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Structural Evolution and Photoluminescence Quenching Across the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) Perovskites

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Abstract:

One of the primary methods for band gap tuning in metal halide perovskites has been halide (I/Br) mixing. Despite widespread usage of this type of chemical substitution in perovskite photovoltaics, there is still little understanding of the structural impacts of halide alloying, with the assumption being the formation of ideal solid solutions. Considering $\text{FAPbI}_{3-x}\text{Br}_x$ ($x = 0 - 3$), this assumption may hold where both parent compounds (FAPbI_3 and FAPbBr_3) crystallize with relatively the same perovskite structure, but the ideal assumption is unlikely to hold in a phase space where the end members have unique structures. The $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) family of compounds provides the first evidence for this wherein instead of an ideal solid solution, the composition space is broken into two unique regimes ($x = 0 - 2.9$; $x = 2.9 - 3$) based on their average structure with the former having a 3D and the latter having an extended 3D (pseudo 0D) structure. While the majority of the phase space ($x = 0 - 2.9$) retains an average cubic FASnI_3 structure, pair distribution function (PDF) analyses suggest a dynamic $5s^2$ lone pair expression resulting in increasing levels of off-centering of the central Sn as the Br concentration is increased. These antiferroelectric distortions indicate that even the $x = 0 - 2.9$ phase space behaves as less than an ideal solid solution. Solid State NMR confirms the difference in local structure obtained from PDF yielding greater insight into the reorientation dynamics of the FA^+ cation that are not as easily garnered from X-ray scattering. In contrast to the $\text{FAPbI}_{3-x}\text{Br}_x$ series a drastic photoluminescence (PL) quenching is observed with $x \geq 1.9$ compounds having no observable PL. Our detailed studies of the long- and short-range structures combined with Raman spectroscopy experiments attribute this quenching to structural transitions induced by the $[\text{SnBr}_6]$ octahedra in response to stereochemically expressed lone pairs of electrons. This is confirmed through density functional theory, having a direct impact on the electronic structure.

1.0 Introduction:

Three-dimensional metal halide perovskites (MHPs) have been a major focus of ongoing research in the realm of photovoltaics (PV) due to their superior optoelectronic properties. These compounds are direct-gap, strong light-absorbing semiconductors with high carrier mobilities and high tolerance to defect states.¹⁻⁷ These favorable properties have allowed for a rapid improvement of perovskite-based PV, exceeding traditional Si-based devices in more recent years. Single junction perovskite solar cells (PSCs) first showed viability, achieving a power conversion efficiency (PCE) of ~11%^{8,9} and has since rapidly improved,¹⁰ achieving closer to the theoretical Shockley-Queisser limit (33.7%) with recent examples of single junction devices having >25% PCE.¹¹⁻¹⁴ Tuning the bandgap for Pb perovskites was successfully performed through the variation of the chemical composition, *i.e.*, by I/Br and/or Pb/Sn mixing.¹⁵⁻¹⁷ These new compositions across the mixed iodide-bromide phase space possess a well-behaved three-dimensional network leading to improved phase stability¹⁸ and monumental efficiency improvements for related solar cells. This includes the mixed cation/halide perovskite used in 31.2% of perovskite/silicon tandem devices.¹⁹ Although there has been success with these phases, there are serious issues with the perovskite layer in a functional solar cell as the perovskite undergoes phase segregation under illumination due to halide migration.²⁰⁻²²

While the highest performing devices use lead (Pb) based halide perovskites and tandem cells use the mixed halide (I/Br) variant,²³⁻²⁵ considerable effort has been made to create Pb-free PSCs due to Pb's toxicity.²⁶ One way of addressing these concerns is by using the $ASnX_3$ compositions. Sn^{2+} based materials have also shown success as light-absorbing layers, but the PCE lags behind only reaching ~14% for a single junction device: a considerable compromise in performance.²⁷ This can be attributed to a number of factors, including the instability of the Sn^{2+} oxidation state, making it more difficult to suppress the creation of performance-killing Sn^{4+} defect states. Nonetheless, due to their structural versatility for compositional management and the existing knowledge of their Pb counterparts, Sn-based PSC are expected to improve in terms of stability and device performance as active research continues.²⁸⁻³⁰

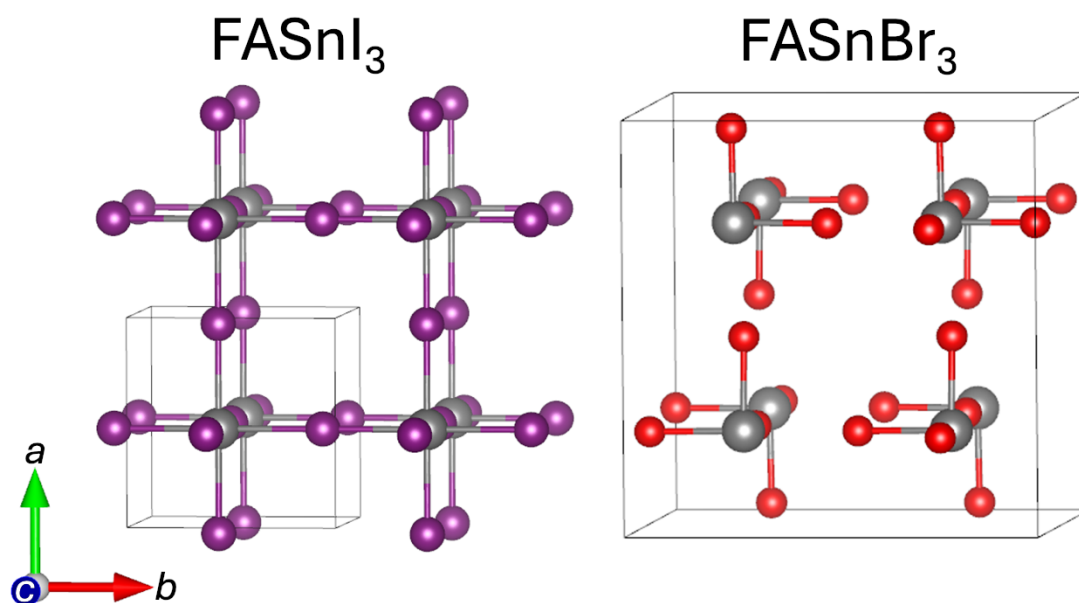


Figure 1: Depicts the 3D inorganic framework of FASnI₃ (left) and the extended 3D framework of FASnBr₃ (right). The atoms are presented as grey, purple, and red for Sn, I, and Br respectively. the FA⁺ cations are omitted for simplicity. FASnI₃ and FASnBr₃ are modeled in $Pm\bar{3}m$ and $Pa\bar{3}$ respectively.

In this vein, we need a holistic understanding of the structural complexities of hybrid mixed halide perovskites. We chose the representative family of compounds called FASnI_{3-x}Br_x (where $x = 0 - 3$) because they have a remarkably broad range of band gap energies and exhibit structural complexity due to the diverse room temperature structures of FASnI₃ and FASnBr₃.^{31, 32} FASnI₃ crystallizes with a typical 3D perovskite framework with SnI₆ octahedra corner sharing in all directions and the FA⁺ cation filling the central voids, counterbalancing the overall negative charge. FASnBr₃, on the other hand, has a structure that is atypical of MHPs based on increased expression of the Sn 5s² lone pair, leading to significant off-centering. The compound deviates from the ideal 3D perovskite framework by lengthening three Sn – Br bonds and shortening the other three in the SnBr₆ octahedra in a coherent fashion, forming what can be thought of as more discrete pyramidal 0D [SnBr₃]⁻ units. Since the orientation and arrangement of these molecular units in space retains the original undistorted architecture, the structure can still be thought of as a 3D perovskite type. The FA⁺ cations then occupy positions within this “distorted cage” to balance the charge (Figure 1).

Here, we study the FASnI_{3-x}Br_x ($x = 0 - 3$) chemical substitution range. Analysis of the average crystal structures shows a composition-dependence splitting the space into two unique regimes, apparently indicating non-idealistic behavior expected for a solid-solution. The $x = 0 -$

2.9 range adopts an average structure in line with the FASnI_3 structure type, and the $x = 2.9 - 3$ range takes on the FASnBr_3 room temperature structure with lower symmetry. However, inspection of the thermal displacement and lattice parameters suggests that the structure modification is already present at the local scale for $x < 2.9$. Single crystal X-ray diffraction analysis, thus, provides evidence for a more gradual structural evolution from the FASnI_3 to the FASnBr_3 structure type, initially exhibiting antiferroelectric distortions at the local scale that finally exhibits long-range ordering. We also find that careful control of the synthetic conditions is necessary to produce bulk crystallites with the desired I/Br ratio in the final product, as the typical synthetic procedures in hydrohalic acid solutions show a non-linear behavior. Furthermore, halide substitution drastically impacts the photoluminescence (PL) as there is a significant decrease in PL intensity with the introduction of Br. PL intensity decreases between $x = 0 - 1.1$, finally falling below the background with no observable emission present for $x \geq 1.9$. Further investigation revealed the above-mentioned systematic structural distortions as the most dominant source for PL quenching in high bromide compositions. The distortions provide a rationale for quenching of the photoluminescence with Br incorporation as the structure distorts and the $5s^2$ lone pair becomes more stereochemically expressed. This suggested mechanism is bolstered by room temperature Raman spectroscopy and pair distribution function (PDF) measurements which show unique scattering signatures and distance vectors for predominantly Br-rich molecular $[\text{SnBr}_{3-x}\text{I}_x]$ type units, and DFT calculations focusing on the activity of the Sn $5s^2$ lone pair of electrons. Solid state NMR also supports the difference in framework closely associated with the Br⁻ concentration. Specifically, the FA^+ cation shows sharper signatures in the ^1H spectrum of Br-rich samples, meaning its motion has more fluidity. These findings are in contrast to PL behavior for the $\text{APbI}_{3-x}\text{Br}_x$ ($x = 0 - 3$; A = MA, FA) analogues, which show consistent PL response across the substitution range.^{33, 34} This study serves as a reminder that structural considerations in compositionally complex MHPs are paramount in understanding the behavior of the materials' performance for optoelectronic applications.

2.0 Materials and Methods:

2.1. General Synthetic Approach: Each of the compounds presented in this study was synthesized using solution-based crystal growth techniques in hydrohalic acid, which is a methodology that has been used on countless occasions by our research team to grow hybrid 3D and 2D phases

alike.^{7, 31, 35-37} The variant of the precipitation reaction used to synthesize materials in the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) family was as follows: desired quantities of $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ (Sigma-Aldrich; 98 wt.%) were dissolved in a solution comprised of hydroiodic (Sigma-Aldrich 57 wt.% in H_2O), hydrobromic (Sigma-Aldrich; 48 wt.% in H_2O), and hypophosphorous acids (Sigma-Aldrich; 50 wt.% in H_2O) under constant stirring while on a hotplate set to $\sim 120^\circ\text{C}$ (Table 1). The hypophosphorous acid was added as a necessary reducing reagent utilized to suppress the oxidation of Sn^{2+} to Sn^{4+} as well as to prevent the conversion of I^- to $[\text{I}_3]^{3-}$.³⁵ Once the solid was dissolved, desired amounts of formamidine acetate (FACH_3COO ; TCI; >98 wt.%) were added to the hot reaction, followed immediately by the rapid crystallization of the desired perovskite phase, the persistence of which was dependent on the ratio of the hydrohalic acids (I-rich generally persisted longer than Br-rich). The temperature of the hotplate was then increased to $\sim 210^\circ\text{C}$ while stirring continued until the solid dissolved and a clear solution was achieved. The reaction was then allowed to cool to room temperature, where the perovskite phase precipitated from the solution and could be extracted for further measurements.

Table 1: Experimental conditions used for the synthesis of the $\text{FASnI}_{3-x}\text{Br}_x$ compounds. The volume percentages are based on the ratio of the two hydrohalic acids added to the reaction solution not considering contributions from the hypophosphorous acid.

Compound	HI (vol.%)	HBr (vol.%)	Mol Fraction χ_{HBr}
FASnI_3	100	0	0
$\text{FASnI}_{2.6}\text{Br}_{0.4}$	66	34	0.38
$\text{FASnI}_{2.3}\text{Br}_{0.7}$	34	66	0.69
$\text{FASnI}_{2.1}\text{Br}_{0.9}$	25	75	0.78
$\text{FASnI}_{1.9}\text{Br}_{1.1}$	33	67	0.70
$\text{FASnI}_{1.1}\text{Br}_{1.9}$	17	83	0.85
$\text{FASnI}_{0.7}\text{Br}_{2.3}$	8	92	0.93
$\text{FASnI}_{0.4}\text{Br}_{2.6}$	7	93	0.94
$\text{FASnI}_{0.1}\text{Br}_{2.9}$	3	97	0.97
FASnBr_3	0	100	1

In our experience, the perovskite phase needed to be extracted once the reaction reached room temperature. As the solid continued to remain in solution, halide exchange was observed with a darkening of the crystals over time. The color of the perovskite phase varied from black (iodide rich) to yellow (bromide rich) depending on the overall ratio of I/Br incorporation (Figure 2b). For more specific synthetic details, the reader is referred to the supporting information for the synthesis conditions for each of the products. Since the samples were all susceptible to oxidation when removed from the mother liquor, the crystals were dried inside a nitrogen-filled glove box or under a vacuum. Air-free powder diffraction patterns were collected to confirm the identity of

the bulk material (Figure S1), and semiquantitative scanning electron microscopy coupled with energy dispersive X-ray spectroscopy (SEM-EDS) then confirmed the elemental composition (Table S5).

2.2 Powder X-ray Diffraction (PXRD): Dry crystallites were ground inside a N₂-filled glovebox with a mortar and pestle until a powder-like consistency was achieved. The powder was then packed into an 8 mm metallic mask with the usage of two polyimide layers of tape (one on both sides of the mask). The PXRD data were then collected at room temperature on a STOE-STADI-P powder diffractometer equipped with an asymmetric curved Germanium monochromator which uses Cu K_{α1} ($\lambda = 1.54056 \text{ \AA}$) radiation for diffraction and a MYTHEN2 1K DECTRIS one-dimensional silicon strip detector. The intensity data were collected within the range 5-60° 2 θ . The instrument was first calibrated against a NIST Silicon standard (640d) prior to diffraction.

2.2.0 Single Crystal X-ray Diffraction Data for FASnI_{3-x}Br_x (x = 0 – 3) Phases at Room Temperature

Table 2: Selected Crystallographic information and refinement statistics for representative FASnI_{3-x}Br_x (x = 0 – 3) compositions. FASnI₃ and FASnBr₃ were synthesized and measured independently of previous research efforts. The full Table can be found in the supporting information Table S1.

Formula	FASnI ₃	FASnI _{2.6} Br _{0.4}	FASnI _{2.3} Br _{0.7}	FASnI _{2.1} Br _{0.9}	FASnI _{1.9} Br _{1.1}	FASnI _{1.7} Br _{1.3}	FASnI _{1.4} Br _{1.6}	FASnI _{1.1} Br _{1.9}	FASnBr ₃	
Formula weight	525.41	518.74	508.41	495.72	488.67	452.02	432.28	418.19	402.62	398.45
Space group	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pa</i> $\bar{3}$	<i>Pa</i> $\bar{3}$
a/b/c (Å)	6.3064(3)	6.3099(2)	6.2824(2)	6.2525(5)	6.2449(1)	6.1354(2)	6.0915(2)	6.0443(2)	12.0637(15)	12.0303(5)
Volume (Å ³)	250.81(4)	251.23(3)	247.96(2)	244.43(6)	243.54(1)	230.96(6)	226.03(2)	220.82(2)	1755.7(7)	1741.1(2)
Z	1	1	1	1	1	1	1	1	8	8
ρ_{calc} (g/cm ³)	3.479	3.429	3.405	3.368	3.332	3.250	3.176	3.145	3.046	3.040
Absorption coefficient (mm ⁻¹)	11.695	12.080	12.441	12.871	13.058	14.537	15.275	15.944	8.707	16.615
Independent reflections	91 [R _{int} = 0.0375]	172 [R _{int} = 0.0117]	166 [R _{int} = 0.0087]	103 [R _{int} = 0.0314]	160 [R _{int} = 0.0183]	68 [R _{int} = 0.0750]	95 [R _{int} = 0.0136]	113 [R _{int} = 0.0132]	688 [R _{int} = 0.0487]	641 [R _{int} = 0.0716]
Data / restraints / parameters	91 / 1 / 8	172 / 1 / 10	166 / 1 / 10	103 / 1 / 9	160 / 1 / 10	68 / 1 / 9	95 / 1 / 10	113 / 1 / 10	688 / 2 / 25	641 / 2 / 24
Final R indices [I > 2 σ (I)]	R _{obs} = 0.0435, wR _{obs} = 0.01248	R _{obs} = 0.0231, wR _{obs} = 0.0766	R _{obs} = 0.0239, wR _{obs} = 0.0877	R _{obs} = 0.0429, wR _{obs} = 0.1006	R _{obs} = 0.0231, wR _{obs} = 0.0846	R _{obs} = 0.0292, wR _{obs} = 0.0950	R _{obs} = 0.0317, wR _{obs} = 0.1092	R _{obs} = 0.0479, wR _{obs} = 0.1540	R _{obs} = 0.0585, wR _{obs} = 0.1451	R _{obs} = 0.0419, wR _{obs} = 0.1011
Largest diff. peak/hole (e ⁻ Å ⁻³)	0.869/-1.372	0.680/-0.836	1.229/-1.299	0.656/-0.944	0.814/-0.828	0.716/-0.4	0.636/-0.610	0.747/-1.260	0.952/-0.695	0.799/-0.643

Single crystals within the FASnI_{3-x}Br_x (x = 0 – 3) range were extracted from the mother liquor and immediately placed under Paratone-N oil on a glass slide to protect the surface from oxidation. The crystals were then transported to an optical microscope where suitable crystals were

selected, cut to size, and mounted onto the goniometer head of a single crystal diffractometer for collection. An inert environment was maintained throughout the collections through the usage of a nitrogen blanket, which was sourced from the liquid, through an Oxford Cryosystems cryostat. This proved to be necessary in order to preserve the desired perovskite phase during diffraction as each of the samples was susceptible to oxidation with exposure to ambient conditions. Intensity data was then collected on either a STOE Stadi Vari diffractometer, which uses an AXO Ag K_{α} micro-focus sealed X-ray A-MiXS source for diffraction ($\lambda = 0.560834 \text{ \AA}$) and a Dectris Platus3 R CdTe 300K Hybrid Photon Counting Detector, or a XtaLAB Synergy diffractometer, equipped with a microfocus sealed X-ray tube PhotonJet (Mo K_{α} : $\lambda = 0.71073 \text{ \AA}$) for diffraction and a Hybrid Pixel Array Detector (HyPix). The data collected on the Stadi Vari diffractometer was then reduced using the X-area software package (STOE). LANA³⁸ was used to perform a semi-empirical absorption correction through outlier rejection and scaling of the reflections. The reduction for the data collected on the Synergy diffractometer was done within the CrysAlisPro software package (Rigaku) using an empirical absorption correction. For all of the room temperature data sets, the reflections were then imported into Olex2³⁹ where the data was solved using the intrinsic phrasing method as implemented in ShelXT⁴⁰ and further refined using least squares on F^2 with ShelXL.⁴¹ Selected crystallographic information and are presented in Table 2.

2.2.1: Low Temperature Single Crystal X-ray Diffraction: Low temperature diffraction experiments were conducted on freshly synthesized $\text{FASnI}_{1.9}\text{Br}_{1.1}$ and $\text{FASnI}_{0.4}\text{Br}_{2.6}$ crystals using the STOE Stadi Vari diffractometer discussed in the previous section. Measurements were conducted at various temperatures which were maintained through a flow of N_2 gas, obtained from the liquid, sustained by an Oxford Cryostream 700 plus cryostat. Data reduction was accomplished in the X-area software (STOE), using a semi-empirical absorption correction, outlier rejection, and frame scaling as applied in LANA.³⁸ $\text{FASnI}_{0.4}\text{Br}_{2.6}$ showed a phase transition at 260K and the low temperature structure was elucidated in Jana2006⁴² due to increased disorder where a structural solution was achieved through SUPERFLIP⁴³ and refined using a least squares method on F^2 , as implemented in Jana2006.⁴²

2.3 Modeling of Disorder in $\text{FASnI}_{0.1}\text{Br}_{2.9}$:

In the refinement of $\text{FASnI}_{0.1}\text{Br}_{2.9}$ it was first apparent that a small fraction of iodide was introduced into the structure based on the color of the bulk material with respect to pure FASnBr_3 (Figure 2b/S2). Further evidence in support of iodide substitution came from both the small increase in the unit cell parameters with respect to FASnBr_3 and a measured redshift in the band gap of the material (Figure 9). When introducing I^- into the single crystal refinement, it became necessary to disorder the halide site. This was achieved by relaxing the positional constraints initially present which forced the Br^- and I^- to occupy the same atomic coordinates within the structure. With this applied constraint, the crystallographic refinement was unstable. However, after refining the two positions separately, the two halides were found to occupy different positions, stabilizing the refinement with a small fraction of I^- . Based on the observed shift in the band gap of the material as well as elemental confirmation of the presence of I^- from SEM-EDS, the disorder was kept in the final refinement.

2.4 Modeling of Disorder in $\text{FASnI}_{0.4}\text{Br}_{2.6}$ (260K):

During the refinement of the 260K structure of $\text{FASnI}_{0.4}\text{Br}_{2.6}$, it became necessary to disorder the halide positions. The disorder was first realized with a non-negligible residual electron density in the vicinity of the initial halide position. Mixing the halide site (I/Br) and relaxing the constraints on the coordinates showed that I^- and Br^- occupied different average positions in the crystal lattice and proved to resolve the residual electron density near the halide site. Despite achieving a reasonable refinement with the above disorder, the model could prove to be inadequate to describe the true average structure of the material. Since the phase transition involves the elongation of 3 bonds in octahedra and a shortening of the remaining 3, induced twinning via different local variations of the transition could yield an average crystal structure with multiple disordered mixed I/Br positions. There can also be a convolution of the antiferroelectric (off-centering) and antiferrodistortive (tilting) distortions, adding additional complexity to the refinement and making a fully detailed refinement difficult. This type of disorder was further confirmed through room temperature pair distribution function (PDF) measurements.

2.5 Steady-state and time-resolved photoluminescence (PL, TRPL):

PL and TRPL spectra of the film samples were measured using an Edinburgh Instruments FS5 Spectrofluorometer. The samples were excited by ps pulsed diode laser. (375 nm excitation

wavelength, pulse width of less than 100ps and repetition rate 5MHz). The spectra were corrected for the monochromator wavelength dependence and photomultiplier response functions provided by the manufacturer. Measurements were performed using dried polycrystalline powder samples and films. The measured TRPL decay ($I(t)$) of each sample was fitted by a three-exponent function, convoluted with the measured instrument response function. $I(t) = \sum_{i=1}^3 a_i e^{-t/\tau_i} + b$, τ_i and a_i are the lifetime and amplitude of the different decay components, and b is the background level. The ratio of photons emitted by each component (Φ_i) can be calculated by $\Phi_i = (a_i \times \tau_i) / (a_1 \times \tau_1 + a_2 \times \tau_2 + a_3 \times \tau_3)$, ($i = 1, 2, 3$). The average lifetime of each sample τ_{avg} is defined by $\tau_{avg} = \sum \Phi_i \times \tau_i$.

2.6 Perovskite film preparation:

The perovskite stock solutions were prepared by dissolving FAI, FABr, SnI₂ and SnBr₂ precursors with the target composition to form stoichiometric 0.8M FASn(I_{1-x}Br_x)₃ in dimethylformamide (DMF)/dimethyl sulfoxide (DMSO) (3:2 volume ratio) mixed solvent. After the precursor was completely dissolved, the prepared solution was spin-coated on the substrate at 1000 rpm for 10 seconds and 4000 rpm for 30 seconds. Chlorobenzene was added as an antisolvent 25 seconds in the second step. Subsequently, the film was annealed at 100°C for 10 minutes. To mitigate the effect of exposure to ambient conditions, PMMA was spin-coated on thin films to form the final encapsulation layer. All film preparation procedures were conducted in a N₂-filled glove box. The light illumination study was conducted in the glovebox (Figure S11). The thin films were taken out of the glovebox for measurements after each period of illumination under 1 sun.

2.7 Pair Distribution Function (PDF) of FASnI_{3-x}Br_x (x = 0, 1.1, 2.6, 3):

Freshly synthesized material was dried under a vacuum and transferred to a nitrogen-filled glovebox. The dried crystallites were then ground in an agate mortar and pestle until a powder-like consistency was achieved. The powder was sieved to 53 μ m particle sizes to ensure dense packing and then transferred to either a quartz or borosilicate capillary with outer diameter dimensions of 0.5 mm (purchased from Charles Supper Co.) that was sealed at one end. Once packed, the capillary was sealed and transported to the diffractometer for measurement. Intensity data was collected using a STOE StadiVari diffractometer (detailed in the SXRD section) using 2-hour exposure time per frame, collecting data from 1-160° 2 θ (Ag K α) over five frames. Data was

also collected for an empty capillary and air-scattering to establish a background effectively subtracting their scattering contributions. The images were imported into GSAS-II⁴⁴ where instrument parameters were calibrated against a LaB₆ standard collection at the same detector distance. Each frame was integrated as implemented in GSAS-II. The resulting diffraction pattern was exported and manually scaled. The 1D diffraction patterns were reduced to the $G(r)$ in PDFgetX3.⁴⁵ Further details are described in the supporting information.

2.8 Solid-state NMR spectroscopy:

All NMR spectra were acquired on polycrystalline materials. Samples were separately packed into airtight zirconia rotors with an outer diameter of 1.3 mm fitted with VESPEL[®] caps. Magic-Angle Spinning (MAS) NMR experiments were carried out at 18.8 T on a Bruker Avance Neo NMR spectrometer (the Larmor frequencies were $^1\text{H} = 800.1$ MHz, and $^{119}\text{Sn} = 298.4$ MHz, respectively) equipped with a 1.3-mm H-X double resonance probe head tuned to ^1H and ^{119}Sn configuration. Unless otherwise specified, all the samples were spun at a MAS frequency of 50 kHz using N₂ gas to prevent the moisture-induced degradation during the data acquisition. The 1D ^{119}Sn MAS NMR spectra were acquired using spin-echo pulse sequence, in which the echo delay was set to 20 microseconds corresponding to one rotor period. For pure FASnI_3 and FASnBr_3 compounds, the ^{119}Sn MAS NMR spectra were acquired by co-adding 2048 transients, and For $\text{FASnI}_{1.1}\text{Br}_{1.9}$ and $\text{FASnI}_{0.4}\text{Br}_{2.6}$ alloys, the 1D ^{119}Sn MAS NMR spectra were acquired by co-adding 2048, using a recycle delay 3 s ($T_1 \sim 1.4$ s). All 1D ^1H MAS NMR spectra were acquired by 32 co-added transients, whereby the recycle delay was set to 50 s, as determined from saturation recovery measurements and analyses. 2D ^1H - ^1H spin diffusion NMR experiments were acquired using with times (50, 200 and 500 ms) under fast MAS (55 kHz). A rotor-synchronized increment of 20 μs was applied to detect the indirect dimension using 400 t_1 increments, with 2 co-added transients, leading to an experimental time of ~ 9 h each. The ^1H experimental shift was calibrated with respect to neat TMS using adamantane as an (^1H resonance, 1.82 ppm). The experimental ^{119}Sn shifts were calibrated using liquid SnCl_2 as an external standard, according to IUPAC recommendation.¹⁰³ Data were processed from Bruker Topspin 4.1.4 inbuilt package.

2.9 $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0, 1.1, 2.6, 3$) Raman Spectroscopy:

Selected materials were freshly synthesized using the experimental procedures detailed above and in the supporting information. The synthesized material was then removed from the solution, placed on a piece of filter paper to allow most of the solution to be absorbed and then quickly placed into a 9/7 mm (outer diameter/inner diameter) fused silica tube. The tube was placed under dynamic vacuum for ~24-48 hours, allowing the remainder of the solution to evaporate off. These tubes were then sealed with an O₂/CH₄ torch (vacuum reaching ~10⁻² mbar) and transported to a N₂ filled glovebox. The ampules were opened, and the material was extracted. The compounds were mechanically ground with an agate mortar and pestle and inserted into a quartz cuvette. The powder was more densely packed by adding glass wool, which was added to the cuvette on top of the powder. The top of the cuvette was sealed with epoxy to maintain an inert environment during the measurement. Once the epoxy was cured, the cuvettes were transferred into a plastic bag and vacuum sealed for transportation to the instrument. An example of the sample holders is shown in Figure S10. Raman scattering was collected on these samples using a 660 nm laser on low power settings to avoid laser induced degradation. Raster scans were also utilized for the same purpose. Contributions from the background were then subtracted through a third-order polynomial fit function.

2.10 Computational Methods:

All density functional theory (DFT) calculations were performed using the plane wave code Quantum ESPRESSO.^{46, 47} We employed optimized norm-conserving Vanderbilt pseudopotentials⁴⁸ and the Perdew-Burke-Ernzerhof revised for solids (PBEsol) functional.⁴⁹ We set the kinetic energy cutoff to 120 Ry and fixed the lattice constants of FASnI_{3-x}Br_x for various *x* to the experimental values. To accommodate the Sn lone pairs in FASnI_{3-x}Br_x we employed a 2×2×2 supercell (96 atoms) of the idealized cubic unit cell consisting of 12 atoms [i.e. one formula unit (f.u.)]. This choice of supercell also allowed us to account for local disorder (or polymorphism)⁵⁰ in FASnI_{3-x}Br_x, both for the inorganic network and the FA molecules. We stress that employing a random distribution of locally distorted cells in static DFT calculations for halide perovskites has been shown to represent an accurate physical approach to describe the ultraslow structural dynamics, not captured by standard X-ray diffraction.^{50, 51} Here, accounting for structural disorder in FASnI₃ leads to a band gap opening at the R point of 0.38 eV (Figure S11b), alleviating the spurious semi-metallic behavior calculated for its high-symmetry counterpart.⁵¹ We further

achieved randomly disordered structures of all $\text{FASnI}_{3-x}\text{Br}_x$ compositions via optimization of the nuclear coordinates, following the strategy described by Zhao et al.⁵¹ In our simulations of FASnBr_3 , we initially utilized the experimental crystal structure at room temperature, which exhibits the $P\bar{a}3$ space group. Notably, our DFT optimization of the FASnBr_3 structure to mimic structural disorder preserves the Sn lone pair expression, namely the initial average distortion as obtained from X-ray diffraction. For comparison purposes, we also generated idealized structures of FASnI_3 and FASnBr_3 by fixing the atoms of the inorganic network to their high symmetry $Pm\bar{3}m$ positions and allow the FA^+ ions to relax. All geometry optimizations were performed using scalar relativistic pseudopotentials.

We employed the band structure unfolding technique to investigate the effect of electronic properties, computed with the inclusion of spin-orbit coupling, of the various compositions in the same Brillouin zone: the fundamental Brillouin zone of an idealized cubic unit cell. Band structure unfolding⁵² was performed as implemented for plane waves and norm-conserving, fully relativistic pseudopotentials in the ZG module of the EPW code.^{53, 54} Fully-relativistic electron spectral functions of $\text{FASnI}_{3-x}\text{Br}_x$ compounds were calculated for 300 \mathbf{k} -points to ensure a correct mapping and dense sampling of the X-R-M- Γ path in the fundamental Brillouin zone of the idealized unit cell. Hole and electron effective masses at the R point were determined by finite differences.

3.0 Results and Discussion

3.1 Synthetic Aspects

Each of the compounds was synthesized from hydrohalic acid mixtures (HI/HBr) by dissolving desired amounts of $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ with FACH_3COO followed by cooling the reaction to promote crystallite growth, where the acids were intended to serve as a halide anion source for the perovskite formation. Based on these synthetic conditions necessary to sweep across the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) composition space, it became clear that there was a strong preference for the incorporation of I⁻ into the structure even with higher relative concentrations of Br⁻ in the starting reaction solution.

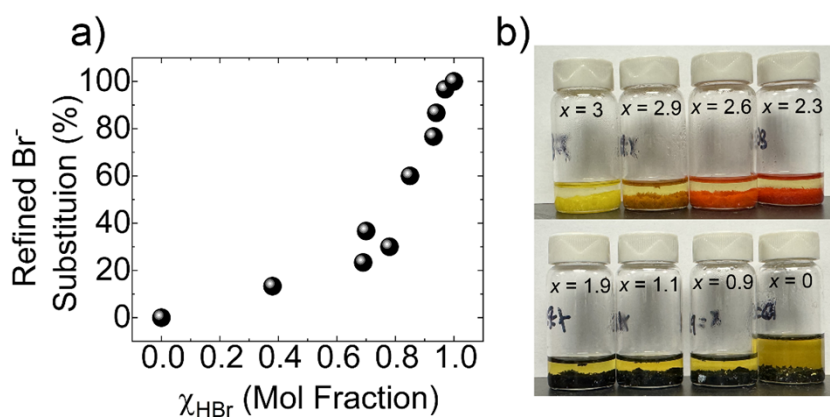


Figure 2: a) A plot of the refined Br⁻ stoichiometry based on single crystal X-ray diffraction refinements against the mol fraction (χ_{HBr}) of HBr present during the synthesis. Note that the mol fraction only relates the molar ratios of HI and HBr in the reaction solution. b) An image of the bulk material for selected compositions.

This is most evident in the synthesis of $\text{FASnI}_{1.1}\text{Br}_{1.9}$, where the refined formula achieved a rough ratio of 2/1 (Br/I). However, during the synthesis, there was an overwhelming excess of Br⁻ in the reaction solution (with a mol fraction $\chi_{\text{HBr}} = 0.85$). Through experimental findings, it was discovered that only small volumes of hydroiodic acid solution were necessary to isolate materials with high Br⁻ concentrations. This fact is supported by the difference in synthetic conditions between $\text{FASnI}_{0.4}\text{Br}_{2.6}$ and $\text{FASnI}_{0.1}\text{Br}_{2.9}$, which were synthesized with only a 0.03 difference in the HBr mol fraction. This relationship is seen when plotting the refined Br⁻ stoichiometry against the mol fraction of HBr present during the synthesis (Figure 2a). At low HBr mol fractions χ_{HBr} (0 – 0.7), there is little change in the refined Br⁻ stoichiometry, leading to a maximum of $\sim 1/3$ Br⁻ substitution with a 0.7 HBr mol fraction. Within the range of 0.7-0.9 HBr, the Br⁻ substitution increases an additional $1/3$. The final $1/3$ substitution is then achieved within a 0.1 HBr mol fraction window, making precise control over the acid volumes paramount to receiving the desired phases. Despite these limited concentration windows, homogeneous material with respect to composition was still obtained with single crystal measurements confirming a consistent composition and SEM-EDS providing a composition consistent with refined stoichiometries (Table S5) within the bounds of the semiquantitative nature of EDS measurements. 2D ^1H - ^1H spin diffusion NMR I/Br intermixing in the bulk sample suggesting a consistent composition and a lack of phase separation.

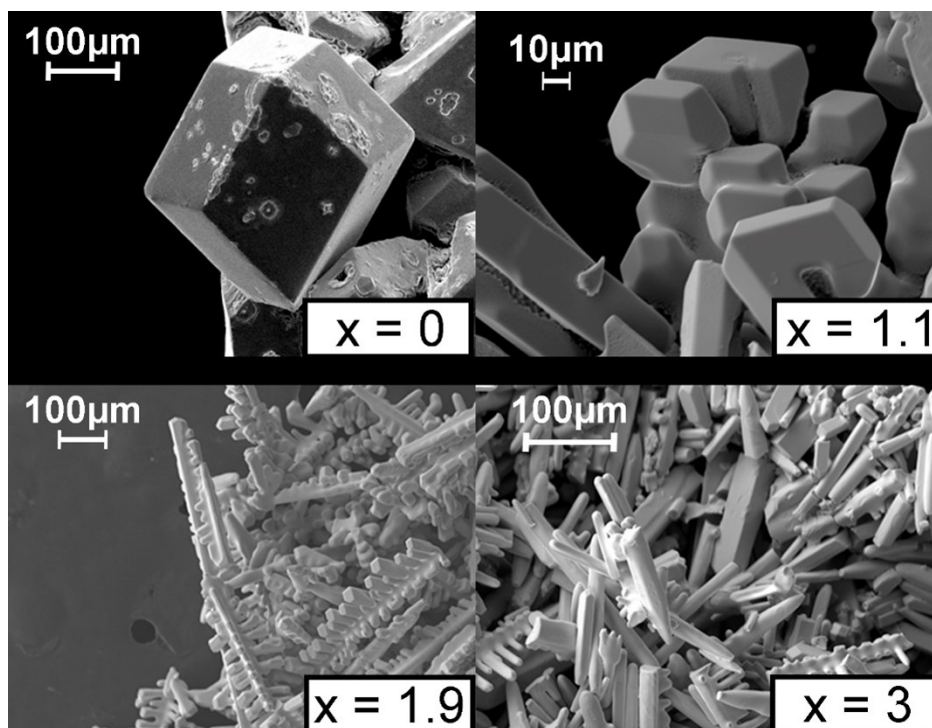


Figure 3: Scanning electron microscopy images of crystallites for selected compositions in the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) substitution range, showing the typical crystal habit of the materials and their related morphology transition from iodide-rich composition to bromide-rich composition.

During the crystallization process, two additional components play a significant role: the oxidation of Sn^{2+} to Sn^{4+} and the decomposition of formamidine to ammonia. These by-products were observed in excessive amounts during longer crystallization times lasting for 6 hours, with the crystals being cooled down at a rate of $7\text{-}10^\circ\text{C}/\text{h}$. We detected the presence of two Sn^{4+} phases: SnI_4 and $(\text{NH}_4)_2\text{SnBr}_6$. These phases indicate the instability of the Sn^{2+} oxidation state as well as the FA^+ cation, which converted to NH_4^+ ions. For detailed information on the single crystal structure refinement parameters for these secondary phases, please refer to the supporting information (Table S6).

The level of halide mixing also impacted the crystal habit as seen in scanning electron microscopy images of the isolated crystals (Figure 3). FASnI_3 takes on a rhombic dodecahedral shape, typical of 3D hybrid halide perovskite materials. This morphology also agrees with the findings of previous studies of the material.³¹ FASnBr_3 , on the other hand, is a rod-like shape that can be generated by elongating the rhombic dodecahedron in a singular direction, creating a crystal shape with a pyramidal-like cap at the end. Noticeably, the crystal habit of the $\text{FASnI}_{3-x}\text{Br}_x$ phases shows deviation along these lines with $\text{FASnI}_{1.9}\text{Br}_{1.1}$ having a morphology more closely

resembling FASnI_3 whereas $\text{FASnI}_{1.1}\text{Br}_{1.9}$ crystallizes with an extended rhombic dodecahedral shape, more closely resembling FASnBr_3 . SEM images on the remainder of the compositions confirm the trend in crystal morphology (Figure S3). Additionally, energy-dispersive X-ray spectroscopy (EDS) on individual crystals yielded compositional information that was consistent with the refined composition based on single crystal X-ray diffraction (Table S5) given the semi-quantitative nature of EDS.

3.3.0 Structural Description and Phase Transitions:

The end members of the present series FASnI_3 and FASnBr_3 , have previously been structurally characterized through single crystal and Rietveld refinement in previous research efforts.^{31, 32} However, we revisit these two structures as they pertain to their solid solutions.

3.3.1 Structural Description of FASnI_3 : When considering only the crystallographic aspects of FASnI_3 , the compound is best described by a cubic structure (space group $Pm\bar{3}m$) adopting the ideal perovskite architecture with SnI_6 octahedra corner sharing in all three crystallographic directions, forming a cage with 180° Sn – I – Sn angles. The FA^+ cation then sits in the center of the cage to balance the overall negative charge of the framework. This organic cation, though, is heavily disordered, intended to represent the dynamic nature of the position of the cation (tumbling). Based on the symmetrical constraints of the space group, the disorder generates a pseudo carbon-centered “octahedra” where the caps are 1/3 occupied N atoms. This type of model is an approximation to the rotation where the molecule which creates a “sphere” of electron density surrounding the central carbon atom. This model, however, does not abide by traditional chemical understanding since the structure of the organic FA^+ cation is not considered. Alternatively, since FA^+ has a net dipole moment that cannot be canceled out (as might be suggested by the $Pm\bar{3}m$ model) the symmetry can be reduced to non-centrosymmetric ($Amm2$), allowing for ordering the FA^+ cations. This symmetry setting is artificial, however, so the cubic model ($Pm\bar{3}m$) will be considered in further discussions.

It should be noted that FASnI_3 (as well as MASnI_3) undergoes a smooth phase transition at low temperatures characterized in calorimetric measurements by weak endothermic peaks and a long tail at the lower temperature.³² This behavior in Pb-based compounds is commonly associated with antiferrodistortive instabilities on cooling from elevated temperatures, which result in the transition to tetragonal or orthorhombic structures at lower temperatures. From the symmetry

viewpoint, these antiferrodistortive and non-polar instabilities are characterized by the M_3^+ and R_4^+ irreducible representations of the $Pm\bar{3}m$ parent phase. These order parameters are attributed by symmetry to octahedra rotations at the microscopic level. They are indeed associated experimentally to anisotropic thermal motions with large amplitudes of the halide atoms perpendicular to the metal halide bonds,⁵⁵ and diffuse scattering rods along the M-R lines in reciprocal space.⁵⁶ The slow dynamics related to these strongly anharmonic octahedra rotations is difficult to capture precisely by diffraction techniques. It led to the proposition of the polymorphous picture for the high temperature $Pm\bar{3}m$ cubic phase, leading to some improvement for the refinement of pair distribution functions (PDF).⁵⁰

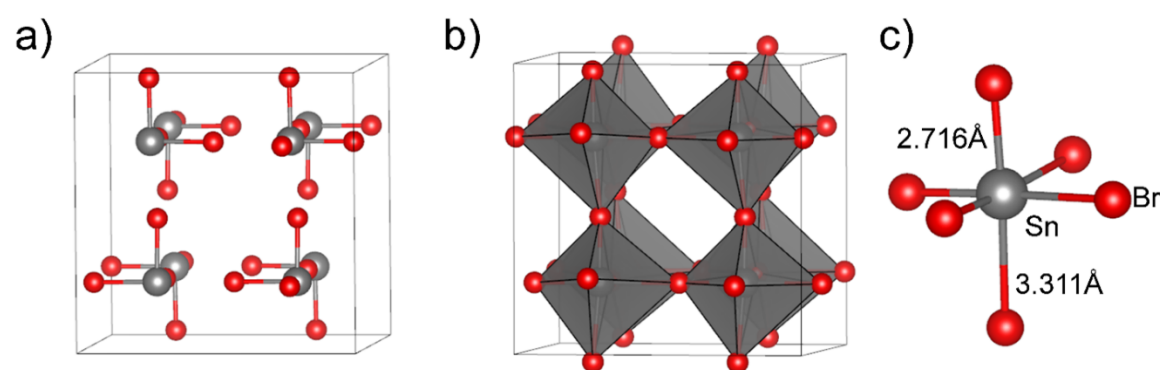


Figure 4: Depiction of the $FASnBr_3$ structure ($Pa\bar{3}$) in three panels. a) The overall structure with FA^+ cations omitted for simplicity and b) the same view with polyhedra and elongated bonds included to show how the perovskite framework is retained c) the Sn center with the unique bond distances highlighted. The atoms are presented as grey and red for Sn and Br respectively

3.3.2 Structural Description of $FASnBr_3$: The structure of $FASnBr_3$ has been resolved from high quality Rietveld refinement previously.³² However, since our work presents the first single crystal study, we shall endeavor to describe its structure in this section as it is key to understanding structural alterations in $FASnI_{3-x}Br_x$ ($x = 0 - 3$) phases and drastic deviations in optical properties of these materials. Unlike $FASnI_3$ the bromide analogue shows increased stereochemical expression of its $5s^2$ lone pair of electrons, which “breaks” the cage framework in an ordered fashion (Figure 4a). 3 of the 6 bonds in the $SnBr_6$ octahedra extend, creating a set of 3 short 2.716(1) Å bonds and 3 long 3.311(1) Å distances (Figure 4c). This perturbation in the perovskite structure creates what can be thought of as $[SnBr_3]^-$ molecular units (pyramidal geometry) that are charged balanced with FA^+ cations. However, this view is a simplification used here for clarity as the 3.311(1) Å Sn – Br bonds undoubtedly retain bonding-type interactions. The geometric constraints placed on the framework by the size of FA^+ are of equal consideration. Being the largest

A-site cage cation typically seen in MHP materials, the Sn–Br framework presents the geometric limit for the FA^+ cation before the perovskite cage becomes unstable.⁵⁷ This $[MX_3]^-$ type unit is not unprecedented in the perovskite ABX_3 stoichiometry as the compounds $RbGeBr_3$,⁵⁸ $CsGeX_3$ ($X = Cl, Br, I$),⁵⁹ $MAGeI_3$,^{60, 61} $FAGeI_3$,⁶¹ $FAGe_{0.5}Sn_{0.5}Br_3$,⁶² $MAGeBr_3$,⁶² $FA_{0.5}MA_{0.5}GeBr_3$,⁶² $FAGeBr_3$,⁶² $N(CH_3)_4GeCl_3$,⁶³ $(CH_3)_2NH_2SnBr_3$,⁶⁴ $(CH_3)_3NH_2SnBr_3$,⁶⁵ $NH(CH_3)_3SnBr_3$,⁶⁶ $NH(CH_3)_3SnCl_3$,⁶⁶ and $C(NH_2)_3SnCl_3$ ⁶⁷ and $MASnCl_3$ ¹⁰⁴ display the same “pyramidal” geometry (Table 3). Therefore, $FASnBr_3$ is more accurately described as an extended 3D framework (pseudo 0D) at room temperature by considering 0D pyramidal $[SnBr_3]^-$ units more weakly interacting and arranging in the 3D perovskite architecture (Figure 4b). The lone pair-induced structural distortion, which can also be viewed as a second-order antiferroelectric Jahn-Teller distortion reduces the dimensionality of the 3D network, moving it closer to 0D. Furthermore, this is supported by theoretical studies which probed the limit of the perovskite framework in the $FAPb_{1-x}Sn_xBr_3$ composition space suggesting the dynamic presence of these distortions.⁵⁷ The pseudo-dimensional reduction also has a direct impact on the symmetry of the compounds, as it crystallizes in the lower symmetry space group $Pa\bar{3}$ resulting in a 2-fold expansion of the unit cell parameters which can easily be seen in the precession images of reciprocal space (Figure S10). The distortion showed by $FASnBr_3$ can be alleviated by increasing the temperature whereby the typical 3D perovskite framework is obtained above 312 K,³² which in agreement with an analogous phase transition exhibited by the $CsGeX_3$ ($X = Cl, Br, I$) compositions.

From the symmetry viewpoint, the structural phase transition from the high-temperature $Pm\bar{3}m$ structure to the room-temperature $Pa\bar{3}$ structure is completely different from the non-polar and antiferrodistortive instabilities attributed to M_3^+ and R_4^+ order parameters seen for the low temperature transitions of $FASnI_3$. The symmetry analysis of the $Pm\bar{3}m/Pa\bar{3}$ group-subgroup relationship reveals that the structural instability is mainly driven by an X_5^- order parameter. Group symmetry thus predicts a polar instability related to the creation of an antiferroelectric array at room temperature. The antiferroelectric pattern is expected to exhibit phase factors for the atomic motions related to the wavevector \vec{k}_X . Among the three atomic sites (A,B,X) usually defining the regular ABX_3 cubic perovskite lattice at high temperature, the A site (FA^+) is not affected by the X_5^- structural instability. In contrast, both the B site (Sn) and the X site (Br) are expected to undergo atomic axial displacement patterns. This feature is in perfect agreement with the reported

experimental structure. The condensation at $T = 312$ K of the X_5^- structural instability in $FASnBr_3$ has a calorimetric signature, which is also completely different from the signature of the antiferrodistortive instability in $FASnI_3$.³² As expected, the thermal motions obtained from X-ray diffraction also exhibit new features for $FASnBr_3$ (*vide infra*). Therefore, a competition between polar and non-polar structural instabilities is expected, something commonly observed in perovskite lattices.⁶⁸ Experimentally, a complex superposition of structural signatures of different origins is indeed observed (*vide infra*).

3.3.3 Discrepancy Between $CsSnBr_3$ and $FASnBr_3$: Besides being fully inorganic and hybrid, respectively, $CsSnBr_3$ and $FASnBr_3$ structurally vary from one another at room temperature. $CsSnBr_3$ retains a 3D perovskite framework and expected $Pm\bar{3}m$ space group symmetry, while $FASnBr_3$ distorts reducing the symmetry to $Pa\bar{3}$. This difference can be attributed to the difference in “pressure” exerted by the A-site cation on the inorganic framework. Based on the geometric size, FA^+ within a Sn – Br perovskite framework represents the limit with respect to the tolerance of the perovskite lattice, i.e., the FA^+ cation is too large at room temperature (253pm).⁶⁹ This is reconciled with $FASnBr_3$ generating a perovskite framework at higher temperatures whereby the basic cell and cage can expand to more easily accommodate the larger organic. Cs^+ , on the other hand, typically represents the other end of the tolerance spectrum for halide perovskite templating A-site cations (184 pm).⁷⁰ Therefore, it can more comfortably template a Sn – Br based perovskite. These structural variations highlight the strict size limitations for perovskite forming compositions.

Table 3: A list of compounds that have $[MX_3]^-$ 0D molecular units with an AMX_3 perovskite stoichiometry and an extended 3D architecture. Relevant optical properties of each material are also listed.

Formula	Temperature (K)	Band Gap (eV)	Photoluminescence*	Reference
$CsGeI_3$	293	1.6	N/A	59
$MAGeI_3$	293	1.9	N	60, 61
$FAGeI_3$	293	2.2	N	61
$CsGeBr_3$	293	2.42	Y	59 62
$RbGeBr_3$	293	N/A	N/A	58
$MAGeBr_3$	298	2.91	N	62
$FA_{0.5}MA_{0.5}GeBr_3$	298	3.02	N	62

FAGeBr ₃	298	3.13	N	62
CsGeCl ₃	293	3.69	N/A	59
N(CH ₃) ₄ GeCl ₃	293	N/A	N/A	63
FAGe _{0.5} Sn _{0.5} Br ₃	298	2.75	N	62
FASnI _{0.4} Br _{2.6}	260	N/A	N/A	This Work
FASnBr _{2.9} I _{0.1}	300	2.05	N	This Work
FASnBr ₃	290	2.24	N	This Work, ⁷¹
(CH ₃) ₂ NH ₂ SnBr ₃	293	N/A	N/A	64
(CH ₃) ₃ NH ₂ SnBr ₃	293	N/A	N/A	65
NH(CH ₃) ₃ SnBr ₃	296	2.76	N/A	66
NH(CH ₃) ₃ SnCl ₃	296	3.59	N/A	66
C(NH ₂) ₃ SnCl ₃	295	N/A	N/A	67
MASnCl ₃	297	3.46	N/A	104,105

*Photoluminescence is given a Y if the property was observed, a N if it was not, and a N/A if not reported.

3.3.4 Synthetic Insights Garnered from Structure: The structural differences between the two end-member materials might also give insight into the synthetic conditions necessary for synthesizing the FASnI_{3-x}Br_x ($x = 0 - 3$). As mentioned in the synthetic portion of the discussion, to achieve a material with 2/3 Br⁻ substitution or greater ($x = 2 - 3$) the mol fraction of hydrobromic acid (χ_{HBr}) must be > 0.9 . The pronounced inclination towards I⁻ during the synthesis process aligns well with the underlying structure. Given that FASnBr₃ possesses more “discrete” [SnBr₃]⁻ pyramidal units, it essentially functions more like a molecular salt, represented as (FA⁺)([SnBr₃]⁻), and is associated with a comparatively weaker lattice structure. This makes FASnBr₃ more soluble in the polar acidic media employed during the synthesis. In contrast, FASnI₃ features a 3D network of robustly interconnected corner-sharing SnI₆ octahedra, resulting in diminished solubility in polar solvents when compared to FASnBr₃. Therefore, bromide-rich compositions tend to have higher solubility than their iodide-rich counterparts. Such differential solubilities cause compositions with a higher iodide content to precipitate more easily from the solution. It also supports the idea of halide exchange (iodide for bromide) if exposure to the mother liquor is prolonged since, from a solubility perspective, precipitation of I-rich phases is more favorable.

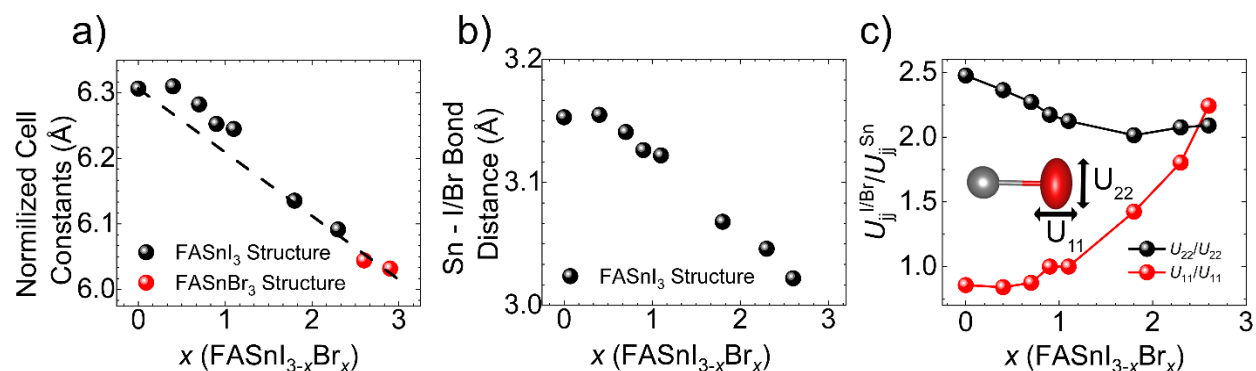


Figure 5: a) The normalized unit cell constants, based on single crystal X-ray diffraction data, for each compound synthesized in the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) system. Compounds are labeled by their structure type in black and red for the FASnI_3 ($Pm\bar{3}m$) and FASnBr_3 ($Pa\bar{3}$) structure type, respectively. The dashed line displays the ideal behavior based on Vegard's Law analysis. b) The bond distances for each compound with the FASnI_3 structure plotted against composition. c) A plot of the U_{11} (red) and U_{22} (black) anisotropic displacement parameters as a function of composition normalized to the displacement parameters of the central Sn considering the same direction for all $\text{FASnI}_{3-x}\text{Br}_x$ compounds that retain the FASnI_3 cubic structure. Note that the U_{22} and the U_{33} parameters are equivalent for both the halide and metal atoms.

3.3.5 Structural Description of the FASnBr_3 ($x = 0 - 3$) Compositions: Upon the introduction of Br^- into the structure, there is a corresponding decrease in the unit cell parameters of the cubic structure (denoted as FASnI_3 structure type) following Vegard's Law (Figure 5a). The variations of the standard lattice parameters do not exhibit discontinuities that might be attributed to a sudden crossover from a lattice dominated by fluctuations of the octahedra tilts ($\text{M}_3^+/\text{R}_4^+$, FASnI_3 -like) to a lattice dominated by atomic translations related to antiferroelectric fluctuations (X_5^- , FASnBr_3 -like). The average FASnI_3 structure type was retained for the refinements of the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 2.9$) structures leading to Br^- substituted on the I site and having the same atomic coordinates. In these intermediate compositions, the distribution of local static disorder is artificially represented in the refined crystallographic structures through the thermal displacement tensor U_{ij} , and is entangled with contributions related to thermal (phonon) displacements.

The inspection of the anisotropic displacement parameters nevertheless allows for the characterization of the interplay between the various ($\text{M}_3^+/\text{R}_4^+$ versus X_5^-) structural fluctuations. From Figure 5c, we first observe that the U_{22} and U_{33} anisotropic displacement parameters are very strong in FASnI_3 and mainly reflect antiferrodistortive fluctuations related to octahedra rotations. The thermal displacement parameter U_{11} related to axial displacements (stretching of the Sn-I bonds) is smaller by comparison. When the Br content increases, the most noticeable difference is the elongation of the U_{11} thermal displacement parameters from 36(1) to 148(4) $\text{\AA}^2 \times 10^3$ for FASnI_3 and $\text{FASnI}_{0.4}\text{Br}_{2.6}$ respectively. A very strong increase of the U_{11} parameter is observed for $x > 1$

leading to a maximum value for $\text{FASnI}_{0.4}\text{Br}_{2.6}$. The steep increase for intermediate compositions can be partially attributed to the difference in average bond length between Sn – Br and Sn – I and the structural differences between FASnI_3 and FASnBr_3 . As the Br⁻ increases, the number of $[\text{SnBr}_3]^-$ and $[\text{SnIBr}_2]^-$ units also increase. This leads to a shortening in the bond lengths for regions with this motif and respective lengthening of inter-unit distances. In contrast, the $[\text{SnBr}_3]^-$ and $[\text{SnI}_2\text{Br}]^-$ units present in the structure prefer shorter inter-unit distances with small or negligible differences between intra-unit Sn-I and inter-unit Sn-I bonds, thereby forming the connected 3D framework, requiring much longer interatomic distances. This then leads to the apparent elongation of the anisotropic displacement parameter of the halide sites for the Br⁻ rich compositions in the cases where the two different halide positions cannot be resolved. This hypothesis is confirmed through low temperature single crystal X-ray diffraction, and room temperature pair distribution function (PDF)/Raman spectroscopy *vide infra*. The suggestion is also in line with theoretical findings in the $\text{FAPb}_{1-x}\text{Sn}_x\text{Br}_3$ composition space, which suggest that the off-centering through the lengthening and shortening of bonds is expected to be present up until reaching the Pb-rich regime at which point equalization occurs at $\text{FAPb}_{0.5}\text{Sn}_{0.5}\text{Br}_3$.⁵⁷ The distribution of local static disorder in intermediate compositions is entangled in U_{11} with the contributions related to thermal (phonon) displacements. Both reflect the propensity of the perovskite lattice to undergo locally X_5^- structural distortions. It should be noted that the refinements of the average crystallographic structures lead to a clear $Pa\bar{3}$ space group only for very high Br⁻ contents. This is expected when the correlation lengths related to the X_5^- fluctuations diverge and when the associated diffuse scattering contributions merge into new Bragg-like contributions that can be included in a structure refinement within the $Pa\bar{3}$ space group. It may be further noticed (Figure 5c) that the values of the U_{22} and U_{33} anisotropic displacement parameters are only slightly reduced when increasing the Br content by comparison to pure FASnI_3 . It suggests that antiferrodistorsive fluctuations are still present whatever the Br content, even when antiferroelectric fluctuations start to dominate.

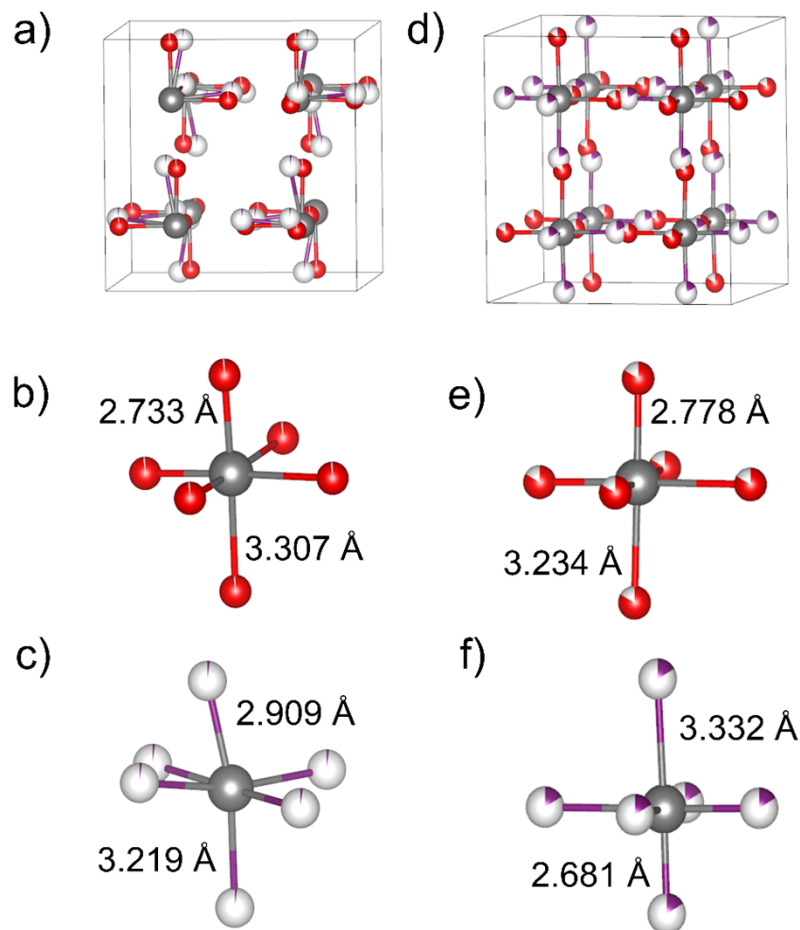


Figure 6: a) depiction of the overall structure of $\text{FASnI}_{0.1}\text{Br}_{2.9}$ with the organic FA^+ cations omitted. c) a closer look at the Sn coordination sphere to Br^- and c) I^- for $\text{FASnI}_{0.1}\text{Br}_{2.9}$. d) the overall structure of $\text{FASnI}_{0.4}\text{Br}_{2.6}$ at 260K with the organic cations omitted. e) a closer view of the short and f) long Sn – X distances in $\text{FASnI}_{0.4}\text{Br}_{2.6}$ at 260K. Both are molded in the $Pa\bar{3}$ space group.

While most of the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) series retains, on average, the structure of FASnI_3 when $x = 2.9$ the structure more clearly shifts towards the FASnBr_3 motif but with noticeable differences. $\text{FASnI}_{0.1}\text{Br}_{2.9}$ crystallizes in the same $Pa\bar{3}$ space group as FASnBr_3 with a 2-fold enlargement of the cell in all three directions; however, the halides are positionally disordered with respect to one another, with the Br and I having independent atomic coordinates (Figure 6a). The disorder allows the small amounts of I^- present to modulate its distance from the Sn center. The covalently bonded I atoms obtain a longer bond (2.91(6) Å) compared to an equivalent Br atom (2.733(2) Å) whereas the more non-covalent I atom achieves a shorter distance (3.22(5) Å) than the equivalent Br atom (3.307(3) Å) which is consistent with the I atoms attempting to establish a

more stable 3D frameworks compared to the Br atoms, which are stabilized in an extended coordination environment (Figure 6b and 6c).

3.3.6 Temperature-Dependent Phase Transitions: To further investigate the presence of a 3D-0D phase transition, low temperature single crystal X-ray diffraction experiments were conducted on two members of the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) substitution range, specifically focusing on I-rich and Br-rich compounds that retained the FASnI_3 3D structure at room temperature. Therefore, $\text{FASnI}_{1.9}\text{Br}_{1.1}$ and $\text{FASnI}_{0.4}\text{Br}_{2.6}$, were selected as representative candidates. Upon cooling, $\text{FASnI}_{1.9}\text{Br}_{1.1}$ did not display the anticipated phase change; however, at $\sim 260\text{K}$ the hypothesized 3D-0D transition was observed for $\text{FASnI}_{0.4}\text{Br}_{2.6}$, marked by additional reflections in reciprocal space (Figure S8). The resolved structure resembles the room temperature structure $\text{FASnI}_{0.1}\text{Br}_{2.9}$ with disordered halide positions, but its unique differences (Figure 6d). The best crystallographic model was obtained by relaxing the constraints on the coordinates of I and Br, refining them independently. As a result, the I and Br occupy different positions with two unique interatomic distances to each Sn center each: one bonding (Figure 6e) and one non-bonding distance (Figure 6f). The “bonding” distances are 2.681 \AA and 2.778 \AA for Sn – I and Sn – Br, respectively and the “non-bonding” distances are 3.332 \AA and 3.234 \AA for Sn – I and Sn – Br, respectively. This places the iodide atoms within bonding distance closer than the bromide and on the opposite side of the octahedra. Note that while these distances are referred to as “bonding” and “non-bonding,” the longer distances are expected to have a bonding character, albeit they are much weaker.

While this model achieves reasonable agreement statistics, increased levels of disorder could be present that is not accounted for (see section 2.4). Nonetheless, the presence of the $Pm\bar{3}m/Pa\bar{3}$ structural transition at low temperatures is related to the condensation of the X_5^- structure fluctuations observed at room temperature through the U_{11} parameter (Figure 5c). It confirms that the trend in the room temperature thermal parameters can be attributed to an increased presence of off-centering locally while retaining a 3D framework on average and provides a rationale for observed PL quenching, *vide infra*, as these distortions have already been shown to drastically decrease PL intensity in MAGeI_3 .⁶⁰ Further information on 260K structure of $\text{FASnI}_{0.4}\text{Br}_{2.6}$ can be found in the supporting information. By conducting additional experiments using temperature-dependent UV-Vis spectroscopy, we can further validate the existence of the

phase transition. This confirmation would be evident through the sudden widening of the band gap once the transition temperature is reached on cooling.

3.4. Analyses of the Local Structures for $FASnI_{3-x}Br_x$ ($x = 0, 1.1, 2.6, 3$) Compositions: Pair Distribution Function (PDF):

To garner a more in-depth understanding of the local structural distortions of the inorganic framework within the mixed halide phases, experimental PDF curves were generated from high-resolution X-ray powder diffraction patterns using equations S1 – S4. Four compositions were selected: $FASnI_3$ and $FASnBr_3$, to obtain a baseline PDF curve for the two unique structure types, as well as $FASnI_{1.9}Br_{1.1}$ and $FASnI_{0.4}Br_{2.6}$ since these compositions were tested for temperature-dependent phase transitions through single crystal X-ray diffraction.

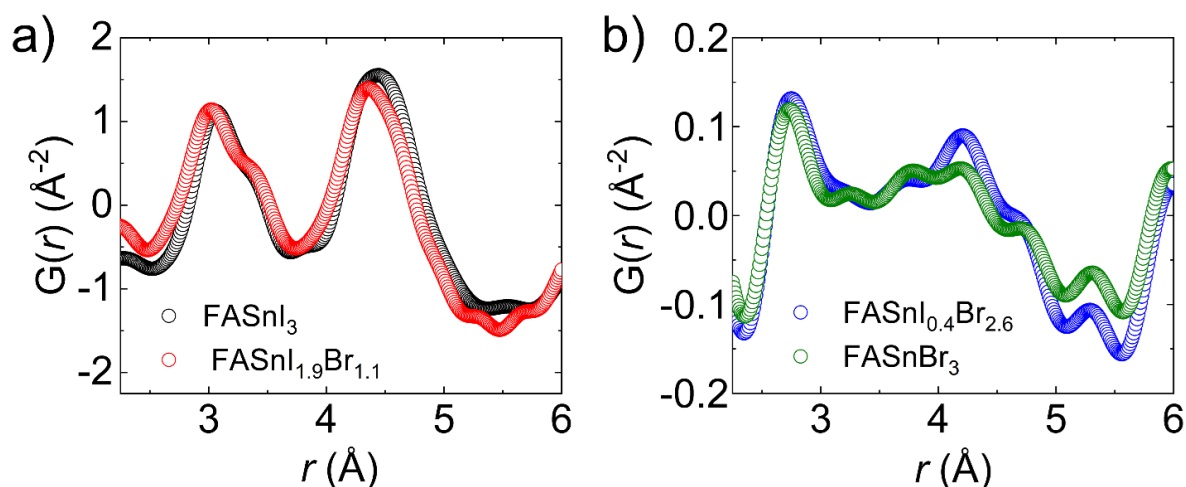


Figure 7: The experimental pair distribution function curves ($G(r)$) for a) $FASnI_3$ b) $FASnI_{1.9}Br_{1.1}$ c) $FASnI_{0.4}Br_{2.6}$ and d) $FASnBr_3$ with the range of 0-6 Å

Experimental PDF curves provide information on the density of atoms present at a distance r (Å) away from an arbitrary center. Based on the average crystal structure for $FASnI_3$ the local structure of 3D Sn MHP inorganic framework contains two main components consisting of primary distance vectors of ~ 3 Å and 4.5 Å for Sn – I bonding and I – I nearest neighbors. On the other hand, due to the distortions of the perovskite lattice at room temperature, $FASnBr_3$ contains two unique Sn – Br distances at 2.7 and 3.3 Å and a broader distribution of nearest neighbor Br – Br vectors providing contrast between the two structure types that can be identified in the $G(r)$. Therefore, examination of the low r regions (2-5 Å) of the PDF curves indicates a distribution of

distortions with short coherence lengths. A more extended range of the calculated $G(r)$, however, can be seen in Figure S5.

As expected, the experimental PDF of FASnI_3 (Figure 7a) has a strong feature centered at $\sim 3 \text{ \AA}$. This vector corresponds to the Sn – I bond in the FASnI_3 structure, which deviates $\sim 0.1 \text{ \AA}$ from the distance obtained from the average crystal structure (3.15 \AA). However, the position of the peak is consistent with the previous experimental PDF conducted on the same phase.⁷² There is, however, identifiable shouldering towards higher r , which could provide evidence for emphanitic behavior: a phenomenon previously identified in the MHP literature⁷³ despite having roots in chalcogenide chemistry.⁷⁴⁻⁷⁶ The experimental PDF also contains a feature centered at 4.5 \AA , in line with I – I nearest neighbor distance vectors. Refining the local structure of FASnI_3 by fitting the experimental PDF within the $2\text{-}5 \text{ \AA}$ range shows a reasonable agreement as well as small distortions of the SnI_6 octahedra: off-centering the Sn atom presumably due to activity of the $5s^2$ lone pair (Figure S6). Thus, weak structural fluctuations of the X_5^- type are probably already present in pure FASnI_3 structure.

FASnBr_3 , on the other hand, shows a much broader distribution of distance vectors within the $2.5\text{-}5 \text{ \AA}$ region (Figure 7b), suggesting higher degrees of local dynamicity in the Sn – Br bond length as well as other vectors. A sharp feature centering at $\sim 2.7 \text{ \AA}$ is in excellent agreement with the short, bonding Sn – Br distance. Additionally, broader features at 3.18 and 3.42 \AA can be attributed to the long Sn – Br distances in the 0D unit because the average between the two is 3.3 \AA . The presence of a split distance vector indicates a higher degree of dynamicity in the 3.311 \AA . Broad features in the $G(r)$ between 4 and 5 \AA reflect the fluidity in the nearest neighbor Br – Br distance vectors. The fitting of the experimental PDF curve at low r shows that the average crystal structure aligns with the local structure (Figure S7). The curve is also consistent with previous experimental data collected for FASnBr_3 , though our local structure explanation differs significantly since here Pa-3 model was used as the basis structure instead of Pm-3m.⁷⁷

Comparisons of the mixed halide PDF curves with the end members show a remarkable trend in the short-range structure of these mixed halide phases. The PDF of $\text{FASnI}_{1.9}\text{Br}_{1.1}$ resembles that of FASnI_3 with a well-resolved peak in the curve at $\sim 3 \text{ \AA}$ (Figure 7a). Splitting of both the bonding and nearest neighbor halide peaks indicates local discrepancy of these distances, likely associated with mixed I/Br on the halide position. On the other end of the substitution range, $\text{FASnI}_{0.4}\text{Br}_{2.6}$ displays a curve most similar to that of FASnBr_3 despite the average crystal structure

being consistent with FASnI_3 . Furthermore, the PDF of this Br-rich phase shows a prominent distance vector at the same 2.7 Å corresponding to the short distance in a $[\text{SnBr}_3]$ OD unit (Figure 7b). The presence of this distance vector indicates a dynamic competition between the concealment and expression of the $5s^2$ lone pair of electrons a local level that is not captured in the average crystal structure, with the exception of the elongation of the displacement parameters. Attempts to model the experimental PDF curves for these mixed halide phases using supercell approximations to the halide substitutions and Reverse Monte Carlo simulations could yield a more in-depth understanding of this competition. Such modeling, however, is outside the scope of the current work. The definitive presence of significant Sn off-centering in the short-range does explain the trends in the optical properties of the bulk materials.

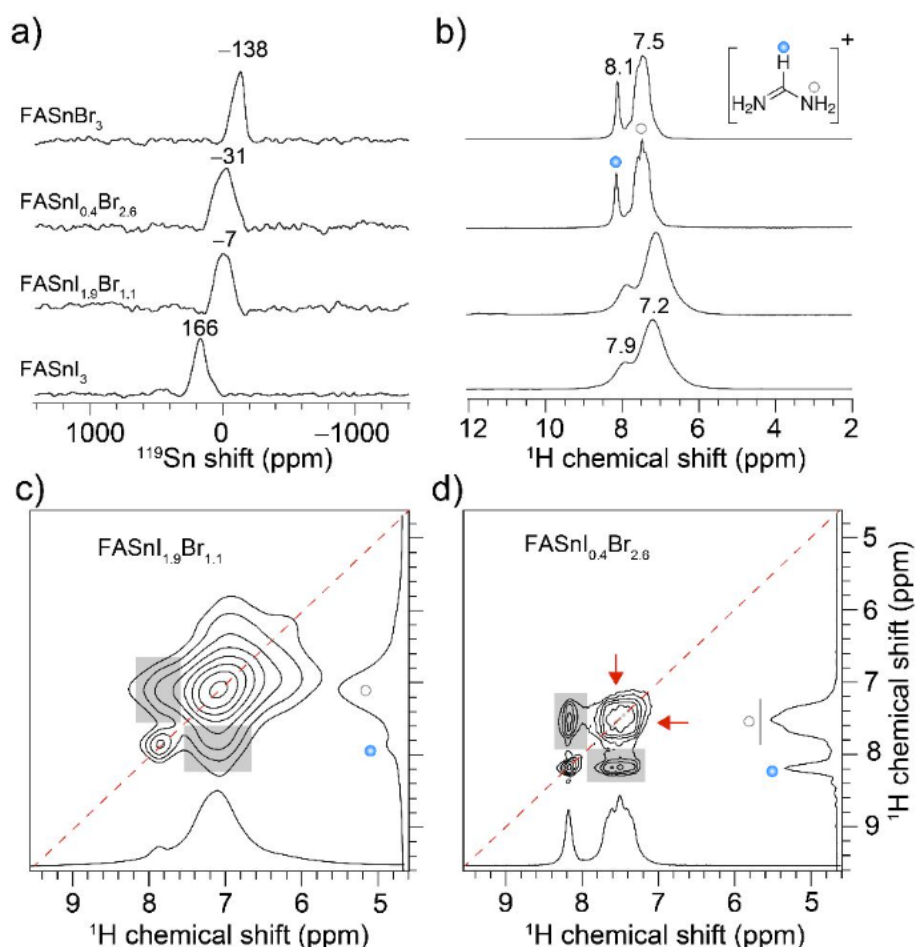


Figure 8: Solid-state 1D (a) ^{119}Sn and (b) ^1H magic-angle spinning NMR spectra of FASnX_3 alloys as indicated. Solid-state 2D ^1H - ^1H spin-diffusion (SD) NMR spectra of (c) $\text{FASn}_{1.9}\text{Br}_{1.1}$ and (d) $\text{FASn}_{0.4}\text{Br}_{2.6}$ phases plotted with the sky-line projections presented on horizontal and vertical axes in the insets. All spectra were acquired at 18.8 T (^1H = 800.1 MHz and ^{119}Sn = 298.4 MHz), 50 kHz MAS (a-b) or 55 KHz (c-d) and at room temperature.

3.5 Solid State ^{119}Sn and ^1H NMR Studies on $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0, 1.1, 2.6, 3$):

Solid-state NMR spectroscopy can analyze local chemical environments of organic cations in the cuboctahedral cages and organic-inorganic interfaces, which does not require long-range order.⁷⁸⁻⁸¹ Figure 8 presents ^{119}Sn and ^1H spectra of pure phases and alloys. For example, ^{119}Sn shifts are sensitive to the oxidation state of the Sn atoms, Sn – X bond distances, Sn – X – Sn bond angles and octahedral distortions. The octahedral Sn atoms in the (II) oxidation state produce ^{119}Sn NMR peaks in the range of -1000 and 500 ppm.^{82, 83} For the 3D FASnI_3 (Figure 8a), the peak centered at 166 ppm is attributed to the Sn atoms in an octahedral coordinated tin iodide network. By comparison, the 3D FASnBr_3 materials produced a peak at -138 ppm due to the Sn atoms coordinated to Br atoms. For the $\text{FASnI}_{1.9}\text{Br}_{1.1}$ and $\text{FASnI}_{0.4}\text{Br}_{2.6}$ alloys, the peaks centered at -7 and -31 ppm, respectively, indicate the different local chemical environments of the Sn atoms, which are coordinated to both I and Br sites. The full-width-at-half-maximum (fwhm) values associated with the $\text{FASnI}_{1.9}\text{Br}_{1.1}$ (fwhm: 178 ppm, ~53 kHz) and $\text{FASnI}_{0.4}\text{Br}_{2.6}$ (322 ppm, ~96 kHz) compounds, as compared to the pure phases: FASnI_3 (121 ppm, ~36 kHz) and FASnBr_3 (131 ppm, ~36 kHz), further corroborate these results. Specifically, the fwhm of ~322 ppm (96 kHz) in Br-rich phase, which is identical to the chemical shift difference $\Delta\delta(^{119}\text{Sn}) = 304$ ppm (~91 kHz) between FASnI_3 and FASnBr_3 . The different lineshapes associated with the $\text{FASnI}_{1.9}\text{Br}_{1.1}$ and $\text{FASnI}_{0.4}\text{Br}_{2.6}$ compounds by means of both chemical shifts and fwhm values suggests halide mixing. It is noteworthy that halide hopping may occur in such species, and may also occur in such species, and degradation products may also form upon exposure to ambient, as previously studied by ssNMR spectroscopy. Additionally, the ^1H NMR spectra of FASnI_3 and $\text{FASnI}_{1.9}\text{Br}_{1.1}$ phases (Figure 8b) exhibited peaks associated with FA cations corresponding to NH_2 (7.2 ppm) and CH (7.9 ppm) sites. For the FASnI_3 and $\text{FASnI}_{1.9}\text{Br}_{1.1}$ phases, the relatively narrow features appeared for NH_2 (7.5 ppm) and CH (8.1 ppm) sites. These narrow features indicate the faster re-orientational dynamics of FA^+ cations in the bromine-rich phases than the iodine-rich phases, due to the different tolerance factors. In addition, the relative difference in the ^1H chemical shifts $\Delta\delta(^1\text{H}(\text{NH}_2)) = 0.3$ ppm, and $\Delta\delta(^1\text{H}(\text{NH})) = 0.2$ ppm between the bromine-rich and iodine-rich phases indicate the different non-covalent interactions at the organic-inorganic interface. It is noteworthy that the ^1H chemical shifts of the FA^+ cations FASnI_3 phases (7.2 and 7.9 ppm) are different than the FAPbI_3 phases (7.5 and 8.1), further indicating the different local structures and dynamics of cage cations.⁸⁴ The solid-state NMR data reinforces the different local environments for the Sn

centers, specifically being well aligned with the distribution of distance vectors in the PDF. The unique ability to probe the organic cation, which is not easily seen through X-ray scattering techniques, adds additional evidence for the above-mentioned structural distortions that increase on a local scale with Br^- concentration as the FA^+ cations can reorient relatively faster due to different local chemical environments; with an extended pseudo-0D framework as opposed to the more rigid SnI_6 cage structure. The different local chemical environment of FA^+ and their intermixing nature is further corroborated by analyzing 2D ^1H - ^1H spin-diffusion NMR spectra of $\text{FASnI}_{1.9}\text{Br}_{1.1}$ and $\text{FASnI}_{0.4}\text{Br}_{2.6}$ compounds. A beneficial feature of 2D 1H spin diffusion experiment is that it allows spin magnetization to exchange between dipole-dipole coupled ^1H - ^1H sites, enabling the through space proximities between them to be probed and distinguished. Close proximities are manifested as off-diagonal peaks, while the on-diagonal peaks are characteristic to chemical shifts. For the I-rich $\text{FASnI}_{1.9}\text{Br}_{1.1}$, the SD spectrum acquired with 200 ms showed broad on-diagonal features for NH_2 and CH sites, and the off-diagonal features (gray bands) indicate the strong dipolar interactions between them. By comparison, the Br-rich $\text{FASnI}_{0.4}\text{Br}_{2.6}$ compound displays narrow features for NH_2 with up to five partially resolved contributions (Figure S8a) due to the different local of these sites and CH sites. The well-resolved off-diagonal features between these sites suggests stronger dipolar interactions due to the close inter- and intramolecular proximity. More importantly, the peaks depicted in the red arrows indicate the close proximities between the NH_2 groups in FA cations at different local chemical environments; indicating the intermixing of Br/I halide sites rather than a phase separation. This is further corroborated by acquiring and analyzing the ^1H SD spectra of this latter compound with different spin diffusion mixing times (Figures S8). Overall, the 2D solid-state NMR analysis confirms the different local environments of FA cations and their proximities in I-rich and Br-rich alloys.

3.6. Optical properties:

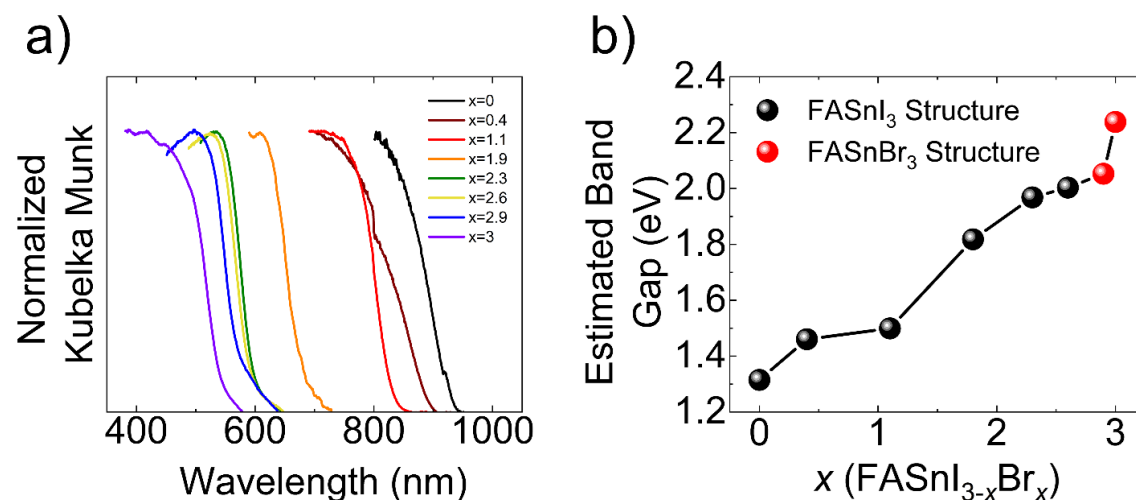


Figure 9: a) Diffuse reflectance UV-Vis spectra for selected compositions, highlighting the positions of the absorption edges and b) the estimated optical band gap for selected compositions in the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) composition space. The compounds are labeled in black and red depending on if it adopts the FASnI_3 or FASnBr_3 structure type.

3.6.1 Diffuse Reflectance UV-Vis Spectroscopy: The optical diffuse reflectance absorption edges for selected compositions (Figure 9a) shows a blue shifting (widening) of the band gap across the composition space from $x = 0 - 3$ based on movement of the linear onset of the absorption. The band gap can then be approximated through the linear extrapolation of the linear onset of the absorption with the observed background before the absorption edge.⁸⁵ Through this approximation, we estimate the band gap of FASnI_3 to be ~ 1.31 eV and FASnBr_3 to be ~ 2.24 eV which is within range of band gaps obtained for these materials in previous works^{31, 32} given that it has been shown that the band gap of hybrid perovskite materials can vary based on the preparation method.³¹ These band gaps values can be compared to both end compositions of their lead counterparts, where FAPbI_3 (α -phase) and FAPbBr_3 have a band gap of 1.48eV ^{31, 34} and 2.30eV ,⁸⁶ respectively.

When plotting the estimated gap for the title compounds with respect to composition (Figure 9b), we find that for those compounds that adopt the FASnI_3 , $Pm\bar{3}m$, structure there is a near linear behavior consistent with increasing concentrations of the smaller Br^- frontier orbitals. However, with the shift towards the FASnBr_3 , $Pa\bar{3}$, structure, there is a sharp widening of the gap from 2.05 to 2.24 eV, which the disruption in the structure can explain. As 3 of the 6 bonds elongate, the overall orbital overlap of the material drastically decreases, leading to a sharp decrease in the band dispersion. Such an explanation is confirmed through the calculation of the band structures (*vide infra*). Therefore, The FASnBr_3 compositions can be considered the extreme example where the overlap is removed almost entirely for half of the $\text{Sn} - \text{X}$ bonds. This idea can also be reconciled with other studies on “hollow” perovskites where substitution of $[\text{MX}_6]$ octahedra for an organic molecule leads to a blue shifting of the gap as the overall orbital overlap between the metal and halide reduces with increased substitution levels.^{81, 87}

These trends can also be compared with that of CsSnBr_3 with its 3D perovskite structure.⁷³ The observed difference in bandgap between both ends of halide members in our compounds is 0.93eV : 1.31eV for FASnI_3 compared to 2.24eV for FASnBr_3 . This can be compared to a 0.6eV difference in the cesium lead halide perovskites: 1.68eV band gap for black CsPbI_3 ⁸⁸ and 2.29 eV for CsPbBr_3 .⁸⁹ Another relatively smaller difference in bandgap is 0.47eV when comparing the bandgaps of CsPbBr_3 (2.29 eV) and CsSnBr_3 (1.82eV).^{73, 90} We therefore attribute the higher

bandgap difference in our compounds between the bromide and iodide compounds to the emerged structural changes leading to the disconnection of the proper 3D perovskite network.

3.6.2 Photoluminescence Spectroscopy: The Photoluminescence (PL) spectroscopy for selected compositions was performed using thin film samples (Figure 10a). A stock solution of 0.8M was used for spin coating the tin perovskite thin films in the glovebox. Given the sensitivity of the tin perovskites, our PL measurements on thin films gave stronger PL peaks compared to powder samples.

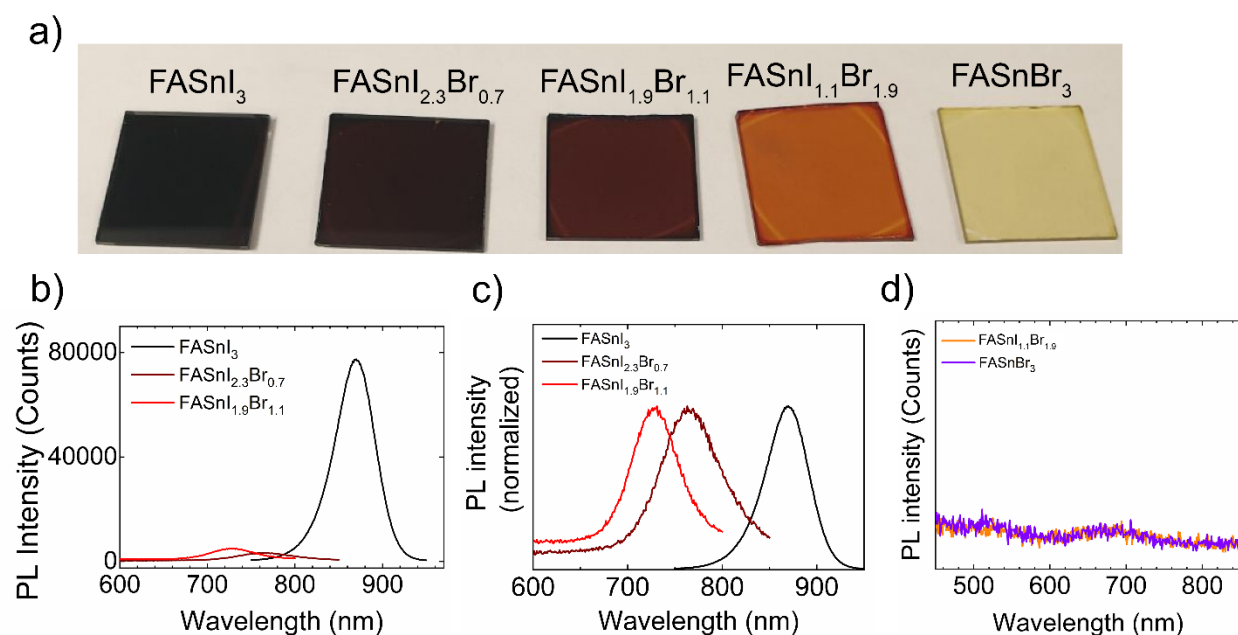


Figure 10: Photoluminescence (PL) of thin films for selected compositions to investigate the PL transition in $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) series, a) an image of representative thin film samples b) PL absolute value spectra showing drastic decrease in intensity with Br incorporation, c) normalized PL spectra of the first three selected composition from iodide rich region, and d) no PL intensity for bromide rich compositions.

For the first three selected samples, the PL peak position increases in energy with respect to composition as the emission was detected at 869nm, 763nm, and 729nm for FASnI_3 , $\text{FASnI}_{2.3}\text{Br}_{0.7}$, and $\text{FASnI}_{1.9}\text{Br}_{1.1}$ respectively (Figure 10b, c). These results are in accordance with our optical band gap measurements on these samples. However, as the concentration of incorporated bromide into the crystalline structure increased, there was a drastic quenching of the PL intensity. Comparing the PL intensity of FASnI_3 vs $\text{FASnI}_{2.3}\text{Br}_{0.7}$ (Figure 10b) more than 90% of the observed intensity was lost. This quenching effect increased as PL emission fell below the background for $\text{FASnI}_{1.1}\text{Br}_{1.9}$ and FASnBr_3 . (Figure 10d). Time-resolved photoluminescence (TRPL) spectra showed a significant drop in PL lifetime by increasing the bromide concentration.

The $\text{FASnI}_{2.3}\text{Br}_{0.7}$, and $\text{FASnI}_{1.9}\text{Br}_{1.1}$ samples have a lifetime shorter than 1 nanosecond and their decay curve interferes with the width of our instrument response function (IRF). (Figure S9).

The strong structural transitions induced by increasing the concentration of bromide can be the origin of the observed PL quenching and reduced lifetime. Through the compositional changes from iodide rich phase to bromide rich phase, the dominance of the pseudo 0D $[\text{SnBr}_3]^-$ molecular units (antiferroelectric distortions) across the lattice was observed rather than corner-sharing $[\text{SnBr}_6]^{4-}$ octahedral units. As discussed in the structural section, these changes happen when 3 of the 6 bonds in the SnBr_6 octahedra extend to make room for the lone pair. Formation of these isolated $[\text{SnBr}_3]^-$ structural units limits the charge transfer across the lattice, increasing the non-radiative recombination and eventually leading to quenching of the PL intensity. In contrast, the perovskite structure of three-dimensional CsSnBr_3 possesses corner-sharing SnBr_6 units and shows photoluminescence.⁷³ The observed structural transition in FASnBr_3 and the evolution of isolated more $[\text{SnBr}_3]^-$ units can be attributed to the presence of FA cation, which is bulkier (with an effective radius of 258pm)⁶⁹ compared to Cs (184pm)⁷⁰ leading to deformation of $[\text{SnX}_6]^{4-}$ octahedral units by decreasing the size of halide and the cavity between the corner shared units.

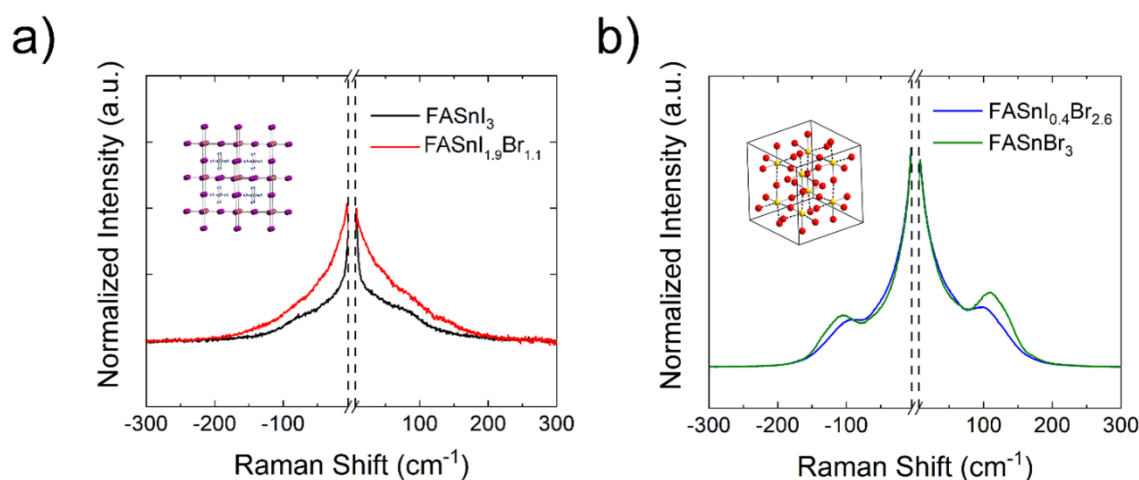


Figure 11: a) the Raman spectrum for FASnI_3 and $\text{FASnI}_{1.9}\text{Br}_{1.1}$ in black and red, respectively. The inset shows the 3D FASnI_3 perovskite structure. b) the Raman spectrum of $\text{FASnI}_{0.4}\text{Br}_{2.6}$ and FASnBr_3 in blue and green, respectively. The inset depicts the FASnBr_3 0D structure. Both graphs have the $-7 - 7 \text{ cm}^{-1}$ range omitted to remove the intensity from the excitation laser.

These results are in accordance with pressure-induced structural changes that directly impact the optoelectronic properties of tin bromide compounds.⁷¹ Moreover, the Ge off-centering observed in germanium iodide perovskites (with different cations, FA, MA or Cs) was observed leading to undetectable PL intensity for this material at ambient conditions while higher pressure-

induced recovery of 3D structure and improving related PL intensity.⁶⁰ While similar pressure-induced phase transitions studies were performed on tin halide perovskites,⁷¹ to our knowledge, no studies have been done on the mixed halide (specifically $\text{FASnI}_{3-x}\text{Br}_x$) compositions. We eagerly propose performing this study where our results indicate similar PL behavior will be observed. To investigate the mechanism of PL quenching further, low frequency Raman spectroscopy was conducted on select samples.

3.6.3 Raman Spectroscopy: Given the presence of structural differences between FASnI_3 and FASnBr_3 , the observed temperature-dependent phase transition of $\text{FASnI}_{0.4}\text{Br}_{2.6}$, deviation in the local inorganic framework, and the complete PL quenching for samples having Br⁻ fractions exceeding and including $x = 1.9$, room temperature low frequency Raman spectroscopy was conducted on 4 select samples to confirm further a lattice distortions characteristic of the $\text{Pa}\bar{3}$ phase for compositions that retain an average 3D perovskite structure at room temperature. Presented in Figure 11, spectra for FASnI_3 and FASnBr_3 were collected to form a baseline for the two different structural variations as well as for $\text{FASnI}_{1.9}\text{Br}_{1.1}$ and $\text{FASnI}_{0.4}\text{Br}_{2.6}$ since these compositions were structurally studied at low temperatures through single crystal X-ray diffraction and retain an average 3D structure at room temperature.

The vibrational density of states of hybrid halide perovskites typically exhibits 3 different regions based on the shift, with the regions being well defined for the Pb analogues: 10 – 50 cm^{-1} (PbX_6 lattice modes mostly related to octahedra rotations), 50-500 cm^{-1} (coupled lattice and organic modes, including Pb – X stretching modes), and 500-3500 cm^{-1} (individual molecular modes).⁹¹ Here we present data within the two spectral ranges corresponding to the lattice and organic-lattice coupled vibrational modes within the 7-300 cm^{-1} range. The Raman scattering selection rules for the $\text{Pm}\bar{3}m$ perovskite lattice indicates that in the harmonic approximation, no lattice optical modes should be Raman active.⁹² These selection rules can be broken when anharmonic and relaxation processes are present, leading to quasi-elastic signatures in hybrid and inorganic perovskites.^{92, 93} The observed spectrum of FASnI_3 is consistent with this behavior (Figure 11a), where a small contribution appears around 88 cm^{-1} as a shoulder. It is attributed to the Raman activation of a lattice mode by anharmonic processes. This broadness behavior at low frequencies highlights the dynamicity of the inorganic lattice and is similar to other hybrid halide perovskite materials that have been studied previously.^{91, 93, 94} FASnBr_3 similarly to FASnI_3 is

broad at very low energies, suggesting the same dynamicity for the inorganic framework, likely caused by relaxation processes related to local rotations. Additionally, there is a sharper, more intense higher energy feature centered around 110 cm^{-1} . Studies conducted on MASnI_3 would suggest that this stretch corresponds to a vibration mode of the organic coupled with Sn – Br stretching.⁹⁵ However, studies conducted by Gao, *et al.* on the CsMBr_3 family (M = Ge, Sn, Pb) suggest a more adequate assignment of this feature to structural distortions due to expression of 5s-electron lone pairs of Sn. A similar, albeit higher energy, feature is experimentally observed in the Raman scattering of CsGeBr_3 assigned to Ge off-centering.⁹⁶ The observation of the 110 cm^{-1} feature fits nicely with the assignment of the $P\bar{a}3$ space group, where Raman scattering selection rules are different and optical lattice modes can be observed even in the harmonic approximation. It should also be noted that the components and irreducible representations of the Raman modes can be mapped using a similar methodology used to analyze the CsGeX_3 (X = I, Br, Cl) series,¹⁰⁸ but such analysis falls outside the scope of the presented work.

The I-rich and Br-rich compounds tested in the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) mixed halide space showed identical behavior to the end member closest to in composition (Figure 11a & 11b). $\text{FASnI}_{1.9}\text{Br}_{1.1}$ has a broad spectrum with a slightly more intense peak at the lowest energies. This supports the idea that the structure does not locally distort with appreciable concentrations for the experiment since a high intensity feature around $90\text{-}110\text{ cm}^{-1}$ is not present. $\text{FASnI}_{0.4}\text{Br}_{2.6}$, on the other hand, displays nearly identical behavior to FASnBr_3 with a higher energy feature, which is slightly broadened and shifted to lower energies (peak center around 99 cm^{-1}). The shift and broadening of the peak are consistent with both the incorporation of increased I⁻ fractions, as the Sn – I bond is weaker and longer than the Sn – Br bond, and the reduction of distortions. The presence of this feature does, however, support the presence of relatively isolated pyramidal-like structural units which get more numerous with higher bromide concentration (See the related peak in Raman spectra of $\text{FASnI}_{0.4}\text{Br}_{2.6}$ and FASnBr_3 in Figure 11b). The distribution of local low symmetry lattice distortions is leading to the breaking of the Raman selection rules despite the refinement of the average crystal structure in a $P\bar{m}\bar{3}m$ space group. Combining these findings with the conclusions drawn by the room temperature and low temperature single crystal diffraction experiments indicates that although the lattice is dynamic and maintains a 3D structure, the Sn lone pairs locally compete for their own space. Further theoretical studies into the vibrational modes of these mixed halide compositions could verify the assignments of these peaks.

3.6 Photostability of $FASnI_{3-x}Br_x$ Films:

The photostability of mixed halide lead perovskite in operational conditions is an important research topic and has been investigated considerably.^{97,98} A common practice for the synthesis of wide bandgap perovskites ($>1.65\text{eV}$) is through the substitution of iodide with bromide (more than 20%).⁹⁹ These compositions, however, destabilize under prolonged illumination through phase segregation, *i.e.* under light illumination, Iodide-rich and Iodide-poor regions are formed. This phenomenon is called “halide segregation” and can be investigated by the photoluminescence (PL) study of related thin films upon exposure to light.

Here, we studied this phenomenon for the Sn-mixed halide films including $FASnI_3$, $FASnI_{2.6}Br_{0.4}$, $FASnI_{2.3}Br_{0.7}$, and $FASnI_{1.9}Br_{1.1}$. Since the primary method for observing this halide segregation is observing shifts in the PL peak position, only a limited scope of compositions was studied. The PL peak shift position is a measure of the quantity of iodide-rich phase formed. A detailed description of the film fabrication and the study is presented in the experimental section. The obtained PL spectra of each thin film as a function of illumination time are presented in Figure 12.

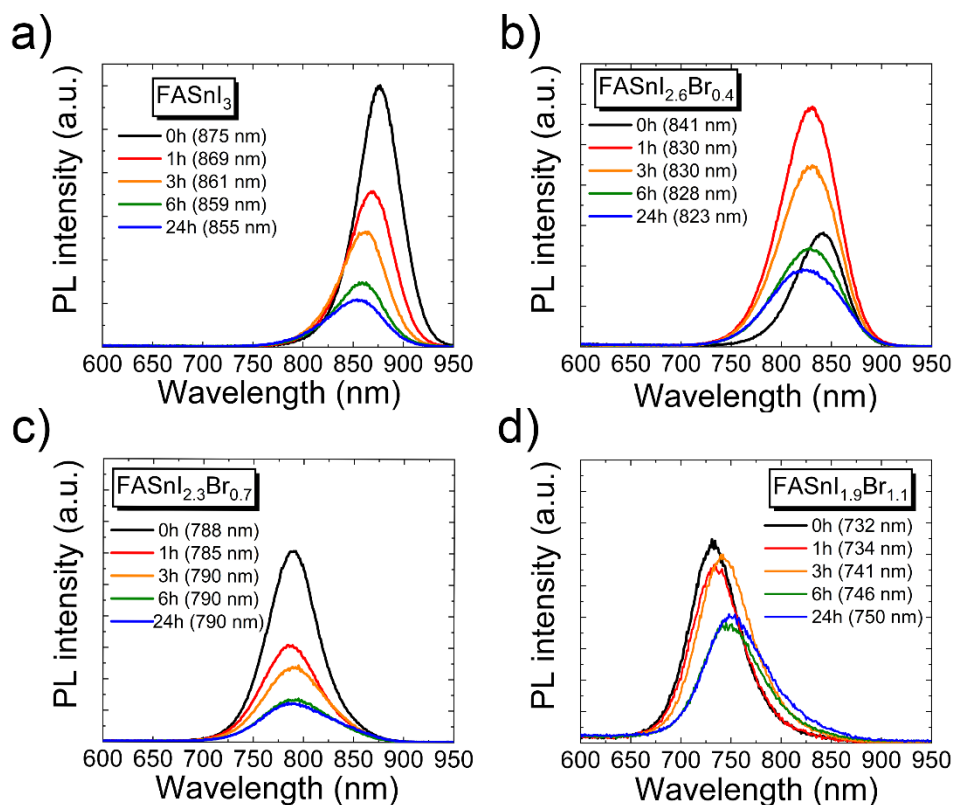


Figure 12 Steady-state PL emission spectra under continuous illumination (a) FASnI₃ (b) FASnI_{2.6}Br_{0.4}, (c) FASnI_{2.3}Br_{0.7} and (d) FASnI_{1.9}Br_{1.1}. Each graph presents the PL emission spectra of related films before illumination at 0 time and after 1, 3, 6 and 24 hours of illumination under 1 sun. Detailed PL peak positions are listed in Table S8.

As a general reflection on the PL graphs for all the samples, we observed a decay in PL intensity for all samples after light illumination. This process is typical for perovskite thin films and is often induced by ambient exposure, high temperature, and illumination. For FASnI₃ film a blue shift of 20 nm was observed after 24 hours of illumination, which is solely induced by film degradation under ambient and to a lesser extent induced by high temperature due to light illumination. The ambient exposure in tin perovskites can induce tin (II) partial oxidations to tin (IV) causing such blue shifting.

For the mixed halide phases, peak shifts of 18 nm, 2 nm, and 18 nm were observed for FASnI_{2.6}Br_{0.4}, FASnI_{2.3}Br_{0.7}, and FASnI_{1.9}Br_{1.1} respectively. The observed shift in FASnI_{2.6}Br_{0.4} is towards higher wavelength (similar to that of FASnI₃ thin films) indicating the origin of the shift is degradation of the perovskite films due to ambient atmosphere and heat exposure (rather than halide segregation). Considering the energy difference between the valence band maximum position of iodide rich compositions (compared to that of bromide rich) they are more susceptible to oxidative degradation, hence a blue shift of the PL peak position was observed. A temporary increase in PL intensity is also observed after 1 and 3 hours of illumination. The origins of this, though, would require further investigation but it can be referred to light-induced passivation caused by a rapid increase of quasi-fermi level splitting ($\Delta\mu$) which was observed in perovskite mixed halide compositions short after light illumination.^{108,109} Enhanced PL intensity by increasing the quasi-fermi level splitting is mostly effective in short light illumination time when a limited bandgap shift is detected. Our findings suggest that we observed the same phenomenon where enhanced PL intensity with limited PL peak position was observed after 1 and 3 hours of light soaking.

FASnI_{1.9}Br_{1.1} thin film showed a red shift of 18 nm after 24 hours of illumination. This is indicative of a dominating halide segregation effect due to the formation of iodide-rich regions of the film, which have narrower band gaps and lower energy PL emissions. For FASnI_{2.3}Br_{0.7}, only a 2 nm shift was observed alongside decreased PL intensity, suggesting that both film degradation and halide segregation are occurring simultaneously. This is clear when considering the shape of PL spectra of the FASnI_{2.3}Br_{0.7} composition after illumination, where peak broadening happens

for this specific composition more than others (Figure 12a – d). We detected a FWHM of 62 nm before illumination which gradually increased after light illumination to 86 nm after 24h (Table S9).

These degree of PL peak shifts for these Sn perovskites mimic their lead counterparts, suggesting that these phases may benefit from the same approaches used to control halide segregation investigated for the Pb-based materials such as dimensional control¹⁰⁰ or octahedral tilting distortions through structural modifications.^{101, 102}

3.7 Impact of Lone Pair Expression Studied with Density Functional Theory (DFT):

Based on first-principles calculations (see computational details), we investigate the structural and electronic properties of $\text{FASnI}_{3-x}\text{Br}_x$, for $x = 0, 0.417, 2.583, \text{ and } 3$. We include the effect of local disorder (polymorphism, see computational details) that has been demonstrated to be ubiquitous in perovskite physics to describe the distribution of local octahedra rotations in nominally $\text{Pm}\bar{3}m$ structures.⁵¹ In the case of FASnI_3 and FASnBr_3 , accounting for local disorder leads to an energy stabilization of 87.3 meV/f.u. and 124.8 meV/f.u. respectively compared to their idealized $\text{Pm}\bar{3}m$ structures. In addition, this computational protocol provides DFT-optimized structures consistent with the experimentally determined averaged structures, exhibiting very clear structural distortions characteristic of stereochemically expressed Sn-5s² lone-pair for FASnBr_3 . In contrast, it is found to a lesser extent for FASnI_3 (Figure 12a). Let us note that larger supercells might lead to a better description of the effect in FASnI_3 .

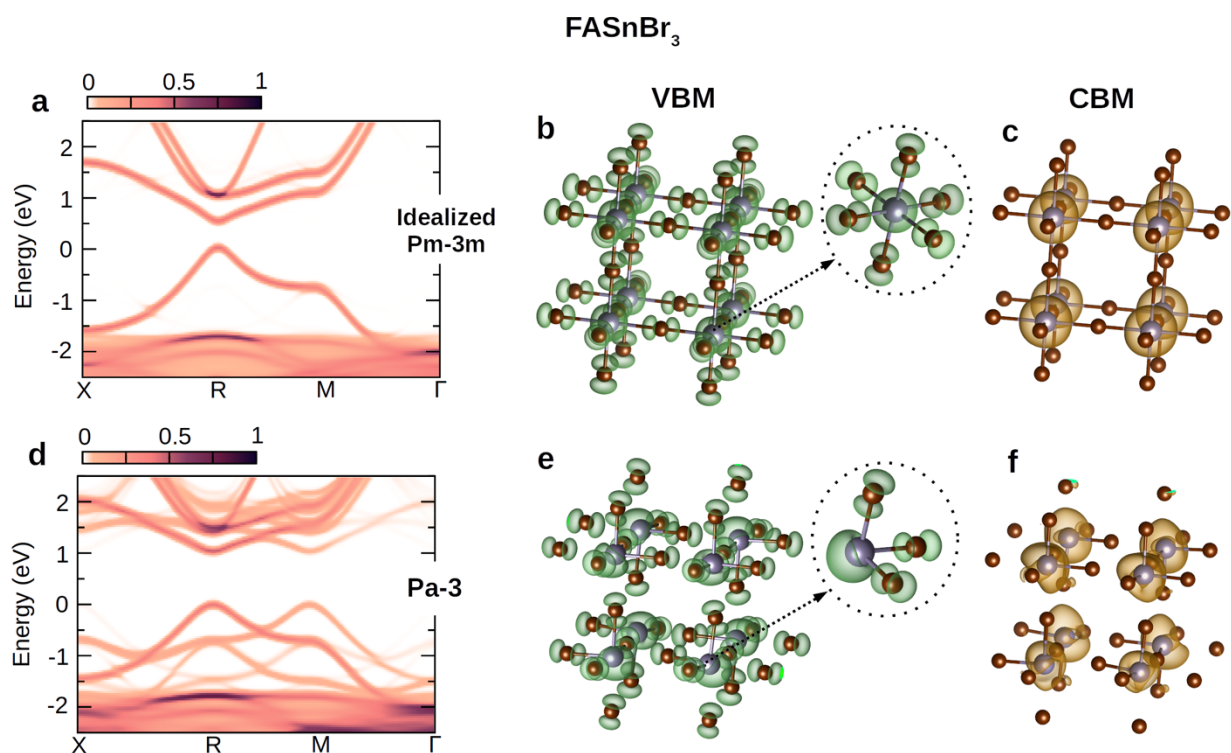


Figure 13: Electronic properties of idealized ($Pm\bar{3}m$) and distorted ($Pa\bar{3}$) $FASnBr_3$. Electron spectral functions (color maps) and charge densities of the idealized $FASnBr_3$ (a,b,c) and distorted $FASnBr_3$ (d,e,f). Electron spectral functions (a,d) are evaluated using band structure unfolding. The energy axes are adjusted so that the VBM is set at zero energy. Charge densities at the VBM (b,e) and CBM (c,f) are evaluated at the R-point of the fundamental Brillouin zone of the idealized $FASnBr_3$ $Pm\bar{3}m$ unit cell. In the ball and stick models, the FA molecules are removed for clarity.

To ease comparison between the various compositions, we use the band structure unfolding technique, leading to representations of the distorted $Pa\bar{3}$ electronic structure in the Brillouin zone of the parent $Pm\bar{3}m$ structure (Figure 13d).⁵² This representation also has the advantage of linking the additional electronic contributions to structural lattice distortions concerning the parent cubic structure. All structures show a direct band gap at the R point. Consistently with experimental findings, increasing the bromine concentration sizably increases the computed fundamental band gap, from 0.38 eV for $FASnI_3$ to 1.04 eV for $FASnBr_3$ (Figure S13b-e). Such an increase is expected upon halide substitution. Concomitantly, band curvature at the band edges increases and bands undergo smearing across the Brillouin zone. In order to disentangle the respective effect of local antiferrodistorsive disorder and stereochemical expression of the Sn-5s² lone-pair, we further compare the electronic structure of $FASnBr_3$ to that of related model structures.

Firstly, the comparison is carried between the momentum-resolved density of states (electron spectral function) computed for $FASnBr_3$ in the cubic $Pa\bar{3}$ space group with and without taking into account local antiferrodistortive disorder. Both plots show no significant differences

(Figure S14). This suggests this structural disorder does not play a predominant role in the new features observed with increasing bromine content (Figure 13d). Then, to inspect the specific effect of the structural distortion attributed to the lone-pair expression in the $P\bar{a}3$ structure, we compute the electronic properties of the idealized structure of FASnBr_3 where atoms of the inorganic network are fixed to the Wyckoff positions of the $Pm\bar{3}m$ symmetry (Figure 13a), for which this structural feature is absent. The corresponding electronic structure exhibits a direct band gap of 0.52 eV and hole (electron) effective masses of $m_h = 0.086 m_0$ ($m_e = 0.117 m_0$), where m_0 is the free electron mass. The charge density plots of the valence band maximum (VBM) and conduction band minimum (CBM) at the R-point reveal that the VBM is determined by the antibonding coupling of the Sn-5s and Br-4p orbitals (Figure 13b), while the CBM mainly stems from Sn-5p orbitals (Figure 13c). Conversely, the corresponding charge densities computed for the $P\bar{a}3$ structure (Figs. 13e and f, respectively) provide clear evidence of asymmetric charge redistribution due to the lone pair-induced structural distortion. Specifically, the lone pair manifests as an off-center lobe of electron density around the Sn atom, which diminishes the antibonding interaction between the Sn-5s and Br-4p orbitals in the three shortest Sn – Br bonds. Consequently, the band gap increases markedly to 1.04 eV, alongside a significant change in the effective masses, with the hole mass $m_h = 0.167 m_0$ and $m_e = 0.240 m_0$. The observed energy smearing with the formation of new states at the X and M points (Figure 13d) can also be traced back to the stereochemical expression of the Sn 5s² lone-pair. The formation of these new states at the X and M points can be understood as replicas of the states at the R point induced by lowering the symmetry due to the lone pair-induced lattice distortion. For completeness, we also report the projected density of states calculated for the two structures in Figure S14.

4.0 Conclusions:

The $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) series represents a group of compounds that, on the surface, fulfills the role of a more environmentally sustainable alternative to Pb MHPs given their suitable band gaps for single and multi-junction solar cell devices. However, an in-depth analysis of the structure-property relationships suggests that local structural dynamics leads to the degradation of the coveted optoelectronic properties, namely the photoluminescence and lifetime. The room temperature crystal structures are the first indication of such fluctuations with the phase space

behaving as a non-ideal “solid-solution” where the $x = 0 - 2.9$ compounds crystallize in $Pm\bar{3}m$ while $FASnI_{0.1}Br_{2.9}$ and $FASnBr_3$ are of lower symmetry ($Pa\bar{3}$) due to significant Sn off-centering from $5s^2$ lone pair expression. Probing the local perturbations of the lattice for the I-rich and Br-rich regions through Raman scattering and Pair Distribution Function (PDF) elucidates augmentation of the structure consistent with the same antiferroelectric distortions. The short-range PDF curve for $FASnI_{0.4}Br_{0.6}$ provides the most informative view of the inorganic framework as it is consistent with a $FASnBr_3$ -type structure ($Pa\bar{3}$) yet averages to a $Pm\bar{3}m$ structure type. Solid-state ^{119}Sn and 1H NMR bolster this claim with varying chemical shifts of the Sn and the interrogation of the local structure of the organic. The FA^+ cation shows sharper features for Br-rich samples as opposed to I-rich mostly likely due to a more loosely connected framework associated with a relatively weaker cage. Competition between the concealment and expression of the Sn lone pair then provides a rationale for the observed PL quenching upon adding Br^- starting from $FASnI_3$. Theoretical calculations further support the complex dynamics and the origins of the dissipation of the typically robust PL and electronic properties where the calculated effective mass for both holes and electrons effectively doubles between a hypothetical pristine $Pm\bar{3}m$ and the true distorted $Pa\bar{3}$ structure of $FASnBr_3$. The phase space may prove to be even more problematic for adoption in photovoltaics given the observation of halide segregation upon light illumination, which was explored for those compounds that showed an observable PL emission above the background. $FASnI_{1.9}Br_{1.1}$ shows a gradual redshifting of the peak position after 0 to 24 hours of 1 sun light exposure, consistent with halide segregation. It remains to be seen, though, if these materials would benefit from the same methods used to mitigate halide segregation of the Pb-based counterparts. This research provides a fundamental guide to synthesizing and characterizing these compounds for further study while simultaneously developing a cautionary stance towards blind assumptions regarding halide perovskite structure and application. To fully grasp the potential applications for these chemically substituted phases, a prior understanding of the fundamental chemical influences at play remains crucial.

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Competing Interests:

The authors declare no competing interests.

Data and Materials Availability:

The crystallographic information files (CIFs) for the compounds are available free of charge as depositions in the Cambridge Crystallographic Data Centre (CCDC) based on the following

deposition numbers: 2335370 (FASnI₃), 2335364 (FASnI_{2.6}Br_{0.4}), 2335363 (FASnI_{2.3}Br_{0.7}), 2335362 (FASnI_{2.1}Br_{0.9}), 2335361 (FASnI_{1.9}Br_{1.1}), 2335369 (FASnI_{1.1}Br_{1.9}), 2335368 (FASnI_{0.7}Br_{2.3}), 2335367 (FASnI_{0.4}Br_{2.6}; 295K), 2335360 (FASnI_{0.4}Br_{2.6}; 260K), 2335359 (FASnI_{0.1}Br_{2.9}), 2335358 (FASnBr₃), 2335366 (SnI₄), and 2335365 (NH₄)₂SnBr₆.

The calculations (input and output files) employed for this study will be made available via the NOMAD repository [<https://nomad-lab.eu/>].

Author Contributions:

A.B. and M.S. conceived the idea behind this project. A.B. and M.S. established processes for crystal growth. A.B. carried out XRD experiments, both powder and single crystal, and analyzed/interpreted the results. A.B. conducted the PDF measurements, reduced the data, and analyzed the curves with the help of C.D.M. M.S. conducted SEM-EDS experiments. M.S. and D.K. established the film casting procedures and conducted subsequent characterization, including PL and stability studies, on the films. A.B. carried out the UV-Vis spectroscopy on the bulk material. E.O. and R.D.S. conducted Raman spectroscopy and time-resolved photoluminescence spectroscopy. Theoretical calculations were conducted by M.Z. and M.K. with assistance from J.E. for the analysis. V.K. helped with early work on the structural determination of the compounds. C.W. conducted solid state ¹⁹⁹Sn and ¹H NMR experiments with M.R. C.W. and M.R. interpreted the NMR results. M.R. J.E. L.X.C. M.G.K and R.D.S provided funding for the research conducted. All authors contributed to the review and the discussion of the results presented in this manuscript.

References:

- (1) Xing, G.; Mathews, N.; Sun, S.; Lim, S. S.; Lam, Y. M.; Grätzel, M.; Mhaisalkar, S.; Sum, T. C. Long-Range Balanced Electron- and Hole-Transport Lengths in Organic-Inorganic $\text{CH}_3\text{NH}_3\text{PbI}_3$. *Science* **2013**, *342* (6156), 344-347. DOI: doi:10.1126/science.1243167.
- (2) Dong, Q.; Fang, Y.; Shao, Y.; Mulligan, P.; Qiu, J.; Cao, L.; Huang, J. Electron-hole diffusion lengths in solution-grown $\text{CH}_3\text{NH}_3\text{PbI}_3$ single crystals. *Science* **2015**, *347* (6225), 967-970. DOI: doi:10.1126/science.aaa5760.
- (3) Yin, W.-J.; Shi, T.; Yan, Y. Unique Properties of Halide Perovskites as Possible Origins of the Superior Solar Cell Performance. *Advanced Materials* **2014**, *26* (27), 4653-4658. DOI: <https://doi.org/10.1002/adma.201306281>.
- (4) Motta, C.; El-Mellouhi, F.; Sanvito, S. Charge carrier mobility in hybrid halide perovskites. *Scientific Reports* **2015**, *5* (1), 12746. DOI: 10.1038/srep12746.
- (5) Roy, P.; Kumar Sinha, N.; Tiwari, S.; Khare, A. A review on perovskite solar cells: Evolution of architecture, fabrication techniques, commercialization issues and status. *Solar Energy* **2020**, *198*, 665-688. DOI: <https://doi.org/10.1016/j.solener.2020.01.080>.
- (6) Stoumpos, C. C.; Kanatzidis, M. G. Halide Perovskites: Poor Man's High-Performance Semiconductors. *Advanced Materials* **2016**, *28* (28), 5778-5793. DOI: <https://doi.org/10.1002/adma.201600265>.
- (7) Stoumpos, C. C.; Kanatzidis, M. G. The Renaissance of Halide Perovskites and Their Evolution as Emerging Semiconductors. In *Accounts of Chemical Research*, 2015; Vol. 48, pp 2791-2802.
- (8) Chung, I.; Lee, B.; He, J. Q.; Chang, R. P. H.; Kanatzidis, M. G. All-solid-state dye-sensitized solar cells with high efficiency. *Nature* **2012**, *485* (7399), 486-U494. DOI: 10.1038/nature11067.
- (9) Lee, M. M.; Teuscher, J.; Miyasaka, T.; Murakami, T. N.; Snaith, H. J. Efficient Hybrid Solar Cells Based on Meso-Superstructured Organometal Halide Perovskites. *Science* **2012**, *338* (6107), 643-647. DOI: 10.1126/science.1228604.
- (10) Wang, R.; Mujahid, M.; Duan, Y.; Wang, Z. K.; Xue, J.; Yang, Y. A Review of Perovskites Solar Cell Stability. *Advanced Functional Materials* **2019**, *29* (47), 1808843. DOI: 10.1002/adfm.201808843.
- (11) Peng, W.; Mao, K.; Cai, F.; Meng, H.; Zhu, Z.; Li, T.; Yuan, S.; Xu, Z.; Feng, X.; Xu, J.; et al. Reducing nonradiative recombination in perovskite solar cells with a porous insulator contact. *Science* **2023**, *379* (6633), 683-690. DOI: doi:10.1126/science.ade3126.

- (12) Park, J.; Kim, J.; Yun, H.-S.; Paik, M. J.; Noh, E.; Mun, H. J.; Kim, M. G.; Shin, T. J.; Seok, S. I. Controlled growth of perovskite layers with volatile alkylammonium chlorides. *Nature* **2023**, *616* (7958), 724-730. DOI: 10.1038/s41586-023-05825-y.
- (13) Zhao, Y.; Ma, F.; Qu, Z.; Yu, S.; Shen, T.; Deng, H.-X.; Chu, X.; Peng, X.; Yuan, Y.; Zhang, X.; et al. Inactive (PbI₂)₂RbCl stabilizes perovskite films for efficient solar cells. *Science* **2022**, *377* (6605), 531-534. DOI: doi:10.1126/science.abp8873.
- (14) *Best Research-Cell Efficiency Chart*. The National Renewable Energy Laboratory, 2024. <https://www.nrel.gov/pv/cell-efficiency.html> (accessed 2024 02/03/2024).
- (15) Noh, J. H.; Im, S. H.; Heo, J. H.; Mandal, T. N.; Seok, S. I. Chemical Management for Colorful, Efficient, and Stable Inorganic–Organic Hybrid Nanostructured Solar Cells. *Nano Letters* **2013**, *13* (4), 1764-1769. DOI: 10.1021/nl400349b.
- (16) Gil-Escrig, L.; Dreesen, C.; Palazon, F.; Hawash, Z.; Moons, E.; Albrecht, S.; Sessolo, M.; Bolink, H. J. Efficient Wide-Bandgap Mixed-Cation and Mixed-Halide Perovskite Solar Cells by Vacuum Deposition. *ACS Energy Letters* **2021**, *6* (2), 827-836. DOI: 10.1021/acsenergylett.0c02445.
- (17) Hao, F.; Stoumpos, C. C.; Chang, R. P. H.; Kanatzidis, M. G. Anomalous Band Gap Behavior in Mixed Sn and Pb Perovskites Enables Broadening of Absorption Spectrum in Solar Cells. *Journal of the American Chemical Society* **2014**, *136* (22), 8094-8099. DOI: 10.1021/ja5033259.
- (18) Masi, S.; Gualdrón-Reyes, A. F.; Mora-Seró, I. Stabilization of Black Perovskite Phase in FAPbI₃ and CsPbI₃. *ACS Energy Letters* **2020**, *5* (6), 1974-1985. DOI: 10.1021/acsenergylett.0c00801.
- (19) Chin, X. Y.; Turkay, D.; Steele, J. A.; Tabean, S.; Eswara, S.; Mensi, M.; Fiala, P.; Wolff, C. M.; Paracchino, A.; Artuk, K.; et al. Interface passivation for 31.25%-efficient perovskite/silicon tandem solar cells. *Science* **2023**, *381* (6653), 59-63. DOI: doi:10.1126/science.adg0091.
- (20) Hoke, E. T.; Slotcavage, D. J.; Dohner, E. R.; Bowring, A. R.; Karunadasa, H. I.; McGehee, M. D. Reversible photo-induced trap formation in mixed-halide hybrid perovskites for photovoltaics. *Chemical Science* **2015**, *6* (1), 613-617, 10.1039/C4SC03141E. DOI: 10.1039/C4SC03141E.
- (21) Slotcavage, D. J.; Karunadasa, H. I.; McGehee, M. D. Light-Induced Phase Segregation in Halide-Perovskite Absorbers. *ACS Energy Letters* **2016**, *1* (6), 1199-1205. DOI: 10.1021/acsenergylett.6b00495.

- (22) DuBose, J. T.; Kamat, P. V. Hole Trapping in Halide Perovskites Induces Phase Segregation. *Accounts of Materials Research* **2022**, *3* (7), 761-771. DOI: 10.1021/accountsmr.2c00076.
- (23) McMeekin, D. P.; Sadoughi, G.; Rehman, W.; Eperon, G. E.; Saliba, M.; Hörantner, M. T.; Haghighirad, A.; Sakai, N.; Korte, L.; Rech, B.; et al. A mixed-cation lead mixed-halide perovskite absorber for tandem solar cells. *Science* **2016**, *351* (6269), 151-155. DOI: 10.1126/science.aad5845.
- (24) Tan, H. R.; Jain, A.; Voznyy, O.; Lan, X. Z.; de Arquer, F. P. G.; Fan, J. Z.; Quintero-Bermudez, R.; Yuan, M. J.; Zhang, B.; Zhao, Y. C.; et al. Efficient and stable solution-processed planar perovskite solar cells via contact passivation. *Science* **2017**, *355* (6326), 722-726. DOI: 10.1126/science.aai9081.
- (25) Chen, H.; Maxwell, A.; Li, C. W.; Teale, S.; Chen, B.; Zhu, T.; Ugur, E.; Harrison, G.; Grater, L.; Wang, J. K.; et al. Regulating surface potential maximizes voltage in all-perovskite tandems. *Nature* **2023**, *613* (7945), 676-+. DOI: 10.1038/s41586-022-05541-z.
- (26) Abate, A. Perovskite Solar Cells Go Lead Free. *Joule* **2017**, *1* (4), 659-664. DOI: <https://doi.org/10.1016/j.joule.2017.09.007>.
- (27) Lye, Y.-E.; Chan, K.-Y.; Ng, Z.-N. A Review on the Progress, Challenges, and Performances of Tin-Based Perovskite Solar Cells. *Nanomaterials* **2023**, *13* (3), 585.
- (28) Ke, W.; Stoumpos, C. C.; Kanatzidis, M. G. “Unleaded” Perovskites: Status Quo and Future Prospects of Tin-Based Perovskite Solar Cells. *Advanced Materials* **2019**, *31* (47), 1803230. DOI: <https://doi.org/10.1002/adma.201803230>.
- (29) Ke, W.; Kanatzidis, M. G. Prospects for low-toxicity lead-free perovskite solar cells. *Nature Communications* **2019**, *10* (1), 965. DOI: 10.1038/s41467-019-08918-3.
- (30) Abate, A. Stable Tin-Based Perovskite Solar Cells. *ACS Energy Letters* **2023**, *8* (4), 1896-1899. DOI: 10.1021/acsenergylett.3c00282.
- (31) Stoumpos, C. C.; Malliakas, C. D.; Kanatzidis, M. G. Semiconducting Tin and Lead Iodide Perovskites with Organic Cations: Phase Transitions, High Mobilities, and Near-Infrared Photoluminescent Properties. In *Inorganic Chemistry*, 2013; Vol. 52, pp 9019-9038.
- (32) Yamada, K.; Fujise, K.; Hino, S.; Yamane, Y.; Nakagama, T. Characterization of Sn(II)-based Perovskites by XRD, DTA, NQR and ¹¹⁹Sn NMR for Photovoltaic Applications. *Chemistry Letters* **2019**, *48* (7). DOI: <https://doi.org/10.1246/cl.190262>.

- (33) Sadhanala, A.; Deschler, F.; Thomas, T. H.; Dutton, S. E.; Goedel, K. C.; Hanusch, F. C.; Lai, M. L.; Steiner, U.; Bein, T.; Docampo, P.; et al. Preparation of Single-Phase Films of $\text{CH}_3\text{NH}_3\text{Pb}(\text{I}_{1-x}\text{Br}_x)_3$ with Sharp Optical Band Edges. *The Journal of Physical Chemistry Letters* **2014**, *5* (15), 2501-2505. DOI: 10.1021/jz501332v.
- (34) Eperon, G. E.; Stranks, S. D.; Menelaou, C.; Johnston, M. B.; Herz, L. M.; Snaith, H. J. Formamidinium lead trihalide: a broadly tunable perovskite for efficient planar heterojunction solar cells. *Energy & Environmental Science* **2014**, *7* (3), 982-988, 10.1039/C3EE43822H. DOI: 10.1039/C3EE43822H.
- (35) Li, X.; Hoffman, J. M.; Kanatzidis, M. G. The 2D Halide Perovskite Rulebook: How the Spacer Influences Everything from the Structure to Optoelectronic Device Efficiency. *Chemical Reviews* **2021**, *121* (4), 2230-2291. DOI: <https://doi.org/10.1021/acs.chemrev.0c01006>.
- (36) Stoumpos, C. C.; Cao, D. H.; Clark, D. J.; Young, J.; Rondinelli, J. M.; Jang, J. I.; Hupp, J. T.; Kanatzidis, M. G. Ruddlesden–Popper Hybrid Lead Iodide Perovskite 2D Homologous Semiconductors. *Chemistry of Materials* **2016**, *28* (8), 2852-2867. DOI: 10.1021/acs.chemmater.6b00847.
- (37) Vasileiadou, E. S.; Hadar, I.; Kepenekian, M.; Even, J.; Tu, Q.; Malliakas, C. D.; Friedrich, D.; Spanopoulos, I.; Hoffman, J. M.; Dravid, V. P.; et al. Shedding Light on the Stability and Structure–Property Relationships of Two-Dimensional Hybrid Lead Bromide Perovskites. *Chemistry of Materials* **2021**, *33* (13), 5085-5107. DOI: 10.1021/acs.chemmater.1c01129.
- (38) Koziskova, J.; Hahn, F.; Richter, J.; Kožíšek, J. Comparison of different absorption corrections on the model structure of tetrakis(μ -2-acetato)-diaqua-di-copper(II). In *Acta Chimica Slovaca*, 2016; Vol. 9, pp 136-140.
- (39) Dolomanov, O. V.; Bourhis, L. J.; Gildea, R. J.; Howard, J. A. K.; Puschmann, H. OLEX2: a complete structure solution, refinement and analysis program. *Journal of Applied Crystallography* **2009**, *42* (2), 339-341. DOI: <https://doi.org/10.1107/S0021889808042726>.
- (40) Sheldrick, G. M. SHELXT - Integrated space-group and crystal-structure determination. *Acta Crystallographica A* **2015**, *A71*, 3-8. DOI: <https://doi.org/10.1107/S2053273314026370>.
- (41) Sheldrick, G. M. Crystal structure refinement with SHELXL. *Acta Crystallographica C* **2014**, *C71* (1), 3-8. DOI: <https://doi.org/10.1107/S2053229614024218>.

- (42) Petříček, V.; Dušek, M.; Palatinus, L. Crystallographic Computing System JANA2006: General features. *Zeitschrift für Kristallographie - Crystalline Materials* **2014**, *229*, 345-352. DOI: 10.1515/zkri-2014-1737.
- (43) Palatinus, L.; Chapuis, G. SUPERFLIP – a computer program for the solution of crystal structures by charge flipping in arbitrary dimensions. *Journal of Applied Crystallography* **2007**, *40*, 786-790. DOI: 10.1107/S0021889807029238.
- (44) Andrews, R. H.; Clark, S. J.; Donaldson, J. D.; Dewan, J. C.; Silver, J. Solid-state properties of materials of the type Cs_4MX_6 (where M = Sn or Pb and X = Cl or Br). *Journal of the Chemical Society, Dalton Transactions* **1983**, (4), 767. DOI: 10.1039/dt9830000767.
- (45) Juhas, P.; Davis, T.; Farrow, C. L.; Billinge, S. J. L. PDFgetX3: a rapid and highly automatable program for processing powder diffraction data into total scattering pair distribution functions. *Journal of Applied Crystallography* **2013**, *46* (2), 560-566. DOI: doi:10.1107/S0021889813005190.
- (46) Giannozzi, P.; Baroni, S.; Bonini, N.; Calandra, M.; Car, R.; Cavazzoni, C.; Ceresoli, D.; Chiarotti, G. L.; Cococcioni, M.; Dabo, I.; et al. QUANTUM ESPRESSO: a modular and open-source software project for quantum simulations of materials. *Journal of Physics: Condensed Matter* **2009**, *21* (39), 395502. DOI: 10.1088/0953-8984/21/39/395502.
- (47) Giannozzi, P.; Andreussi, O.; Brumme, T.; Bunau, O.; Buongiorno Nardelli, M.; Calandra, M.; Car, R.; Cavazzoni, C.; Ceresoli, D.; Cococcioni, M.; et al. Advanced capabilities for materials modelling with Quantum ESPRESSO. *Journal of Physics: Condensed Matter* **2017**, *29* (46), 465901. DOI: 10.1088/1361-648X/aa8f79.
- (48) Hamann, D. R. Optimized norm-conserving Vanderbilt pseudopotentials. *Physical Review B* **2013**, *88* (8), 085117. DOI: 10.1103/PhysRevB.88.085117.
- (49) Perdew, J. P.; Ruzsinszky, A.; Csonka, G. I.; Vydrov, O. A.; Scuseria, G. E.; Constantin, L. A.; Zhou, X.; Burke, K. Restoring the Density-Gradient Expansion for Exchange in Solids and Surfaces. *Physical Review Letters* **2008**, *100* (13), 136406. DOI: 10.1103/PhysRevLett.100.136406.
- (50) Zhao, X.-G.; Dalpian, G. M.; Wang, Z.; Zunger, A. Polymorphous nature of cubic halide perovskites. *Physical Review B* **2020**, *101* (15), 155137. DOI: 10.1103/PhysRevB.101.155137.

- (51) Zacharias, M.; Volonakis, G.; Giustino, F.; Even, J. Anharmonic electron-phonon coupling in ultrasoft and locally disordered perovskites. *npj Computational Materials* **2023**, *9* (1), 153. DOI: 10.1038/s41524-023-01089-2.
- (52) Popescu, V.; Zunger, A. Extracting E versus k effective band structure from supercell calculations on alloys and impurities. *Physical Review B* **2012**, *85* (8), 085201. DOI: 10.1103/PhysRevB.85.085201.
- (53) Zacharias, M.; Giustino, F. Theory of the special displacement method for electronic structure calculations at finite temperature. *Physical Review Research* **2020**, *2* (1), 013357. DOI: 10.1103/PhysRevResearch.2.013357.
- (54) Lee, H.; Poncé, S.; Bushick, K.; Hajinazar, S.; Lafuente-Bartolome, J.; Leveillee, J.; Lian, C.; Lihm, J.-M.; Macheda, F.; Mori, H.; et al. Electron–phonon physics from first principles using the EPW code. *npj Computational Materials* **2023**, *9* (1), 156. DOI: 10.1038/s41524-023-01107-3.
- (55) Baikie, T.; Barrow, N. S.; Fang, Y.; Keenan, P. J.; Slater, P. R.; Piltz, R. O.; Gutmann, M.; Mhaisalkar, S. G.; White, T. J. A combined single crystal neutron/X-ray diffraction and solid-state nuclear magnetic resonance study of the hybrid perovskites $\text{CH}_3\text{NH}_3\text{PbX}_3$ ($X = \text{I}, \text{Br}$ and Cl). *Journal of Materials Chemistry A* **2015**, *3* (17), 9298-9307, 10.1039/C5TA01125F. DOI: 10.1039/C5TA01125F.
- (56) Lanigan-Atkins, T.; He, X.; Krogstad, M. J.; Pajerowski, D. M.; Abernathy, D. L.; Xu, G. N. M. N.; Xu, Z.; Chung, D. Y.; Kanatzidis, M. G.; Rosenkranz, S.; et al. Two-dimensional overdamped fluctuations of the soft perovskite lattice in CsPbBr_3 . *Nature Materials* **2021**, *20* (7), 977-983. DOI: 10.1038/s41563-021-00947-y.
- (57) Pisanu, A.; Mahata, A.; Mosconi, E.; Patrini, M.; Quadrelli, P.; Milanese, C.; De Angelis, F.; Malavasi, L. Exploring the Limits of Three-Dimensional Perovskites: The Case of $\text{FAPb}_{1-x}\text{Sn}_x\text{Br}_3$. *ACS Energy Letters* **2018**, *3* (6), 1353-1359. DOI: 10.1021/acsenerylett.8b00615.
- (58) Thiele, G.; Rotter, H. W.; Schmidt, K. D. Die Kristallstrukturen und Phasentransformationen von RbGeBr_3 . *Zeitschrift für anorganische und allgemeine Chemie* **1988**, *559* (1), 7-16. DOI: <https://doi.org/10.1002/zaac.19885590101>.
- (59) Thiele, G.; Rotter, H. W.; Schmidt, K. D. Kristallstrukturen und Phasentransformationen von Caesiumtrihalogenogermanaten(II) CsGeX_3 ($X = \text{Cl}, \text{Br}, \text{I}$). *Zeitschrift für anorganische und allgemeine Chemie* **1987**, *545* (2), 148-156. DOI: 10.1002/zaac.19875450217.

- (60) Lü, X.; Stoumpos, C.; Hu, Q.; Ma, X.; Zhang, D.; Guo, S.; Hoffman, J.; Bu, K.; Guo, X.; Wang, Y.; et al. Regulating off-centering distortion maximizes photoluminescence in halide perovskites. *National Science Review* **2020**, *8* (9). DOI: 10.1093/nsr/nwaa288 (accessed 6/20/2023).
- (61) Stoumpos, C. C.; Frazer, L.; Clark, D. J.; Kim, Y. S.; Rhim, S. H.; Freeman, A. J.; Ketterson, J. B.; Jang, J. I.; Kanatzidis, M. G. Hybrid Germanium Iodide Perovskite Semiconductors: Active Lone Pairs, Structural Distortions, Direct and Indirect Energy Gaps, and Strong Nonlinear Optical Properties. *Journal of the American Chemical Society* **2015**, *137* (21), 6804-6819. DOI: 10.1021/jacs.5b01025.
- (62) Liu, Y.; Gong, Y. P.; Geng, S.; Feng, M. L.; Manidaki, D.; Deng, Z.; Stoumpos, C. C.; Canepa, P.; Xiao, Z.; Zhang, W. X.; et al. Hybrid Germanium Bromide Perovskites with Tunable Second Harmonic Generation. *Angewandte Chemie International Edition* **2022**, *61* (43). DOI: 10.1002/anie.202208875.
- (63) Depmeier, W.; Moller, A.; Klaska, K.-H. The structure of antiferroelectric tetramethylammonium trichlorogermanate(II) at room temperature. *Acta Crystallographica Section B* **1980**, *36* (4), 803-807. DOI: doi:10.1107/S0567740880004578.
- (64) Thiele, G.; Serr, B. R. Crystal structure of dimethylammonium tribromostannate(II), $(\text{CH}_3)_2\text{NH}_2\text{SnBr}_3$. *Zeitschrift für Kristallographie - Crystalline Materials* **1996**, *211* (1), 47-47. DOI: doi:10.1524/zkri.1996.211.1.47 (accessed 2023-05-11).
- (65) Thiele, G.; Serr, B. R. Crystal structure of trimethylammonium tribromostannate(II), $(\text{CH}_3)_3\text{NHSnBr}_3$. **1996**, *211* (1), 46-46. DOI: doi:10.1524/zkri.1996.211.1.46 (accessed 2023-05-11).
- (66) Dang, Y.; Zhong, C.; Zhang, G.; Ju, D.; Wang, L.; Xia, S.; Xia, H.; Tao, X. Crystallographic Investigations into Properties of Acentric Hybrid Perovskite Single Crystals $\text{NH}(\text{CH}_3)_3\text{SnX}_3$ (X = Cl, Br). *Chemistry of Materials* **2016**, *28* (19), 6968-6974. DOI: 10.1021/acs.chemmater.6b02653.
- (67) Szafranski, M.; Ståhl, K. Crystal structure and phase transitions in perovskite-like $\text{C}(\text{NH}_2)_3\text{SnCl}_3$. *Journal of Solid State Chemistry* **2007**, *180* (8), 2209-2215. DOI: <https://doi.org/10.1016/j.jssc.2007.05.024>.
- (68) Varignon, J.; Bristowe, N. C.; Bousquet, E.; Ghosez, P. Coupling and electrical control of structural, orbital and magnetic orders in perovskites. *Scientific Reports* **2015**, *5* (1), 15364. DOI: 10.1038/srep15364.

- (69) Saporov, B.; Mitzi, D. B. Organic–Inorganic Perovskites: Structural Versatility for Functional Materials Design. *Chemical Reviews* **2016**, *116* (7), 4558-4596. DOI: 10.1021/acs.chemrev.5b00715.
- (70) Kieslich, G.; Sun, S.; Cheetham, A. K. Solid-state principles applied to organic–inorganic perovskites: new tricks for an old dog. *Chemical Science* **2014**, *5* (12), 4712-4715, 10.1039/C4SC02211D. DOI: 10.1039/C4SC02211D.
- (71) Coduri, M.; Shiell, T. B.; Strobel, T. A.; Mahata, A.; Cova, F.; Mosconi, E.; De Angelis, F.; Malavasi, L. Origin of pressure-induced band gap tuning in tin halide perovskites. *Materials Advances* **2020**, *1* (8), 2840-2845, 10.1039/D0MA00731E. DOI: 10.1039/D0MA00731E.
- (72) Laurita, G.; Fabini, D. H.; Stoumpos, C. C.; Kanatzidis, M. G.; Seshadri, R. Chemical tuning of dynamic cation off-centering in the cubic phases of hybrid tin and lead halide perovskites. *Chemical Science* **2017**, *8* (8), 5628-5635, 10.1039/C7SC01429E. DOI: 10.1039/C7SC01429E.
- (73) Fabini, D. H.; Laurita, G.; Bechtel, J. S.; Stoumpos, C. C.; Evans, H. A.; Kontos, A. G.; Raptis, Y. S.; Falaras, P.; Van der Ven, A.; Kanatzidis, M. G.; et al. Dynamic Stereochemical Activity of the Sn²⁺ Lone Pair in Perovskite CsSnBr₃. *Journal of the American Chemical Society* **2016**, *138* (36), 11820-11832. DOI: 10.1021/jacs.6b06287.
- (74) Knox, K. R.; Bozin, E. S.; Malliakas, C. D.; Kanatzidis, M. G.; Billinge, S. J. L. Local off-centering symmetry breaking in the high-temperature regime of SnTe. *Physical Review B* **2014**, *89* (1), 014102. DOI: 10.1103/PhysRevB.89.014102.
- (75) Yu, R.; Bozin, E. S.; Abeykoon, M.; Sangiorgio, B.; Spaldin, N. A.; Malliakas, C. D.; Kanatzidis, M. G.; Billinge, S. J. L. Emphanitic anharmonicity in PbSe at high temperature and anomalous electronic properties in the PbQ (Q= S, Se, Te) system. *Physical Review B* **2018**, *98* (14), 144108. DOI: 10.1103/PhysRevB.98.144108.
- (76) Xie, H.; Bozin, E. S.; Li, Z.; Abeykoon, M.; Banerjee, S.; Male, J. P.; Snyder, G. J.; Wolverton, C.; Billinge, S. J. L.; Kanatzidis, M. G. Hidden Local Symmetry Breaking in Silver Diamondoid Compounds is Root Cause of Ultralow Thermal Conductivity. *Advanced Materials* **2022**, *34* (24), 2202255. DOI: <https://doi.org/10.1002/adma.202202255>.
- (77) Morana, M.; Wiktor, J.; Coduri, M.; Chiara, R.; Giacobbe, C.; Bright, E. L.; Ambrosio, F.; De Angelis, F.; Malavasi, L. Cubic or Not Cubic? Combined Experimental and Computational Investigation of the Short-Range Order of Tin Halide Perovskites. *The Journal of Physical Chemistry Letters* **2023**, *14* (8), 2178-2186. DOI: 10.1021/acs.jpcclett.3c00105.

- (78) Kubicki, D. J.; Stranks, S. D.; Grey, C. P.; Emsley, L. NMR spectroscopy probes microstructure, dynamics and doping of metal halide perovskites. *Nature Reviews Chemistry* **2021**, 5 (9), 624-645. DOI: 10.1038/s41570-021-00309-x.
- (79) Dahlman, C. J.; Kubicki, D. J.; Reddy, G. N. M. Interfaces in metal halide perovskites probed by solid-state NMR spectroscopy. *Journal of Materials Chemistry A* **2021**, 9 (35), 19206-19244, 10.1039/D1TA03572J. DOI: 10.1039/D1TA03572J.
- (80) Raval, P.; Akhavan Kazemi, M. A.; Ruellou, J.; Trébosc, J.; Lafon, O.; Delevoye, L.; Sauvage, F.; Manjunatha Reddy, G. N. Examining a Year-Long Chemical Degradation Process and Reaction Kinetics in Pristine and Defect-Passivated Lead Halide Perovskites. *Chemistry of Materials* **2023**, 35 (7), 2904-2917. DOI: 10.1021/acs.chemmater.2c03803.
- (81) Spanopoulos, I.; Hadar, I.; Ke, W.; Guo, P.; Mozur, E. M.; Morgan, E.; Wang, S.; Zheng, D.; Padgaonkar, S.; Manjunatha Reddy, G. N.; et al. Tunable Broad Light Emission from 3D “Hollow” Bromide Perovskites through Defect Engineering. *Journal of the American Chemical Society* **2021**, 143 (18), 7069-7080. DOI: 10.1021/jacs.1c01727.
- (82) Kubicki, D. J.; Prochowicz, D.; Salager, E.; Rakhmatullin, A.; Grey, C. P.; Emsley, L.; Stranks, S. D. Local Structure and Dynamics in Methylammonium, Formamidinium, and Cesium Tin(II) Mixed-Halide Perovskites from ^{119}Sn Solid-State NMR. *Journal of the American Chemical Society* **2020**, 142 (17), 7813-7826. DOI: 10.1021/jacs.0c00647.
- (83) Fu, P.; Quintero, M. A.; Vasileiadou, E. S.; Raval, P.; Welton, C.; Kepenekian, M.; Volonakis, G.; Even, J.; Liu, Y.; Malliakas, C.; et al. Chemical Behavior and Local Structure of the Ruddlesden–Popper and Dion–Jacobson Alloyed Pb/Sn Bromide 2D Perovskites. *Journal of the American Chemical Society* **2023**, 145 (29), 15997-16014. DOI: 10.1021/jacs.3c03997.
- (84) Raval, P.; Kennard, R. M.; Vasileiadou, E. S.; Dahlman, C. J.; Spanopoulos, I.; Chabinyc, M. L.; Kanatzidis, M.; Manjunatha Reddy, G. N. Understanding Instability in Formamidinium Lead Halide Perovskites: Kinetics of Transformative Reactions at Grain and Subgrain Boundaries. *ACS Energy Letters* **2022**, 7 (4), 1534-1543. DOI: 10.1021/acsenerylett.2c00140.
- (85) Kortüm, G.; Braun, W.; Herzog, G. Principles and Techniques of Diffuse-Reflectance Spectroscopy. *Angewandte Chemie International Edition in English* **1963**, 2, 333-341. DOI: 10.1002/anie.196303331.
- (86) Liu, Y.; Cai, B.; Yang, H.; Boschloo, G.; Johansson, E. M. J. Solvent Engineering of Perovskite Crystallization for High Band Gap FAPbBr₃ Perovskite Solar Cells Prepared in

Ambient Condition. *ACS Applied Energy Materials* **2023**, *6* (13), 7102-7108. DOI: 10.1021/acsaem.3c00791.

(87) Spanopoulos, I.; Ke, W.; Stoumpos, C. C.; Schueller, E. C.; Kontsevoi, O. Y.; Seshadri, R.; Kanatzidis, M. G. Unraveling the Chemical Nature of the 3D “Hollow” Hybrid Halide Perovskites. *Journal of the American Chemical Society* **2018**, *140* (17), 5728-5742. DOI: 10.1021/jacs.8b01034.

(88) Yu, Z.; Leilaoui, M.; Holman, Z. Selecting tandem partners for silicon solar cells. *Nature Energy* **2016**, *1* (11), 16137. DOI: 10.1038/nenergy.2016.137.

(89) Straus, D. B.; Cava, R. J. Tuning the Band Gap in the Halide Perovskite CsPbBr₃ through Sr Substitution. *ACS Applied Materials & Interfaces* **2022**, *14* (30), 34884-34890. DOI: 10.1021/acsaem.2c09275.

(90) Heo, J.-M.; Cho, H.; Lee, S.-C.; Park, M.-H.; Kim, J. S.; Kim, H.; Park, J.; Kim, Y.-H.; Yun, H. J.; Yoon, E.; et al. Bright Lead-Free Inorganic CsSnBr₃ Perovskite Light-Emitting Diodes. *ACS Energy Letters* **2022**, *7* (8), 2807-2815. DOI: 10.1021/acsaem.2c01010.

(91) Ibaceta-Jaña, J.; Muydinov, R.; Rosado, P.; Mirhosseini, H.; Chugh, M.; Nazarenko, O.; Dirin, D. N.; Heinrich, D.; Wagner, M. R.; Kühne, T. D.; et al. Vibrational dynamics in lead halide hybrid perovskites investigated by Raman spectroscopy. *Physical Chemistry Chemical Physics* **2020**, *22* (10), 5604-5614, 10.1039/C9CP06568G. DOI: 10.1039/C9CP06568G.

(92) Létoublon, A.; Paofai, S.; Rufflé, B.; Bourges, P.; Hehlen, B.; Michel, T.; Ecolivet, C.; Durand, O.; Cordier, S.; Katan, C.; et al. Elastic Constants, Optical Phonons, and Molecular Relaxations in the High Temperature Plastic Phase of the CH₃NH₃PbBr₃ Hybrid Perovskite. *The Journal of Physical Chemistry Letters* **2016**, *7* (19), 3776-3784. DOI: 10.1021/acsaem.6b01709.

(93) Yaffe, O.; Guo, Y.; Tan, L. Z.; Egger, D. A.; Hull, T.; Stoumpos, C. C.; Zheng, F.; Heinz, T. F.; Kronik, L.; Kanatzidis, M. G.; et al. Local Polar Fluctuations in Lead Halide Perovskite Crystals. *Physical Review Letters* **2017**, *118* (13), 136001. DOI: 10.1103/PhysRevLett.118.136001.

(94) Damle, V. H.; Gouda, L.; Tirosh, S.; Tischler, Y. R. Structural Characterization and Room Temperature Low-Frequency Raman Scattering from MAPbI₃ Halide Perovskite Films Rigidized by Cesium Incorporation. *ACS Applied Energy Materials* **2018**, *1* (12), 6707-6713. DOI: 10.1021/acsaem.8b01539.

- (95) Badrooj, M.; Jamali-Sheini, F.; Torabi, N. Optoelectronic Properties of Mixed Sn/Pb Perovskite Solar Cells: The Study of Compressive Strain by Raman Modes. *The Journal of Physical Chemistry C* **2020**, *124* (49), 27136-27147. DOI: 10.1021/acs.jpcc.0c07999.
- (96) Gao, L.; Yadgarov, L.; Sharma, R.; Korobko, R.; McCall, K. M.; Fabini, D. H.; Stoumpos, C. C.; Kanatzidis, M. G.; Rappe, A. M.; Yaffe, O. Metal cation s lone-pairs increase octahedral tilting instabilities in halide perovskites. *Materials Advances* **2021**, *2* (14), 4610-4616, 10.1039/D1MA00288K. DOI: 10.1039/D1MA00288K.
- (97) Motti, S. G.; Patel, J. B.; Oliver, R. D. J.; Snaith, H. J.; Johnston, M. B.; Herz, L. M. Phase segregation in mixed-halide perovskites affects charge-carrier dynamics while preserving mobility. *Nature Communications* **2021**, *12* (1), 6955. DOI: 10.1038/s41467-021-26930-4.
- (98) Lin, Y.; Chen, B.; Fang, Y.; Zhao, J.; Bao, C.; Yu, Z.; Deng, Y.; Rudd, P. N.; Yan, Y.; Yuan, Y.; et al. Excess charge-carrier induced instability of hybrid perovskites. *Nature Communications* **2018**, *9* (1), 4981. DOI: 10.1038/s41467-018-07438-w.
- (99) Kim, D.; Jung, H. J.; Park, I. J.; Larson, B. W.; Dunfield, S. P.; Xiao, C.; Kim, J.; Tong, J.; Boonmongkolras, P.; Ji, S. G.; et al. Efficient, stable silicon tandem cells enabled by anion-engineered wide-bandgap perovskites. *Science* **2020**, *368* (6487), 155-160. DOI: 10.1126/science.aba3433 (accessed 2024/01/22).
- (100) Wang, Z.; Lin, Q.; Chmiel, F. P.; Sakai, N.; Herz, L. M.; Snaith, H. J. Efficient ambient-air-stable solar cells with 2D–3D heterostructured butylammonium-caesium-formamidinium lead halide perovskites. *Nature Energy* **2017**, *2* (9), 17135. DOI: 10.1038/nenergy.2017.135.
- (101) Wang, Z.; Zeng, L.; Zhu, T.; Chen, H.; Chen, B.; Kubicki, D. J.; Balvanz, A.; Li, C.; Maxwell, A.; Ugur, E.; et al. Suppressed phase segregation for triple-junction perovskite solar cells. *Nature* **2023**, *618* (7963), 74-79. DOI: 10.1038/s41586-023-06006-7.
- (102) Prasanna, R.; Gold-Parker, A.; Leijtens, T.; Conings, B.; Babayigit, A.; Boyen, H.-G.; Toney, M. F.; McGehee, M. D. Band Gap Tuning via Lattice Contraction and Octahedral Tilting in Perovskite Materials for Photovoltaics. *Journal of the American Chemical Society* **2017**, *139* (32), 11117-11124. DOI: 10.1021/jacs.7b04981.
- (103) Harris, R. K.; Becker, E. D.; Cabral de Menezes, S. M.; Goodfellow, R.; Granger, P. NMR nomenclature. Nuclear spin properties and conventions for chemical shifts(IUPAC Recommendations 2001). **2001**, *73* (11), 1795-1818. DOI: doi:10.1351/pac200173111795

(104) Yamada, K.; Kuranaga, Y.; Ueda, K.; Goto, S.; Okuda, T.; Furukawa, Y. Phase Transition and Electric Conductivity of ASnCl_3 (A = Cs and CH_3NH_3). *Bulletin of the Chemical Society of Japan* **1998**, *71* (1), 127-134. DOI: 10.1246/bcsj.71.127

(105) Yagyū, H.; Katagami, S. Effect of Cs partial substitution on crystal systems and bandgap values of MASnCl_3 . *Physica B: Condensed Matter* **2022**, *633*, 413784. DOI: <https://doi.org/10.1016/j.physb.2022.413784>

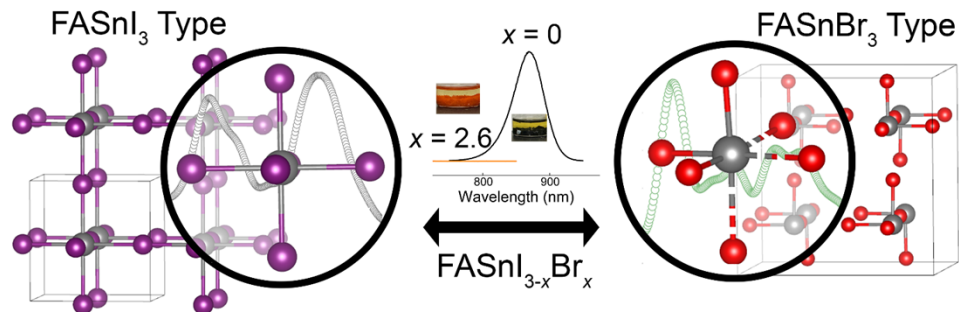
(106) Cacovich, S.; Messou, D.; Bercegol, A.; Béchu, S.; Yaiche, A.; Shafique, H.; Rousset, J.; Schulz, P.; Bouttemy, M.; Lombez, L. Light-Induced Passivation in Triple Cation Mixed Halide Perovskites: Interplay between Transport Properties and Surface Chemistry. *ACS Applied Materials & Interfaces* **2020**, *12* (31), 34784-34794. DOI: 10.1021/acsami.0c06844

(107) Motti, S. G.; Gandini, M.; Barker, A. J.; Ball, J. M.; Srimath Kandada, A. R.; Petrozza, A. Photoinduced Emissive Trap States in Lead Halide Perovskite Semiconductors. *ACS Energy Letters* **2016**, *1* (4), 726-730. DOI: 10.1021/acseenergylett.6b00355

(108) Huang, L.-y.; Lambrecht, W. R. L. Vibrational spectra and nonlinear optical coefficients of rhombohedral CsGeX_3 halide compounds with $X = \text{I, Br, Cl}$. *Physical Review B* **2016**, *94* (11), 115202. DOI: 10.1103/PhysRevB.94.115202

(109) Motti, S. G.; Patel, J. B.; Oliver, R. D. J.; Snaith, H. J.; Johnston, M. B.; Herz, L. M. Phase segregation in mixed-halide perovskites affects charge-carrier dynamics while preserving mobility. *Nature Communications* **2021**, *12* (1), 6955. DOI: 10.1038/s41467-021-26930-4

TOC Graphic:



The interaction within FASnI_{3-x}Br_x ($x = 0 - 3$) involves competition between concealing and revealing Sn lone pairs, dramatically affecting off-centering and ultimately, optical properties, particularly photoluminescence, reduced in Br-rich conditions.

Supporting Information

Structural Evolution and Photoluminescence Quenching Across the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) Perovskites

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Additional Synthetic Procedures for $FASnI_{3-x}Br_x$ ($x=0-3$) Compounds:

Synthesis of $FASnI_3$: 677 mg (3 mmol) of $SnCl_2 \cdot 2H_2O$ (Sigma-Aldrich; 98 wt.%) was massed and placed into a 20 mL scintillation vial. 5 mL of HI (Sigma-Aldrich; 57 wt.% in H_2O) and 1.7 mL of H_3PO_2 (Sigma-Aldrich; 50 wt.% in H_2O) was added to the solid along with a magnetic stir bar. The vial was heated on a hotplate ($\sim 120^\circ C$) under constant stirring until all of the solids dissolved and a clear solution was achieved. 312 mg (3 mmol) of $FACH_3COO$ (TCI; >98 wt.%) was then added to the hot reaction solution followed by immediate precipitation of a black solid. The temperature was then increased to $\sim 210^\circ C$ where the precipitate redissolved, creating a clear solution. The hotplate was then set to $110^\circ C$ and cooled to room temperature at a rate of $10^\circ C/hr$. Crystals of $FASnI_3$ were then isolated as black crystals from the solution.

Synthesis of $FASnI_{2.6}Br_{0.4}$: 677 mg (3 mmol) of $SnCl_2 \cdot 2H_2O$ (Sigma-Aldrich; 98 wt.%) was massed and placed into a 20 mL scintillation vial. 3.3 mL of HI (Sigma-Aldrich; 57 wt.% in H_2O), 1.7 mL (Sigma-Aldrich; 48 wt.% in H_2O), and 1.7 mL of H_3PO_2 (Sigma-Aldrich; 50 wt.% in H_2O) was added to the solid along with a magnetic stir bar. The vial was heated on a hotplate ($\sim 120^\circ C$) under constant stirring until all of the solids dissolved and a clear solution was achieved. 312 mg (3 mmol) of $FACH_3COO$ (TCI; >98 wt.%) was then added to the hot reaction solution followed by immediate precipitation of a black solid. The temperature was then increased to $\sim 210^\circ C$ where the precipitate redissolved, creating a clear solution. The hotplate was then set to $110^\circ C$ and cooled to room temperature at a rate of $10^\circ C/hr$. Crystals of $FASnI_{2.6}Br_{0.4}$ were then isolated as black crystals from the solution.

Synthesis of $FASnI_{2.3}Br_{0.7}$: 677 mg (3 mmol) of $SnCl_2 \cdot 2H_2O$ (Sigma-Aldrich; 98 wt.%) was massed and placed into a 20 mL scintillation vial. 1.7 mL of HI (Sigma-Aldrich; 57 wt.% in H_2O), 3.3 mL (Sigma-Aldrich; 48 wt.% in H_2O), and 1.7 mL of H_3PO_2 (Sigma-Aldrich; 50 wt.% in H_2O) was added to the solid along with a magnetic stir bar. The vial was heated on a hotplate ($\sim 120^\circ C$) under constant stirring until all of the solids dissolved and a clear solution was achieved. 312 mg (3 mmol) of $FACH_3COO$ (TCI; >98 wt.%) was then added to the hot reaction solution followed by immediate precipitation of a black solid. The temperature was then increased to $\sim 210^\circ C$ where the precipitate redissolved, creating a clear solution. The hotplate was then set to $110^\circ C$ and cooled

to room temperature at a rate of 10°C/hr. Crystals of $\text{FASnI}_{2.3}\text{Br}_{0.7}$ were then isolated as black crystals from the solution.

Synthesis of $\text{FASnI}_{2.1}\text{Br}_{0.9}$: 451 mg (2 mmol) of $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ (Sigma-Aldrich; 98 wt.%) was massed out and placed into a 20 mL scintillation vial. 2.25 mL of HBr (Sigma-Aldrich; 48 wt.% in H_2O), 0.75 mL of HI (Sigma-Aldrich 57 wt.% in H_2O), and 0.75 mL of H_3PO_2 (Sigma-Aldrich; 50 wt.% in H_2O) was added to the vial along with a magnetic stir bar. $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ was intended to be the limiting reagent during the reaction. The vial was heated on a hotplate (~120°C) under constant stirring until all solids dissolved creating a clear solution. 312 mg (3 mmol) of FACH_3COO (TCI; >98 wt.%) was then added to the hot reaction solution followed by immediate precipitation of a black solid. The temperature was then increased to ~210°C where the precipitate redissolved, creating a clear solution. Stirring continued for ~5 minutes before the hotplate was shut off, the stir bar was removed, and the reaction was allowed to cool to room temperature on the hotplate. Crystals of $\text{FASnI}_{2.1}\text{Br}_{0.9}$ were then isolated as black crystals from the solution.

Synthesis of $\text{FASnI}_{1.9}\text{Br}_{1.1}$: 451 mg (2 mmol) of $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ (Sigma-Aldrich; 98 wt.%) was massed out and placed into a 20 mL scintillation vial. 2 mL of HBr (Sigma-Aldrich; 48 wt.% in H_2O), 1 mL of HI (Sigma-Aldrich 57 wt.% in H_2O), and 0.75 mL of H_3PO_2 (Sigma-Aldrich; 50 wt.% in H_2O) was added to the vial along with a magnetic stir bar. $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ was intended to be the limiting reagent during the reaction. The vial was heated on a hotplate (~120°C) under constant stirring until all solids dissolved creating a clear solution. 312 mg (3 mmol) of FACH_3COO (TCI; >98 wt.%) was then added to the hot reaction solution followed by immediate precipitation of a black solid. The temperature was then increased to ~210°C where the precipitate redissolved, creating a clear solution. Stirring continued for ~5 minutes before the hotplate was shut off, the stir bar was removed, and the reaction was allowed to cool to room temperature on the hotplate. Crystals of $\text{FASnI}_{1.9}\text{Br}_{1.1}$ were then isolated as black crystals from the solution.

Synthesis of $\text{FASnI}_{1.1}\text{Br}_{1.9}$: 451 mg (2 mmol) of $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ (Sigma-Aldrich; 98 wt.%) was massed out and placed into a 20 mL scintillation vial. 2.5 mL of HBr (Sigma-Aldrich; 48 wt.% in H_2O), 0.5 mL of HI (Sigma-Aldrich 57 wt.% in H_2O), and 0.75 mL of H_3PO_2 (Sigma-Aldrich; 50 wt.% in H_2O) was added to the vial along with a magnetic stir bar. $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ was intended to

be the limiting reagent during the reaction. The vial was heated on a hotplate ($\sim 120^{\circ}\text{C}$) under constant stirring until all solids dissolved creating a clear solution. 312 mg (3 mmol) of FACH_3COO (TCI; >98 wt.%) was then added to the hot reaction solution followed by immediate precipitation of a black solid. The temperature was then increased to $\sim 210^{\circ}\text{C}$ where the precipitate redissolved, creating a clear solution. Stirring continued for ~ 5 minutes before the hotplate was shut off, the stir bar was removed, and the reaction was allowed to cool to room temperature on the hotplate. Crystals of $\text{FASnI}_{1.1}\text{Br}_{1.9}$ were then isolated as black crystals from the solution.

Synthesis of $\text{FASnI}_{0.7}\text{Br}_{2.3}$: 451 mg (2 mmol) of $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ (Sigma-Aldrich; 98 wt.%) was massed out and placed into a 20 mL scintillation vial. 2.75 mL of HBr (Sigma-Aldrich; 48 wt.% in H_2O), 0.25 mL of HI (Sigma-Aldrich 57 wt.% in H_2O), and 0.75 mL of H_3PO_2 (Sigma-Aldrich; 50 wt.% in H_2O) was added to the vial along with a magnetic stir bar. $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ was intended to be the limiting reagent during the reaction. The vial was heated on a hotplate ($\sim 120^{\circ}\text{C}$) under constant stirring until all solids dissolved creating a clear solution. 312 mg (3 mmol) of FACH_3COO (TCI; >98 wt.%) was then added to the hot reaction solution followed by immediate precipitation of a red solid. The temperature was then increased to $\sim 210^{\circ}\text{C}$ where the precipitate redissolved, creating a clear solution. Stirring continued for ~ 5 minutes before the hotplate was shut off, the stir bar was removed, and the reaction was allowed to cool to room temperature on the hotplate. Crystals of $\text{FASnI}_{0.7}\text{Br}_{2.3}$ were then isolated as red crystals from the solution.

Synthesis of $\text{FASnI}_{0.4}\text{Br}_{2.6}$: 451 mg (2 mmol) of $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ (Sigma-Aldrich; 98 wt.%) was massed out and placed into a 20 mL scintillation vial. 2.8 mL of HBr (Sigma-Aldrich; 48 wt.% in H_2O), 0.2 mL of HI (Sigma-Aldrich 57 wt.% in H_2O), and 0.75 mL of H_3PO_2 (Sigma-Aldrich; 50 wt.% in H_2O) was added to the vial along with a magnetic stir bar. $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ was intended to be the limiting reagent during the reaction. The vial was heated on a hotplate ($\sim 120^{\circ}\text{C}$) under constant stirring until all solids dissolved creating a clear solution. 312 mg (3 mmol) of FACH_3COO (TCI; >98 wt.%) was then added to the hot reaction solution followed by immediate precipitation of a red solid. The temperature was then increased to $\sim 210^{\circ}\text{C}$ where the precipitate redissolved, creating a clear solution. Stirring continued for ~ 5 minutes before the hotplate was shut off, the stir bar was removed, and the reaction was allowed to cool to room temperature on the hotplate. Crystals of $\text{FASnI}_{0.4}\text{Br}_{2.6}$ were then isolated as red-orange crystals from the solution.

Synthesis of $FASnI_{0.1}Br_{2.9}$: 451 mg (2 mmol) of $SnCl_2 \cdot 2H_2O$ (Sigma-Aldrich; 98 wt.%) was massed out and placed into a 20 mL scintillation vial. 2.9 mL of HBr (Sigma-Aldrich; 48 wt.% in H_2O), 0.1 mL of HI (Sigma-Aldrich 57 wt.% in H_2O), and 0.75 mL of H_3PO_2 (Sigma-Aldrich; 50 wt.% in H_2O) was added to the vial along with a magnetic stir bar. $SnCl_2 \cdot 2H_2O$ was intended to be the limiting reagent during the reaction. The vial was heated on a hotplate ($\sim 120^\circ C$) under constant stirring until all solids dissolved creating a clear solution. 312 mg (3 mmol) of $FACH_3COO$ (TCI; >98 wt.%) was then added to the hot reaction solution followed by immediate precipitation of an orange-yellow solid. The temperature was then increased to $\sim 210^\circ C$ where the precipitate redissolved, creating a clear solution. Stirring continued for ~ 5 minutes before the hotplate was shut off, the stir bar was removed, and the reaction was allowed to cool to room temperature on the hotplate. Crystals of $FASnI_{0.1}Br_{2.9}$ were then isolated as orange-yellow crystals from the solution.

Synthesis of $FASnBr_3$: 451 mg (2 mmol) of $SnCl_2 \cdot 2H_2O$ (Sigma-Aldrich; 98 wt.%) was massed out and placed into a 20 mL scintillation vial. 3 mL of HBr (Sigma-Aldrich; 48 wt.% in H_2O) and 1 mL of H_3PO_2 (Sigma-Aldrich; 50 wt.% in H_2O) was added to the vial along with a magnetic stir bar. $SnCl_2 \cdot 2H_2O$ was intended to be the limiting reagent during the reaction. The vial was heated on a hotplate ($\sim 120^\circ C$) under constant stirring until all solids dissolved creating a clear solution. 312 mg (3 mmol) of $FACH_3COO$ (TCI; >98 wt.%) was then added to the hot reaction solution followed by immediate precipitation of a yellow solid. The temperature was then increased to $\sim 210^\circ C$ where the precipitate redissolved, creating a clear solution. Stirring continued for ~ 5 minutes before the hotplate was shut off, the stir bar was removed, and the reaction was allowed to cool to room temperature on the hotplate. $FASnBr_3$ was then isolated as yellow crystals from the solution.

Diffuse Reflectance:

Dry, bulk materials were mechanically ground in a mortar and pestle inside a N₂ filled glovebox and then combined with varying amounts of barium sulfate (BaSO₄). BaSO₄ serves as the 100% reflectance standard for the measurements and dilutes the sample to reduce the overall absorbance such that the data could be collected in a reflection geometry. The optical diffuse reflectance data were collected on a Cary 5000 UV-Vis-NIR double beam spectrophotometer equipped with a monochromator and an integrating sphere detector. The room temperature data collection covered the range of 200 – 1100 nm. The collected data were then used to estimate the band gap of the material by first converting the reflectance data to absorption, through the use of the Kubelka-Munk transformation, and subsequently extrapolating the absorption edge of the curve.¹

Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS):

Scanning Electron Microscopy (SEM) analyses were performed using a Schottky field-emission SEM (JEOL JSM-7900FLV SEM) at 10 kV. Energy-dispersive X-ray spectroscopy was performed using an Oxford 65 EDS detector with a 65 mm² detection area.

Pair Distribution Function Calculations:

Pair distribution function analyses are a unique method allowing for a more direct understanding of the local structure of materials. Since both the Bragg reflections and diffuse scattering are weighted equally, long-range order is not a requirement unlike traditional diffraction techniques, making it ideal for structural insight into non-crystalline phases (glasses for example). PDF analyses can be crucial to understanding if perturbations in the chemical structure seen for a typical single crystal is representative of the bulk material. It can also be critical to understand distortions on a local level which are not captured in the average. The data collected for these analyses are high resolution X-ray diffraction powder diffraction patterns. The coherent part of the measured intensity $I_c(Q)$ is used to calculate the total scattering structure function for each compound $S(Q)$ (eq. 1).

$$S(Q) = \frac{I_c(Q) - \sum c_i |f_i(Q)|^2}{|\sum c_i f_i(Q)|^2} + 1 \quad \text{eq.1}$$

Here the intensity is found by subtraction of the background from air and scattering from the glass vessel as well as accounting for several other effects. The data is also normalized against

the flux of the radiation source and number of atoms contained within the sample. Within eq. 1, c_i are the atomic concentration and $f_i(Q)$ is the X-ray atomic form factor for the atomic species of type i , and momentum transfer is determined through eq. 2.

$$Q = \frac{4\pi \sin \theta}{\lambda} \quad \text{eq.2}$$

The atomic pair distribution function (PDF) is then obtained through a Fourier transformation of the expression $Q(S(Q)-1)$ (eq. 3)

$$G(r) = (2/\pi) \int_{Q_{min}}^{Q_{max}} Q(S(Q) - 1) \sin(Q \cdot r) dQ \quad \text{eq.3}$$

The atomic PDF is also related to the average atomic number density (ρ_0) and the atomic pair-density ($\rho(r)$), which is a function of radial distance (r) typically in angstroms). This relation is calculated through eq. 4.

$$G(r) = 4\pi \cdot r(\rho(r) - \rho_0) \quad \text{eq. 4}$$

$G(r)$ then provides information regarding the density of atoms residing in an infinitesimally small shell at a distance of r away from a designated reference atom. The experimental atomic PDF can then be refined against a theoretical PDF generated based on a structural model. Notably the higher the Q_{max} that can be used, the higher the resolution will be. In an ideal case $Q > 20 \text{ \AA}^{-1}$ is desired but is entirely dependent on the structural features needed to be resolved compared to the real space resolution (δr) based on eq. 5. In this case, shorter wavelengths are more optimal based on eq. 2.

$$\delta r = \frac{2\pi}{Q_{max}} \quad \text{eq.5}$$

Modeling of Local Structures:

The local structure of FASnI_3 and FASnBr_3 was obtained by relaxing the average crystal structure to P1 (only identity symmetry) and reducing each organic FA^+ cation to a centralized C atom with the same electron density. These models were then used as a starting point for refining the structure against the low r regions of the $G(r)$ curves which can be done through eq. 5.

$$G(r) + 4\pi \cdot r \cdot \rho_0 = \frac{1}{r} \sum_v \sum_\mu \frac{f^{(0)}_v f^{(0)}_\mu}{\langle f^{(0)} \rangle^2} \delta(r - r_{v\mu}) \quad \text{eq.5}$$

Refining of the local structure against the experimental PDF curve was then accomplished through PDFgui² by freely refining several corrective factors as well as the unit cell parameters and the positions of the atoms in the lower symmetry unit cell.

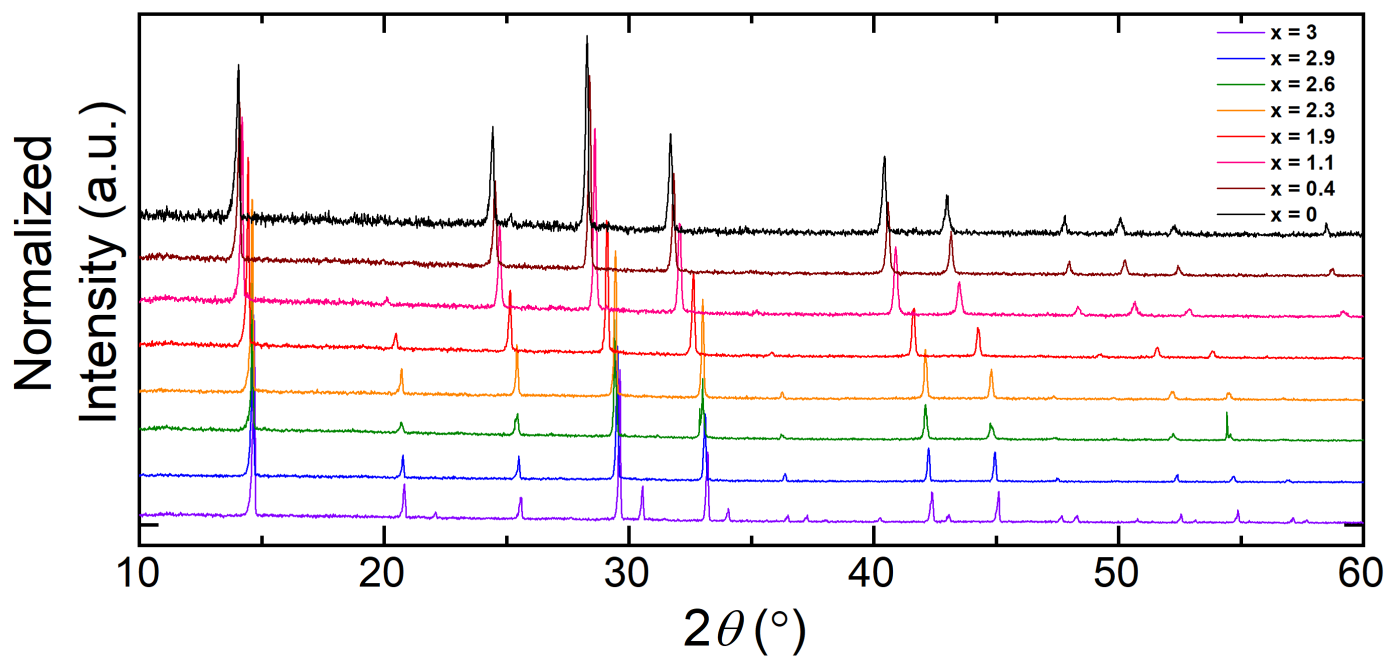


Figure S1: Selected experimental powder diffraction patterns for $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) compositions. The presented range was shortened to $10\text{-}60^\circ 2\theta$ due to air scattering at low angles.

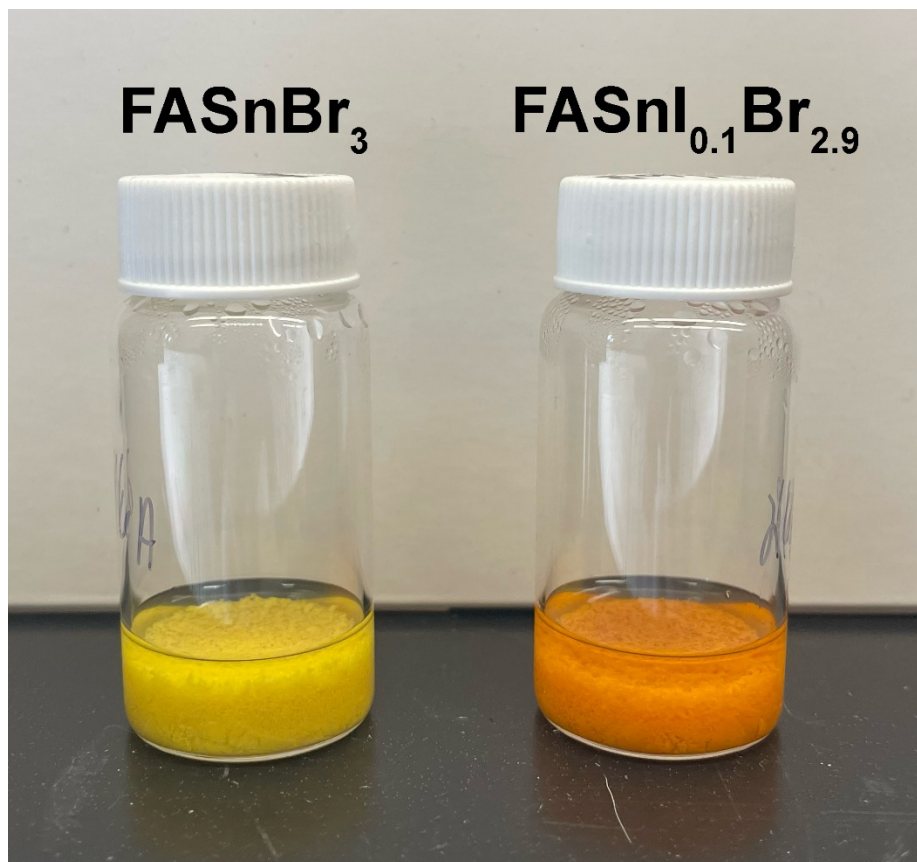


Figure S2: As synthesized crystallites of FASnBr_3 and $\text{FASnI}_{0.1}\text{Br}_{2.9}$. The compounds are shown on the left (yellow) and right (orange) respectively.

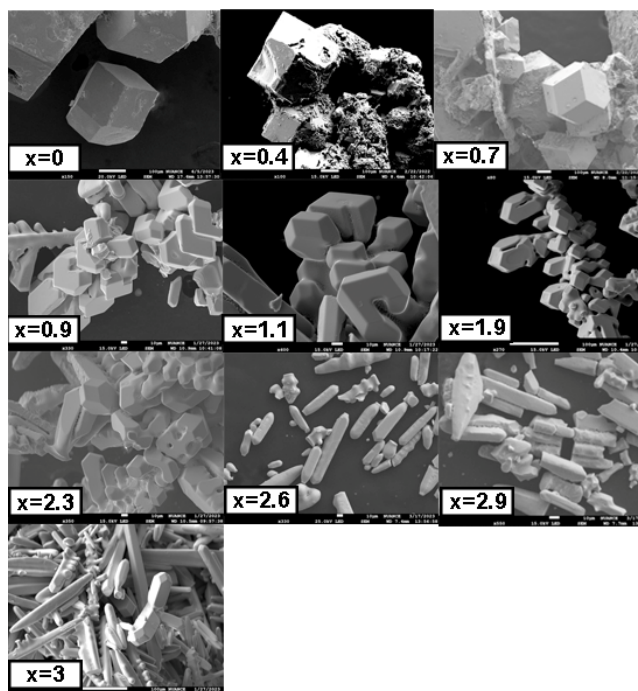


Figure S3: The crystal habit for each of the synthesized compounds in the FASnI_{3-x}Br_x ($x = 0 - 3$) substitution range.

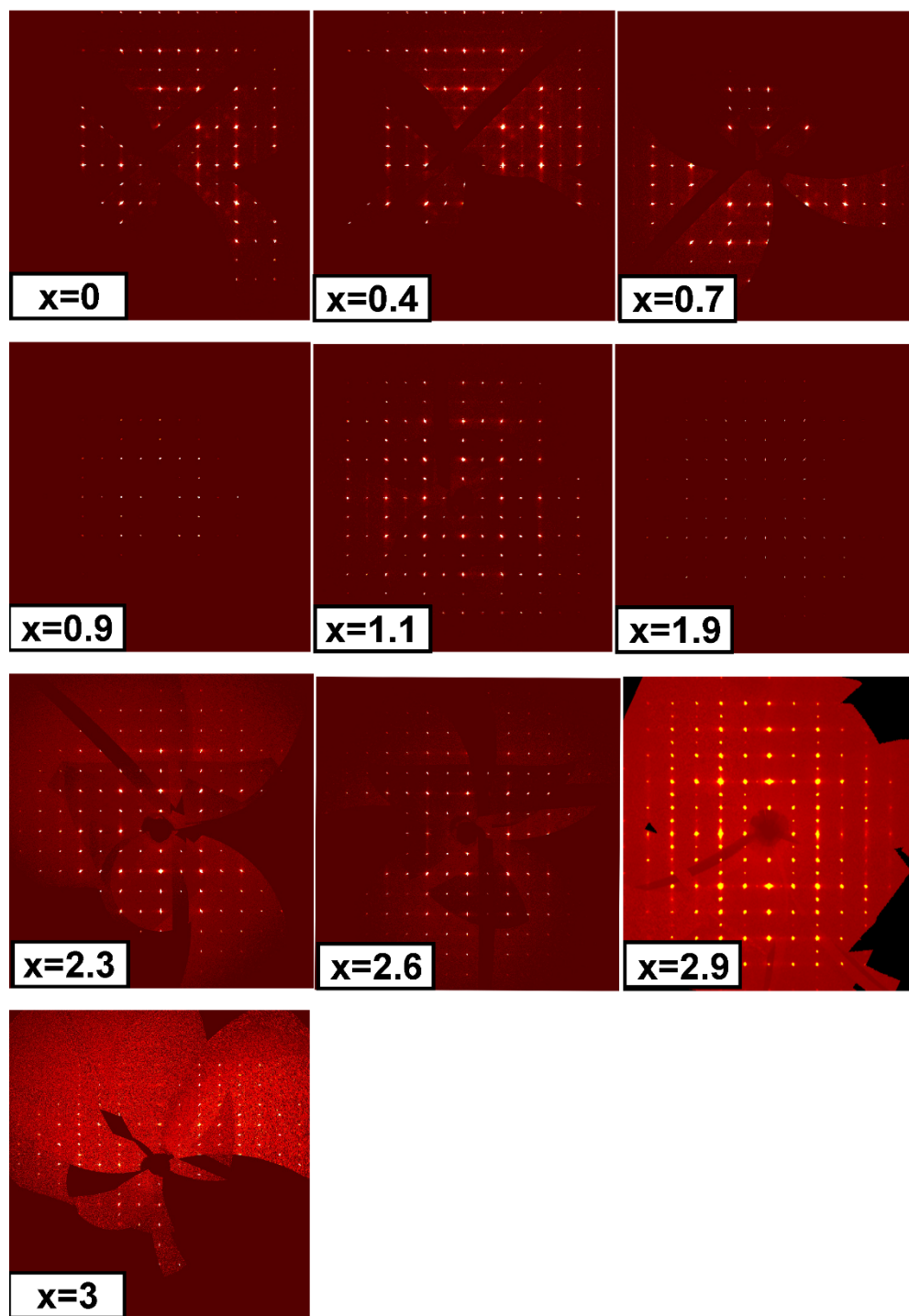


Figure S4: Precession images of reciprocal space for each of the synthesized compounds in the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) family. The presence of additional reflections for the $x = 2.9$ and 3 compositions provides direct evidence for the structural change.

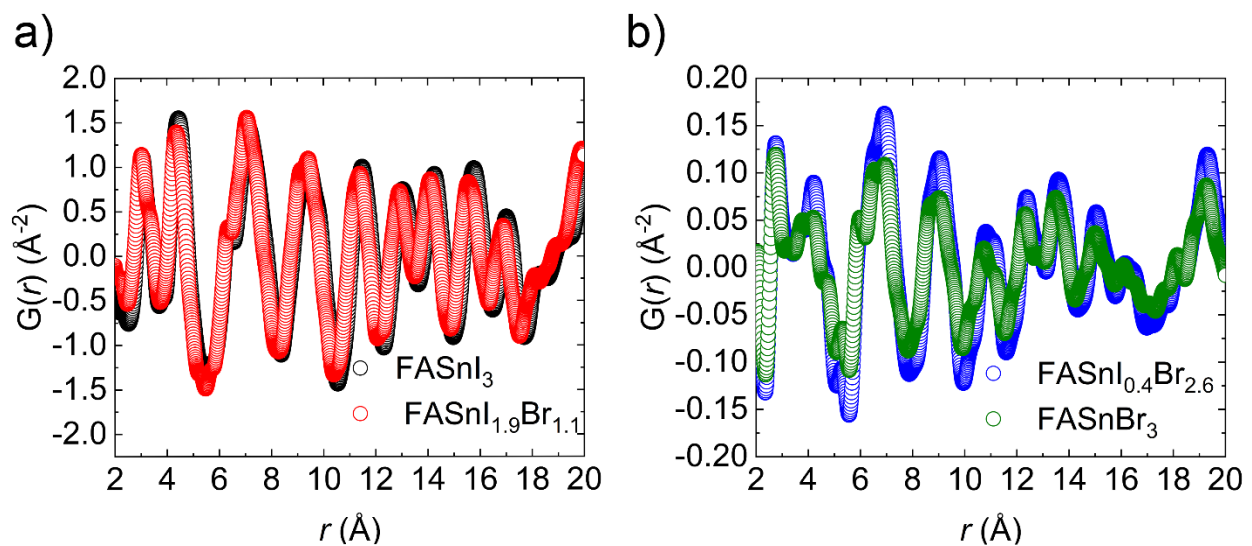


Figure S5: a) the PDF curve from 2 – 20 \AA for FASnI_3 and $\text{FASnI}_{1.9}\text{Br}_{1.1}$ overlaid on one another and b) the PDF curve from 2 – 20 \AA for $\text{FASnI}_{0.4}\text{Br}_{2.6}$ and FASnBr_3 overlaid on one another.

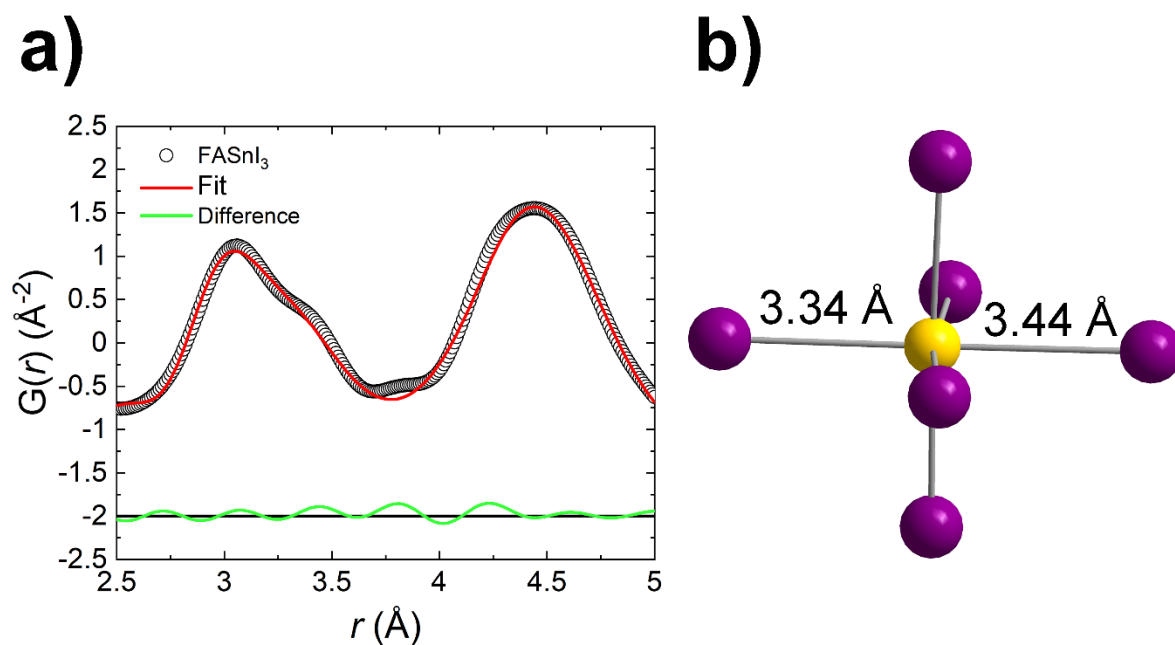


Figure S6: a) Experimental and theoretical $G(r)$ curves as well as the difference curve within the range of 2.5-5 \AA . b) The SnI_6 octahedral unit based on refinements of the local structure against the $G(r)$. The off-centering of the Sn atom is highlighted by the bond distances of opposite Iodine atoms. The structure was relaxed to P1 space group symmetry for modeling of the curve.

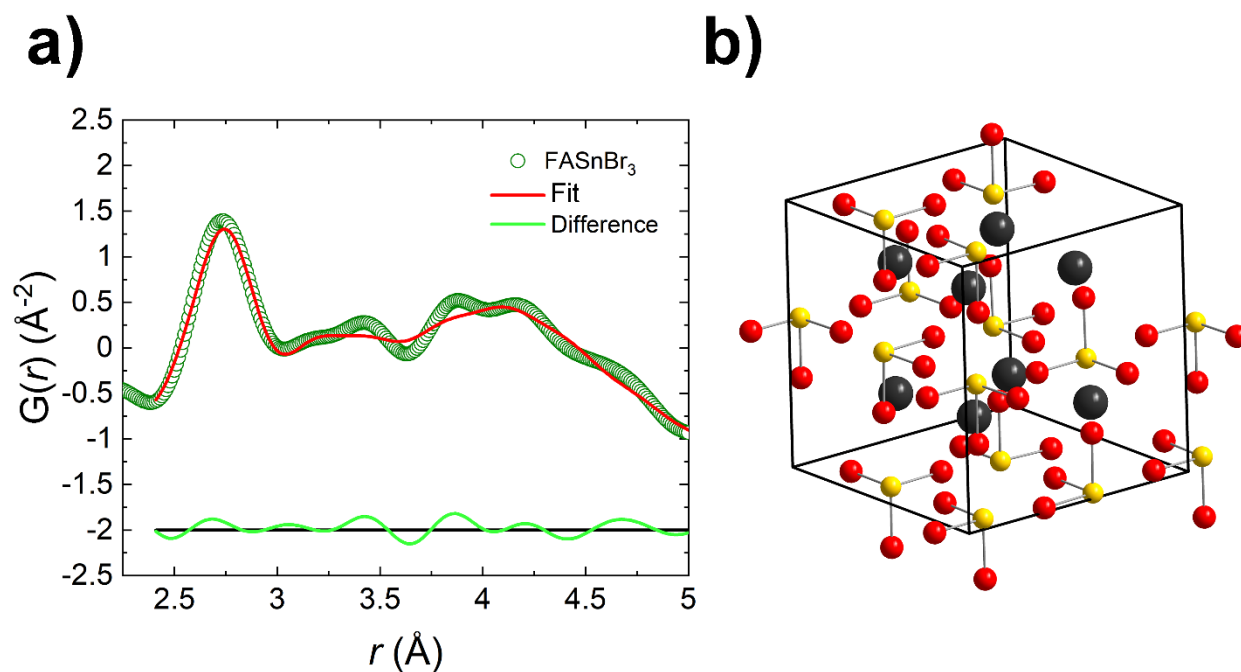


Figure S7: a) Experimental and theoretical $G(r)$ curves as well as the difference curve within the range of 2.5-5 Å. b) the refined local structure model of FASnBr_3 . The space group symmetry was relaxed to P1 for the model.

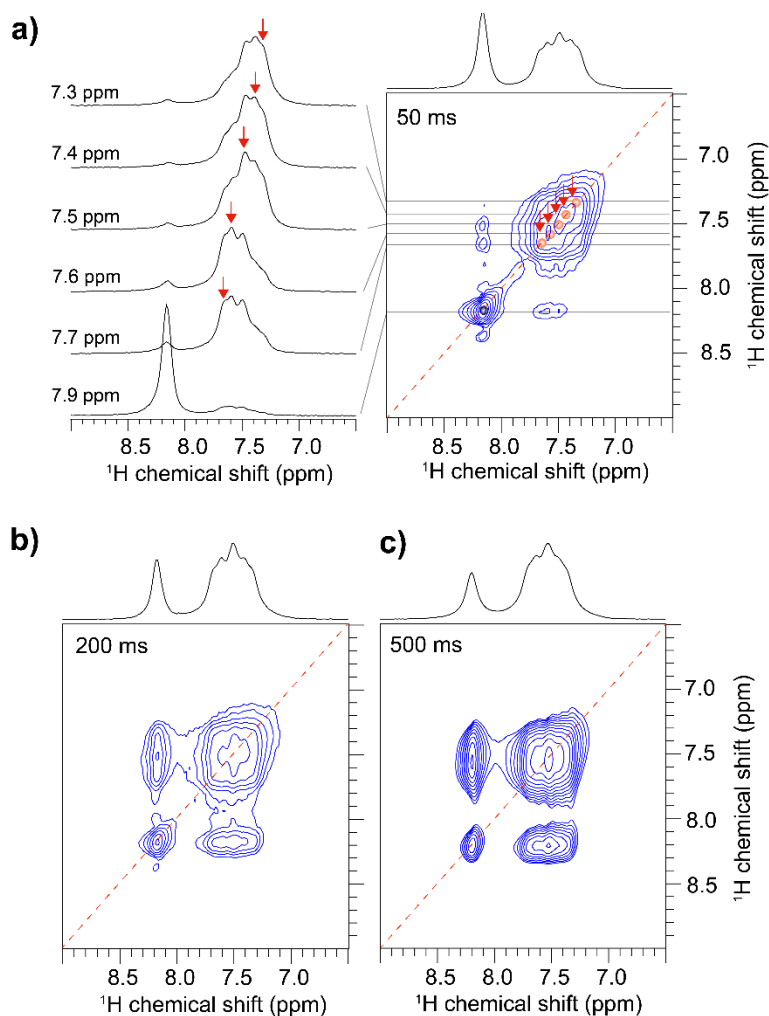


Figure S8: Solid-state (a) 2D ^1H - ^1H spin-diffusion (SD) NMR spectrum acquired with 50 ms of mixing time together with the line-cut NMR spectra drawn at different chemical shifts as indicated. Identical 2D NMR spectra acquired with (b) 200 ms and (c) 500 ms of spin diffusion mixing times. All spectra were acquired at 18.8 T (^1H = 800.1 MHz) with 55 kHz MAS and at room temperature.

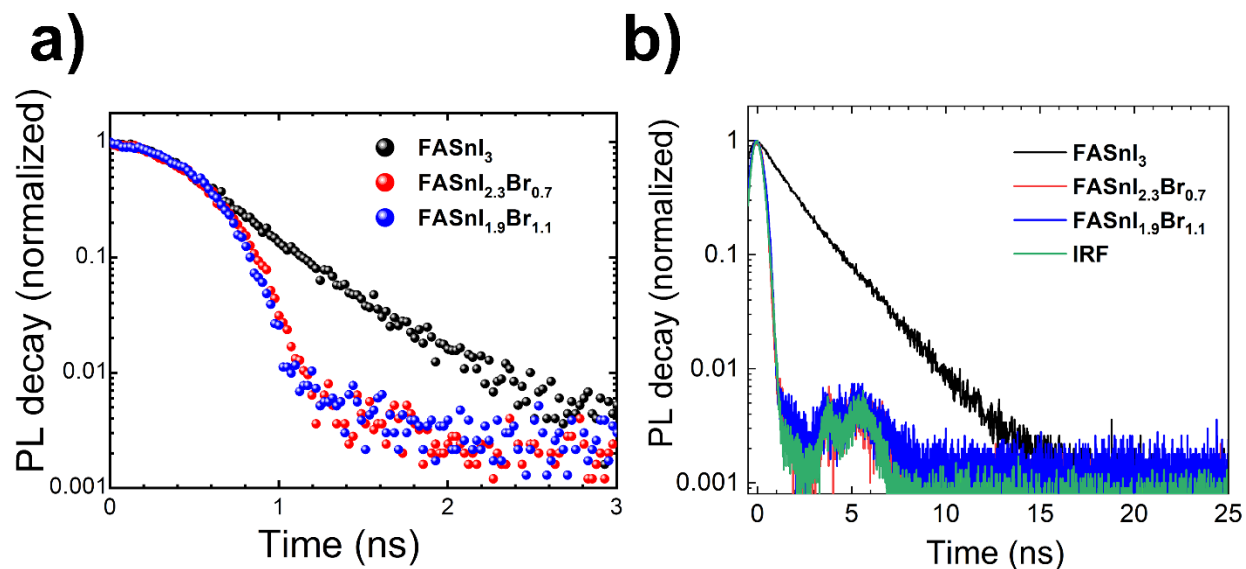


Figure S9: Time resolved photoluminescence a) for selected thin film samples for which PL intensity was observed and b) time resolved photoluminescence with the instrument response function plotted. Note that due to instrumental limitations at low lifetimes, the lifetime cannot be well resolved against the instrument response function (IRF) due to its width. The decay fitting does, however, give an approximation to the lifetime for the as synthesized thin film samples.

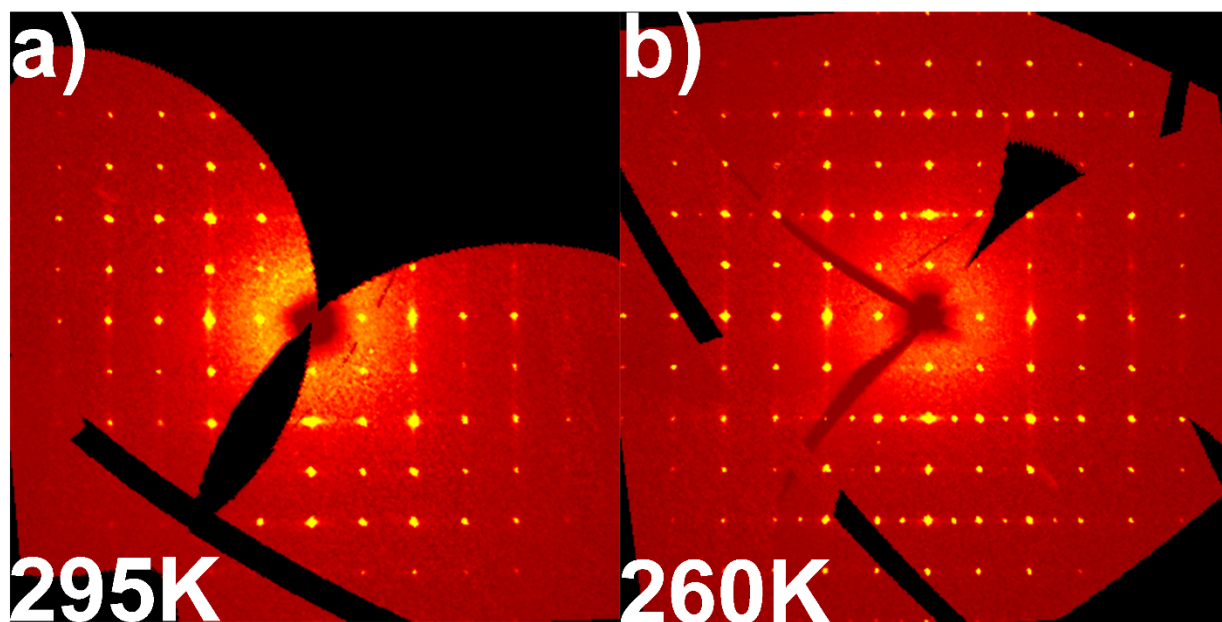


Figure S10: Precession images of reciprocal space for $\text{FASnI}_{0.4}\text{Br}_{2.6}$ at a) 295K and b) 260K. Data was collected on the same crystal to highlight the change in reflection conditions while leaving all other parameters constant. The presence of additional reflections at $\frac{1}{2} hkl$ indices at 260K provide evidence for this structural transition.



Figure S11: Light illumination of the related thin films was performed under 5000k white LED source (EverWatt, EW-HB-06-V-150W) with $100\text{mW}/\text{cm}^2$ intensity in a nitrogen-filled glovebox. The samples were then taken out of the glovebox for measurement after 1-3-6-24 hours of illumination.



Figure S12: Sample holders containing FASnBr₃ (left) and FASnI₃ (right) prepared for Raman spectroscopy. The holders are quartz glass with glass wool inserted to better compact the sample with epoxy being used to seal the narrow (~1 mm) width opening.

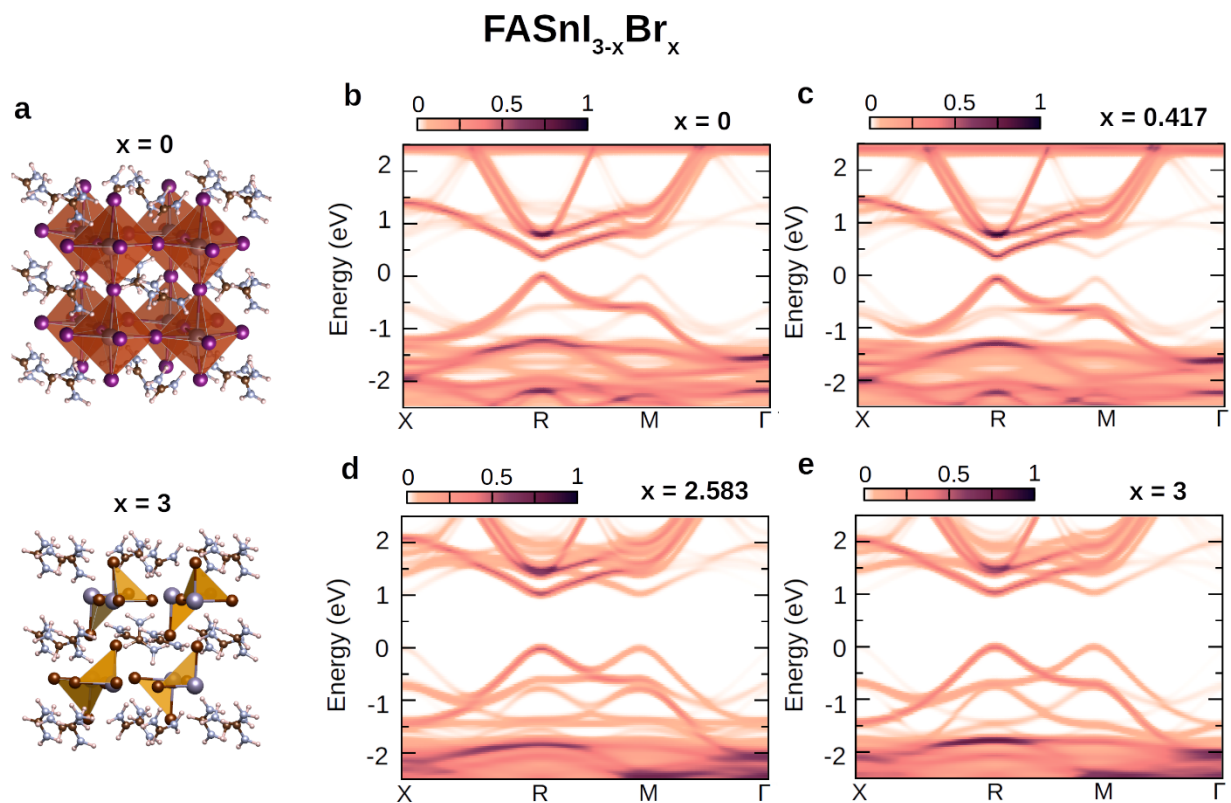


Figure S13: Electron spectral functions of FASnI_{3-x}Br_x. (a) DFT optimized structures of cubic FASnI₃ ($x = 0$) and FASnBr₃ ($x = 3$) accounting for local disorder (polymorphism).^{3,4} (b-e) DFT electron spectral functions (color map) of FASnI_{3-x}Br_x for $x = 0$ (b), $x = 0.417$ (c), $x = 2.583$ (d), and $x = 3$ (e) calculated using band structure unfolding^{5,6} and the PBEsol approximation.

Note S1: In Fig. S11a, we report the calculated structures of FASnI₃ (top) and FASnBr₃ (bottom). With respect to their idealized Pm-3m structures, we found energy stabilization of 87.3 meV/f.u. and 124.8 meV/f.u. for the distorted FASnI₃ and FASnBr₃, respectively, i.e. accounting for random local disorder for both, which leads to the expression of lone pairs (on average) for the latter. Figure S11b reports the calculated electron spectral function (color map) of cubic FASnI₃ which exhibits a band gap at the R point of 0.38 eV. Increasing the Br content in FASnI_{3-x}Br_x further opens the band gap as shown in Figures S11c-e. In particular, our calculations for $x = 0.417$, $x = 2.583$, and $x = 3$ yield a direct band gap at the R point of 0.430, 1.043, and 1.039 eV, respectively. We observe that, while the typical pattern is to raise the band gap with an increase in the Br content, the slightly greater band gap for $x = 2.583$ compared to $x = 3$ can be attributed to the larger lattice constant when $x = 2.583$. We note that our calculations are performed at the DFT level and thus underestimation of all the band gaps is to be expected. A correction of around 1 eV due to the use

of a higher-level correlation functional has been reported previously.³ Interestingly, raising the Br content also leads to the increase in the spectral weight (occupation probability) at the M point [see for example Fig. S11e]. The new states at the M point are replicas of the states at the R point emerging due to symmetry reduction of $\text{FASnI}_{3-x}\text{Br}_x$ upon Br substitution. The state at the M point is absent in the electron spectral function of the idealized $Pm\bar{3}m$ FASnBr_3 (Figure 12a), highlighting that its origin is the symmetry reduction induced by the stereochemical expression of Sn-5s lone pairs. Furthermore, Br substitution causes the enhancement of energy smearing and the increase of the effective masses.

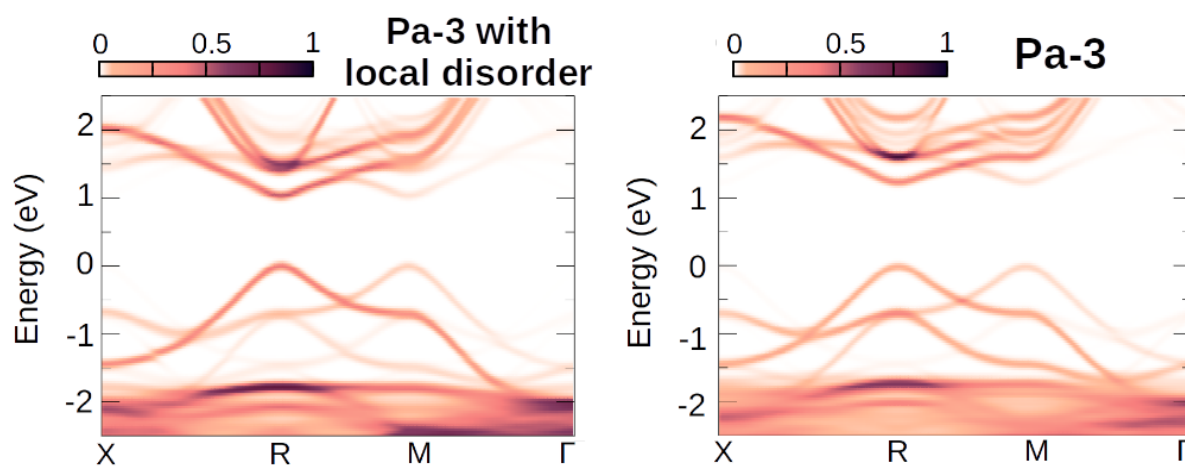


Figure S14: Effect of local disorder on the electronic band structure of FASnBr₃. DFT electron spectral functions (color map) of FASnBr₃ considering cubic $Pa\bar{3}$ space group, calculated using band structure unfolding^{5, 6} and the PBEsol approximation (left) accounting for local disorder (polymorphism)^{3, 4} and (right) without, i.e. using experimental crystallographic data for the inorganic atomic positions.

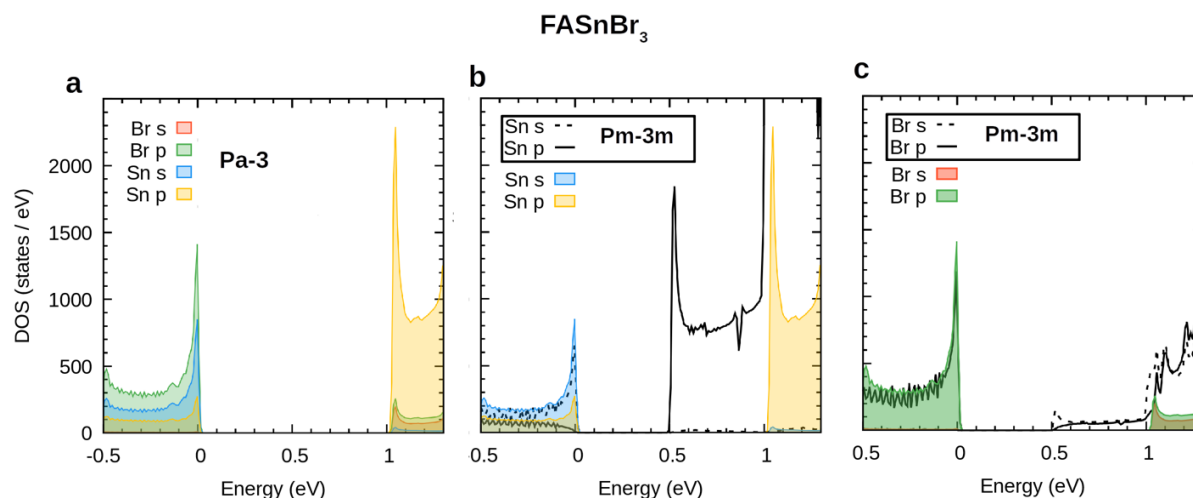


Figure S15: Projected density of states of FASnBr₃. (a) Projected density of states (PDOS) showing the contribution of Br-4s (red), Br-4p (green), Sn-5s (blue), and Sn-5p (yellow) orbitals to the formation of the band edges of the distorted ($Pa\bar{3}$) FASnBr₃. (b) Projected density of states showing the contribution of Sn-5s (black dashed line) and Sn-5p (black solid line) orbitals to the formation of the band edges of the idealized $Pm\bar{3}m$ FASnBr₃. (c) Projected density of states showing the contribution of Br-4s (black dashed line) and Br-4p (black solid line) orbitals to the formation of the band edges of the idealized $Pm\bar{3}m$ FASnBr₃. In (b) and (c) the corresponding PDOS calculated for the distorted FASnBr₃ (colored) is shown for comparison. The energy axes are adjusted so that the VBM is set at zero energy.

Note S2: Figure S13a shows the projected density of states (PDOS) calculated for FASnBr₃ in the cubic $Pa\bar{3}$ space group. As expected, the density of states varies proportionally to the square root of energy consistent with the parabolic band approximation. In comparison to the PDOS of the idealized $Pm\bar{3}m$ FASnBr₃ (black lines in Figures S13b and c), the contributions from the Sn-5s and Br-4p orbitals to the valence band remain nearly unchanged, while the contribution from Sn-5p orbitals is significantly enhanced. Regarding the conduction band, the dominant contribution remains from the Sn-5p orbitals with small contributions arising from the Br-4p, Sn-5s, and Br-4s orbitals. From the comparison of the PDOS in Figs. S13b and c, it is also apparent that the structural distortion induced by the stereochemical expression of the Sn-5s lone pair leads to the energy broadening of the density of states.

Table S1: Selected Crystallographic information and refinement statistics for representative FASnI_{3-x}Br_x (x = 0 – 3) compositions. FASnI₃ and FASnBr₃ were synthesized and measured independently of previous research efforts.

Formula	FASnI ₃	FASnI _{2.6} Br _{0.4}	FASnI _{2.3} Br _{0.7}	FASnI _{2.1} Br _{0.9}	FASnI _{1.9} Br _{1.1}	FASnI _{1.7} Br _{1.3}	FASnI _{1.4} Br _{1.6}	FASnI _{1.1} Br _{1.9}	FASnBr ₃	
Formula weight	525.41	518.74	508.41	495.72	488.67	452.02	432.28	418.19	402.62	398.45
Temperature (K)	295	295	295	295	295	295	295	295	300	290
Wavelength (Å)	0.71073	0.71073	0.71073	0.71073	0.71073	0.71073	0.71073	0.71073	0.56083	0.71073
Crystal system	Cubic									
Space group	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pm</i> $\bar{3}$ <i>m</i>	<i>Pa</i> $\bar{3}$	<i>Pa</i> $\bar{3}$
<i>a</i> / <i>b</i> / <i>c</i> (Å)	6.3064(3)	6.3099(2)	6.2824(2)	6.2525(5)	6.2449(1)	6.1354(2)	6.0915(2)	6.0443(2)	12.0637(15)	12.0303(5)
Volume (Å ³)	250.81(4)	251.23(3)	247.96(2)	244.43(6)	243.54(1)	230.96(6)	226.03(2)	220.82(2)	1755.7(7)	1741.1(2)
Z	1	1	1	1	1	1	1	1	8	8
ρ_{calc} (g/cm ³)	3.479	3.429	3.405	3.368	3.332	3.250	3.176	3.145	3.046	3.040
Absorption coefficient (mm ⁻¹)	11.695	12.080	12.441	12.871	13.058	14.537	15.275	15.944	8.707	16.615
Independent reflections	91 [R _{int} = 0.0375]	172 [R _{int} = 0.0117]	166 [R _{int} = 0.0087]	103 [R _{int} = 0.0314]	160 [R _{int} = 0.0183]	68 [R _{int} = 0.0750]	95 [R _{int} = 0.0136]	113 [R _{int} = 0.0132]	688 [R _{int} = 0.0487]	641 [R _{int} = 0.0716]
Completeness	100% (θ = 25.242°)	100% (θ = 25.242°)	100% (θ = 25.242°)	100% (θ = 25.242°)	100% (θ = 25.242°)	100% (θ = 25.190°)	100% (θ = 25.242°)	100% (θ = 25.242°)	100% (θ = 19.664°)	100% (θ = 25.242°)
Data / restraints / parameters	91 / 1 / 8	172 / 1 / 10	166 / 1 / 10	103 / 1 / 9	160 / 1 / 10	68 / 1 / 9	95 / 1 / 10	113 / 1 / 10	688 / 2 / 25	641 / 2 / 24
Goodness-of-fit	1.550	1.232	1.207	1.430	1.198	1.413	1.117	1.204	1.273	1.052
Final R indices [I > 2 σ (I)]	R _{obs} = 0.0435, wR _{obs} = 0.01248	R _{obs} = 0.0231, wR _{obs} = 0.0766	R _{obs} = 0.0239, wR _{obs} = 0.0877	R _{obs} = 0.0429, wR _{obs} = 0.1006	R _{obs} = 0.0231, wR _{obs} = 0.0846	R _{obs} = 0.0292, wR _{obs} = 0.0950	R _{obs} = 0.0317, wR _{obs} = 0.1092	R _{obs} = 0.0479, wR _{obs} = 0.1540	R _{obs} = 0.0585, wR _{obs} = 0.1451	R _{obs} = 0.0419, wR _{obs} = 0.1011
R indices [all data]	R _{all} = 0.0556, wR _{all} = 0.1254	R _{all} = 0.0258, wR _{all} = 0.0786	R _{all} = 0.0273, wR _{all} = 0.0908	R _{all} = 0.0443, wR _{all} = 0.1070	R _{all} = 0.0247, wR _{all} = 0.0859	R _{all} = 0.0292, wR _{all} = 0.0950	R _{all} = 0.0317, wR _{all} = 0.1092	R _{all} = 0.0479, wR _{all} = 0.1540	R _{all} = 0.0849, wR _{all} = 0.1619	R _{all} = 0.0679, wR _{all} = 0.1139
Largest diff. peak/hole (e ⁻ Å ⁻³)	0.869/-1.372	0.680/-0.836	1.229/-1.299	0.656/-0.944	0.814/-0.828	0.716/-0.4	0.636/-0.610	0.747/-1.260	0.952/-0.695	0.799/-0.643

$$R = \frac{\sum ||F_o| - |F_c||}{\sum |F_o|}, wR = \left\{ \frac{\sum [w(|F_o|^2 - |F_c|^2)^2]}{\sum [w(|F_o|^4)]} \right\}^{1/2} \text{ and } w = 1 / [\sigma^2(F_o^2) + (0.0163P)^2 + 1.6916P] \text{ where } P = (F_o^2 + 2F_c^2) / 3$$

Table S2: Atomic Coordinates ($\times 10^4$) and equivalent isotropic displacement parameters ($\text{\AA}^2 \times 10^3$) for the compositions in the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) substitution range with standard deviations in parenthesis. The temperature of the data collection is also listed.

Label	x	y	z	Occupancy	U_{eq}^*
FASnI₃ (295K)					
Sn	5000	5000	5000	1	42(1)
I	0	5000	5000	1	81(1)
C	0	0	0	1	110(20)
N	2170(30)	0	0	0.3334	170(40)
FASnI_{2.6}Br_{0.4} (295K)					
Sn	5000	5000	5000	1	44(1)
I	0	5000	5000	0.854(17)	82(1)
Br	0	5000	5000	0.146(17)	82(1)
C	0	0	0	1	150(20)
N	2180(30)	0	0	0.3334	141(12)
FASnI_{2.3}Br_{0.7} (295K)					
Sn	5000	5000	5000	1	48(1)
I	0	5000	5000	0.78(2)	87(1)
Br	0	5000	5000	0.22(2)	87(1)
C	0	0	0	1	220(40)
N	2100(30)	0	0	0.3334	185(14)
FASnI_{2.1}Br_{0.9} (295K)					
Sn	5000	5000	5000	1	52(1)
I	0	5000	5000	0.69(3)	92(1)
Br	0	5000	5000	0.31(3)	92(1)
C	0	0	0	1	130(20)
N	2150(30)	0	0	0.3334	160(20)
FASnI_{1.9}Br_{1.1} (295K)					
Sn	5000	5000	5000	1	56(1)
I	0	5000	5000	0.640(19)	98(1)
Br	0	5000	5000	0.360(19)	98(1)
C	0	0	0	1	180(20)
N	2130(30)	0	0	0.3334	203(19)
FASnI_{1.1}Br_{1.9} (295K)					
Sn	5000	5000	5000	1	66(1)
I	0	5000	5000	0.38(3)	120(2)
Br	0	5000	5000	0.62(3)	120(2)
C	0	0	0	1	190(30)
N	2220(30)	0	0	0.3334	210(40)
FASnI_{0.7}Br_{2.3} (295K)					
Sn	5000	5000	5000	1	66(1)
I	0	5000	5000	0.25(3)	131(2)
Br	0	5000	5000	0.75(3)	131(2)
C	0	0	0	1	190(40)
N	2240(30)	0	0	0.3334	210(40)
FASnI_{0.4}Br_{2.6} (295K)					

Sn	5000	5000	5000	1	66(1)
I	0	5000	5000	0.13(4)	141(2)
Br	0	5000	5000	0.87(4)	141(2)
C	0	0	0	1	170(40)
N	2290(30)	0	0	0.3334	250(80)
FASnI_{2.6}Br_{0.4} (260K)					
Sn	2529(1)	2529(1)	2529(1)	1	58(1)
Br	2550(5)	2572(5)	218(5)	0.842(11)	107(2)
I	2500(20)	2423(19)	-241(14)	0.158(11)	107(2)
C1	5000	0	0	1	150(190)
C2	0	0	0	1	200(200)
N1	4400(70)	-920(80)	390(120)	0.3333	250(50)
N2	-210(70)	830(100)	790(100)	0.3333	330(90)
FASnI_{0.1}Br_{2.9} (300K)					
Sn	2430(1)	7430(1)	7570(1)	1	50(1)
Br	4695(2)	7397(3)	7613(4)	0.970(10)	93(1)
I	4790(40)	7680(60)	7140(80)	0.030(10)	93(1)
C1	5000	5000	5000	1	150(30)
C2	0	0	0	1	170(30)
N1	653(9)	653(9)	653(9)	1	360(40)
N2	4910(120)	5320(110)	3900(40)	0.3333	310(70)
FASnBr₃ (290K)					
Sn	7597(1)	2403(1)	7403(1)	1	47(1)
Br	5340(1)	2384(1)	7370(1)	1	90(1)
C1	5000	5000	5000	1	156(18)
C2	5000	0	5000	1	160(20)
N1	6114(16)	4940(30)	4900(40)	0.3333	200(20)
N2	9028(16)	5340(30)	4600(30)	0.3333	125(11)

* U_{eq} is defined as one third of the trace of the orthogonalized U_{ij} tensor.

Table S3: Selected Anisotropic displacement parameters ($\text{\AA}^2 \times 10^3$) for compounds in the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) family, with estimated standard deviations in parenthesis. The temperature of the data collection is also listed.

Label	U_{11}	U_{22}	U_{33}	U_{12}	U_{13}	U_{23}
FASnI₃ (295K)						
Sn	42(1)	42(1)	42(1)	0	0	0
I	36(1)	104(2)	104(2)	0	0	0
FASnI_{2.6}Br_{0.4} (295K)						
Sn	44(1)	44(1)	44(1)	0	0	0
I	37(1)	104(1)	104(1)	0	0	0
Br	37(1)	104(1)	104(1)	0	0	0
FASnI_{2.3}Br_{0.7} (295K)						
Sn	48(1)	48(1)	48(1)	0	0	0
I	42(1)	109(1)	109(1)	0	0	0
Br	42(1)	109(1)	109(1)	0	0	0
FASnI_{2.1}Br_{0.9} (295K)						
Sn	52(1)	52(1)	52(1)	0	0	0
I	52(1)	113(2)	113(2)	0	0	0
Br	52(1)	113(2)	113(2)	0	0	0
FASnI_{1.9}Br_{1.1} (295K)						
Sn	56(1)	56(1)	56(1)	0	0	0
I	56(1)	119(1)	119(1)	0	0	0
Br	56(1)	119(1)	119(1)	0	0	0
FASnI_{1.1}Br_{1.9} (295K)						
Sn	66(1)	66(1)	66(1)	0	0	0
I	94(2)	133(2)	133(2)	0	0	0
Br	94(2)	133(2)	133(2)	0	0	0
FASnI_{0.7}Br_{2.3} (295K)						
Sn	66(1)	66(1)	66(1)	0	0	0
I	119(2)	137(2)	137(2)	0	0	0
Br	119(2)	137(2)	137(2)	0	0	0
FASnI_{0.4}Br_{2.6} (295K)						
Sn	66(1)	66(1)	66(1)	0	0	0
I	148(4)	138(3)	138(3)	0	0	0
Br	148(4)	138(3)	138(3)	0	0	0
FASnI_{0.4}Br_{2.6} (260K)						
Sn	58(1)	58(1)	58(1)	1(1)	1(1)	1(1)
Br	130(2)	126(3)	64(3)	-7(7)	-5(3)	-7(3)
I	130(2)	126(3)	64(3)	-7(7)	-5(3)	-7(3)
FASnI_{0.1}Br_{2.9} (300K)						
Sn	50(1)	50(1)	50(1)	0(1)	0(1)	0(1)
I	52(1)	112(2)	114(2)	-5(1)	-4(1)	12(2)
Br	52(1)	112(2)	114(2)	-5(1)	-4(1)	12(2)
FASnBr₃ (290K)						
Sn	47(1)	47(1)	47(1)	1(1)	1(1)	-1(1)
Br	46(1)	106(1)	119(1)	5(1)	-2(1)	-8(1)

The anisotropic displacement factor exponent takes the form: $-2\pi^2[h^2a^{*2}U_{11} + \dots + 2hka^*b^*U_{12}]$.

Table S4: Selected interatomic distances (Å) for compounds in the $\text{FASnI}_{3-x}\text{Br}_x$ ($x = 0 - 3$) family with estimated standard deviations in parenthesis. The temperature of each data collection is also listed.

Label	Distance
	FASnI₃ (295K)
Sn-I	3.15320(15)
	FASnI_{2.6}Br_{0.4} (295K)
Sn-I/Br	3.15495(10)
	FASnI_{2.3}Br_{0.7} (295K)
Sn-I/Br	3.14120(10)
	FASnI_{2.1}Br_{0.9} (295K)
Sn-I/Br	3.1263(3)
	FASnI_{1.9}Br_{1.1} (295K)
Sn-I/Br	3.12245(5)
	FASnI_{1.1}Br_{1.9} (295K)
Sn-I/Br	3.06770(10)
	FASnI_{0.7}Br_{2.3} (295K)
Sn-I/Br	3.04575(10)
	FASnI_{0.4}Br_{2.6} (295K)
Sn-I/Br	3.02215(10)
	FASnI_{0.4}Br_{2.6} (295K)
Sn-I	2.681(17)
Sn-I	3.332(17)
Sn-Br	2.778(7)
Sn-Br	3.234(7)
	FASnI_{0.1}Br_{2.9} (300K)
Sn-I	2.91(6)
Sn-I	3.22(5)
Sn-Br	2.733(2)
Sn-Br	3.307(3)
	FASnBr₃ (290K)
Sn-Br	2.7164(10)

Table S5: Average* atomic percentages based on scanning electron microscopy coupled with energy dispersive X-ray spectroscopy (SEM-EDS) with estimated standard deviations. The composition was then estimated normalizing the atomic percentages to that of Sn.

Compound	Sn (At. %)	I (At. %)	Br (At%)	Average Composition
FASnI ₃	25.6 ± 0.46	74.34 ± 0.45	-----	FASnI _{2.91}
FASnI _{2.6} Br _{0.4}	24.3 ± 0.96	69.72 ± 0.50	5.98 ± 0.89	FASnI _{2.76} Br _{0.24}
FASnI _{2.3} Br _{0.7}	25.2 ± 1.32	61.97 ± 3.6	12.8 ± 2.85	FASnI _{2.48} Br _{0.51}
FASnI _{2.1} Br _{0.9}	26.3 ± 0.45	45.8 ± 0.90	27.8 ± 0.81	FASnI _{1.74} Br _{1.06}
FASnI _{1.9} Br _{1.1}	25.7 ± 0.41	46 ± 1.1	28 ± 1.4	FASnI _{1.80} Br _{1.10}
FASnI _{1.1} Br _{1.9}	26.1 ± 0.99	30.9 ± 0.30	43 ± 1.3	FASnI _{1.18} Br _{1.65}
FASnI _{0.7} Br _{2.3}	26 ± 1.8	13.6 ± 0.44	61 ± 1.9	FASnI _{0.53} Br _{2.3}
FASnI _{0.4} Br _{2.6}	26 ± 2.3	9.6 ± 0.95	64 ± 3.3	FASnI _{0.36} Br _{2.43}
FASnI _{0.1} Br _{2.9}	24 ± 1.4	4.0 ± 0.24	72 ± 1.6	FASnI _{0.16} Br _{2.96}
FASnBr ₃	26.2 ± 0.64	-----	73.8 ± 0.64	FASnBr _{2.82}

*The average is compiled across 3-5 independent spectra

Table S6: Crystallographic information and refinement parameters for (NH₄)₂SnBr₆ and SnI₄ impurity phases.

Formula	(NH ₄) ₂ SnBr ₆	SnI ₄
Formula weight (g/mol)	626.17	626.29
Temperature (K)	295	295
Wavelength (Å)	0.71073	0.71073
Crystal system	Cubic	Cubic
Space group	<i>Fm</i> $\bar{3}$ <i>m</i>	<i>Pa</i> $\bar{3}$
<i>a</i> / <i>b</i> / <i>c</i> (Å)	10.64150(10)	12.2493(4)
Volume (Å ³)	1205.06(3)	1837.95
<i>Z</i>	4	8
ρ_{calc} (g/cm ³)	3.451	4.527
μ (mm ⁻¹)	21.957	16.118
Independent reflections	206 [R _{int} = 0.0671]	905 [R _{int} = 0.0131]
Completeness to $\theta = 25.242^\circ$	100%	100%
Data / restraints / parameters	206 / 0 / 6	905 / 0 / 16
Goodness-of-fit	1.200	1.084
Final R indices [I > 2 σ (I)]	R _{obs} = 0.0258, wR _{obs} = 0.0687	R _{obs} = 0.0266, wR _{obs} = 0.0568
R indices [all data]	R _{all} = 0.0310, wR _{all} = 0.0702	R _{all} = 0.0436, wR _{all} = 0.0618
Largest diff. peak and hole	0.832 and -0.567 e \cdot Å ⁻³	0.505 and -0.560 e \cdot Å ⁻³

$$R = \frac{\sum ||F_o| - |F_c||}{\sum |F_o|}, wR = \frac{\{\sum [w(|F_o|^2 - |F_c|^2)^2] / \sum [w(|F_o|^4)]\}^{1/2}}{\text{and}} = 1 / [\sigma^2(F_o^2) + (0.0167P)^2 + 2.7543P] \text{ where } P = (F_o^2 + 2F_c^2) / 3$$

Note S3: The crystallographic refinement and unit cell parameters compare well with previous reports of these two compounds in the literature.^{7, 8}

Table S7: Crystallographic information and refinement parameters for FASnI_{0.4}Br_{2.6} at 260K with estimated standard deviations in parenthesis

Refined Formula	FASnI _{0.5} Br _{2.5} *
Formula weight (g/mol)	420.7
Temperature (K)	260
Wavelength (Å)	0.56083
Crystal system	Cubic
Space group	<i>Pa</i> $\bar{3}$
<i>a/b/c</i> (Å)	12.018(4)
Volume (Å ³)	1735.9(10)
<i>Z</i>	8
ρ_{calc} (g/cm ³)	3.2197
μ (mm ⁻¹)	8.624
Independent reflections	302 [<i>R</i> _{int} = 0.0931]
Completeness to $\theta = 26.48^\circ$	98
Data / restraints / parameters	302 / 2 / 28
Goodness-of-fit	1.59
Final <i>R</i> indices [<i>I</i> > 2 σ (<i>I</i>)]	<i>R</i> _{obs} = 0.0544, <i>wR</i> _{obs} = 0.1039
<i>R</i> indices [all data]	<i>R</i> _{all} = 0.0932, <i>wR</i> _{all} = 0.1193
Largest diff. peak and hole	1.28 and -0.64 e \cdot Å ⁻³

$R = \Sigma||F_o| - |F_c|| / \Sigma|F_o|$, $wR = \{\Sigma[w(|F_o|^2 - |F_c|^2)^2] / \Sigma[w(|F_o|^4)]\}^{1/2}$ and $= 1 / [\sigma^2(F_o^2) + (0.0167P)^2 + 2.7543P]$ where $P = (F_o^2 + 2F_c^2) / 3$

* The refined formula differs from the true formula determined based on room temperature single crystal diffraction on the same crystal. For simplicity the formula FASnI_{0.4}Br_{2.6} is adopted in the discussion of the material.

Table S8: PL peak position and peak shift under 1 sun light illumination

	0 Hours	1 Hour	3 Hours	6 Hours	24 Hours
FASnI₃ Peak Position (nm)	875	869	861	859	855
FASnI₃ Peak Shift (nm)	-----	6	14	16	20
FASnI_{2.6}Br_{0.4} Peak Position (nm)	841	830	830	828	823
FASnI_{2.6}Br_{0.4} Peak Shift (nm)	-----	11	11	13	18
FASnI_{2.3}Br_{0.7} Peak Position (nm)	788	785	790	790	790
FASnI_{2.3}Br_{0.7} Peak Shift (nm)	-----	3	2	2	2
FASnI_{1.9}I_{1.1} Peak Position	732	734	741	746	750
FASnI_{1.9}Br_{1.1} Peak Shift (nm)	-----	2	9	14	18

Table S9: The Full Width at Half Maximum (FWHM) of PL spectra for $\text{FASnI}_{2.3}\text{Br}_{0.7}$ thin film. by increasing the illumination time. The FWHM is increased under longer illumination time.

Illumination time at 1sun (hours)	FWHM of PL spectra for $\text{FASnI}_{2.3}\text{Br}_{0.7}$ thin films (nm)
0	62
1	70
3	75
6	79
24	86

References:

- (1) Kortüm, G.; Braun, W.; Herzog, G. Principles and Techniques of Diffuse-Reflectance Spectroscopy. In *Angewandte Chemie International Edition in English*, 1963; Vol. 2, pp 333-341.
- (2) Farrow, C. L.; Juhas, P.; Liu, J. W.; Bryndin, D.; Božin, E. S.; Bloch, J.; Proffen, T.; Billinge, S. J. L. PDFfit2 and PDFgui: computer programs for studying nanostructure in crystals. *Journal of Physics: Condensed Matter* **2007**, *19* (33), 335219. DOI: 10.1088/0953-8984/19/33/335219.
- (3) Zacharias, M.; Volonakis, G.; Giustino, F.; Even, J. Anharmonic electron-phonon coupling in ultrasoft and locally disordered perovskites. *npj Computational Materials* **2023**, *9* (1), 153. DOI: 10.1038/s41524-023-01089-2.
- (4) Zhao, X.-G.; Dalpian, G. M.; Wang, Z.; Zunger, A. Polymorphous nature of cubic halide perovskites. *Physical Review B* **2020**, *101* (15), 155137. DOI: 10.1103/PhysRevB.101.155137.
- (5) Popescu, V.; Zunger, A. Extracting E versus k effective band structure from supercell calculations on alloys and impurities. *Physical Review B* **2012**, *85* (8), 085201. DOI: 10.1103/PhysRevB.85.085201.
- (6) Zacharias, M.; Giustino, F. Theory of the special displacement method for electronic structure calculations at finite temperature. *Physical Review Research* **2020**, *2* (1), 013357. DOI: 10.1103/PhysRevResearch.2.013357.
- (7) Ketelaar, J. A. A.; Rietdijk, A. A.; Van Staveren, C. H. Die Kristallstruktur von Ammonium-, Kalium-, Rubidium- und Cäsiumstannibromid. *Recueil des Travaux Chimiques des Pays-Bas* **1937**, *56* (9), 907-908. DOI: 10.1002/recl.19370560913.
- (8) Reuter, H.; Pawlak, R. Zinnhalogenverbindungen. II. Die Molekül- und Kristallstrukturen von Zinn(IV)-bromid und -iodid. *Zeitschrift für Kristallographie - Crystalline Materials* **2001**, *216* (1), 34-38. DOI: doi:10.1524/zkri.216.1.34.18992 (accessed 2023-06-07).