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Towards highly efficient and low cost quantum dot solar cells

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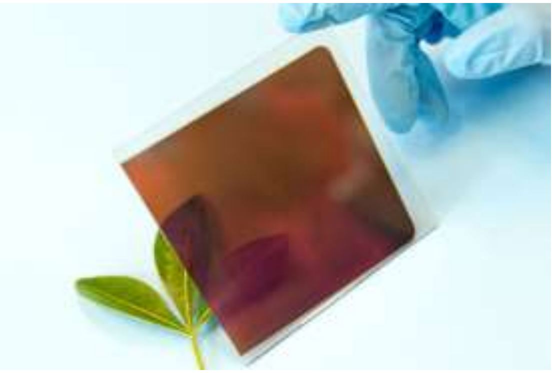
17 Dec 2021

Research background

	Silicon solar cells	Perovskite thin film solar cells	Perovskite QD solar cells
Efficiency	26.3%	25.2%	18.1%
Cost	\$0.70 / Watt	\$0.35 / Watt	-
Stability	> 25 years	<2 years	-
Fabrication	High energy consumption	Low temperature Solution method	Room temperature Facile printing



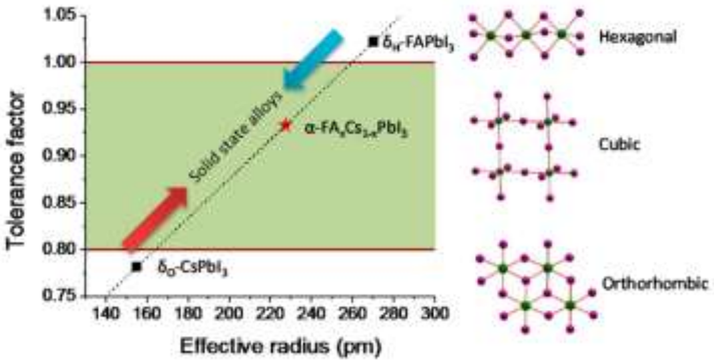
Stability: 1. Shelling by ligand or other material
2. Enlarged surface energy

Low cost: Cheap raw material, solution

Facile fabrication: Printable

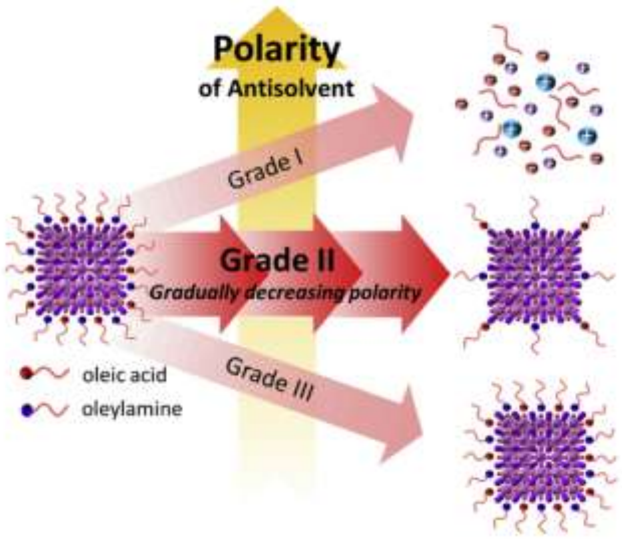
Outline:

- ✓ Improve performance: Composition and ligand management
- ✓ Advantage: QD vs Bulk
- ✓ Extended application: Semitransparent solar cell



$FAPbI_3$ t>1

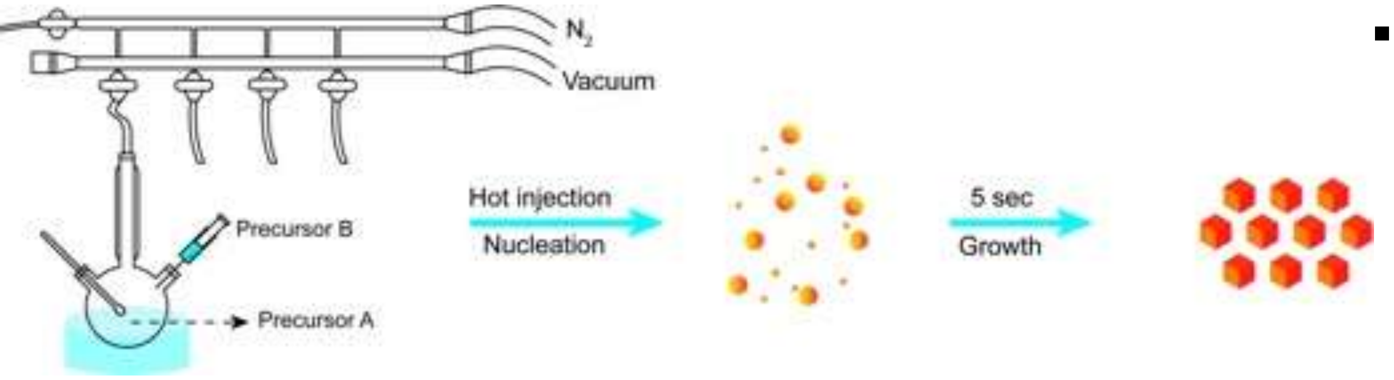
$CsPbI_3$ t<0.8



Chem. Mater. 2016, 28, 284–292

Joule 2, 1–13, September 19, 2018

Synthesis strategy

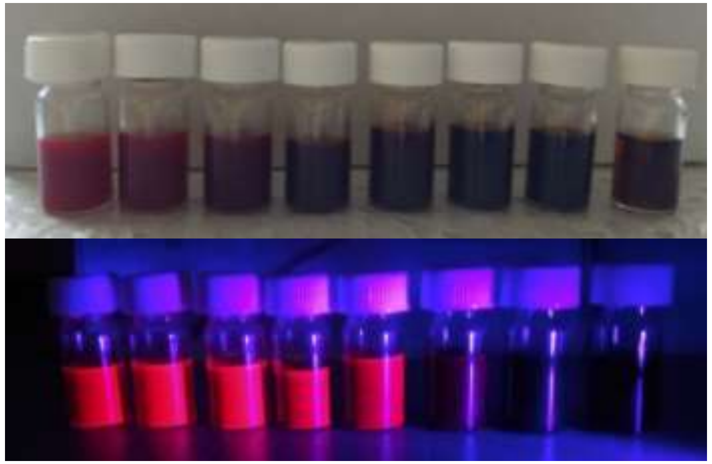


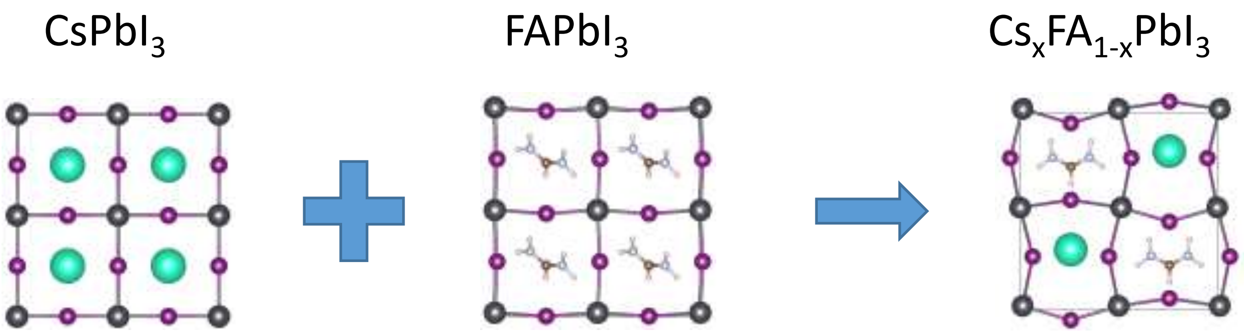
- Direct synthesis of $Cs_xFA_{1-x}PbI_3$ QDs is hard:

  Crystallization is fast, within seconds.

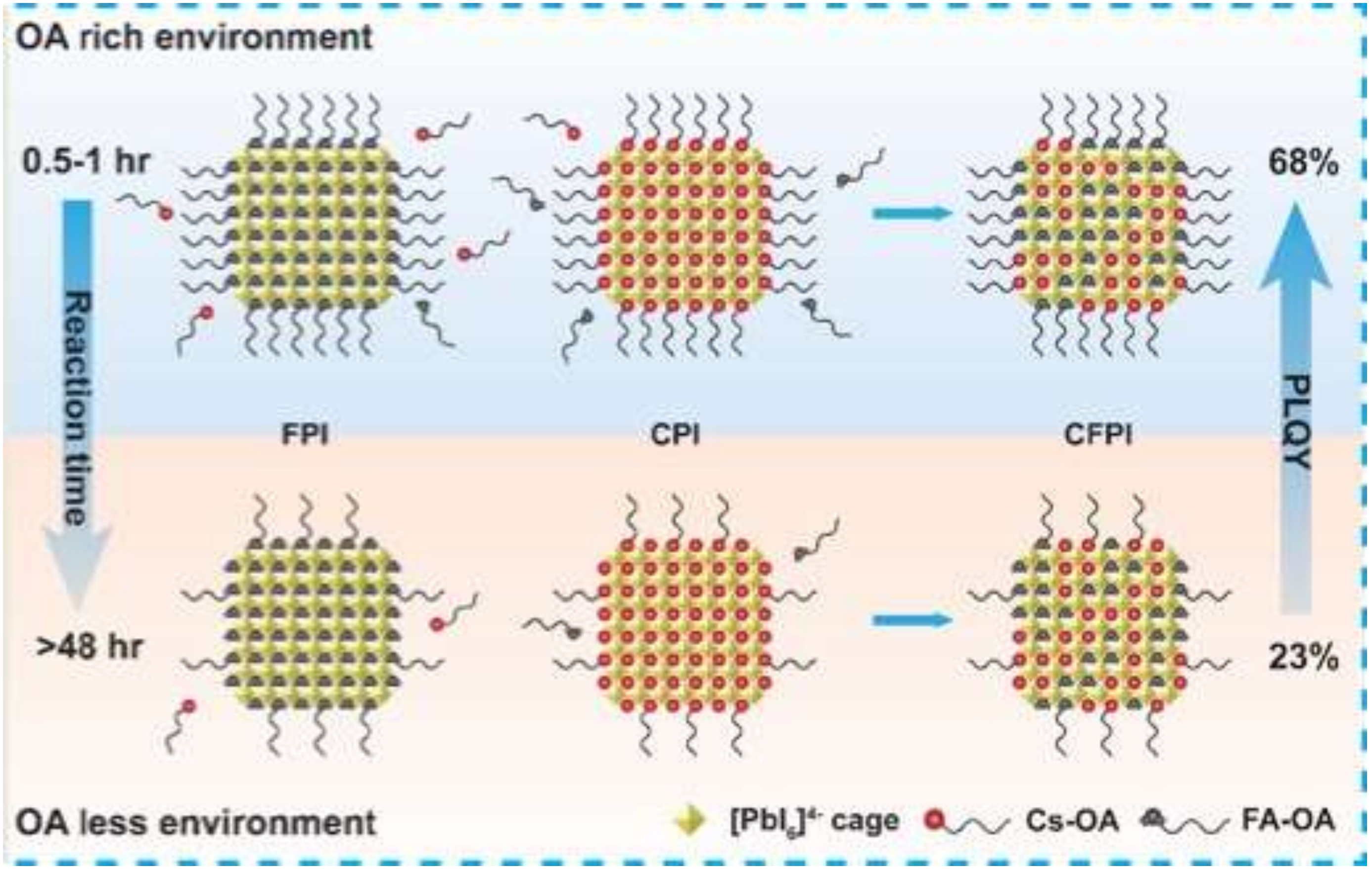
  Coordination force between A cations and PbI_6^{4-} cage is different:
  $Cs^+ > OLA^+ > FA^+$

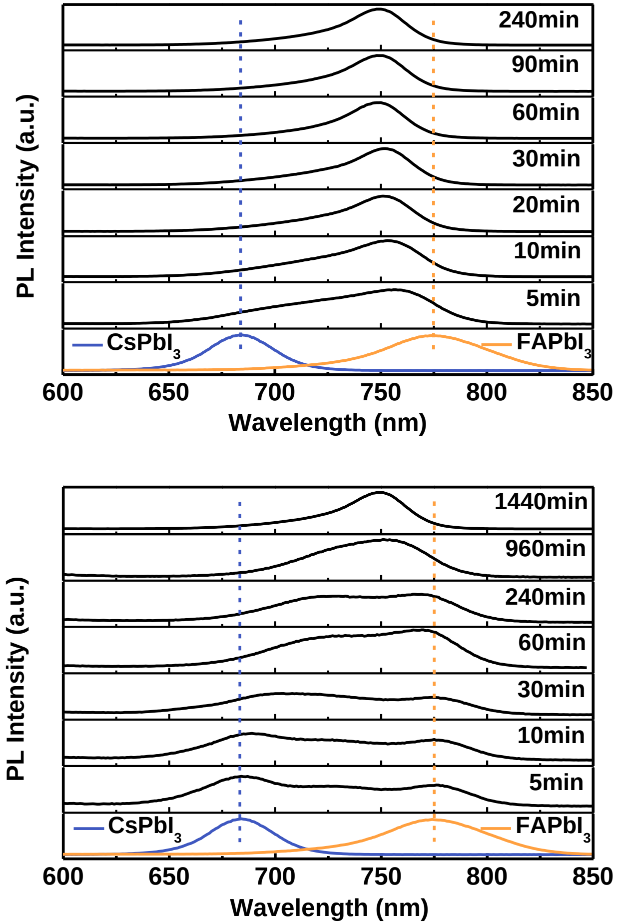
- Cation exchange method:



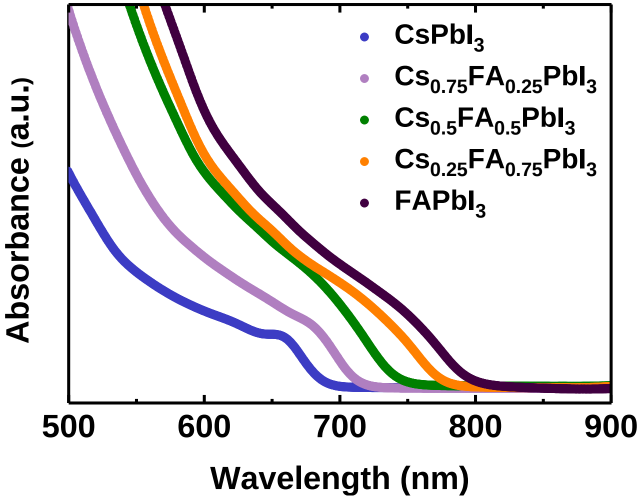


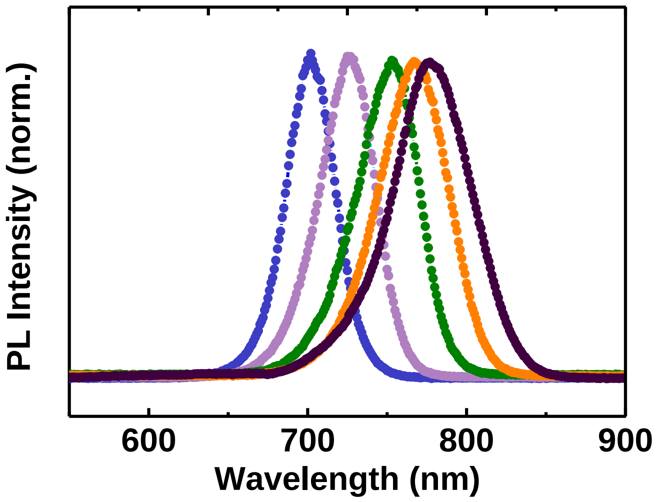
Ligand assisted cation exchange

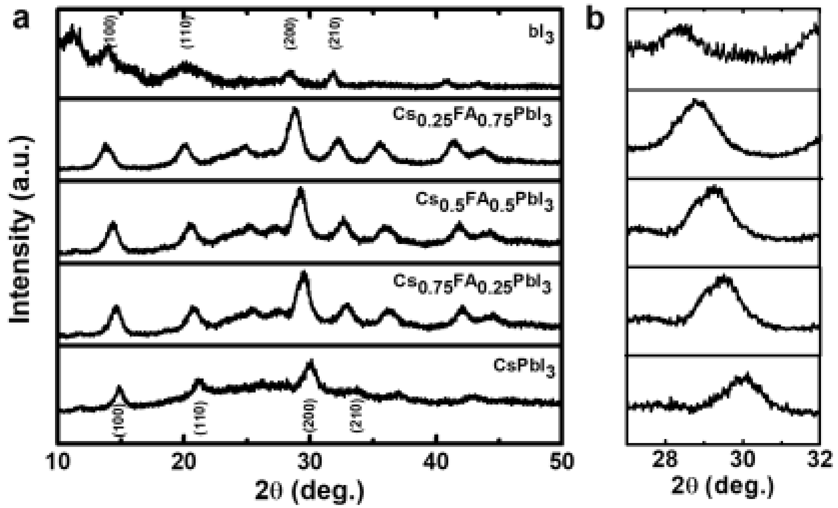


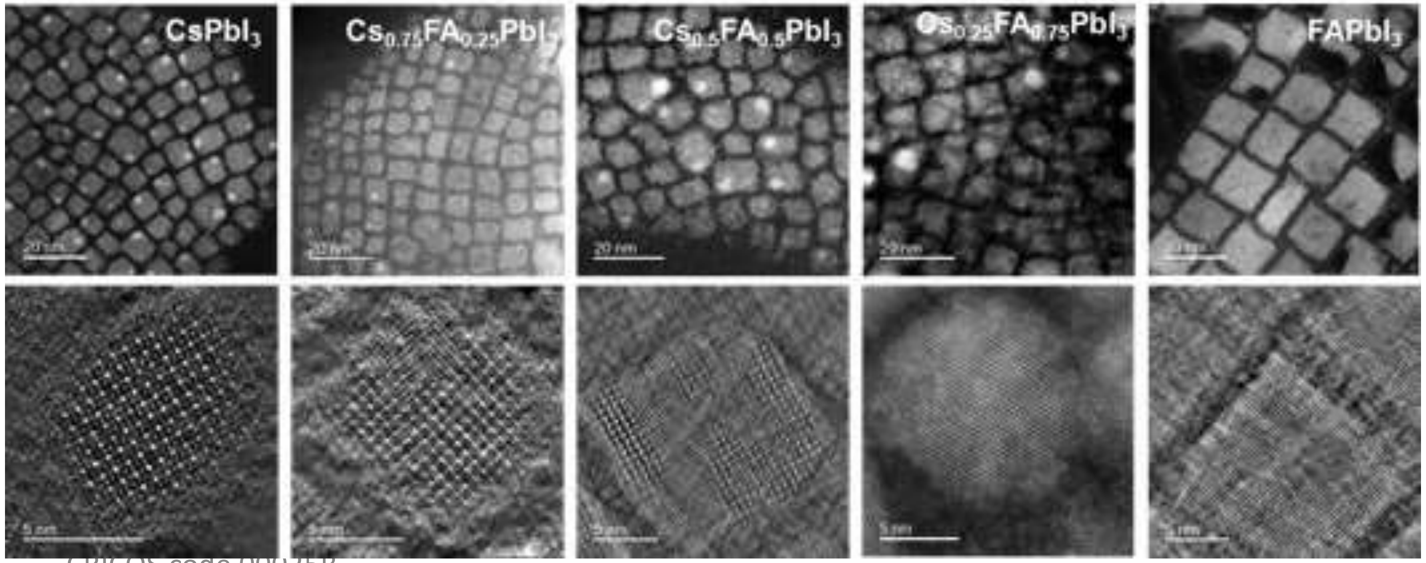


Optical and structure properties



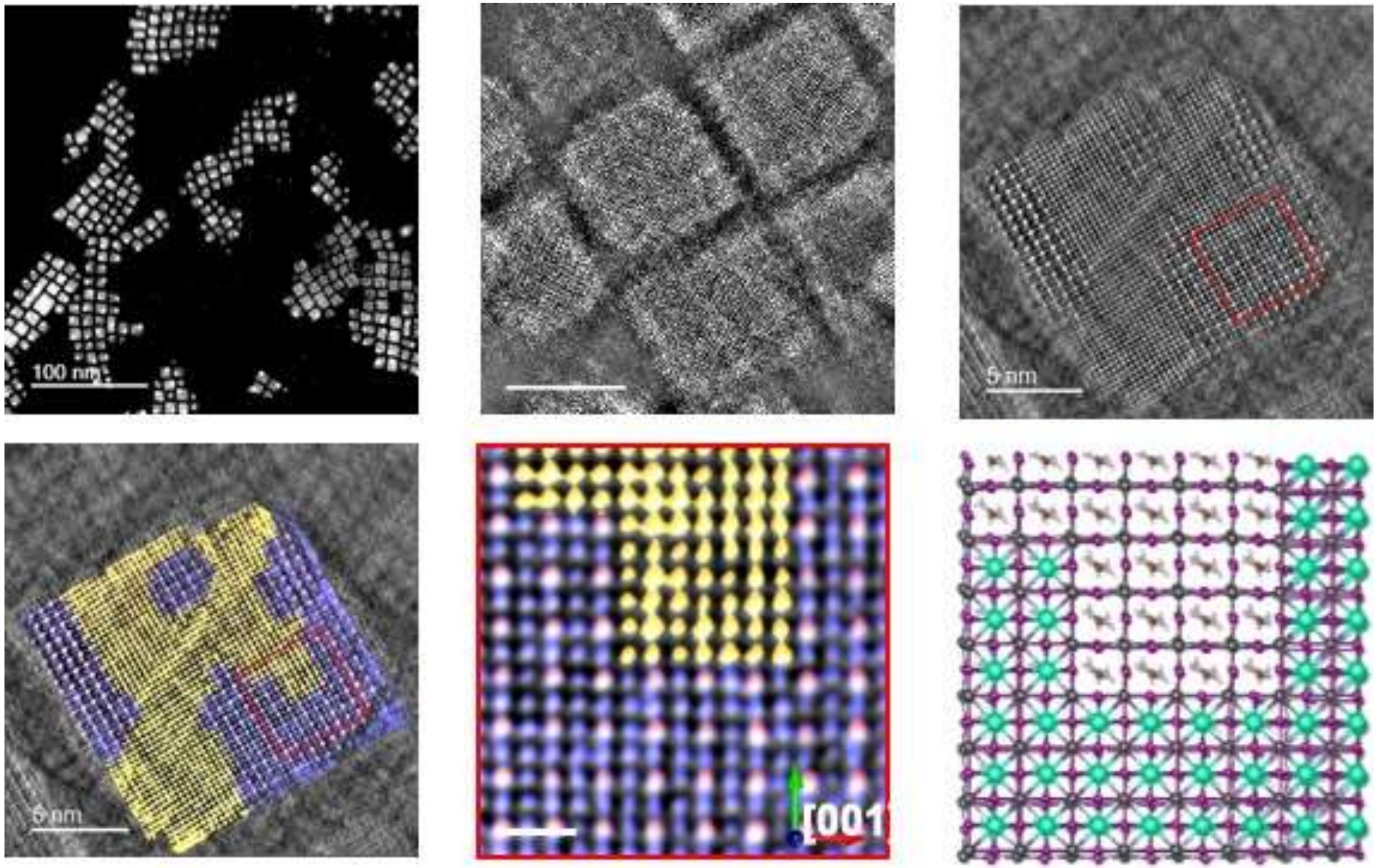






- Tuneable light absorption and PL wavelength
- Black phase perovskite structure
- Uniform particle size ~14 nm

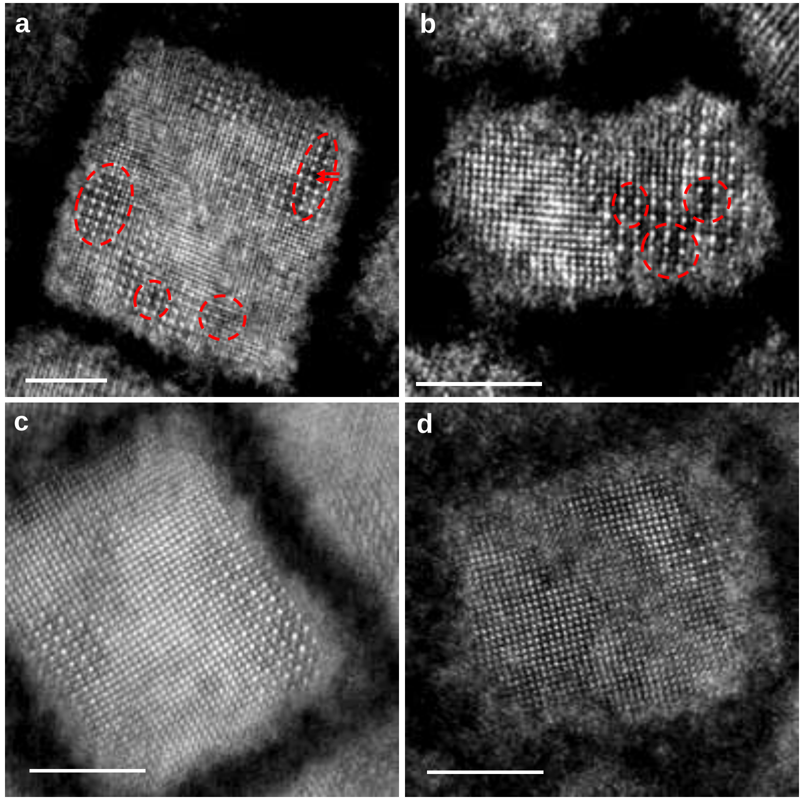
Distribution of A cation



In $Cs_{0.5}FA_{0.5}PbI_3$ QDs

Small $FAPbI_3$ and $CsPbI_3$ domains randomly distributed within an single crystalline particle

Ligands and defects:



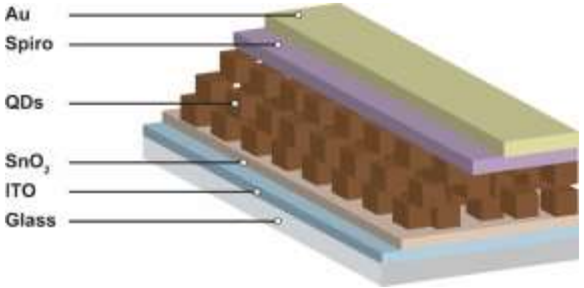
Atomic-resolution HAADF-STEM images of $Cs_{0.5}FA_{0.5}PbI_3$ QDs obtained in OA-less condition (a, b) and $Cs_{0.5}FA_{0.5}PbI_3$ QDs obtained in OA-rich condition (c, d). The circled areas indicate the defective sites.

Ligand density in perovskite QD solutions

Purification times	$CsPbI_3$	$FAPbI_3$
0	25-40	20-35
1	2.5-5.5	9-15
2	0.1-0.2	1-5
	$Cs_{1-x}FA_xPbI_3$	
0	2.5-10	
1	1.0-5.5	
2	0.1-0.5	

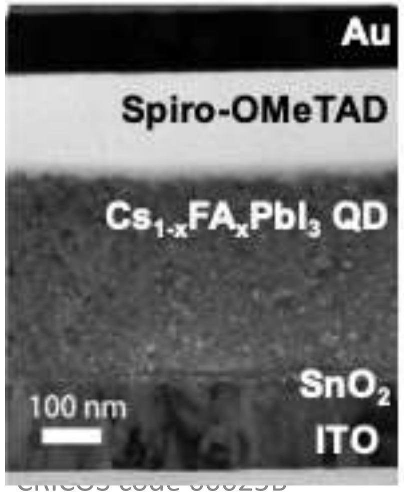
Performance of Solar cell device

Device fabrication

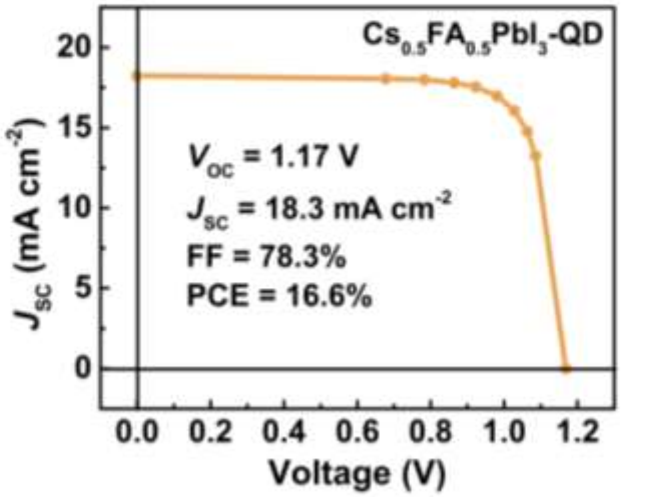


- *Separated process for crystallization and film formation*
- *Room temperature coating process*

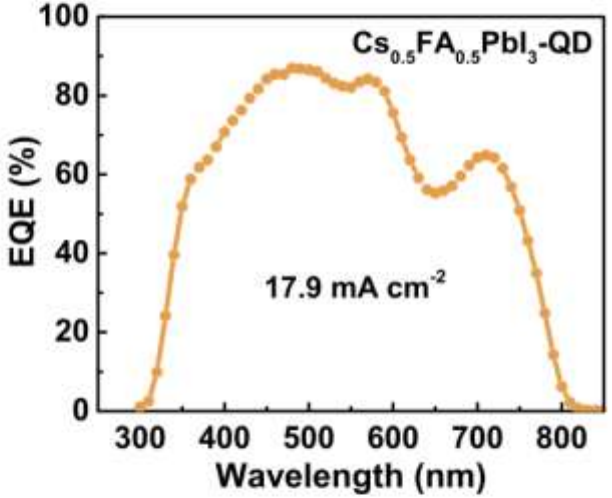
TEM cross-section image



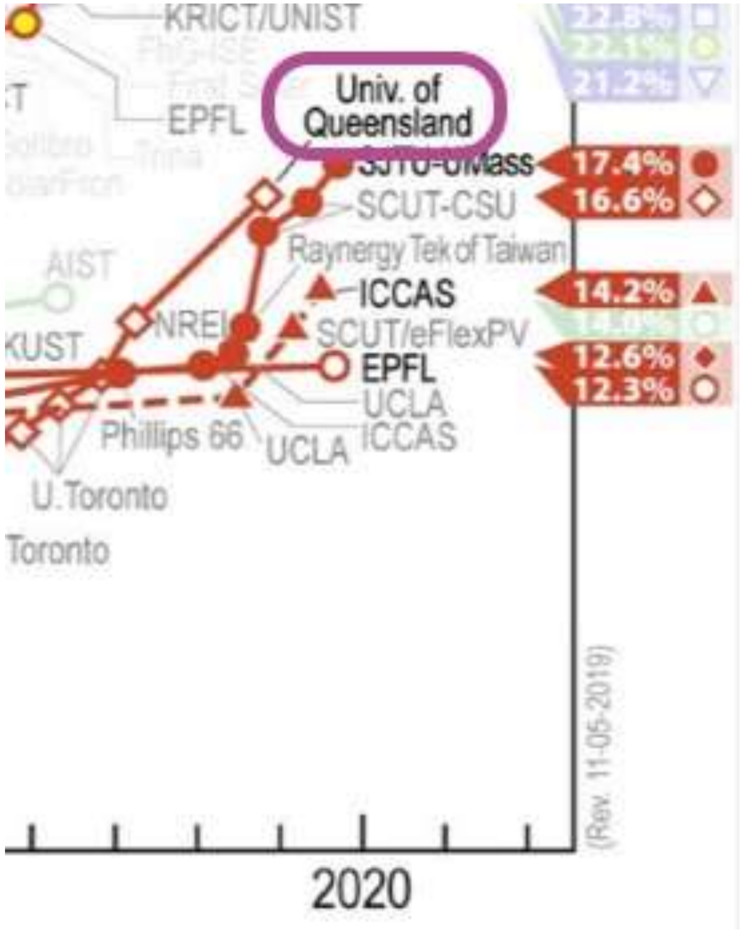
J–V measurement of champion device



External quantum efficiency



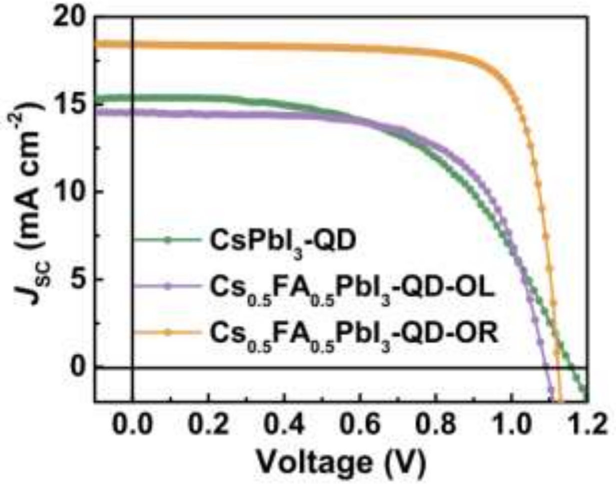
NREL Best Research Cell Efficiencies



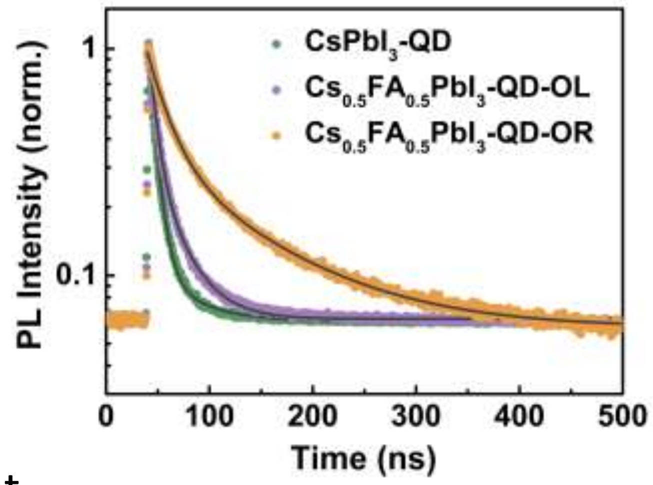
Defect reduction

Co-effect of FA alloying and rich ligands during synthesis

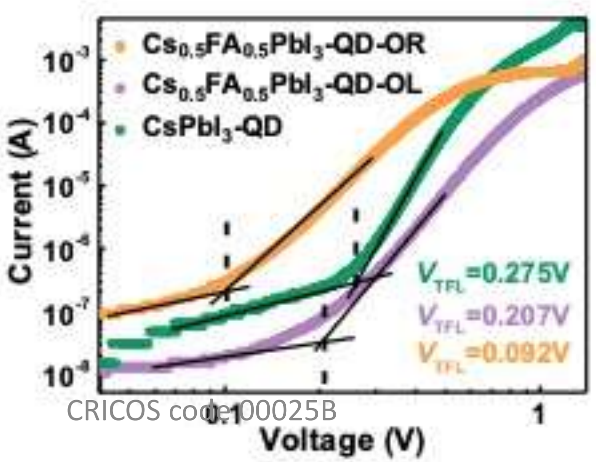
Solar cell performance



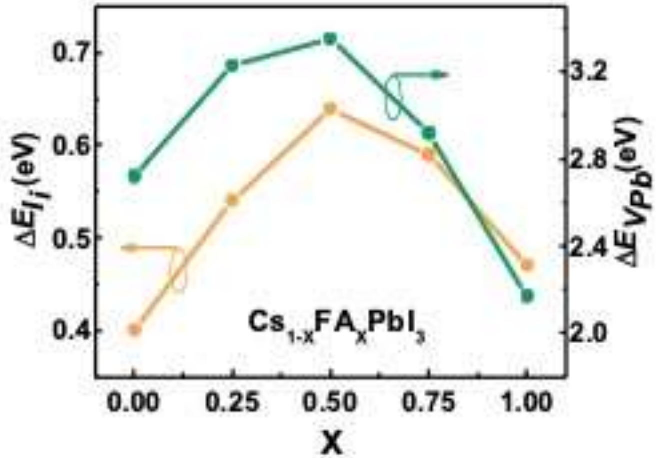
Time-resolved PL (TRPL) decay measurements



The space charge–limited current (SCLC) measurements

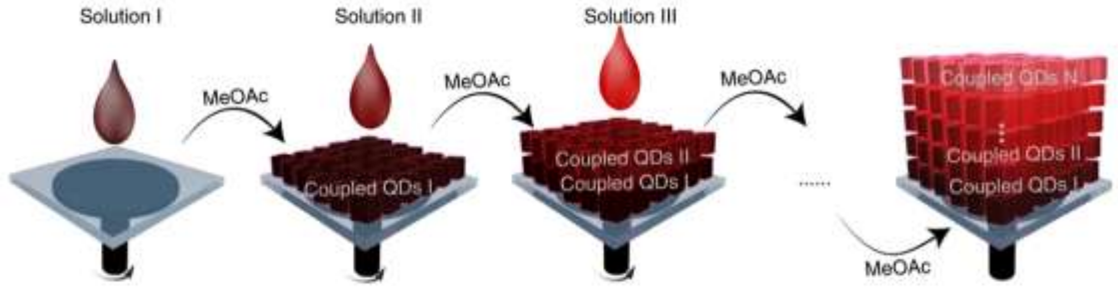


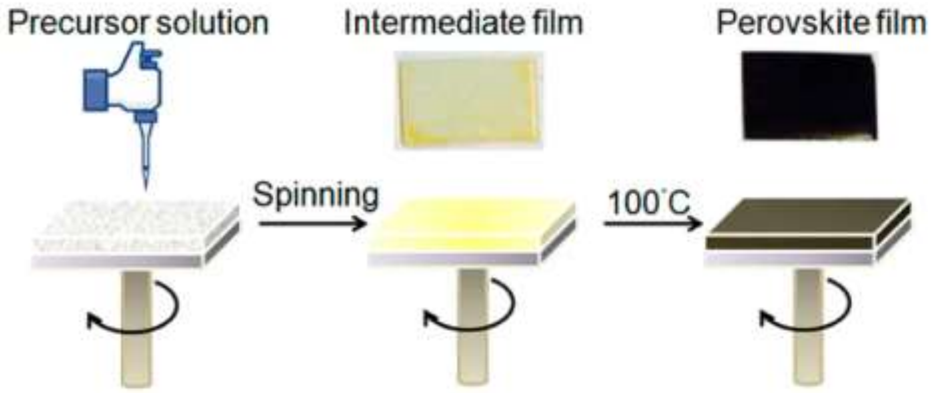
Defect formation energy



	$CsPbI_3$	$Cs_{0.5}FA_{0.5}PbI_3$ ligand rich	$Cs_{0.5}FA_{0.5}PbI_3$ ligand poor
PCE (%)	9.6	16.1	10.1
V_{oc} (V)	1.16	1.13	1.08
J_{sc} (mA cm^{-2})	15.4	18.4	14.6
FF (%)	53.9	77.9	64.1
Carrier lifetime (ns)	26	97	32
V_{tfl} (V)	0.092	0.207	0.275
Defect forming energy I_i (ΔE_{I_i}) (eV)	0.40	0.65	-
Defect forming energy V_{Pb} ($\Delta E_{V_{Pb}}$) (eV)	0.56	0.72	-

QDs vs bulk:





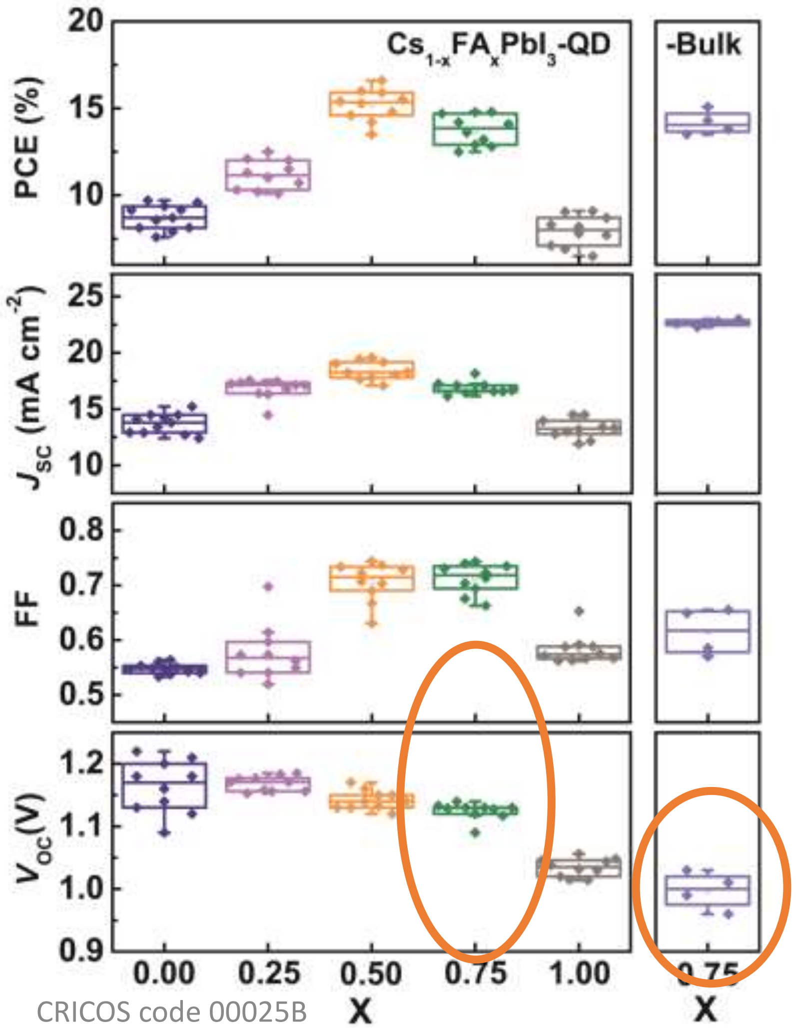
- Separated process for crystallization and film formation
- Room temperature coating process
- Ligand passivate defects and improve stability
- Impeded charge transport

- Large grain, high efficiency
- Substrate dependant
- Sensitive crystallinity control

Nat Commun **2019** *10, 2842*

Journal of the American Chemical Society **2015** *137* (35), 11445-11452

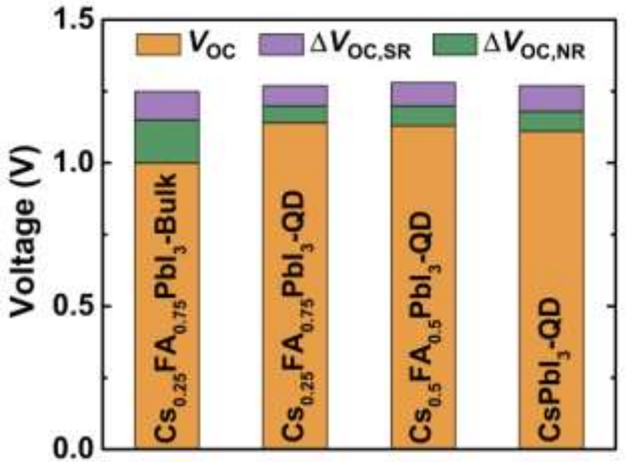
QDs vs bulk: reduction of non-radiative charge recombination



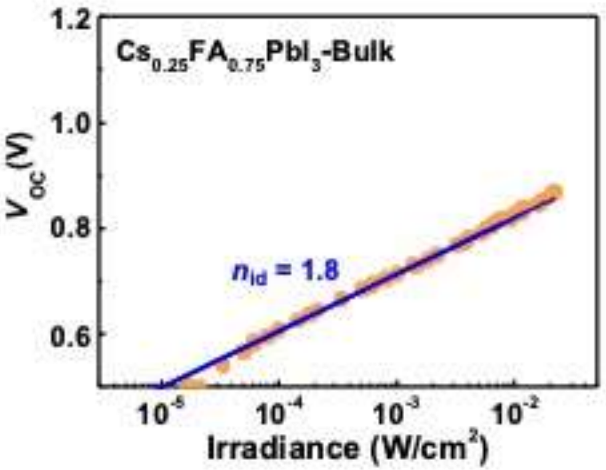
- Larger PLQY
- Ideal factor n_{id} of 1

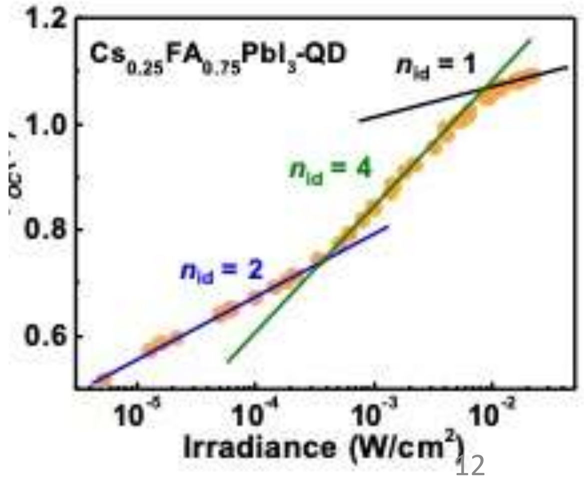
V_{oc} loss

Calculation from PLQY under V_{OC} condition

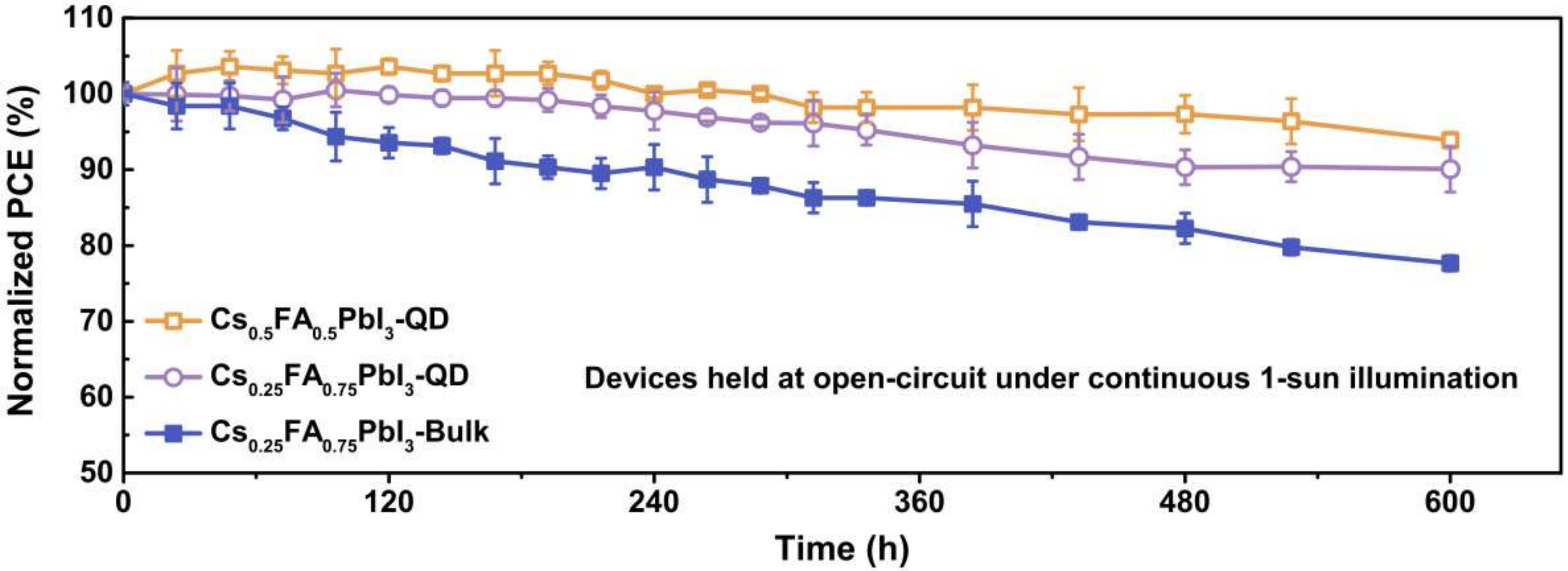


Light intensity dependent V_{OC} measurements





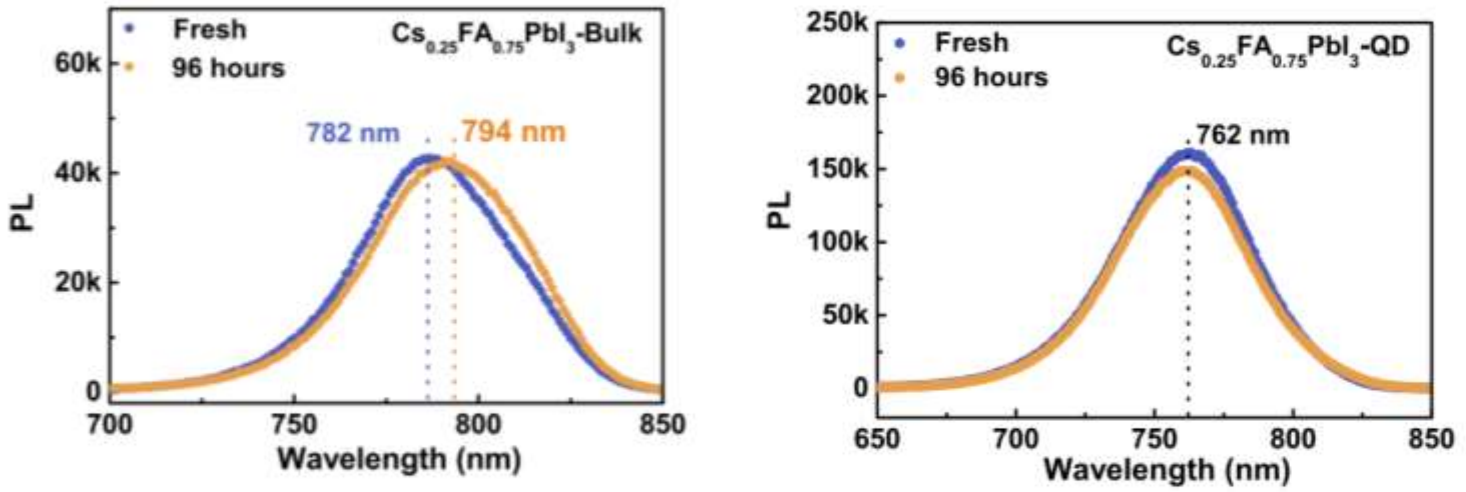
Device stability



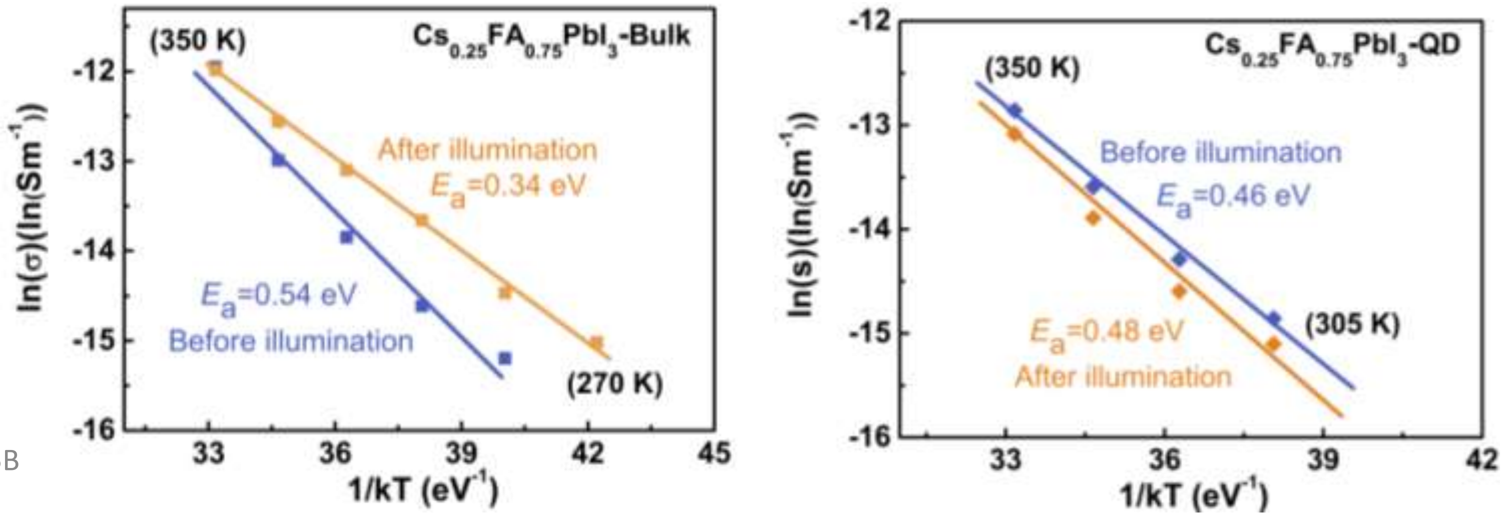
- ✓ $Cs_{0.25}FA_{0.75}PbI_3$-Bulk device. Quickly lost over ***20%*** of initial efficiency
- ✓ $Cs_{0.25}FA_{0.75}PbI_3$-QD devices. Retained ***90%*** of original PCEs.
- ✓ $Cs_{0.5}FA_{0.5}PbI_3$-QD devices. Retained ***94%*** of original PCEs.

Suppressed phase segregation

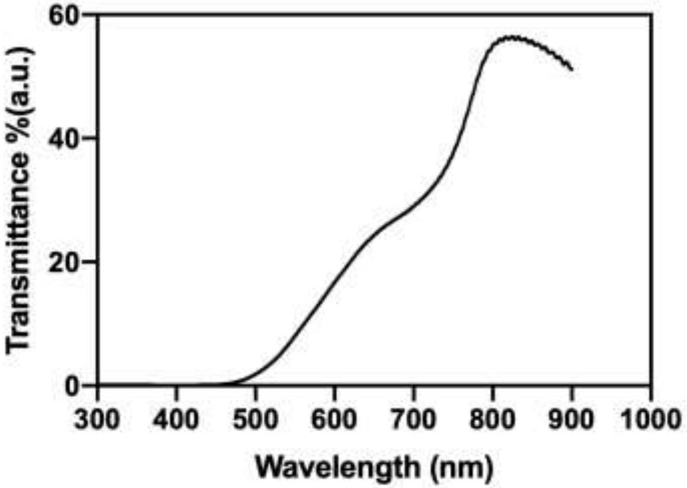
PL evolution under continuous illumination

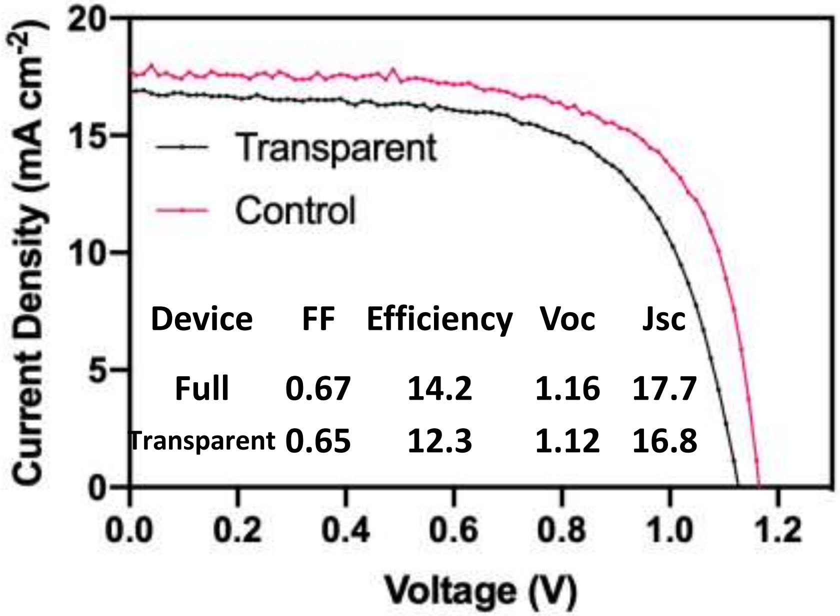


Ion conductivity measurements



Semitransparent





Thank you

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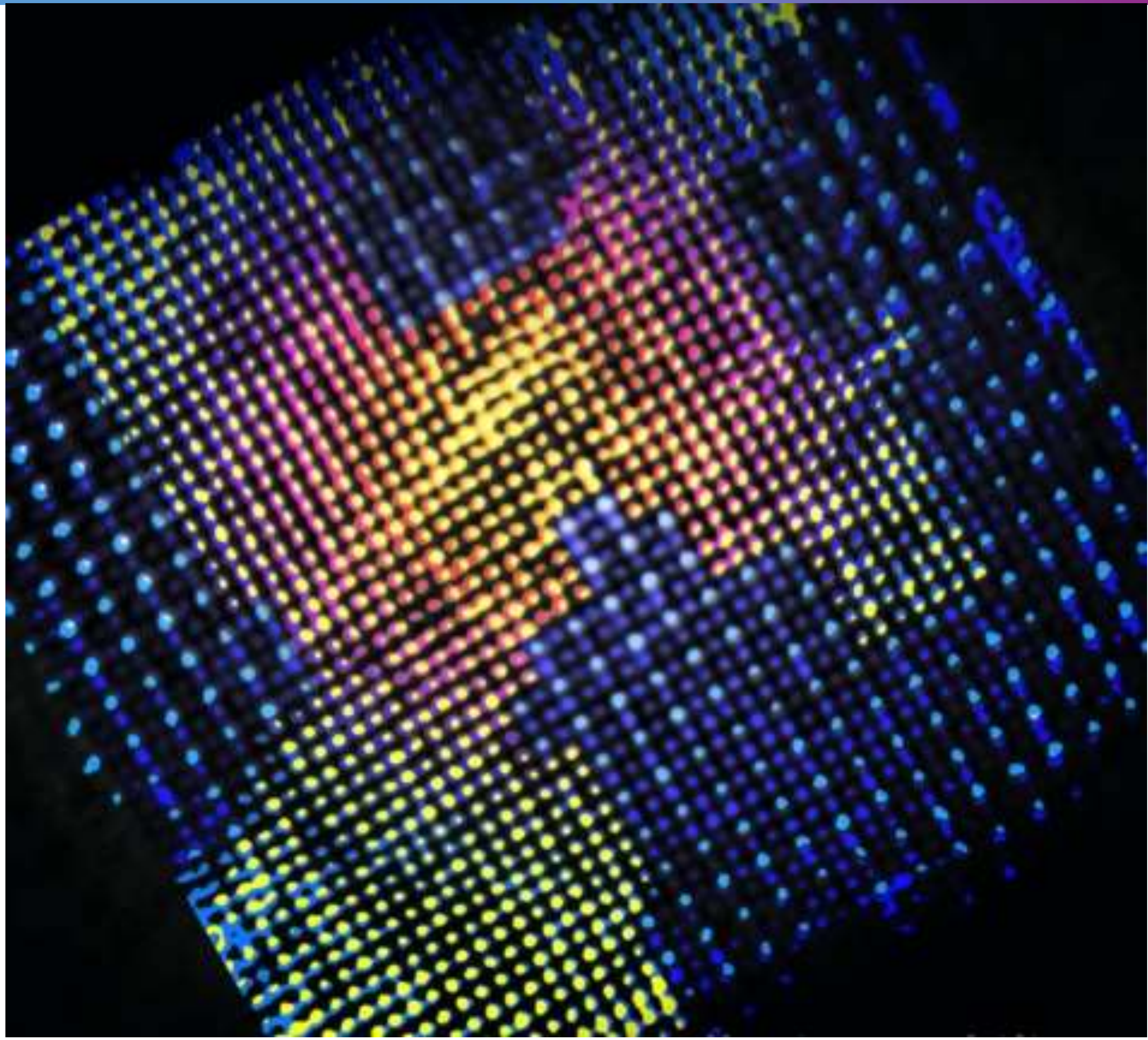
- Dr. Long Ren, Ms. Ningyan Cheng and Dr. Yi Du from University of Wollongong;
- Mr. Junxian Liu and Prof. Yun Wang from Griffith University;
- Prof. Yongbo Yuan from Central South University;



Hao et al. Nat Energy 5, 79–88 (2020). (Front cover)