating system. Samples were heated up to a maximum temperature of 623 K with heating and cooling rates of 10 °C min^{−1}. XRD patterns were recorded every 10–15 K from 10 to 60° in 2-theta with a step scan of 0.014° and 0.3 s per step. An approximately 1.5 cm² square shape glass sample with the nanoparticles in a solvent spread over with a spatula or as-prepared thin films was put on the alumina sample holder close to the S-type platinum (Rh10Pt) thermocouple.

CsPbBr₃ NPs synthesis and characterization

CsPbBr₃ NPs were synthesized according to a previously published procedure,³ which was slightly adjusted. Lead bromide (PbBr₂, 99.9%), cesium carbonate (Cs₂CO₃, 99.9%), octadecene (ODE, Tech. 90%), oleic acid (OA, Tech. 90%), and oleylamine (OLA, Tech. 70%) were purchased from Sigma-Aldrich. Briefly, 0.207 g of PbBr₂ was dissolved in 15 mL of ODE, 1.5 mL of OA, and 1.5 mL of OLA in a three-necked-flask, and then degassed at 393 K. 0.4 g of Cs₂CO₃ was dissolved in 15 mL of ODE and 1.25 mL of OA in a three-necked-flask, and degassed at 393 K. Then, under argon atmosphere, a hot syringe was used to swiftly inject 1.2 mL of the Cs precursor into the PbBr₂ precursor solution (which was at 393 K). The reaction was quenched with an ice bath for 10 seconds after the injection of the Cs precursor, yielding a shiny green-yellow colloid. The colloid was then divided into three vials, two of which were thermally treated: one vial was heated to 428 K, while the other was heated to 563 K. The third vial did not undergo any thermal treatment. Finally, the NPs were precipitated by centrifugation (6000 rpm for 10 minutes), and the supernatant was discarded. The NPs were re-dispersed in hexane, and bulky byproducts were precipitated by centrifugation (3000 rpm for 5 minutes).



Characterization. Transmission electron microscopy (TEM) observations were carried out using a Tecnai F20 G2 (FEI Company, USA). The samples were prepared as follows: a 3 μL drop of the NPs dispersion was placed on a copper grid coated with amorphous carbon film, followed by evaporation of the solvent by a vacuum pump.

CsPbBr₃ films deposition

CsPbBr₃ films were prepared on clean microscope glass substrates by two-step deposition technique (as described in ref. 16). Briefly, a 1 M solution of PbBr₂ ($\geq 98\%$ Sigma-Aldrich) in dimethylformamide and a 20 mg mL⁻¹ CsBr solution (99.999% Sigma-Aldrich) in methanol were dissolved overnight on a hot plate at 70 °C and 50 °C, respectively. PbBr₂ solution was spin-coated for 30 s at 1200 rpm and dried on a hot plate at 70 °C for 10 min. After drying, the substrates were dipped for 5 min in a hot solution of CsBr (50 °C) and annealed for 10 min at 250 °C.

For the thermal treatment, a hot plate was heated stepwise starting at 30 °C reaching up to 563 K. The CsPbBr₃ films were placed on the hot plate. The gradual heating process included the following temperatures: 303 K, 338 K, 368 K, 398 K, 428 K, 458 K, 503 K, 563 K and 623 K, where the temperature was kept constant at each value for 20 minutes.

Characterization. Extra high resolution scanning electron microscopy (XHRSEM) was performed using a Magellan XHR SEM (FEI, Field Emission Instruments, The Netherlands). The measurement conditions were 10 kV, 6.3 pA at a magnification of 100 000.

Conflicts of interest

There are no conflicts to declare.

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