

UC Berkeley

UC Berkeley Previously Published Works

Title

Ligand Mediated Transformation of Cesium Lead Bromide Perovskite Nanocrystals to Lead Depleted Cs₄PbBr₆ Nanocrystals

Permalink

<https://escholarship.org/uc/item/9z08s421>

Journal

Journal of the American Chemical Society, 139(15)

ISSN

0002-7863

Authors

Liu, Zeke

Bekenstein, Yehonadav

Ye, Xingchen

et al.

Publication Date

2017-04-19

DOI

10.1021/jacs.7b01409

Peer reviewed

Ligand Mediated Transformation of Cesium Lead Bromide Perovskite Nanocrystals to Lead Depleted Cs_4PbBr_6 Nanocrystals

Zeke Liu,^{†,‡,||} Yehonadav Bekenstein,^{‡,||} Xingchen Ye,[‡] Son C. Nguyen,[‡] Joseph Swabeck,^{‡,||} Dandan Zhang,^{‡,||} Shuit-Tong Lee,[†] Peidong Yang,^{‡,§,||,⊥} Wanli Ma,^{*,†} and A. Paul Alivisatos^{*,‡,§,||,⊥}

[†]Institute of Functional Nano & Soft Materials (FUNSOM), Collaborative Innovation Center of Suzhou Nano Science and Technology, Soochow University, Suzhou, Jiangsu 215123, China

[‡]Department of Chemistry, University of California Berkeley, Berkeley, California 94720, United States

[§]Department of Materials Science and Engineering, University of California Berkeley, Berkeley, California 94720, United States

^{||}Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States

[⊥]Kavli Energy NanoScience Institute, University of California Berkeley and Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States

Supporting Information

ABSTRACT: Lead halide perovskite nanocrystals (NCs) have emerged as attractive nanomaterials owing to their excellent optical and optoelectronic properties. Their intrinsic instability and soft nature enable a post-synthetic controlled chemical transformation. We studied a ligand mediated transformation of presynthesized CsPbBr_3 NCs to a new type of lead–halide depleted perovskite derivative nanocrystal, namely Cs_4PbBr_6 . The transformation is initiated by amine addition, and the use of alkyl-thiol ligands greatly improves the size uniformity and chemical stability of the derived NCs. The thermodynamically driven transformation is governed by a two-step dissolution–recrystallization mechanism, which is monitored optically. Our results not only shed light on a decomposition pathway of CsPbBr_3 NCs but also present a method to synthesize uniform colloidal Cs_4PbBr_6 NCs, which may actually be a common product of perovskite NCs degradation.

Postsynthetic chemical transformations, such as ion-exchange reactions,¹ galvanic replacement,² or the nanoscale Kirkendall effect,³ can be easily realized in colloidal nanocrystals (NCs) due to their high surface-to-volume ratios and short diffusion path lengths. These transformations give access to a myriad of novel structures that are difficult or impossible to synthesize directly. Lead–halide perovskite NCs including organic–inorganic hybrid perovskites, $\text{CH}_3\text{NH}_3\text{PbX}_3$ ($X = \text{Cl}, \text{Br}, \text{I}$),⁴ and all-inorganic perovskites, CsPbX_3 ,⁵ have emerged as attractive optoelectronic semiconductors. Ion-exchange transformations have been successfully applied to create various halide compositions of perovskite NCs owing to the high migration mobility of the halide anions.⁶

The ionic nature of lead halide perovskites results in their chemical instability in polar solvents.⁷ As a result, it is also more challenging to find the right conditions for exchanging their surface ligands compared to traditional II–VI, III–V, and IV–VI semiconducting NCs, commonly leading to crystal degradation. Understanding the degradation mechanism of these NCs is

therefore a prerequisite for implementation in real-life applications. Meanwhile, the “soft nature” (high ion mobility⁸ and dynamic surface ligand binding⁹) of lead perovskite NCs position them as interesting candidates for studying chemical and crystallographic transformations.

Two stable compounds exist in the phase diagram of a mixed system of CsX–PbX_2 ($X = \text{Cl}, \text{Br}$), the incongruent ternary compounds Cs_4PbX_6 and the congruent compounds CsPbX_3 .¹⁰ The different crystal structures of CsPbX_3 and the lower-symmetry, lead–halide depleted Cs_4PbX_6 are highlighted in Figure 1. In Cs_4PbX_6 , the PbBr_6^{4-} octahedra are separated by

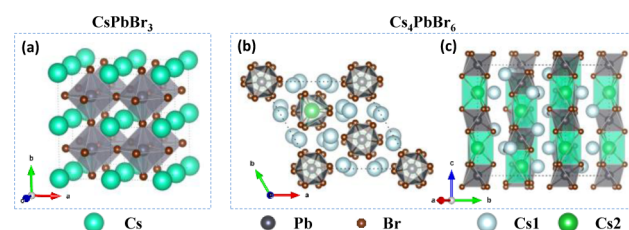


Figure 1. Schematic crystal structure of (a) CsPbBr_3 and Cs_4PbBr_6 (b) along and (c) perpendicular to c axis.

$\text{Cs}^+(2)$ trigonal prisms (there are two distinct kinds of Cs^+ ions in Cs_4PbX_6 crystal, marked as (1) and (2)), forming one-dimensional $[\text{CsPbX}_6]_n^{3-}$ chains. These chains are further isolated from each other by $\text{Cs}^+(1)$ distorted dodecahedra (Figure 1b,c).¹¹ In contrast, CsPbX_3 possesses a higher symmetry simple cubic structure with connected corner-sharing PbBr_6^{4-} octahedra (Figure 1a). Although there have been several reports on bulk Cs_4PbX_6 ,^{10b,12} Cs_4PbX_6 NCs are less investigated, with only several reports¹³ published during the review of this paper.

In this work, we represent a new type of chemical transformation from presynthesized CsPbBr_3 NCs to a lead–halide depleted perovskite derivative Cs_4PbBr_6 NCs. This

Received: February 9, 2017

Published: March 30, 2017

transformation is governed by a two-step dissolution–recrystallization mechanism and mediated by alterations in the ligand shell environment. We study the effect of oleylamine (OLA) and various alkyl thiols. We find that OLA is essential to trigger the process, presumably facilitating the decomposition of CsPbBr₃ NCs through “ligand-assisted exfoliation”.¹⁴ Upon recrystallization, the presence of alkyl-thiol ligands will greatly improve the size uniformity and chemical stability of the derived Cs₄PbBr₆ NCs. We report the degradation pathway of CsPbX₃ NCs and present a new method to access stable uniform Cs₄PbBr₆ NCs.

Synthesis of CsPbBr₃ NCs was performed according to published protocols.^{5a} The transformation process was carried out under ambient conditions at room temperature (Supporting Information (SI)). We found that the photoluminescence (PL) of initially bright CsPbBr₃ NCs was quenched upon adding alkyl thiols together with a trace amount of OLA. The emission loss is correlated with a morphological transformation from CsPbBr₃ nanocubes to polygonal NCs (Figure 2a–c). These newly

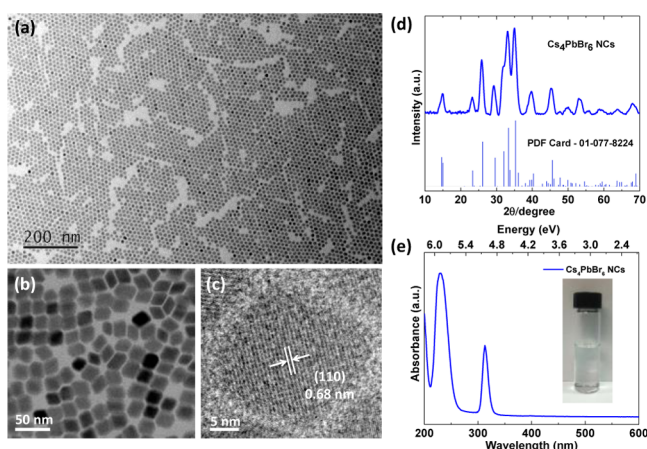


Figure 2. (a,b) Typical TEM image of Cs₄PbBr₆ NCs with different magnifications. (c) HRTEM of a single Cs₄PbBr₆ NC. (d) XRD spectra of trigonal phase Cs₄PbBr₆ NCs with $R\bar{3}c$ space group compared to the standard powder diffraction pattern of bulk Cs₄PbBr₆ ($\lambda_{\text{Co-K}\alpha} = 1.79 \text{ \AA}$). (e) Absorption spectrum of Cs₄PbBr₆ NCs in hexane. Inset shows the photograph of the colorless Cs₄PbBr₆ NCs hexane solution.

derived NCs were characterized by X-ray diffraction (XRD), which matches the diffraction pattern of the rhombohedral Cs₄PbBr₆ phase (Figure 2d). Transmission electron microscopy (TEM) images show well-defined rhombus-shaped NCs (Figure 2b,c). The measured *d*-spacing of 0.68 nm from HRTEM (Figure 2c) agrees well with the {110} plane of rhombohedral Cs₄PbBr₆. The average size of the resulting Cs₄PbBr₆ NCs is $\sim 11.2 \text{ nm}$ (Figure S1b).

The transformed Cs₄PbBr₆ NCs exhibit very different optical properties compared with the initial CsPbBr₃ NCs, showing two sharp absorbance peaks at 220 and 313 nm (Figures 2e and S2). These absorbance features match well with those of bulk thin film, which have been confirmed as the localized $6s_{1/2}$ – $6p_{1/2}$ transitions within the individual PbBr₆⁴⁻ octahedral separated by intervening Cs⁺ ions.^{11,15} The solution is transparent across the visible spectrum, presenting a distinctly colorless appearance (Figure 2e insert). Furthermore, room-temperature emission centered at 375 nm was observed upon 313 nm excitation, which is also in line with the optical measurements carried out on bulk Cs₄PbBr₆ thin films at low temperature (4.2 K).^{10b} The luminescence quantum yield was reduced from as high as 70%

for the initial CsPbBr₃ NCs to values near the detection limit of our apparatus for the final Cs₄PbBr₆ NCs. Although our results are consistent with many early reports,^{10b,12a,15} we cannot ignore recent work on Cs₄PbBr₆ solids¹⁶ and NCs,^{13a} showing bright green emission at over 500 nm. Recently, Akkerman et al.^{13b} have verified these green emissions were from residual doping and untransformed CsPbBr₃ NCs. We further tried this transformation in other halide perovskite NCs. For CsPbCl₃ NCs (Figure S3), this procedure produced pure Cs₄PbCl₆ NCs which show sharp absorbance peaks at 285 nm, which is also consistent with previous reports on the pure bulk and NCs.^{12a,13b} However, we could not induce the transformation of CsPbI₃ NCs to Cs₄PbI₆ NCs.

The effect of different amines on the transformation was also investigated (Figure S4). Both 1-dodecanamine and 1-octylamine function similarly to OLA, giving Cs₄PbBr₆ NCs with nearly the same average size. However, 1-butylamine only gives a product with a very weak absorbance (that is also hard to observe in the TEM), and aniline results in a partial transformation. Additionally, Cs₄PbBr₆ NCs produced with shorter length thiols showed better stability than those with longer thiols. We further expanded the study of these transformations to also include alkyl dithiols with varying lengths. We observe all these can produce Cs₄PbBr₆ NCs. However, the NCs formed by using dithiols show better stability than those with monothiols (same carbon-chain length) (Figure S5). For example, Cs₄PbBr₆ NCs formed by using 1-dodecanethiol will partly transform back to initial CsPbBr₃ NCs, as indicated by the appearance of a PL peak at around 510–520 nm and XRD testing (Figure S6). In contrast, Cs₄PbBr₆ NCs produced by 1,3-propanedithiol (PDT) remain stable in hexane for several months without the reverse transformation occurring. In the following, we will focus on Cs₄PbBr₆ NCs created by PDT.

OLA was found to play a vital role in the transformation. As shown in Figure 3a, when we added OLA dropwise to the CsPbBr₃ NCs solution (PDT/Pb mol ratio = 1300), the 492 nm absorption of CsPbBr₃ decreases with the concomitant increase of the 313 nm absorption arising from Cs₄PbBr₆ NCs. The

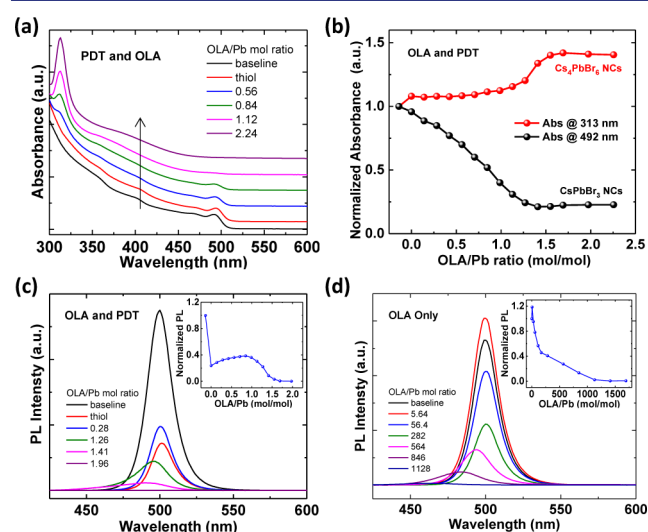
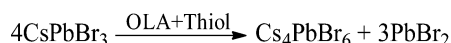


Figure 3. Effect of amount of OLA on the transformation behavior (a–c) with and (d) without PDT (see Figure S8 for absorbance). (a) Absorbance spectra. (b) Absorbance at two spectral features (492 and 313 nm). (c, d) PL spectra of CsPbBr₃ NCs solution after adding different amount of OLA.

evolution of the absorbance at these two spectral positions are plotted in Figure 3b, showing inverse dependence on the OLA concentration. Before adding OLA, large amounts of PDT almost have no effect on the absorption spectrum (Figure 3a), showing that the thiol cannot trigger the transformation unaided. However, the addition of PDT will cause reduction of the PL intensity of CsPbBr₃ NCs by about 80% (Figure 3c). The progressive introduction of OLA initially restores the PL (OLA/Pb < 0.84). However, excess OLA (OLA/Pb > 0.84) leads to reduction in the PL intensity, accompanied by blue-shifting and an increase in the full width half-maximum of the emission peak, suggesting the decomposition of the CsPbBr₃ NCs. After the transformation and isolation of the Cs₄PbBr₆ NCs, yellow precipitates were observed. Energy dispersive X-ray spectroscopy (EDS) analysis of these products detected only Pb, Br, and S signals, which suggested that the complex is primarily composed of PbBr₂ and thiols (Figure S7). Therefore, the transformation process can be outlined in Scheme 1.

Scheme 1. Transformation Process



We further investigated the thermodynamic boundaries of this transformation and found that pure excess OLA (more than 1000 times compared to the case with PDT) will also transform CsPbBr₃ to Cs₄PbBr₆ NCs (Figures 3d and S8). Markedly, the presence of PDT can largely reduce the amount of OLA required to trigger the transformation. This observation is rationalized by using hard–soft acid–base theory. Thiols bind strongly with PbBr₂ and precipitate it from solution, thermodynamically driving the reaction to the right side. Indeed, the immediate appearance of yellow precipitates when adding PDT to PbBr₂ solution supports this rationale. However, the size distribution and shape uniformity of the NCs produced by only OLA are of lower quality (Figure S9). Moreover, NCs formed without thiols are less stable and decompose as confirmed by XRD and the loss of the sharp absorbance around 313 nm (Figure S10). X-ray photoelectron spectroscopy (XPS), Fourier-transform infrared (FTIR), and nuclear magnetic resonance (NMR) were performed to study the surfaces of Cs₄PbBr₆ NCs (produced by both OLA and PDT). High-resolution XPS testing shows the signals of sulfur, which can be assigned to bound thiolate and unbound thiol (or sulfite) (Figure S11b).¹⁷ Meanwhile, FTIR spectra showed drastic differences between Cs₄PbBr₆ NCs and the initial CsPbBr₃ NCs (Figure S12). Specially, the peak around 800 cm⁻¹ can be assigned to sulfur–metal bonds,¹⁸ demonstrating that thiols serve as part of the capping ligands for the final Cs₄PbBr₆ NCs, which may be the reason for the improvement in their stability.

To further probe the mechanism of this transformation, we performed a kinetic study to monitor the reaction progression. The result from the *in situ* UV–vis absorption study is presented in Figure 4a. After injecting a solution mixture of PDT and OLA to a hexane solution of CsPbBr₃ NCs, the absorbance decreases immediately across the whole spectral range due to the concentration reduction. Afterward, the transformation process can be divided into two steps. First, the absorbance at 492 nm decreases to a constant value, which indicates the decomposition of CsPbBr₃ NCs (Figure S14a). This process persists for about 18 s, during which the PL intensity fluctuates (decreasing, increasing and decreasing again). The PL intensity was completely quenched after 15–20 s (Figure 4c,d), which

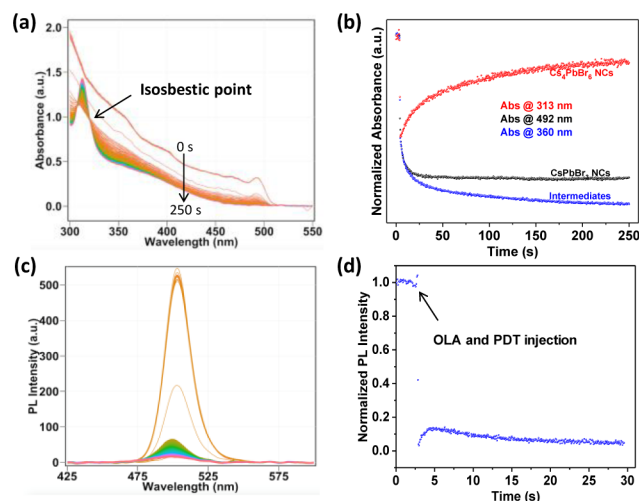


Figure 4. Optical monitoring of the transformation process from CsPbBr₃ NCs to Cs₄PbBr₆ NCs under treatment of OLA and PDT. (a) Time-resolved absorbance spectra. The time resolution is around 300 ms. (b) Temporal evolution of the absorbance at three spectral features in (a): 492, 360, and 313 nm. (c) Time-resolved PL spectra. The time resolution is around 80 ms. (d) Temporal evolution of PL intensity.

matches well with the time scale (18 s) for the absorbance to reduce to a constant value. The second step involves the development of a peak at 313 nm and a broad spectral feature in the region centered at around 360 nm (Figure S14b). The duration of this step is about 240 s. We plotted the evolution of the absorbance at three spectral positions (313, 360, and 492 nm) as a function of time during the whole transformation process (Figure 4b). The growing of the absorbance at 313 nm is concomitant with the decay of the 360 nm peak. A distinct isosbestic point appeared at 322 nm in the absorbance spectra (Figures 4a and S14b). The kinetic study of the transformation process with only OLA shows almost the same trend but with a much slower decomposition of CsPbBr₃ NCs (200 s compared to 18 s in the presence of PDT; see Figure S15). The existence of an isosbestic point indicates that one species is quantitatively transformed into another by complexation,¹⁹ suggesting Cs₄PbBr₆ NCs are quantitatively transformed from some intermediates with an absorbance around 360 nm. Based on the investigation of complexation between Pb²⁺ and different amounts of Br⁻,²⁰ the broad absorbance around 360 nm could be assigned to [PbBr₄]²⁻, corresponding to a monolayer perovskite structure.²¹ The existence of [PbBr₄]²⁻ intermediates could be supported by the small amounts of sheet structures observed in the crude solution after transformation during TEM testing (Figure S16). The detailed mechanism of this process still requires further investigation and supporting data.

In conclusion, a ligand mediated controlled transformation of presynthesized CsPbBr₃ NCs to lead depleted perovskite derivative Cs₄PbBr₆ NCs was reported. While OLA by itself can trigger this process, we have found that by adding alkyl-thiol ligands the size uniformity and chemical stability of the Cs₄PbBr₆ NCs are greatly improved. This thermodynamic transformation process follows a two-step dissolution–recrystallization mechanism which we were able to resolve through optical spectroscopy. This postsynthetic chemical transformation is important in the greater context of improving the stability of lead–halide perovskites. Additionally, it serves as a practical method to achieve monodisperse Cs₄PbBr₆ NCs, broadening the library of metal–halide perovskite nanomaterials.

■ ASSOCIATED CONTENT

S Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.7b01409.

Experimental details, particle characterization, detailed descriptions of fittings (PDF)

■ AUTHOR INFORMATION

Corresponding Authors

*wlma@suda.edu.cn

*alivis@berkeley.edu

ORCID 

Yehonadav Bekenstein: 0000-0001-6230-5182

Son C. Nguyen: 0000-0001-7713-4195

Joseph Swabeck: 0000-0003-2235-2472

Shuit-Tong Lee: 0000-0003-1238-9802

Peidong Yang: 0000-0003-4799-1684

A. Paul Alivisatos: 0000-0001-6895-9048

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, Materials Sciences and Engineering Division, under Contract No. DE-AC02-05-CH11231 within the Physical Chemistry of Inorganic Nanostructures Program (KC3103), by the National Key Research Projects (Grant No. 2016YFA0202402), the National Natural Science Fund (Grant No. 61674111), and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD). Z.L. thanks the National Postdoctoral Program for Innovative Talents (Grant No. BX201600113), State-Sponsored Scholarship for Graduate Students from China Scholarship Council. The authors kindly thank Dan Oron for his insightful ideas and also Brent A. Koscher, Matthew Koc, Alexander Buyanin, and Aizhao Pan for useful discussions, Rongbin Wang for XPS testing, and Hongyuan Jia for assisting the drawing process.

■ REFERENCES

- (1) (a) Son, D. H.; Hughes, S. M.; Yin, Y.; Alivisatos, A. P. *Science* **2004**, *306*, 1009. (b) De Trizio, L.; Manna, L. *Chem. Rev.* **2016**, *116*, 10852.
- (2) Xia, X.; Wang, Y.; Ruditskiy, A.; Xia, Y. *Adv. Mater.* **2013**, *25*, 6313.
- (3) (a) Yin, Y.; Rioux, R. M.; Erdonmez, C. K.; Hughes, S.; Somorjai, G. A.; Alivisatos, A. P. *Science* **2004**, *304*, 711. (b) Wang, W.; Dahl, M.; Yin, Y. *Chem. Mater.* **2013**, *25*, 1179.
- (4) (a) Schmidt, L. C.; Pertegas, A.; Gonzalez-Carrero, S.; Malinkiewicz, O.; Agouram, S.; Minguez Espallargas, G.; Bolink, H. J.; Galian, R. E.; Perez-Prieto, J. *J. Am. Chem. Soc.* **2014**, *136*, 850. (b) Vybornyi, O.; Yakunin, S.; Kovalenko, M. V. *Nanoscale* **2016**, *8*, 6278. (c) Protesescu, L.; Yakunin, S.; Bodnarchuk, M. I.; Bertolotti, F.; Masciocchi, N.; Guagliardi, A.; Kovalenko, M. V. *J. Am. Chem. Soc.* **2016**, *138*, 14202.
- (5) (a) Bekenstein, Y.; Koscher, B. A.; Eaton, S. W.; Yang, P.; Alivisatos, A. P. *J. Am. Chem. Soc.* **2015**, *137*, 16008. (b) Protesescu, L.; Yakunin, S.; Bodnarchuk, M. I.; Krieg, F.; Caputo, R.; Hendon, C. H.; Yang, R. X.; Walsh, A.; Kovalenko, M. V. *Nano Lett.* **2015**, *15*, 3692. (c) Pan, A.; He, B.; Fan, X.; Liu, Z.; Urban, J. J.; Alivisatos, A. P.; He, L.; Liu, Y. *ACS Nano* **2016**, *10*, 7943. (d) Zhang, D.; Eaton, S. W.; Yu, Y.; Dou, L.; Yang, P. *J. Am. Chem. Soc.* **2015**, *137*, 9230.
- (6) (a) Nedelcu, G.; Protesescu, L.; Yakunin, S.; Bodnarchuk, M. I.; Grotevent, M. J.; Kovalenko, M. V. *Nano Lett.* **2015**, *15*, 5635. (b) Akkerman, Q. A.; D'Innocenzo, V.; Accornero, S.; Scarpellini, A.;

Petrozza, A.; Prato, M.; Manna, L. *J. Am. Chem. Soc.* **2015**, *137*, 10276. (c) Koscher, B. A.; Bronstein, N. D.; Olshansky, J. H.; Bekenstein, Y.; Alivisatos, A. P. *J. Am. Chem. Soc.* **2016**, *138*, 12065.

(7) Kim, Y.; Yassitepe, E.; Voznyy, O.; Comin, R.; Walters, G.; Gong, X.; Kanjanaboos, P.; Nogueira, A. F.; Sargent, E. H. *ACS Appl. Mater. Interfaces* **2015**, *7*, 25007.

(8) (a) Mizusaki, J.; Arai, K.; Fueki, K. *Solid State Ionics* **1983**, *11*, 203. (b) Eames, C.; Frost, J. M.; Barnes, P. R.; O'Regan, B. C.; Walsh, A.; Islam, M. S. *Nat. Commun.* **2015**, *6*, 7497.

(9) De Roo, J.; Ibanez, M.; Geiregat, P.; Nedelcu, G.; Walravens, W.; Maes, J.; Martins, J. C.; Van Driessche, I.; Kovalenko, M. V.; Hens, Z. *ACS Nano* **2016**, *10*, 2071.

(10) (a) Nitsch, K.; Cihlár, A.; Dušek, M.; Hamplová, V.; Nikl, M.; Rodová, M.; Ryšavá, N. *physica status solidi (a)* **1993**, *135*, 565. (b) Nikl, M.; Mihokova, E.; Nitsch, K.; Somma, F.; Giampaolo, C.; Pazzi, G.; Fabeni, P.; Zazubovich, S. *Chem. Phys. Lett.* **1999**, *306*, 280.

(11) Velázquez, M.; Ferrier, A.; Péchev, S.; Gravereau, P.; Chaminade, J.-P.; Portier, X.; Moncorgé, R. *J. Cryst. Growth* **2008**, *310*, 5458.

(12) (a) Kondo, S.-i.; Amaya, K.; Saito, T. *J. Phys. Soc. Jpn.* **2001**, *70*, 3751. (b) Kondo, S.; Masaki, A.; Saito, T.; Asada, H. *Solid State Commun.* **2002**, *124*, 211.

(13) (a) Zhang, Y.; Saidaminov, M. I.; Dursun, I.; Yang, H.; Murali, B.; Alarousu, E.; Yengel, E.; Alshankiti, B. A.; Bakr, O. M.; Mohammed, O. F. *J. Phys. Chem. Lett.* **2017**, *8*, 961. (b) Akkerman, Q. A.; Park, S.; Radicchi, E.; Nunzi, F.; Mosconi, E.; De Angelis, F.; Brescia, R.; Rastogi, P.; Prato, M.; Manna, L. *Nano Lett.* **2017**, *17*, 1924. (c) Udayabhaskararao, T.; Kazes, M.; Houben, L.; Teitelboim, A.; Oron, D. arXiv:1702.05382 [cond-mat.mtrl-sci].

(14) Hintermayr, V. A.; Richter, A. F.; Ehrat, F.; Doblinger, M.; Vanderlinden, W.; Sichert, J. A.; Tong, Y.; Polavarapu, L.; Feldmann, J.; Urban, A. S. *Adv. Mater.* **2016**, *28*, 9478.

(15) (a) Leguy, A. M. A.; Hu, Y.; Campoy-Quiles, M.; Alonso, M. I.; Weber, O. J.; Azarhoosh, P.; van Schilfgaarde, M.; Weller, M. T.; Bein, T.; Nelson, J.; Docampo, P.; Barnes, P. R. F. *Chem. Mater.* **2015**, *27*, 3397. (b) Christians, J. A.; Miranda Herrera, P. A.; Kamat, P. V. *J. Am. Chem. Soc.* **2015**, *137*, 1530.

(16) (a) Saidaminov, M. I.; Almutlaq, J.; Sarmah, S.; Dursun, I.; Zhumekenov, A. A.; Begum, R.; Pan, J.; Cho, N.; Mohammed, O. F.; Bakr, O. M. *ACS Energy Letters* **2016**, *1*, 840. (b) Rakita, Y.; Kedem, N.; Gupta, S.; Sadhanala, A.; Kalchenko, V.; Böhm, M. L.; Kulbak, M.; Friend, R. H.; Cahen, D.; Hodes, G. *Cryst. Growth Des.* **2016**, *16*, 5717. (c) Chen, D.; Wan, Z.; Chen, X.; Yuan, Y.; Zhong, J. *J. Mater. Chem. C* **2016**, *4*, 10646.

(17) (a) Tang, J.; Brzozowski, L.; Barkhouse, D. A. R.; Wang, X.; Debnath, R.; Wolowiec, R.; Palmiano, E.; Levina, L.; Pattantyus-Abraham, A. G.; Jamakosmanovic, D. *ACS Nano* **2010**, *4*, 869. (b) Cao, Y.; Stavrinadis, A.; Lasanta, T.; So, D.; Konstantatos, G. *Nature Energy* **2016**, *1*, 16035.

(18) (a) Reznickova, A.; Kolska, Z.; Siegel, J.; Svorcik, V. *J. Mater. Sci.* **2012**, *47*, 6297. (b) Li, Y.-S.; Li, S. *Spectrochim. Acta, Pt. A: Mol. Spectrosc.* **1994**, *50*, 509.

(19) (a) Schmidt, E.; Zhang, H.; Chang, C. K.; Babcock, G. T.; Oertling, W. A. *J. Am. Chem. Soc.* **1996**, *118*, 2954. (b) Yamamoto, K.; Higuchi, M.; Shiki, S.; Tsuruta, M.; Chiba, H. *Nature* **2002**, *415*, 509.

(20) (a) Oldenburg, K.; Vogler, A. *Zeitschrift für Naturforschung B* **1993**, *48*. (b) Yoon, S. J.; Stamplecoskie, K. G.; Kamat, P. V. *J. Phys. Chem. Lett.* **2016**, *7*, 1368.

(21) (a) Mitzi, D. B. *Prog. Inorg. Chem.* **2007**, *48*, 1. (b) Weidman, M. C.; Seitz, M.; Stranks, S. D.; Tisdale, W. A. *ACS Nano* **2016**, *10*, 7830. (c) Gonzalez-Carrero, S.; Espallargas, G. M.; Galian, R. E.; Perez-Prieto, J. *J. Mater. Chem. A* **2015**, *3*, 14039.