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From 2D to 1D Electronic Dimensionality in Halide Perovskites with Stepped and Flat Layers Using Propylammonium as a Spacer

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Abstract

Two-dimensional (2D) hybrid halide perovskites are promising in optoelectronic applications, particularly solar cells and light emitting devices (LEDs), and for their increased stability compared to 3D perovskites. Here, we report a new series of structures using propylammonium (PA⁺) which results in a series of Ruddlesden-Popper (RP) structures with the formula (PA)₂(MA)_{n-1}Pb_nI_{3n+1} (n = 3, 4) and a new homologous series of “step-like” (SL) structures where the PbI₆ octahedra connect in a corner- and face-sharing motif with the general formula (PA)_{2m+4}(MA)_{m-2}Pb_{2m+1}I_{7m+4} (m = 2, 3, 4). The RP structures show a blue-shift in bandgap for decreasing n (1.90 eV for n = 4 and 2.03 eV for n = 3) while the SL structures have an even greater blue-shift (2.53 eV for m = 4, 2.74 eV for m = 3, and 2.93 eV for m = 2). DFT calculations show that, while the RP structures are electronically 2D quantum wells, the SL structures are electronically 1D quantum wires with chains of corner-sharing octahedra “insulated” by blocks of face-sharing octahedra. Dark measurements for RP crystals show high resistivity perpendicular to the layers (10¹¹ Ω·cm) but a lower resistivity parallel to them (10⁷ Ω·cm). The SL crystals have varying resistivity in all three directions, confirming both RP and SL crystals’ utility as anisotropic electronic materials. The RP structures show strong photoresponse, whereas the SL materials exhibit resistivity trends that are dominated by ionic

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3 transport and no photoresponse. Solar cells were made with $n = 3$ giving an efficiency of 7.04%
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5 (average $6.28 \pm 0.65\%$) with negligible hysteresis.
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9 Keywords: solar cell, photovoltaic, quantum confinement, light emitting diode, thin films,
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Introduction

Halide inorganic-organic perovskites have shown remarkable capabilities to be used in a wide variety of optoelectronic devices.¹⁻¹¹ Two-dimensional (2D) halide perovskites are of particular interest because of increased stability in air and light, compared to the heavily studied 3D perovskites, while maintaining properties conducive to making high-efficiency optoelectronic devices.¹²⁻²⁰ These materials derive from the 3D AMX_3 , halide perovskites, in which A^+ must be $CH_3NH_3^+$ (MA^+), $HC(NH_2)_2^+$ (FA^+), or Cs^+ , M^{2+} is generally Pb^{2+} , Sn^{2+} , or Ge^{2+} , and X^- is Cl^- , Br^- , or I^- . When larger hydrophobic cations are used in the synthesis, new phases of perovskites form which show lower dimensionality and significantly improved moisture stability.²¹

Commonly seen are 2D sheets where the 3D perovskite structure is cut along the $\langle 100 \rangle$ plane such as with the most commonly employed cations phenylethylammonium (PEA)^{12, 17, 22} or butylammonium (BA)^{13, 15} among others, which act as spacers between the forming slabs.²³⁻²⁵ These two cases along with other less studied ones²⁶ use monoamines to form the Ruddlesden-Popper (RP) perovskites with the general formula $(A')_2A_{n-1}M_nX_{3n+1}$ (in which A' is the large spacing cation).²⁷ Here, n refers to the thickness of the layers in units of $[MX_{6/2}]^-$ octahedra. Other types of $\langle 100 \rangle$ -oriented perovskites include Dion-Jacobson (DJ) perovskites using certain diamines with the formula $(A')A_{n-1}M_nX_{3n+1}$,²⁸ alternating cations in the interlayer space (ACI) with the formula $(A')_2A_{n-1}M_nX_{3n+1}$,²⁹⁻³⁰ and alkyl diammonium based with the formula $(H_3N(CH_2)_nNH_3)A_{n-1}M_nX_{3n+1}$.³¹ Cases where the cut is along the $\langle 110 \rangle$ plane have been documented as well,^{25, 32-37} such as for $(NH_2C(I)=NH_2)_2$, where the organic I atom interacts strongly with the I atoms at the edges of the inorganic layer along the $\langle 110 \rangle$ plane, thus stabilizing this uncommon structural perovskite type.³⁸⁻³⁹ A few examples also exist of perovskites being cleaved along the $\langle 111 \rangle$ plane, for example with the trivalent metals in metal

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3 deficient $A_3M_2X_9$ perovskites.³⁹⁻⁴⁰ The formulas for each of the structure types are shown in a
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5 hierarchal manner in Scheme 1 using the variables n, m, and q to indicate the different
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7 orientation of the octahedra. All these 2D materials are semiconductors that form natural
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9 quantum wells between the alternating organic and inorganic layers, forcing spatial and dielectric
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11 confinement of electron-hole pairs within the 2D perovskite plane.²⁵ These materials can be
12
13 chemically tuned to give specific layer thickness corresponding to n in the general chemical
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15 formula and can attain different electronic states and bandgaps.⁴¹ This allows further
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17 optimization for optoelectronic applications including solar cells and light emitting diodes.^{13, 15,}
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24 Certain intermediate size cations, that are too large to form a 3D perovskite and too small
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26 to intercalate between 2D perovskite sheets, can lead to unique structure types. Some of these
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28 cations lead to structures which maintain 3D connectivity. For example, in the case of the tin
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30 iodide system, several 3D tin-based hexagonal perovskites with the formula $(A')SnI_3$ have been
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32 reported in which the octahedra connect in both the typical corner-sharing fashion as well as a
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34 face-sharing fashion.⁴⁴ This is done by using EA^+ ($CH_3CH_2NH_3^+$), GA^+ ($C(NH_2)_3^+$), ACA^+
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36 ($CH_3C(NH_2)_2$), and IM^+ ($C_3N_2H_5$) as spacing cations. These are not proper perovskites because
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38 they do not feature exclusively corner-sharing octahedra and in order to distinguish them from
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40 perovskites, they are referred to as perovskitoids.⁴⁴ Other examples of 3D structure types with
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42 intermediate cations include the so-called “hollow” perovskites in which the cation replaces
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44 metal octahedra while maintaining corner-sharing 3D connectivity. A disordered structure can be
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46 stabilized by shorter diamines such as in $(en)MAMI_3$ ($M = Sn, Pb$)⁴⁵⁻⁴⁶ and $(PN/TN)FASnI_3$ (PN
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48 = propylenediammonium; TN = trimethylenediammonium)⁴⁷ while an ordered structure is seen
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54 with alkanolamines such as ethanolamine.⁴⁸ The same tendencies toward the disruption of the
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3 inorganic lattice can be seen in the 2D materials.⁴⁹⁻⁵⁰ For example, materials such as (PPA)₃Pb₂I₇
4 and (PBA)₃Pb₂I₇ (PPA⁺ = C₆H₅(CH₂)₃NH₃⁺ and PBA⁺ = C₆H₅(CH₂)₄NH₃⁺), whose alkyl chain
5 length in these phenylalkylammonium cations varies, can also induce the formation of structures
6 with mixed edge-, face-, and/or corner-sharing.⁵¹ These types of materials are stabilized using
7 intermediate cations but are less explored. Furthermore, 1D perovskitoids derived from the
8 BaNiO₃ structure type have fully face-sharing connectivity⁴⁴ while other 1D halide materials
9 have mixed-sharing connectivity as well⁵² such as (C₆H₅CH₂NH₃)₄Pb₅I₁₄·2H₂O which has
10 corner- and edge-sharing connectivity.⁵³ The shortest spacer length in the RP family which has
11 been studied crystallographically is the butylammonium cation (four carbon chain length).
12 Although one expects longer molecules to also stabilize this 2D halide perovskite family by
13 expanding the inorganic layer spacing,⁵⁴ it is interesting to consider how short the spacer can get
14 before we observe some sort of structural instability. Such destabilization could arise for
15 example from the inorganic layers being pulled too close together and steric repulsion becoming
16 dominant.

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35 Here, we present a new series of materials using propylammonium (PA) chosen
36 specifically because it is the shortest spacer cation among the n-alkylammonium family (three
37 carbon chain length) that can stabilize a perovskite in order to test the limits of phase formation
38 in the RP 2D (PA)₂(MA)_{n-1}Pb_nI_{3n+1} perovskite family. We find that the “n = 1” and “n = 2”
39 members cannot be formed, but instead a new series of step-like (SL) structures forms. In this
40 series, the parent “n = 2” structure, cleaved already along the <100> plane, is further cleaved
41 along the <110> plane, giving the general formula (PA)_{2m+4}(MA)_{m-2}Pb_{2m+1}I_{7m+4}. These structures
42 have corner-sharing as well as face-sharing PbI₆ octahedra, but is distinct from the previously
43 reported (PA)₃Pb₂I₇ structure which also has mixed-sharing connectivity.⁵⁵ For n > 2 the RP
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3 materials are stabilized. For high m ($m = 4$), the structure is most like that of the RP structures
4 while $m = 2$ deviates significantly because of its increased face-sharing connectivity. Thus, this
5 system allows us to carefully tune the structure and compare it to the RP $n = 3$ and $n = 4$
6 structures using the same spacer, giving us the ability to test the effects of connectivity in a
7 logical, controlled manner. The optical properties of the RP materials are blue-shifted relative to
8 MAPbI₃, but for the new SL structures, the band gap is further blue-shifted with increasing
9 bandgap from $m = 4$ to 2, allowing for even further tuning of the bandgap. Band structure
10 calculations show dispersive bands and suggest the SL materials are electronically 1D quantum
11 wires while the RP materials are electronically 2D quantum wells. The RP materials exhibit a
12 strong photoresponse. Because of the good photoresponse of the RP $n = 3$ material, it was
13 employed in photovoltaic devices. By utilizing our previously studied “hotcasting” technique⁵⁶
14 along with so-called solvent engineering,⁵⁷ a preliminary assessment gave an efficiency of 7.04%
15 (average of $6.28 \pm 0.65\%$) was obtained with limited hysteresis and practically no current
16 leakage.

37 Experimental

38 Synthesis.

39 See Table S1 for a summary of synthetic procedures.

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42 **(PA)₈Pb₅I₁₈ ($m = 2$).** PbO (2.232 g, 10 mmol) was dissolved in a mixture of 10.0 mL aqueous HI
43 and 1.7 mL aqueous H₃PO₂ by heating at 190 °C under constant magnetic stirring for 15 min. In
44 a separate vial, 5 mL aqueous HI was cooled in an ice bath. Then, PA (1.316 mL, 16 mmol) was
45 added slowly and allowed 5 min to fully neutralize. To the hot bright yellow solution was added
46 the neutralized PA. The resulting yellow solution was stirred for 5 min. Then, it was allowed to
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3 cool to room temperature and recrystallize for 45 min, giving yellow needles. The needles were
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5 dried through vacuum filtration for 30 min before being dried under vacuum overnight. Yield
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7 4.6979 g (61.80% based on mol Pb).

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10 **(PA)₁₀(MA)Pb₇I₂₅ (m = 3).** PbO (2.232 g, 10 mmol) was dissolved in a mixture of 8.0 mL
11
12 aqueous HI and 1.7 mL aqueous H₃PO₂ by heating at 200 °C under constant magnetic stirring for
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14 15 min. To this was added MACl (196.9 mg, 2.91 mmol), which formed a black precipitate
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16 which was allowed to redissolve. In a separate vial, 2 mL aqueous HI was cooled in an ice bath.
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18 Then, PA (1.028 mL, 12.51 mmol) was added slowly and allowed at least 5 min to fully
19
20 neutralize. To the hot bright yellow solution was added the neutralized PA. The resulting yellow
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22 solution was stirred until it began to boil. Then, it was allowed to cool to room temperature and
23
24 recrystallize overnight, giving orange needles. The plates were dried through vacuum filtration
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26 for 30 min before being dried under vacuum overnight. XRD shows a mixture of m = 2, m = 3,
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28 and a minor phase, (PA)₃Pb₂I₇.

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33 **(PA)₁₂(MA)₂Pb₉I₃₂ (m = 4).** PbO (2.232 g, 10 mmol) was dissolved in a mixture of 10.0 mL
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35 aqueous HI and 1.7 mL aqueous H₃PO₂ by heating at 200 °C under constant magnetic stirring for
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37 15 min. To this was added MACl (338 mg, 5 mmol), which formed a black precipitate which
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39 was allowed to redissolve. In a separate vial, 2 mL aqueous HI was cooled in an ice bath. Then,
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41 PA (822 μL, 10 mmol) was added slowly and allowed at least 5 min to fully neutralize. To the
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43 hot bright yellow solution was added the neutralized PA. The resulting yellow solution was
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45 stirred until it began to boil. Then, it was allowed to cool to room temperature and recrystallize
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47 overnight, giving red elongated plates. The plates were dried through vacuum filtration for 30
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49 min before being dried under vacuum overnight. Yield 1.8494 g (24.81% based on total Pb).
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3 **(PA)₂(MA)₂Pb₃I₁₀ (n = 3).** PbO (2.232 g, 10 mmol) was dissolved in a mixture of 10.0 mL
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5 aqueous HI and 1.7 mL aqueous H₃PO₂ by heating at 190 °C under constant magnetic stirring for
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7 15 min. To this was added MACl (450 mg, 6.67 mmol), which formed a black precipitate which
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9 was allowed to redissolve. In a separate vial, 5 mL aqueous HI was cooled in an ice bath. Then,
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11 PA (548 μL, 6.67 mmol) was added slowly and allowed at least 5 min to fully neutralize. To the
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13 hot bright yellow solution was added the neutralized PA. The resulting yellow solution was
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15 stirred for 5 min. Then, it was allowed to cool to room temperature and recrystallize for 1.5 hr,
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17 giving dark red plates. The plates were dried through vacuum filtration for 30 min before being
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19 dried under vacuum overnight. Yield 2.4019 g (34.73% based on total Pb).
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24 **(PA)₂(MA)₃Pb₄I₁₃ (n = 4).** PbO (2.232 g, 10 mmol) was dissolved in a mixture of 10.0 mL
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26 aqueous HI and 1.7 mL aqueous H₃PO₂ by heating at 190 °C under constant magnetic stirring for
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28 15 min. To this was added MACl (507 mg, 7.5 mmol), which formed a black precipitate which
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30 was allowed to redissolve. In a separate vial, 3 mL aqueous HI was cooled in an ice bath. Then,
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32 PA (411 μL, 5.0 mmol) was added slowly and allowed at least 5 min to fully neutralize. To the
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34 hot bright yellow solution was added the neutralized PA. The resulting yellow solution was
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36 stirred for 5 min. Then, it was allowed to cool to room temperature and recrystallize for 1.5 hr,
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38 giving black plates. The plates were dried through vacuum filtration for 30 min before being
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40 dried under vacuum overnight. XRD shows some impurities such as n = 3 and MAPbI₃. Yield
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42 1.4588 g (21.70% based on total Pb).
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46 **Materials Characterization**

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49 High resolution synchrotron powder X-ray diffraction (SXRD) data were collected at
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51 beamline 11-BM-B of the Advanced Photon Source (APS), Argonne National Laboratory using
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3 $\lambda = 0.412736 \text{ \AA}$. Discrete detectors covering an angular range from -4 to $2^\circ 2\theta$ were scanned over
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5 a $26^\circ 2\theta$ range, with data points collected every $0.001^\circ 2\theta$ and a scan speed of $0.1^\circ/\text{s}$.
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8 Single-crystal X-ray diffraction experiments were performed using a STOE IPDS II or
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10 IPDS 2T diffractometer with Mo $K\alpha$ radiation ($\lambda = 0.71073 \text{ \AA}$) and operating at 50 kV and 40
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12 mA. Integration and numerical absorption corrections were performed using the X-AREA, X-
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14 RED, and X-SHAPE programs. The structures were solved by charge flipping and refined by
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16 full-matrix least-squares on F2 using the Jana2006 package.⁵⁸ The PLATON⁵⁹ software was used
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18 to identify the twinning domains and validate the space groups of the compounds.
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22 A Shimadzu UV-3600 PC double-beam, double-monochromator spectrophotometer was
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24 used to acquire room-temperature optical diffuse reflectance spectra of the powdered samples in
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26 the range of 200–2500 nm. BaSO_4 was used as a non-absorbing reflectance reference, and
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28 reflectance data were converted to absorbance data via Kubelka–Munk transformation. Both
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30 bandgaps and exciton energies were extracted from the data. The exciton energies were
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32 estimated based on the position of the exciton peak residing below the bandgap. The linear
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34 portion of the curve above the exciton was used to extract the bandgap based on its intersection
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36 with the x-axis. Low-energy impurity peaks, appearing as tails in the spectra, were ignored.
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41 First-principles calculations are based on density functional theory (DFT) as implemented
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43 in the SIESTA package.⁶⁰⁻⁶¹ Calculations have been carried out on experimental structures with
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45 the GGA functional in the revPBE form.⁶² Core electrons are described with Troullier-Martins
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47 pseudopotentials.⁶³ The valence wavefunctions are developed over double- ζ polarized basis set of
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49 finite-range numerical pseudoatomic orbitals.⁶⁴ In our calculations, spin-orbit coupling is taken
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51 into account through the on-site approximation as proposed by Fernández-Seivane *et al.*⁶⁵ In all
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53 cases, an energy cutoff of 150 Ry for real-space mesh size has been used.
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Current-voltage (I-V) curves were measured at room temperature in air using a Keithley 6517b picoammeter/voltage supply under -10 to 10 V bias via a two-probe method. Devices were made using single crystals of the compounds. Electrical contacts were applied through 100 μm copper wires adhered to the crystal specimens through colloidal graphite paste.

Measurements were made on single crystals with a specific direction chosen based on the faces of the crystals and correlated using BFDH morphology simulations by the *Mercury* software.⁶⁶

The devices were put inside a guarded dark box for dark measurements. Additionally, they were measured under a white light source with a power setting of 7 W (Taotronics TT-DL11).

Resistivity was calculated using the equation $\rho = R * \frac{A}{l}$ where ρ is resistivity, R is resistance calculated by the slope of the I-V curve collected above, and A and l are the cross-sectional area of the crystal and the length from one contact to the other. It was assumed that the contact resistance was similar for each crystal.

Thin Film Characterization

Thin films were prepared on glass substrates. XRD measurements were carried out on a Rigaku MiniFlex600 X-ray diffractometer (Cu $K\alpha$ radiation, $\lambda = 1.5406 \text{ \AA}$) operating at 40 kV and 15 mA. GIWAXS measurements were performed at Beamline 8-ID-E of the Advanced Photon Source at Argonne National Laboratory. Samples prepared on glass substrates were exposed to an X-ray beam ($\lambda = 1.6868 \text{ \AA}$) at an incident angle of 0.15° for 1 s, and the scattered light was collected by a Pilatus 1 M pixel array detector at 204 mm from the sample. The GIXSGUI program was used to plot images of the patterns.⁶⁷

Solar Cell Device Fabrication

The ITO-coated glass substrates (TEC7, 2.2 mm, Hartford Glass Co. Inc.) were cleaned by sequential sonication in aqueous detergent, deionized water, acetone, and isopropyl alcohol

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3 for 10 min each, followed by a 3 min oxygen plasma treatment. A thin layer of PEDOT:PSS was
4 deposited on the precleaned ITO substrates by spin-coating at 6000 rpm for 30 s and annealed at
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6 150 °C for 30 min in air. The substrates were then transferred to an argon-filled glovebox to
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8 complete the rest of the device fabrication. Solutions of $(\text{PA})_2(\text{MA})_2\text{Pb}_3\text{I}_{10}$ were prepared by
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10 dissolving 60 mg of the oven-dried crystals in 100 μL of DMF and 300 μL of DMSO solvents.
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12 Different volumes of DMSO were incorporated into the total 400 μL when optimizing solvent
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14 choice (0, 100, 200, 300, and 4000). The perovskite layer was deposited by hot-casting 75 μL of
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16 the as-prepared room-temperature solution on the ITO/PEDOT:PSS substrates heated to 110°C
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18 for 20 s at 5000 rpm. Within 6-7 s of spin coating, the films turned from yellow to brown. The
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20 PC_{61}BM (Sigma Aldrich) layer was deposited on the perovskite film from a 30 mg/mL PC_{61}BM
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22 solution in CB at 1000 rpm for 30 s. Finally, 100 nm of Al was thermally evaporated through a
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24 shadow mask at a pressure of $\sim 1 \times 10^{-6}$ Torr. Half of the area was encapsulated by epoxy
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26 (Epoxy Technology) and UV-cured for 30 min. The active area of the device was 0.03 cm^2 .
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33 **Solar Cell Device Characterization**

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35 The current density versus voltage (J–V) characteristics were collected in air using a
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37 Keithley 2400 source meter under simulated AM 1.5G irradiation (100 mW/cm^2) generated by a
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39 standard solar simulator (Abet Technologies). The light intensity was calibrated by using an
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41 NREL-certified monocrystalline Si reference cell to reduce the spectral mismatch.
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45 Stability characterization was performed on a device using 75% DMSO for the precursor
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47 solvent. The device was made with the same architecture used previously and encapsulated with
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49 the same method. The device was then held under 1 solar sun and measured periodically.
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53 **Results and Discussion**

Materials Synthesis

The materials were synthesized by first dissolving lead oxide (PbO) and methylammonium chloride (MACl) in boiling hydroiodic acid (HI) and hydrophosphorous acid (H_3PO_2). Then, propylamine (PA), neutralized by HI, was added to the solution. The reagents were originally added in ratios corresponding to the stoichiometry for RP perovskites for different n values using the general formula $(\text{A}')_2\text{A}_{n-1}\text{M}_n\text{X}_{3n+1}$. Because of the high solubility of the products, concentrations were kept as high as possible (≥ 1 M). Once dissolved, the solutions were cooled to room temperature by removing the solutions from the hot plate, leading to the precipitation of the materials within minutes. Note that the crystals must be completely dried within hours of precipitation because they can undergo a high rate of disproportionation. As seen in Figure S2, over days, other n values began to appear in the PXRD for $(\text{PA})_2(\text{MA})_2\text{Pb}_3\text{I}_{10}$ ($n = 3$), and even within hours, a red tint, indicative of lower n structures, was seen on the edges of the crystals. For $n = 3$ and $(\text{PA})_2(\text{MA})_3\text{Pb}_4\text{I}_{13}$ ($n = 4$), plates colored dark red and black, respectively, precipitated within minutes (Figure 1). For $n = 4$, however, it was fairly common to have impurities of other n members while $n = 3$ was more likely to be pure. For $n < 3$, needles formed instead of plates. For the experimentally stoichiometric “ $(\text{PA})_2(\text{MA})\text{Pb}_2\text{I}_7$ ” samples, red flat needles formed instead and for “ $(\text{PA})_2\text{PbI}_4$ ” yellow needles formed. The “ $(\text{PA})_2\text{PbI}_4$ ” sample matched the calculated PXRD for a previously reported material by Billing and Lemmerer, $(\text{PA})_8\text{Pb}_5\text{I}_{18}$,⁶⁸ but the “ $(\text{PA})_2(\text{MA})\text{Pb}_2\text{I}_7$ ” material did not match any known phase. After resolving the crystal structure for this material, it was revealed that the so-called “ $(\text{PA})_2\text{PbI}_4$ ” and “ $(\text{PA})_2(\text{MA})\text{Pb}_2\text{I}_7$ ” materials were part of a homologous series of SL materials with the general formula $(\text{PA})_{2m+4}(\text{MA})_{m-2}\text{Pb}_{2m+1}\text{I}_{7m+4}$.

To further probe this series for new phases, syntheses were performed using stoichiometric ratios for values of m from 2 to 4. Unexpectedly, doing so led to the precipitation of the yellow $(\text{PA})_8\text{Pb}_5\text{I}_{18}$ ($m = 2$) (Pb:I is 1:3.60) phase in all cases. Using the stoichiometry for “ $(\text{PA})_2(\text{MA})\text{Pb}_2\text{I}_7$ ” (Pb:I is 1:3.50) was the most reliable way to precipitate the red $(\text{PA})_{12}(\text{MA})_2\text{Pb}_9\text{I}_{32}$ ($m = 4$, Pb:I is 1:3.56). When using an intermediate ratio of reagents between the stoichiometry for “ $(\text{PA}_3)_2(\text{MA})\text{Pb}_2\text{I}_7$ ” and $(\text{PA})_{12}(\text{MA})_2\text{Pb}_9\text{I}_{32}$, a mixture of three phases formed: yellow needles identified as $m = 2$, orange needles identified as $(\text{PA})_{11}(\text{MA})\text{Pb}_7\text{I}_{25}$ ($m = 3$, Pb:I is 1:3.57), and white needles identified as the MA-free $(\text{PA})_3\text{Pb}_2\text{I}_7$. The third phase was an impurity, though it was previously reported as the primary product under synthetic conditions similar to those used here to synthesize $m = 2$.⁵⁵ No instances of $m > 4$ were seen as the stoichiometry further approached that of “ $(\text{PA})_2(\text{MA})\text{Pb}_2\text{I}_7$ ”. Furthermore, using limiting or excess of a single reagent simply led to mixtures of the title phases and no new phases were detected.

The SL $(\text{PA})_{2m+4}(\text{MA})_{m-2}\text{Pb}_{2m+1}\text{I}_{7m+4}$ materials are derived from the hypothetical RP “ $n = 2$ ” structure. In this case, when $m = \infty$, the formula collapses to $(\text{PA})_2(\text{MA})\text{Pb}_2\text{I}_7$, which is the equivalent to the RP $(\text{PA})_2(\text{MA})_{n-1}\text{Pb}_n\text{I}_{3n+1}$ “ $n = 2$ ” member. All the SL structures begin to deviate from the RP series because of an increasing ratio of $\text{PA}^+:\text{MA}^+$ from 2:1 for “ $n = 2$ ” to infinity for $m = 2$ and a slightly decreasing ratio of Pb:I from 1:3.5 to 1:3.6.

Description of Crystal Structures.

Step-like Structures. Using propylammonium as a spacer results in a SL structures instead of the expected “ $n = 1$ ” and “ $n = 2$ ” RP homologous members. The SL structures involve both corner-sharing and face-sharing PbI_6 octahedra, which have been colored blue and pink, respectively, in

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3 Figure 2. These compounds form their own homologous series within the “n = 2” window, which
4 are described by the general formula $(\text{PA})_{2m+4}(\text{MA})_{m-2}\text{Pb}_{2m+1}\text{I}_{7m+4}$ ($m \geq 2$). Having identified this
5 new homology here we can see that the previously reported $m = 2$ compound⁶⁸ is a member
6 along with the $m = 3$ and 4 compounds reported here for the first time. Each of these structures,
7 like the RP perovskites, can be imagined as a derivative of a parent structure. For the RP
8 perovskites, the parent structure is MAPbI_3 , which has been cleaved along the $\langle 100 \rangle$ plane by
9 the stoichiometric addition of the iodide salts of the alkylammonium cations. For the SL
10 structures, however, the parent structure is the hypothetical “n = 2” RP structure which, as
11 mentioned earlier, is essentially MAPbI_3 cleaved along the $\langle 100 \rangle$ plane. The SL structure can
12 then be imagined to be cleaved a second time along the $\langle 110 \rangle$ plane of MAPbI_3 , which is
13 described by the m variable in the formula $(\text{PA})_{2m+4}(\text{MA})_{m-2}\text{Pb}_{2m+1}\text{I}_{7m+4}$. The combination of
14 these two perpendicular cleaving events produces a 1D chain of PbI_6 octahedra with thickness n,
15 which always equals 2, and a width of m, which varies between 2-4. The use of m is based on the
16 nomenclature previously reported for 2D corner-sharing perovskite structures cleaved along
17 $\langle 110 \rangle$.⁶⁹

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19 Looking down the monoclinic b axis shows a cross section of the 1D chains for $m = 2$,
20 seen as the blue corner-sharing octahedra in Figure 2. In the case of $m = 2$, the chains are 2 x 2
21 octahedra. The 1D chain for this series is approximately two PbI_6 octahedra thick ($\sim 12.5 \text{ \AA}$) or
22 $2a'$ in length, (where a' is the ideal cubic perovskite lattice constant) corresponding to $n = 2$
23 thickness. The width for $m = 2, 3$, and 4 is 9.1351 \AA ($2a'/\sqrt{2}$), 13.7718 \AA ($3a'/\sqrt{2}$), and 18.1148 \AA
24 ($4a'/\sqrt{2}$), respectively. Looking down the c axis in Figure 3b gives a side view of the chains,
25 which extend infinitely along the b axis. As m increases from 2 to 4, the pure zigzag connectivity
26 subsides as the chain gains more octahedra and the 1D chains begin to more closely resemble a

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3 perovskite-like structure. The zigzag connectivity is like that of the $\langle 110 \rangle$ -oriented 2D
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5 perovskites with proper corner-sharing connectivity as in $m = 2$ $[\text{NH}_2\text{C}(\text{I})=\text{NH}_2]_2\text{Sn}_2\text{I}_8$.³⁹
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8 The 1D chains in the SL structures are connected by a single face-sharing octahedron, for
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10 which the face-sharing connectivity is at the two opposite corners of these rectangles along the
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12 1D chain. This forms the so-called “steps,” as the rectangles are the flat portion of the steps and
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14 the face-sharing octahedra are the raise in height for each step. In $(\text{PA})_{2m+4}(\text{MA})_{m-2}\text{Pb}_{2m+1}\text{I}_{7m+4}$
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16 the face-sharing octahedra face a different direction than the corner-sharing octahedra with an
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18 interval of one octahedron. The few examples of mixed-connectivity structures seen in the halide
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20 perovskite literature have also seen different patterns within the context of SL structures.
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23 Kamminga et. al. describe a phenylbutylammonium-based material with $n = 1$ and $m = 3$ which
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25 is quite similar to the structures reported here.⁴⁹ Interestingly, the shorter chain
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27 phenylpropylammonium forms a new type of structure with $n = 1$ and $m = 4$, but with the face-
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29 sharing octahedra at corners on the same side of the rectangle cross-section, forming a cis-
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31 orientation. Using a different synthesis, Billing et. al. solved the structure with a
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33 phenylpropylammonium spacer with $n = 1$ and $m = 2$, but this structure has chains of three face-
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35 sharing octahedra which also arrange in a cis pattern.⁷⁰ Additionally, an all-inorganic structure
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37 was reported in for a SnI_6 system using a mixture of Rb^+ and Cs^+ .⁷¹ This appears to be the only
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39 other known multilayered structure with mixed-sharing connectivity.
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44 In this homology the MA^+ always is located within the cages of $2 \times 2 \times 2$ corner-sharing
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46 PbI_6 octahedra. To form cages, the width of the chains must be at least $m = 3$. With each
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48 additional layer, another MA^+ can be incorporated. For $\langle 100 \rangle$ -oriented structures in general, the
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50 spacing amines align themselves in the interlayer space with the amine group facing the
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52 inorganic layers and positioned between the four terminal iodide atoms of four different
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3 octahedra. For the general $\langle 110 \rangle$ -oriented structure, the spacing cations orient themselves in a
4 similar manner, but the four octahedra have their edges facing the interlayer space. In the case of
5 the SL structures, the PA^+ orient themselves at both the $\langle 100 \rangle$ and $\langle 110 \rangle$ cleavage of the 1D
6 chains. There are $2m \text{ PA}^+$ along the $\langle 100 \rangle$ cleavage and 2 along the $\langle 110 \rangle$ cleavage, giving $2m$
7 $+ 2 \text{ PA}^+$ oriented toward the inorganic chain and 2 still unaccounted. These 2 PA^+ are found in
8 the large space near the face-sharing octahedra. This large space exists because the SL structure
9 of the inorganic layers is suboptimal to pack tightly together. The intermediate size of the PA^+
10 cations allows them to properly fill up the interlayer spacing. If the cation size were smaller, they
11 may be able to incorporate into the 3D structure in a similar way to MA^+ . Conversely, if the size
12 was a bit larger or just longer such as BA^+ , the interlayer spacing would be too small for all the
13 cations to fit and the structure would be destabilized.

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When attempting to synthesize the $m = 3$ and 4 structures, a minor phase $(\text{PA})_3\text{Pb}_2\text{I}_7$ forms as well (Figure S3).⁵⁵ The structure has also mixed face- and corner-sharing motifs with 1D chains of corner-sharing octahedra cut along the $\langle 100 \rangle$ and $\langle 110 \rangle$ axes, and there is no fully face-sharing octahedron, causing the chains to be at alternating orientations to one another. The $(\text{PA})_3\text{Pb}_2\text{I}_7$ however was only made as an impurity and its study is out of the scope of this paper, so the characterization is not reported here beyond the crystallographic data given in Table 1.

Ruddlesden-Popper Structures. The $n = 3$ and $n = 4$ structures can be classified as Ruddlesden-Popper (RP) materials. Like other RP systems, the $n = 3$ and $n = 4$ structures are fully corner-sharing structures belonging to the formula $(\text{PA})_2(\text{MA})_{n-1}\text{Pb}_n\text{I}_{3n+1}$ but with a considerably contracted stacking repeat length given the short spacer (Figure 3). Crystallographic data is reported in Table 1 and selected bond distances, angles, etc. in Tables S2-16. Like other RP

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3 structures, the structures can be imagined as MAPbI₃ cleaved along the <100> plane by spacing
4 cations, which in this case A' is propylammonium. The PbI₆ octahedra, both terminal and within
5 the layers, experience distortion along all three axes, with the Pb-I-Pb angles ranging from
6 161.77° to 171.28°, similar to other alkylamine-based perovskites.¹³ The n = 3 structure
7 crystallizes in the monoclinic space group *P2₁/a*, as opposed to the n = 3 BA compounds which
8 crystallize in the orthorhombic space group *C2cb* and n = 3 PEA compound which crystallize in
9 the triclinic space group *P1*. The decrease in symmetry for PA n = 3 is caused by the unique
10 alignment of the layers in the structure. In general, RP perovskites have layers shifted by half an
11 octahedral unit length in the layer plane (($\frac{1}{2}$, $\frac{1}{2}$) displacement) so that when looking
12 perpendicular to the layers, the successive layers alternate in position (Figure 3). In the case of
13 the PA system, however, as the layers are brought together in closer proximity, they are not fully
14 shifted and the displacement is closer to ($\frac{1}{4}$, $\frac{1}{4}$), lying in between the stacking sequences of RP
15 and DJ perovskites. A change in the stacking sequence may also occur as a function of
16 temperature for layered perovskites such as (C₅H₁₁NH₃)₂PbI₄.⁷² Different layer alignments are
17 common in 2D halide perovskites when small spacer cations are employed, as seen in the case of
18 GA,²⁹⁻³⁰ in which the layers are ($\frac{1}{2}$, 0) (the ACI perovskite), and for hybrid DJ²⁸ perovskites, in
19 which the layers have no shift (Figure 3c,d). In addition, in the monoclinic setting, the unit cell
20 no longer doubles but instead incorporates only one layer. A similar primitive monoclinic unit
21 cell without cell doubling along the stacking axis was also identified for ([p-
22 FC₆H₅C₂H₄NH₃]₂PbI₄). The reduced point symmetry of the lattice by comparison to RP, DJ, and
23 ACI structures is compensated by the smaller number of atoms in the unit cell.⁷³⁻⁷⁴ Finally, the
24 intermediate-sized propylammonium spacer also results in a relatively short interlayer spacing of
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3 6.03 Å, which is shorter than the width of a PbI_6 in the structure (~ 6.3 Å) and an I-I distance of
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5 only 6.75 Å.
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10 **Optical Properties**

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12 *Optical Absorption.* Freshly dried crystals were used to acquire the optical responses of
13 these materials.⁷⁵ Diffuse reflectance of the bulk polycrystalline powders obtained at room
14 temperature were used to create Kubelka-Munk plots for bandgap determination (Figure 4a).
15 Note that the spectra here contain two features: a bandgap absorption and an excitonic peak at a
16 lower energy. The bandgap was then estimated by the intercept of the linear portion of the
17 spectra with the x-axis, considering only the portion of the spectrum at higher energy than the
18 excitonic peak. Note that strong impurity peaks, likely $n = 1, 2,$ or $3,$ which may have formed on
19 the surfaces of the crystals for the SL structures, are seen as tails toward the low energy end of
20 the spectra. Despite not being able to make the $n = 1$ and $n = 2$ RP structures in bulk, they may
21 be stabilized at the surfaces of the SL compounds, which would influence the optical spectrum.
22 The exciton energy, when possible, was also estimated based on position of the low-energy
23 exciton peak. It should also be noted that the absorption edge extends well beyond the bandgap,
24 as has been seen in previous reports which seemed to depend on the preparation method, in
25 particular when using HI during the synthesis.^{31, 76}
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44 The SL materials show higher bandgap compared to other RP $n = 2$ materials,⁴¹ which
45 reflects the decrease in structural dimensionality, as the perovskite-like connectivity only extends
46 in one dimension, even though the compound remains 2D structurally. Within the homologous
47 series of SL materials, the bandgap increases as m decreases, showing that the width of the
48 quantum wire (and thus its cross-sectional area) plays a key role in the quantum confinement. As
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3 m decreases from 4 to 3 to 2, the bandgap increases from 2.53 eV to 2.74 eV to 2.93 eV,
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5 indicating a further increase in the electronic confinement with decreasing cross-sectional area.
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7 Interestingly, the $m = 2$ structure has a bandgap closer to that of the $\langle 110 \rangle$ -oriented GA $m = 2$
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9 structure (2.49 eV) rather than to BA $n = 2$ (2.17 eV),⁷⁷ revealing a strong structural correlation
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11 between the $\langle 110 \rangle$ -oriented GA and a marked difference with the $\langle 100 \rangle$ -oriented BA, despite
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13 both orientations being present in PA.
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17 As expected, in comparison to the MAPbI₃ bandgap (1.52 eV), the $n = 4$ and $n = 3$
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19 materials were blue-shifted with bandgaps of 1.90 eV and 2.03 eV, respectively. This is because
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21 of increasing quantum and dielectric confinement in the z direction with progressively thinner
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23 perovskite layers. The same trend can be seen from the excitonic peaks, with energies of 1.86 eV
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25 and 2.00 eV.
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28 *Photoluminescence (PL)*. The PL of crystals of the different materials were measured at room
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30 temperature (Figure 4b). The SL structures are again blue-shifted compared to the RP structures
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32 and continue to blue shift with decreasing m . Similar to the optical absorption, $n = 3$ and $n = 4$
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34 were shown to blue shift with decreasing layer thickness. A comparison of the bandgaps and PL
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36 is shown in Figure 4c. A notable difference between the RP and SL structure is the intensity of
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38 the PL peaks, with RP perovskites showing a strong narrow emission and the SL perovskites
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40 exhibiting a weak emission. PL lifetime measurements show that the average lifetime decreases
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42 from 3.10 ns to 2.37 ns to 0.29 ns from $m = 4$ to 3 to 2 (Figure S4). The short lifetimes suggest
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44 that efficient non-radiative decay routes are significant in these materials, dominating that of the
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46 radiative processes. Based on DFT calculations in the next section, it appears that these materials
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48 have indirect bandgaps, suggesting that the PL is a result of a trap-assisted process not directly
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50 produced from the bandgap, leading to weak emissions. This hypothesis is also consistent with
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3 the broadening of the PL peaks down to 1.8 eV, as a broad number of states beyond the bandgap
4 can participate in these processes.
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10 **Electronic Properties.**

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12 DFT electronic structure calculations were performed on each of these materials (Figure
13 5). The SL materials have different electronic structure with significantly less dispersive bands
14 than RP materials. Using the $m = 2$ member as an example, the bands show some dispersion
15 parallel to the 1D chains of corner-sharing PbI_6 octahedra, though less so compared to the RP
16 phases. This is because the 1D corner-sharing chains are similar to the corner-sharing in the RP
17 perovskite derivatives, while the face-sharing connections in the structure along the layer seem to
18 weaken the hybridization of electronic atomic states close to the bandgap. This can be most
19 readily visualized by the partial charge densities computed at the VBM and CBM in Figure 5,
20 where both the intralayer face-sharing and the interlayer directions lead to a localization of the
21 electron densities. As seen by the VBM of $m = 2$, the face-sharing octahedra have negligible
22 electron density, as the main fraction of the electron density localized on the corner-sharing
23 octahedra. Based on this result, we can conclude that the face-sharing octahedra affect the
24 electronic dimensionality of the perovskite-like corner-sharing 1D chains, acting as electronic
25 barrier, a conclusion which agrees well with previous reports of structures with face-sharing
26 connectivity.⁵³ Furthermore, the third direction, running parallel to the chains of corner-sharing
27 octahedra, has little dispersion compared to the calculations for $n = 3$, indicating the zigzag
28 connectivity also leads to poor dispersion. This is consistent with other $\langle 100 \rangle$ -oriented layered
29 halide perovskites, such as ammonium-propyl-imidazole-based structures.⁷⁸ As m increases, the
30 dispersion along the chains of corner-sharing octahedra increases, as expected because of the
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3 increased perovskite-like character of the chains. Furthermore, the $m = 4$ structure begins to
4 show small amounts of coupling between the chains, overcoming the face-sharing octahedra
5 barrier. The local density of states close to the band edges also becomes similar to that of RP
6 structures.
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12 For the $n = 3$ and $n = 4$ RP materials, the band structure show an almost direct bandgap
13 similar to that of the other RP materials.⁴¹ The calculations indicate that the $n = 3$ member is a
14 direct bandgap semiconductor at the Γ point of the Brillouin zone, whereas the $n = 4$ member has
15 a slightly indirect bandgap at the Γ point (Figure 5a). The $n = 4$ member shows a slight deviation
16 from the typical direct bandgap behavior, observed in halide perovskites because of strong
17 Rashba splitting caused by the noncentrosymmetric nature of its structure. Within the layers, the
18 electronic bands are dispersive because of their perovskite-like nature resulting from the corner-
19 sharing PbI_6 octahedra. Across the layers in the z direction, however, the bands show virtually no
20 dispersion because of the structural discontinuity caused by the spacing of the propylammonium
21 cations. As was reported previously, the conduction band maximum (CBM) is made mainly of
22 $6p$ orbitals of Pb located on the top and bottom surface of the perovskite slabs while the valence
23 band maximum (VBM) is made mainly of $5p$ orbitals of I located in the center, similar to the
24 BA-based RP structures.³⁰
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42 It is worth pointing out that $m = 2$ shows a clear indirect bandgap while $m = 3$ and $m = 4$
43 both show almost direct bandgaps. Even though the calculated bandgap is underestimated, which
44 is common for this type of calculations,⁴¹ the general experimental trend is captured by the DFT
45 calculations, with the slight exception of $m = 3$ (Figure S4). In this case, the calculated bandgaps
46 for the materials are 0.51 eV for $n = 4$, 1.03 eV for $n = 3$, 1.75 eV for $m = 4$, 1.60 eV for $m = 3$,
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Electrical Properties

Photoconductivity measurements were taken for $n = 3$ RP perovskite, $m = 2$, and $m = 4$ SL perovskites at room temperature using a two-probe setup. Individual faceted crystals of each compound were measured along different directions with the intention to capture the highly anisotropic properties of the crystals.

For the SL materials, three unique directions are possible. For $m = 2$, the crystals are needles which can be imagined as rectangular prisms elongated along the b -axis. From tip-to-tip for these needles, the crystallographic direction is the b -axis, which is the axis running parallel to the 1D chains of corner-sharing octahedra. The measured resistivity is high along this direction ($\rho \sim 10^{10} \Omega \cdot \text{cm}$), but still an order of magnitude smaller than the one corresponding to the cross-plane direction in RP phases discussed below, while measurements along the a - and c -axes gives resistivities on the order of $\rho \sim 10^7 - 10^8 \Omega \cdot \text{cm}$. While the resistivity values are seemingly quite low here, it has been noted that ion migration is common in perovskites⁷⁹⁻⁸⁰ and increased in 2D perovskites because of octahedral distortion.⁸¹ In the SL structures, the octahedral distortions are significant, as in the RP structures. Also, the layers are no longer flat and thus have more exposure to the interlayer space, which could act as a pathway for ion migration. If this is the case, the measurement would be heavily influenced by ion migration instead of electronic conduction and would lead to inflated values. A similar situation occurs for $m = 4$, with values of resistivity $\rho \sim 10^6 \Omega \cdot \text{cm}$ for the b -axis, $\rho \sim 10^8 \Omega \cdot \text{cm}$ for the a -axis, and $\rho \sim 10^6 \Omega \cdot \text{cm}$ for the c -axis. While these values are only estimates, they demonstrate the anisotropic effects in these crystals.

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3 The $n = 3$ structure crystallizes as thin rectangular plates in the typical morphology for
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5 the RP structures.⁸² Measuring along the tetragonal facets, corresponding to the cross-plane
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7 direction, a resistivity of $\rho = 10^{11} \Omega \cdot \text{cm}$ was obtained, whereas measuring along the thin sides of
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9 the crystals, corresponding to the layer plane direction, resulted in a much smaller resistivity of ρ
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11 $= 10^8 \Omega \cdot \text{cm}$ (Figure 6a). This vividly illustrates the anisotropic nature of the RP perovskites, and
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13 it is also reasonable in the sense that the resistivity of the layer plane is comparable to that
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15 observed for the 3D perovskite ($\rho = 10^7 \Omega \cdot \text{cm}$).⁸³ This is understandable, as the carriers easily
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17 transport through the perovskite-like planes, whereas much higher bias is required to force the
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19 charge carriers to jump across adjacent layers. This observation is in agreement with previously
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21 asserted measurements, even though the anisotropy is higher in the PA system compared to the
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23 GA system, possibly because of the very short interlayer spacing in the ACI perovskites.²⁹ The
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25 photoconductive response, measured using white light is clear along both measured directions.
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27 Parallel to the layers, the resistivity decreased a hundredfold and perpendicular to the layers, it
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29 decreased tenfold. Somewhat surprising is the photoresponse perpendicular to the layers, which
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31 implies that some small current can vertically cross the layers. This suggests that certain cations
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33 are not sufficiently insulating to completely prevent charge transfer across the layers, even if the
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35 transfer is minimal.
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42 It is important to note that the SL materials displayed no difference in the current under
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44 dark and light conditions, showing a lack of photoresponse in all directions for both structures.
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46 This shows that the SL compounds are inappropriate for photovoltaics, yet they may find
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48 applications as dielectric gates in halide perovskite optoelectronics because of their tunable
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50 resistivity as a function of the 1D chain thickness. Furthermore, perovskites have seen utility as
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52 ferroelectrics and magnets, as well as being utilized for ion exchange and reactivity
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3 applications.^{24, 84} Since little is understood about how hybrid halide perovskitoids can be utilized
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5 for these applications, this system may be used as a tunable model to see how a departure from
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7 the perovskite structure affects these materials' behavior in these other applications.
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12 **Thin Films and Solar Cell Devices**

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15 *Thin Films* Because of the negligible photoconductivity of the SL materials, only solar cell
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17 devices using the RP phases were considered. Because of the lower purity of $n = 4$, $n = 3$ was
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19 chosen for device fabrication instead. In a previous report, RP phases were successfully made
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21 into high-efficiency devices by a process known as hotcasting.⁸⁵ In this process, the substrate is
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23 heated (in this case to 110 °C) immediately before spin coating begins, which allows for
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25 increased grain passivation and more preferable perpendicular orientation of the layers to the
26
27 substrate. The devices were shown to have high short-circuit current density (J_{SC}) because of
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29 increased charge transfer. Furthermore, solvent engineering has been shown to increase the
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31 crystallinity of the 2D materials in the films.⁵⁷ This can be done by simply using mixtures of
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33 DMF and DMSO as opposed to only using DMF. The DMSO functions to slow the
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35 crystallization of the films from 1-2 s to 6-7 s and thus leads to better crystallinity. To assess
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37 better conditions for devices, XRD of films was measured using different concentrations of
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39 DMSO in DMF (0%, 25%, 50%, 75%, and 100%). As seen by the PXRD in Figure S6a, the
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41 FWHM of the (-110) peak decreases immediately upon addition of DMSO but does not further
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43 improve with concentrations of DMSO above 25%. DMSO does, however, lead to a decrease in
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45 preferred orientation and a disproportionation of phases, seen by the low angle peaks
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47 corresponding to $n = 4$ which grow in with increasing concentrations of DMSO. GIWAXS
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49 (Figure 7) further backs these trends, though it shows the $n = 3$ material as well based on low
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3 angle peaks. The spots in the GIWAXS spectrum become rounder as DMSO increases, which
4 shows an increase in crystallinity. This data can be further analyzed by taking line-cuts of the 2D
5 spectrum in different directions. By taking the FWHM along the q_z and q_y directions, the
6 crystallinity perpendicular to the substrate and parallel to the substrate, respectively, can be
7 distinguished. As seen in Figure S7, the crystallinity along q_z does not change in a substantially
8 nor consistent manner, indicating that the grains did not change in size perpendicular to the
9 substrate. In contrast, along q_y , the crystallinity overall increased and is greater compared to
10 along q_z . This suggests that the crystallites in the film are plate-like and lie parallel to the
11 substrate. Furthermore, increasing the concentration of DMSO increases the width of the
12 crystallites while not increasing the depth. Further studies will be needed to understand the
13 mechanism which leads to these trends and the effect of DMSO.
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28 *Solar Cells.* Encapsulated devices were prepared using an inverted structure:

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30 ITO/PEDOT:PSS/Perovskite/PCBM/Al, in which PEDOT:PSS functioned as the hole-
31 transporting material (HTM) and PCBM as the electron-transporting material (ETM). By tuning
32 the percent of DMSO in solution, a respectable average device efficiency of $6.28 \pm 0.65\%$ was
33 found by using 75% DMSO, much higher than the $3.70 \pm 0.37\%$ efficiency for pure DMF.
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35 Typical device curves are seen in Figure 8b, and the average parameters are seen in Table S32.
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37 Furthermore, the average V_{OC} decreased slightly from 1.07 ± 0.06 V to 1.00 ± 0.03 V, the
38 average J_{SC} increased significantly from 5.33 ± 0.66 mA/cm² to 10.95 ± 0.57 mA/cm², and the
39 FF decreased slightly from $68.6 \pm 4.6\%$ to $57.0 \pm 3.5\%$. The increase in J_{SC} is attributed to a
40 slower growth rate of the film from DMSO, which leads to better crystallinity, as mentioned
41 above. The decrease in preferred orientation seems to be less essential in this case than the
42 crystallinity. Even so, DMSO has also shown to lead to very large grain size on the order of over
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3 a micron, which may lead to small gaps between the grains, negatively affecting the V_{OC} and FF,
4 as seen here.⁵⁷ The external quantum efficiency (EQE) was also measured for the devices and is
5 shown in Figure 8c with an integrated J_{SC} of 9.23 mA cm^{-2} for 75% DMSO which is slightly
6 lower than the J_{SC} of 11.86 mA cm^{-2} based on the J-V curve from the same device. Another point
7 of interest is the broadening in the EQE spectrum with addition of DMSO. Even at 25% DMSO,
8 the curve has broadened significantly at lower wavelength. However, all films show a very broad
9 spectrum, especially at higher wavelength, as seen by the appearance of a shoulder at around 720
10 nm. This broadening could be attributed to disproportionation in the films, as evidenced by the
11 presence of $n = 4$ in the XRD. The broader EQE implies that this disproportionation is
12 potentially advantageous to absorb a broader range of wavelengths of light.
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26 The wide EQE of the films, potentially due to the disproportionation in the films based on
27 XRD, is promising. In fact, the disproportionation of the n values in the film based on XRD
28 implies that low n values are also in existence in the film, as has been reported for other systems
29 spectroscopically.⁸⁶ Here, however, the RP $n = 1$ and $n = 2$ structures are less likely to form than
30 the SL structures, which have no photoresponse and are detrimental to device performance. The
31 fact that the J_{SC} was not as high as expected, along with lower FF and V_{OC} suggests that the
32 issues arising here derive from the film morphology and presence of SL structures, not the RP n
33 = 3 material itself. Furthermore, the increase of J_{SC} from DMSO additive implies the changes in
34 morphology and makeup alleviate some of the potential issues, suggesting that further tuning of
35 the conditions for film fabrication could lead to higher J_{SC} . In fact, for films using the GA
36 spacing cation, fine tuning using antisolvent addition has given efficiencies of 14.7% once the
37 determinantal $(GA)_2PbI_4$ impurity was suppressed. Also like the GA structures, the short
38 interlayer space allows for a lower organic volume in the structure and thus a higher volume of
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3 perovskite character in the structure, which should allow for a high absorption coefficient. Each
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5 of these observations implies the potential for greater J_{SC} for PA-based devices once optimization
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7 takes place. As a preliminary way to analyze these devices and to better understand this system,
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9 further device studies were performed.

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12 Series resistance (R_S) can be a major limitation for J_{SC} and is here estimated by the slope
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14 at the open-circuit voltage, where lower slopes resulting from resistive “tails” near the V_{OC} lead
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16 to increased R_S . For films with only DMF, a high resistivity is seen, likely due to poor interfaces
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18 or defects in film morphology such as low crystallinity and poor mosaicity. This can be tamed by
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20 the previously mentioned processing techniques of hotcasting and solvent engineering. In fact,
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22 by using solvent engineering through mixing DMF and DMSO, the resistive “tail” seen near the
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24 open-circuit voltage disappears entirely under high concentrations of DMSO (Figure 9).
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28 Likewise, the series resistance (R_{SH}) is estimated by the slope at the J_{SC} , where a greater slope
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30 shows more shunt pathways. Once again, this is an effect of the film quality, not the material,
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32 and is improved substantially by the addition of DMSO, as seen clearly by the dark curves in
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34 Figure 9c,f,i.
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38 The final issue tackled in this system was the hysteresis, which is seen both by varying
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40 the scan speed and direction. While using pure DMF gave large hysteresis, DMSO addition
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42 diminished the hysteresis substantially. Though full optimization of these devices is out of the
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44 scope of this paper, they show the potential for further improvements because of the excellent
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46 properties of the crystalline materials and the widened EQE curve, allowing for a broader range
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48 of the solar spectrum to be absorbed. It should be noted that, despite having similar bandgaps to
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50 the BA system and even shorter interlayer spacing, the performance is still far from that of BA.⁸⁵
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54 Based on the above analysis, it appears that the intrinsic properties of the PA materials are not to
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3 blame, but the film morphology and makeup hinders the performance. Once the optimal
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5 conditions of film formation for this material are better understood, higher films made from pure
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7 crystals of these materials can be prepared, and the wide spread of n values in the films can be
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9 utilized to get high J_{SC} and thus improved efficiencies.
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14 **Conclusions**

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17 Using the short PA^+ spacing cation in PAI/MAI/ PbI_2 reactions results in two homologous
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19 series of 2D organic-inorganic hybrid lead iodide materials: RP perovskites $(PA)_2(MA)_{n-1}Pb_nI_{3n+1}$
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21 $(n = 3 \text{ and } 4)$ and SL perovskitoids $(PA)_{2m+4}(MA)_{m-2}Pb_{2m+7}I_{7m+4}$ $(m = 2, 3, \text{ and } 4)$. What is quite
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23 remarkable is that, by simply changing the PA:MA ratio, this system gives both the
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25 electronically 1D SL materials and the electronically 2D RP materials, showing the huge range
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27 of electronic and structural tunability within the same series. These trends are not found in the
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29 longer n-alkyl ammonium 2D perovskites. Along with GA and MA in the ACI 2D perovskites,
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31 PA is among the shortest organic spacers in 2D perovskites. The SL structures in these materials
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33 have a new type of connectivity in the lead iodide layers in which chains of corner-sharing PbI_6
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35 octahedra are connected by face-sharing octahedra to form structurally 2D SL slabs. Optically,
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37 the PA $n = 3$ and $n = 4$ structures are like other known RP structures with bandgaps for $n = 3$ and
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39 4 of 2.03 eV and 1.90 eV while the SL structures have bandgaps over a wider range for $m = 2, 3,$
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41 and 4 of 2.93 eV, 2.74 eV, and 2.53 eV. This shows that the bandgap can be further tuned by
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43 adjusting not only the thickness of the slabs n, but also the width m, which could be useful in
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45 designing materials with very specific bandgaps without relying on halide mixing which can
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47 result in phase segregation. Unlike the RP structures which are electronically 2D, the SL
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49 structures are electronically 1D with dispersion along the corner-sharing chains. Even though the
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3 chains incorporate every component of the MAPbI₃ structure for m = 3 and 4, the materials are
4 confined to one dimension, showing the possibility for 2D perovskite-like materials which are
5 electronically 1D, further enhancing the ability to play with the optical and electronic properties
6 of these materials by simply adjusting the spacing cation.
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12 The RP materials have good charge transport along the lead-iodide slabs along with a
13 good photoresponse, allowing them to be used in solar cells. By using solvent engineering with
14 varying DMF/DMSO mixtures, crystalline films can be made, leading to solar cells with
15 respectable efficiencies. While the efficiencies are not yet competitive with other 2D perovskite
16 materials, the PA system seems to have greater disproportionation than other cations such as BA
17 based on the EQE spectrum.⁸⁵ If this property can be utilized with improved film morphology,
18 these materials have the potential for higher J_{SC} by absorbing a greater range of wavelengths of
19 light. Also, it is fundamentally interesting that, when compared to the BA system, by simply
20 removing a carbon atom from the BA spacer, the film kinetics change so dramatically. We can
21 therefore use these materials to better understand film formation and define the techniques
22 suitable for shorter spacer cations. A systematic comparison between the film forming properties
23 of PA and BA films will further understanding of the disproportionation of n values in films,
24 important for LED applications.^{17, 87}
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45 **ASSOCIATED CONTENT**

46 **Supporting Information**

47
48 Materials and methods, synthetic details, additional supplementary figures and tables about
49 material characterization, SEM images, X-ray diffraction measurements, photoluminescence
50 measurements, thermogravimetric analysis, profilometry measurements and film stability
51 studies.
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Notes

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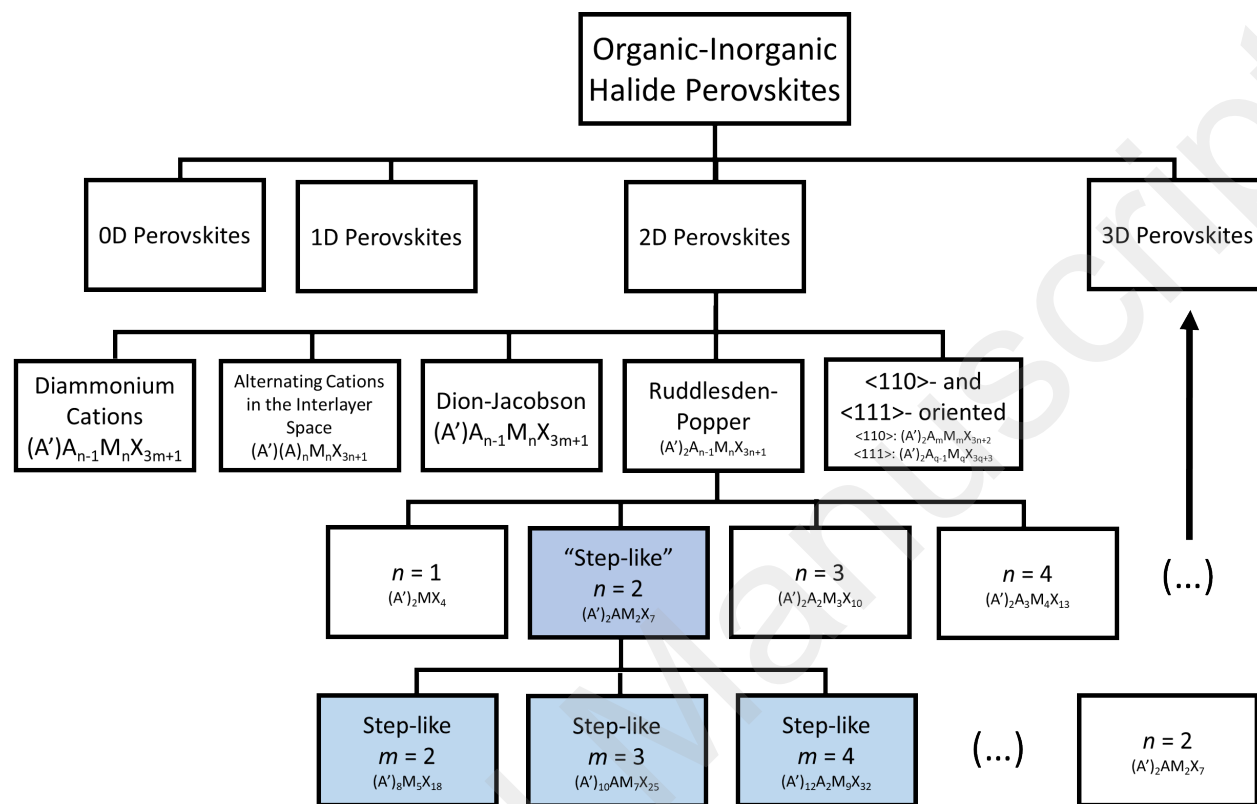
Tables

Table 1. Crystal Data and Structure Refinement for PA Materials.

| | (PA) ₃ Pb ₂ I ₇ | <i>m</i> = 3 | <i>m</i> = 4 | <i>n</i> = 3 | <i>n</i> = 4 |
|---|--|--|--|---|---|
| Empirical formula | C ₉ H ₃₀ I ₇ N ₃ Pb ₂ | C ₃₂ H ₁₀₆ I ₂₅ N ₁₁ Pb ₇ | C ₃₈ H ₁₃₂ I ₃₂ N ₁₄ Pb ₉ | C ₈ H ₃₂ I ₁₀ N ₄ Pb ₃ | C ₉ H ₃₈ N ₅ Pb ₄ I ₁₃ |
| Formula weight | 1483 | 5268 | 6727 | 2075 | 2695 |
| Temperature (K) | 293 | 293 | 293 | 293 | 293 |
| Wavelength (Å) | 0.71073 | 0.71073 | 0.71073 | 0.71073 | 0.71073 |
| Crystal system | orthorhombic | monoclinic | monoclinic | monoclinic | monoclinic |
| Space group | <i>P</i> 2 ₁ 2 ₁ 2 ₁ | <i>P</i> 2/ <i>c</i> | <i>C</i> 2 | <i>P</i> 2 ₁ / <i>a</i> | <i>C</i> <i>c</i> |
| Crystal Shape | White | Needles | Needles | Plates | Plates |
| Crystal Color | Needles | Orange | Red | Dark Red | Black |
| Unit cell dimensions (Å) | <i>a</i> = 8.79150(10) | <i>a</i> = 19.2010(17) | <i>a</i> = 45.276(2) | <i>a</i> = 8.850(4) | <i>a</i> = 62.405(5) |
| | <i>b</i> = 15.3917(3) | <i>b</i> = 8.8414(5) | <i>b</i> = 8.8555(3) | <i>b</i> = 8.9262(8) | <i>b</i> = 8.9358(7) |
| | <i>c</i> = 22.3423(4) | <i>c</i> = 37.707(3) | <i>c</i> = 19.1635(10) | <i>c</i> = 25.0700(10) | <i>c</i> = 8.8712(6) |
| | | β = 119.351(9)° | β = 113.372(4)° | β = 96.474(11)° | β = 92.947(6)° |
| Volume (Å ³) | 3023.27(9) | 5579.5(9) | 7053.1(6) | 1967.9(9) | 4940.4(6) |
| <i>Z</i> | 4 | 2 | 2 | 2 | 4 |
| Density (calculated, g/cm ³) | 3.2583 | 3.1358 | 3.1676 | 3.5018 | 3.6152 |
| Absorption coefficient (mm ⁻¹) | 18.27 | 17.464 | 17.731 | 20.65 | 21.724 |
| <i>F</i> (000) | 2560 | 4536 | 5784 | 1768 | 4576 |
| Crystal size (mm ³) | 0.042 x 0.049 x 0.110 | 0.018 x 0.055 x 0.030 | 0.061 x 0.023 x 0.018 | 0.587 x 0.462 x 0.024 | 0.012 x 0.176 x 0.188 |
| θ range for data collection (°) | 1.61 to 23.4° | 2.12 to 29.27° | 1.79 to 29.27 | 2.81 to 29.27° | 1.96 to 29.26 |
| | -9 ≤ <i>h</i> ≤ 9 | -26 ≤ <i>h</i> ≤ 26 | -61 ≤ <i>h</i> ≤ 61 | -11 ≤ <i>h</i> ≤ 12 | -85 ≤ <i>h</i> ≤ 85 |
| Index ranges | -17 ≤ <i>k</i> ≤ 17 | -10 ≤ <i>k</i> ≤ 12 | -12 ≤ <i>k</i> ≤ 12 | -12 ≤ <i>k</i> ≤ 12 | -12 ≤ <i>k</i> ≤ 12 |
| | -24 ≤ <i>l</i> ≤ 24 | -51 ≤ <i>l</i> ≤ 51 | -26 ≤ <i>l</i> ≤ 26 | -34 ≤ <i>l</i> ≤ 33 | -11 ≤ <i>l</i> ≤ 11 |
| Reflections collected | 73278 | 51123 | 34061 | 12017 | 19790 |
| Independent reflections | 4406 | 10105 | 12755 | 2798 | 7973 |
| | [<i>R</i> _{int} = 0.0735] | [<i>R</i> _{int} = 0.3233] | [<i>R</i> _{int} = 0.0892] | [<i>R</i> _{int} = 0.1657] | [<i>R</i> _{int} = 0.1462] |
| Completeness to θ = 29.27° | 100% | 99% | 99% | 82% | 98% |
| Refinement method | Full-matrix least-squares on <i>F</i> ² | Full-matrix least-squares on <i>F</i> ² | Full-matrix least-squares on <i>F</i> ² | Full-matrix least-squares on <i>F</i> ² | Full-matrix least-squares on <i>F</i> ² |
| Data / restraints / parameters | 4406 / 15 / 121 | 10105 / 26 / 214 | 12755/31/267 | 2798/6/82 | 7973/13/203 |
| Goodness-of-fit | 1.13 | 0.32 | 3.00 | 3.43 | 2.62 |
| Final <i>R</i> indices [<i>I</i> > 3σ(<i>I</i>)] | <i>R</i> _{obs} = 0.0268 w <i>R</i> _{obs} = 0.0546 | <i>R</i> _{obs} = 0.0361 w <i>R</i> _{obs} = 0.0817 | <i>R</i> _{obs} = 0.1077 w <i>R</i> _{obs} = 0.1973 | <i>R</i> _{obs} = 0.0851 w <i>R</i> _{obs} = 0.1893 | <i>R</i> _{obs} = 0.1161 w <i>R</i> _{obs} = 0.2277 |
| <i>R</i> indices [all data] | <i>R</i> _{all} = 0.0401 w <i>R</i> _{all} = 0.0585 | <i>R</i> _{all} = 0.4073 w <i>R</i> _{all} = 0.2329 | <i>R</i> _{all} = 0.1940 w <i>R</i> _{all} = 0.2113 | <i>R</i> _{all} = 0.1247 w <i>R</i> _{all} = 0.1910 | <i>R</i> _{all} = 0.2447 w <i>R</i> _{all} = 0.2460 |

| | | | | | |
|---|----------------|----------------|----------------|----------------|----------------|
| Largest diff. peak and hole ($e \cdot \text{\AA}^{-3}$) | 0.52 and -0.47 | 1.45 and -1.39 | 5.98 and -4.04 | 1.98 and -2.61 | 8.26 and -5.97 |
|---|----------------|----------------|----------------|----------------|----------------|

Figures



Scheme 1. A partial hierarchy diagram of different halide perovskite phases resulting from different spacing cations. Boxes labelled in blue represent materials with face-sharing octahedra. The first line divides the structure types by dimensionality. The 2D structure types are then divided into several categories based on spacing cations and cleaving direction. One of these categories, RP perovskites, is expanded upon here to show the various thicknesses n which can form within the category, which is the structure type of the $n > 2$ PA series. When n approaches ∞ , the structure collapses to the so-called 3D GdFeO_3 structure types. The Ruddlesden-Popper “ $n = 2$ ” PA structure is replaced by the perovskitoid series of SL materials with width m . As m approaches ∞ , the structure collapse to “ $n = 2$.”

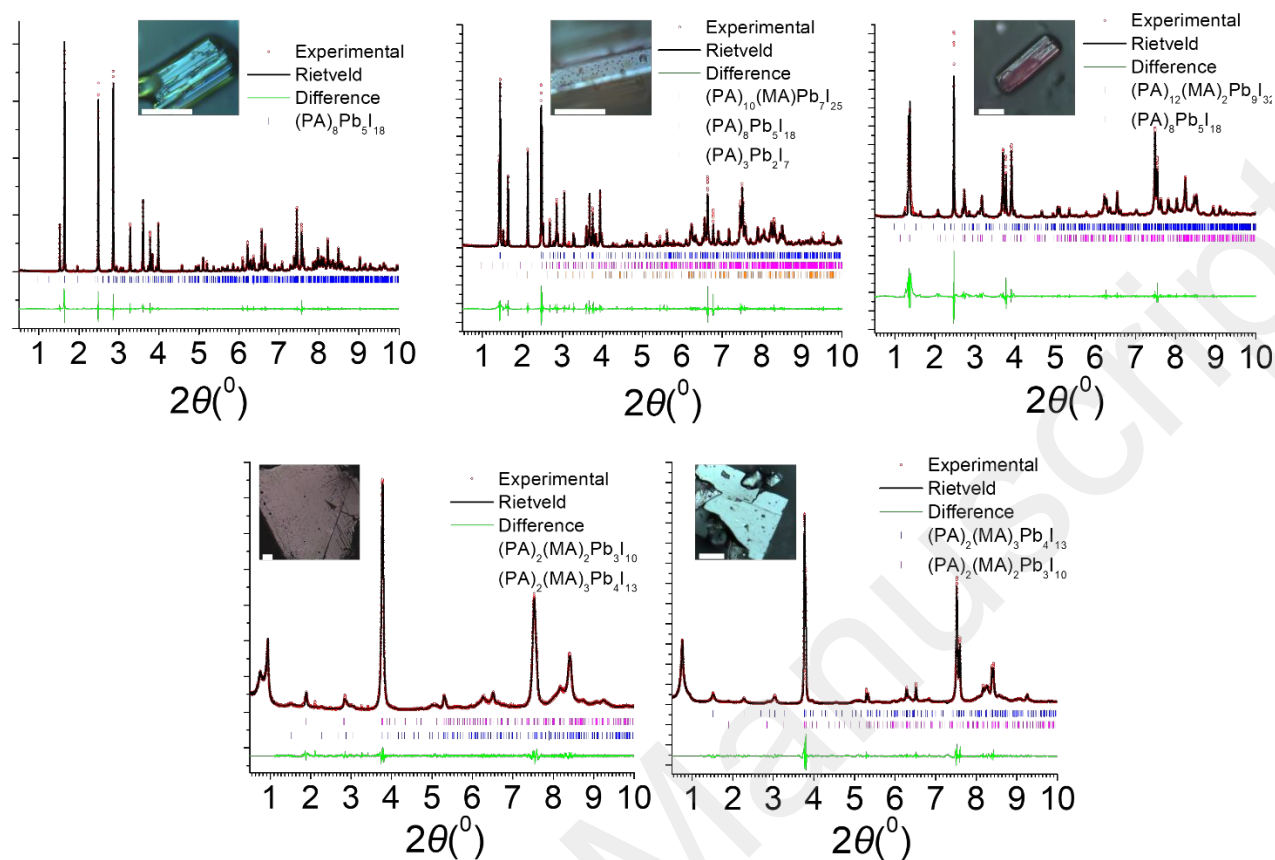


Figure 1. Rietveld analysis of synchrotron-quality PXRD data for each of the five explored structures. For $n = 4$, the low angle peak was not able to be resolved because it was disproportionately intense, so it was excluded from the calculations. Scale bar for inset images is 1 mm.

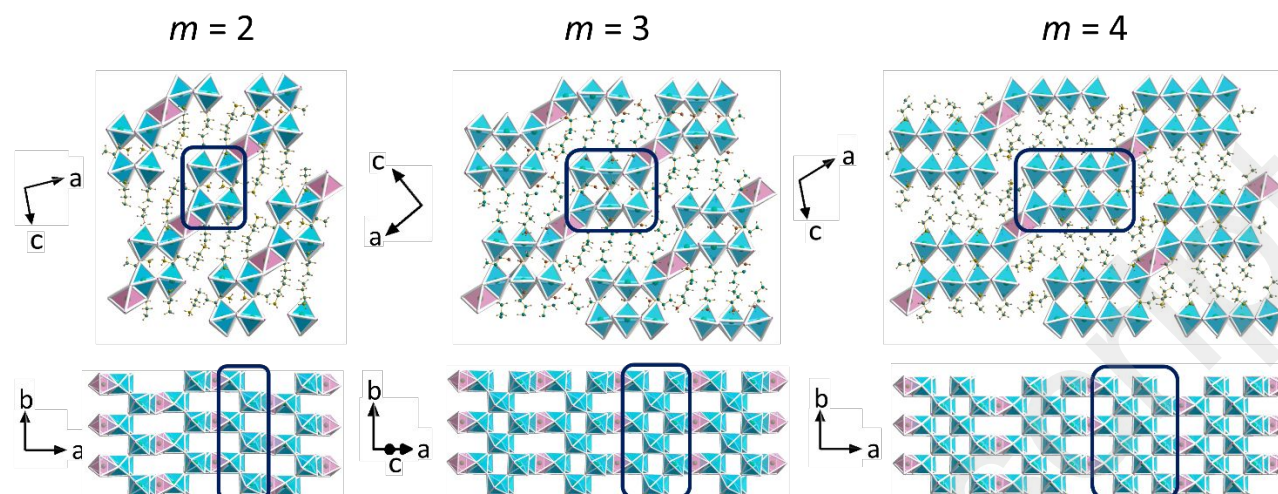


Figure 2. The homologous series of SL materials. The blue octahedra are at least partially corner-sharing and the pink octahedra are fully face-sharing. The top row shows structures looking down the *b*-axis perpendicular to the 1D corner-sharing chains. The bottom row shows the structures down the *c*-axis (excluding $m = 3$), parallel to the chains and emphasizing the $\langle 110 \rangle$ cleavage of the chains by the pink-colored face-sharing octahedra. The same 1D chain has been boxed in both viewing directions to emphasize the corner-sharing connectivity.

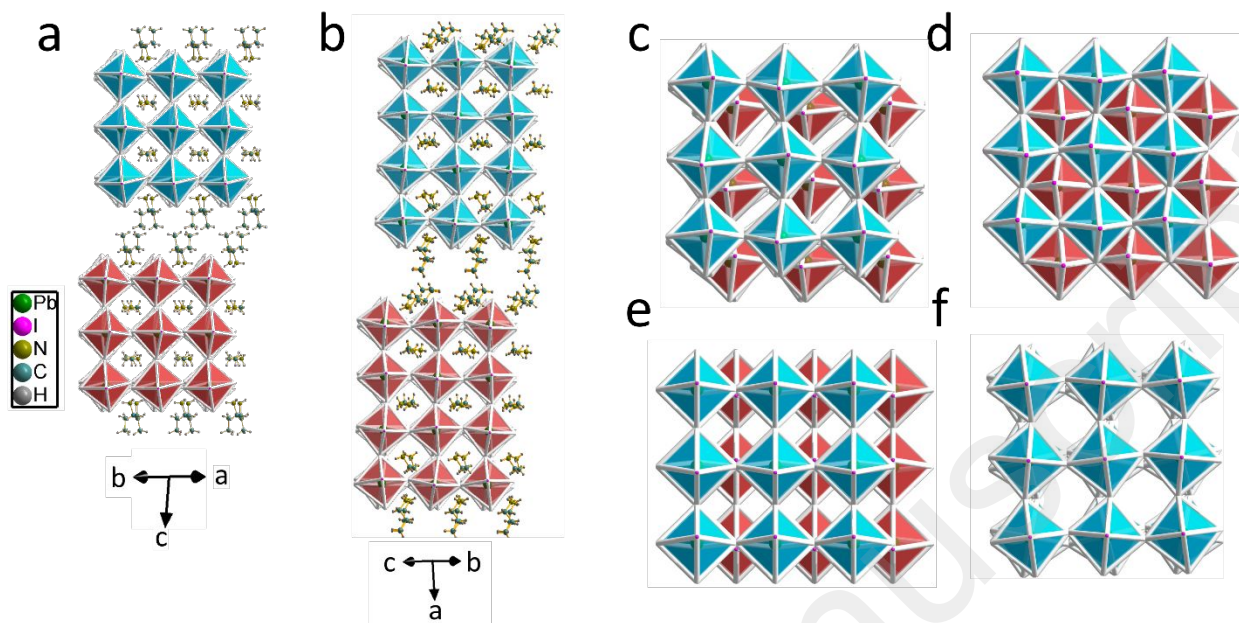


Figure 3. (a,b) The $n = 3$ and $n = 4$ Ruddlesden-Popper materials. (c-f) The alignment of the inorganic layers for various cations, all using $n = 3$. Two layers are shown with the top layer in blue and the bottom in red, with the layers aligned so that the layers themselves are perpendicular to the viewing direction to give a better view of the alignment of the layers. (c) PA. (d) BA. (e) GA. (f) 3-AMP.

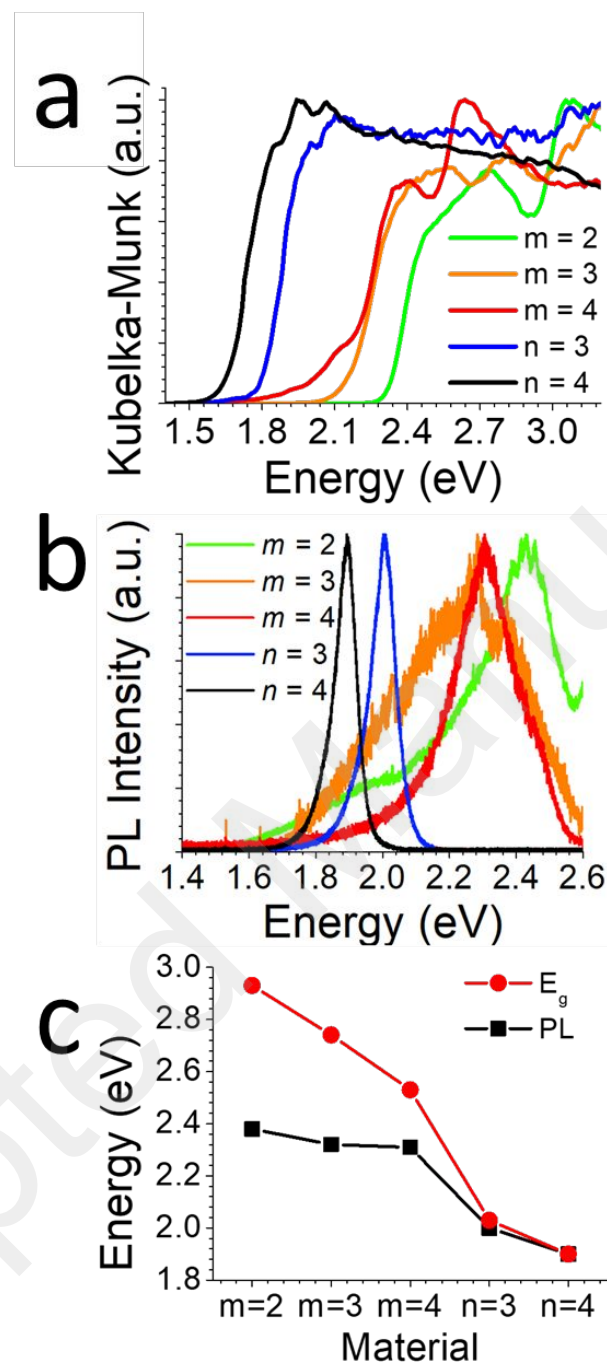


Figure 4. Optical properties of the PA based materials. The intensity of (a) and (b) have been normalized for comparison purposes. However, due to the weak intensity of the emission, spikes can be seen in the data, which are merely artifacts of the instrument. (a) The Kubelka-Munk Plot for the crystals showing the blue shift of the SL structures compared to the RP structures. (b) The photoluminescence for each of the crystals. (c) A comparison of the bandgaps and photoluminescence for the PA series.

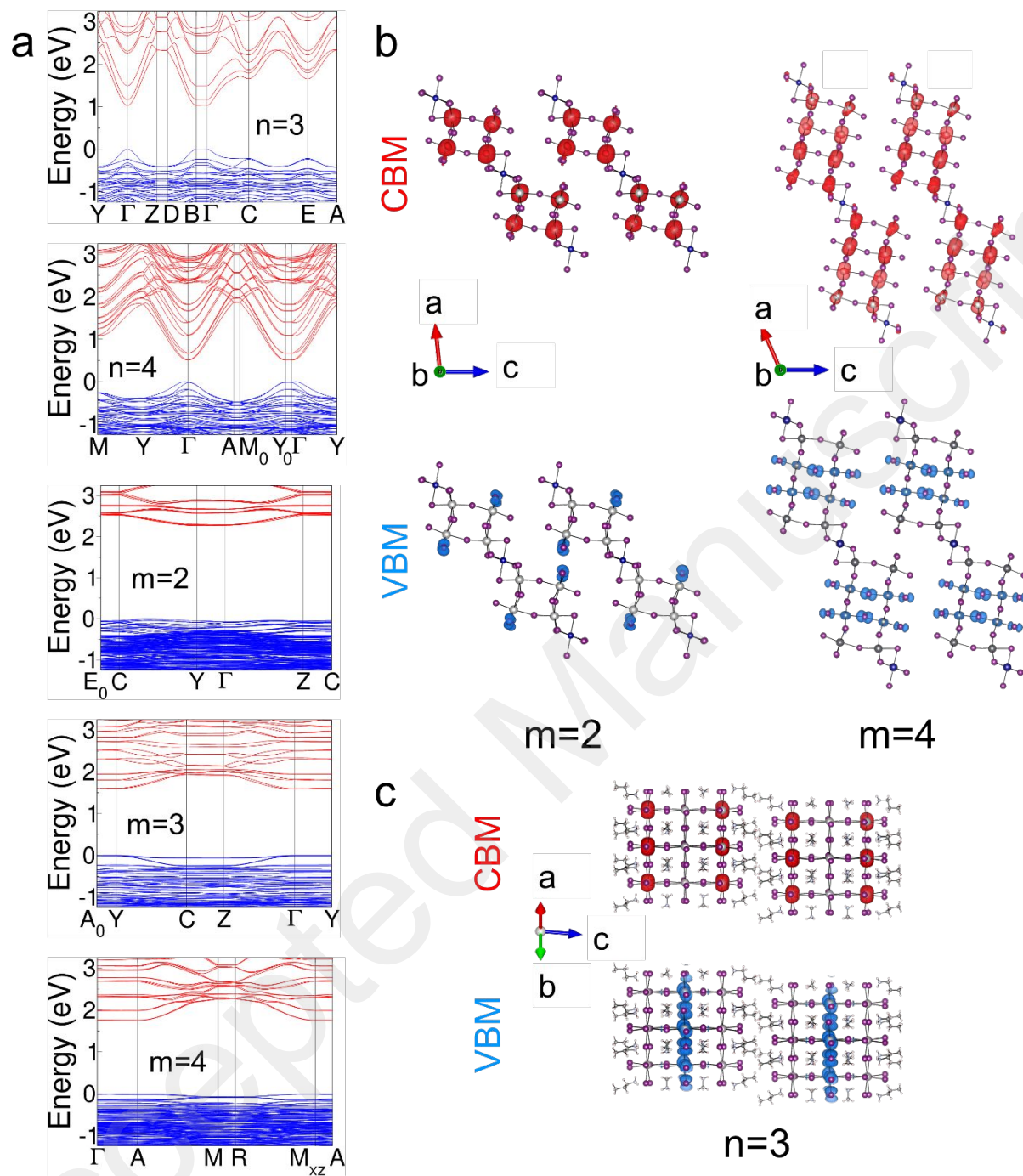


Figure 5. (a) Electronic band structures of the PA series. (b) Partial charge densities computed at the CBM (top, red) and VBM (bottom, blue) for $m = 2$ and $m = 4$, showing the localization of electronic density between the face-sharing octahedra. (c) Same for the CBM (top, red) and VBM (bottom, blue) of $n = 3$.

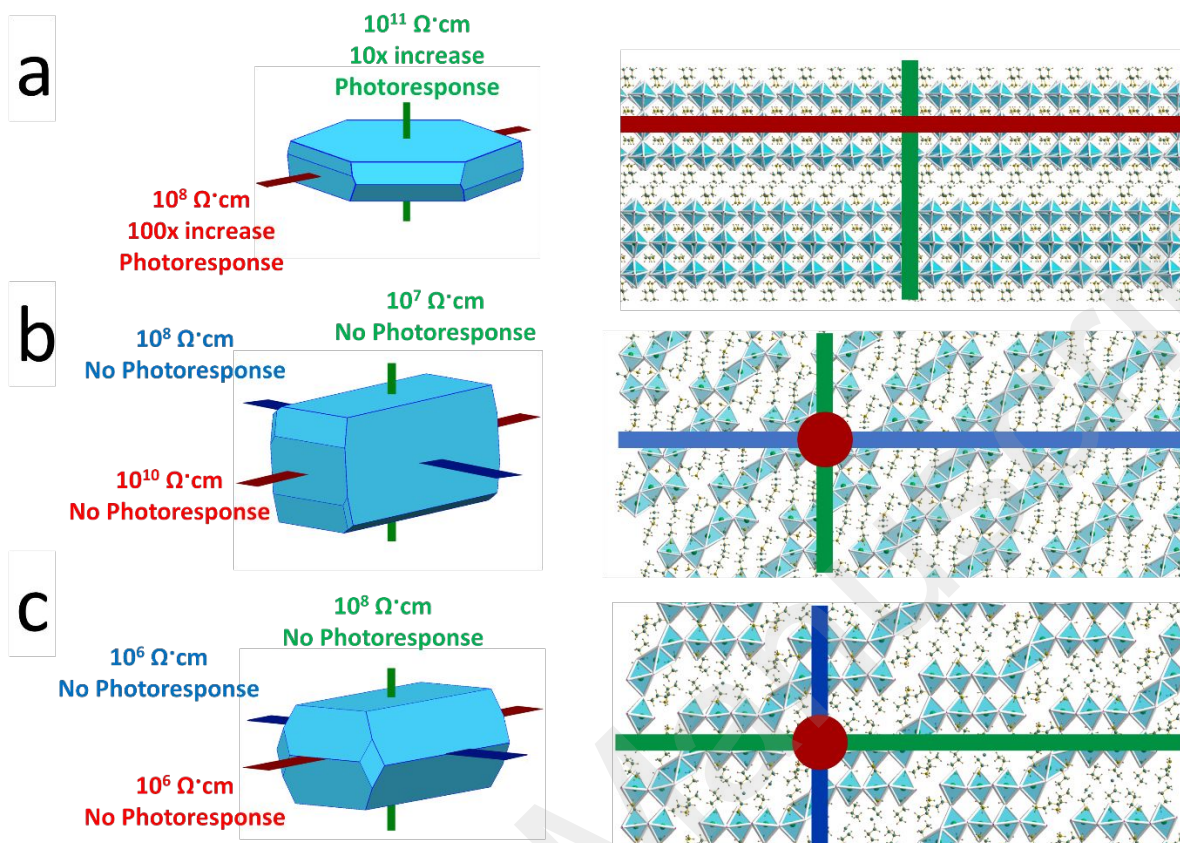


Figure 6. Resistivity measurements for (a) $n = 3$, (b) $m = 2$, and (c) $m = 4$. The top row shows simulated crystal shapes created in Mercury and the various directions tested for each material. The lines simulate the wires attached to each material and the color of each line correlates to the images in the bottom row, showing the direction in the structure. Photoconductivity is shown in the top row based on how much decrease in resistivity was measured. Note that, for $m = 2$, the green and blue directions (the sides of the needle) could not be discerned experimentally, so these two directions were assigned arbitrarily.

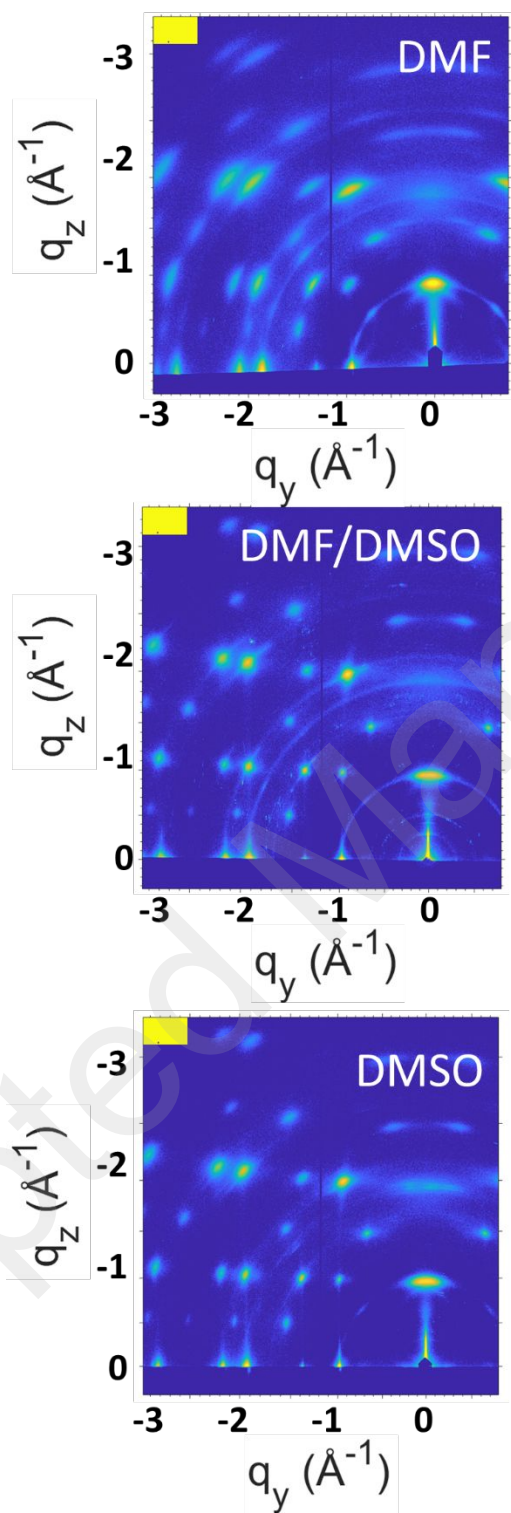


Figure 7. GIWAXS of the thin films of the $n = 3$ material using various concentrations of DMSO in DMF.

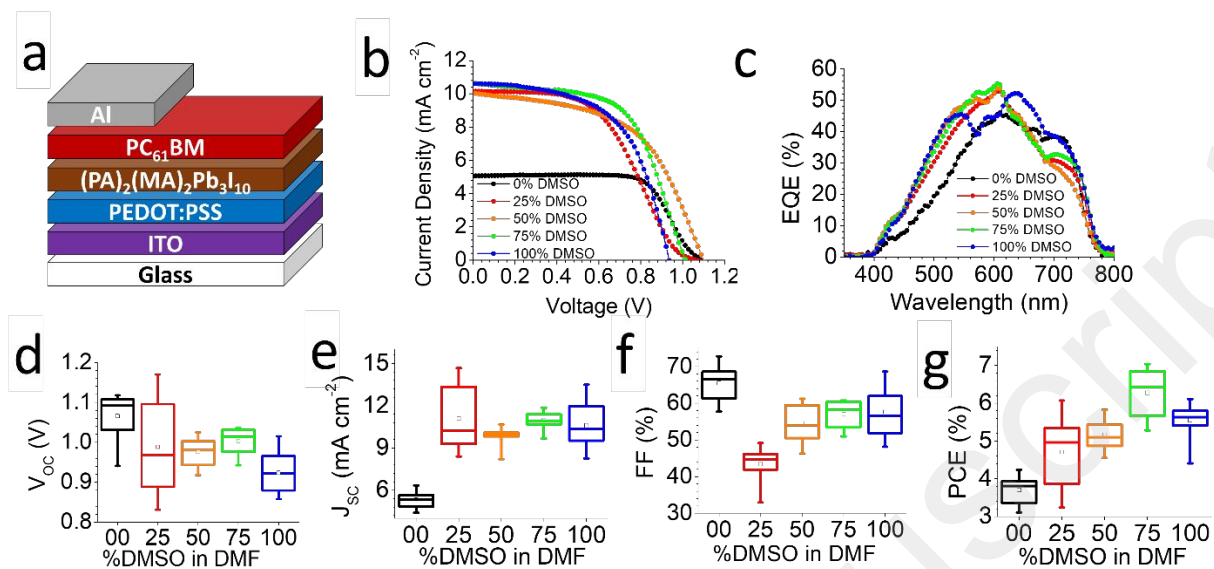


Figure 8. Solar cell devices made from $n = 3$. (a) The device architecture used here. (b) Representative device curves using different concentrations of DMSO in DMF. (c) EQE of the devices. (d-g) Statistics from ten devices on V_{OC} , J_{SC} , FF, and PCE, respectively.

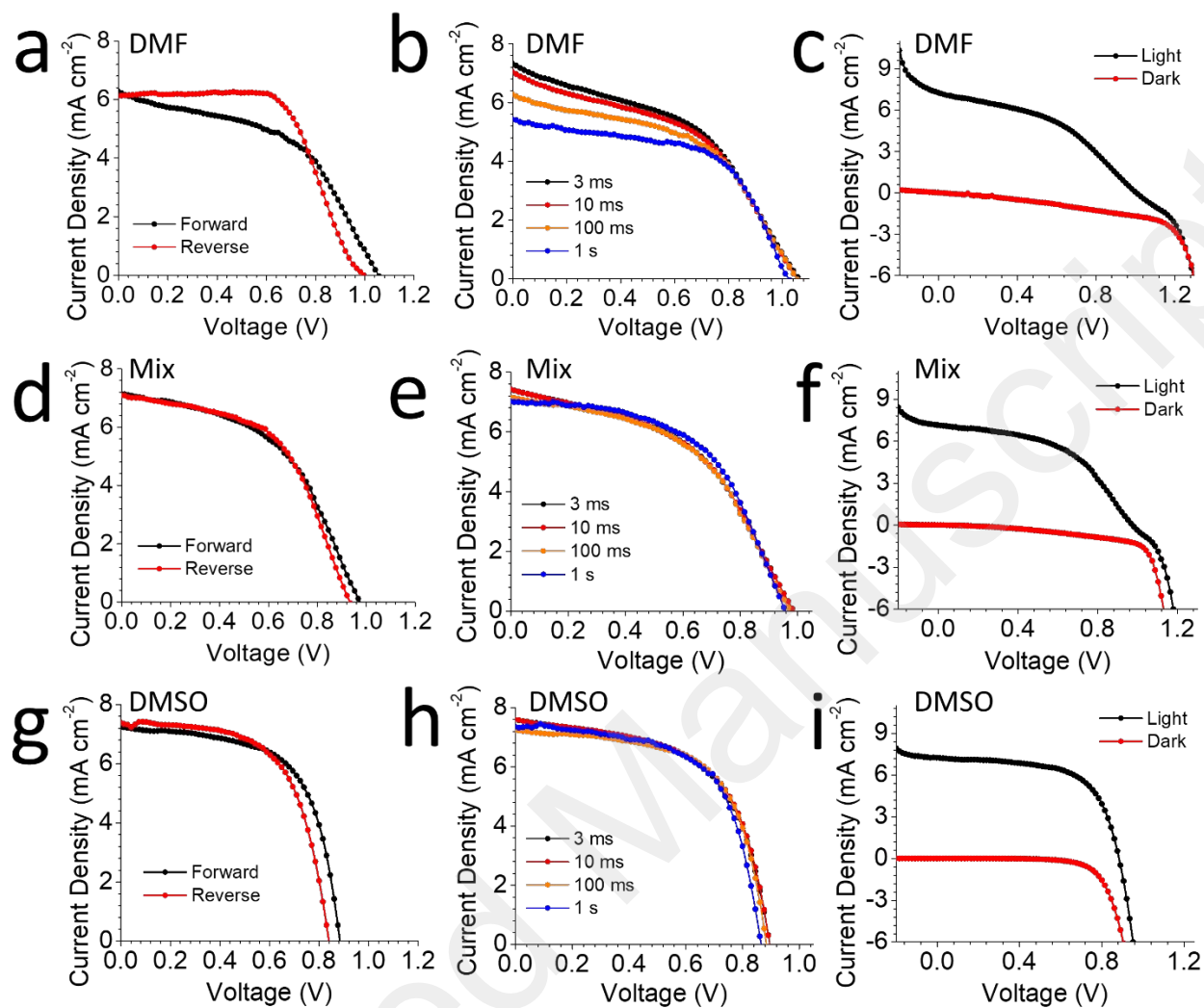


Figure 9. Device analysis for the $n = 3$ solar cells. (a-c) The devices made with pure DMF solutions show a high degree of hysteresis based on scan direction and scan speed as well as low R_{SH} and high R_S . (d-f) Devices with 50% DMSO/ 50% DMF show little hysteresis and less leakage. (g-i) Devices with pure DMSO have negligible hysteresis, leakage, and series resistance.

TOC Graphic:

