Solution-Printed Perovskite Tandem Solar Cells

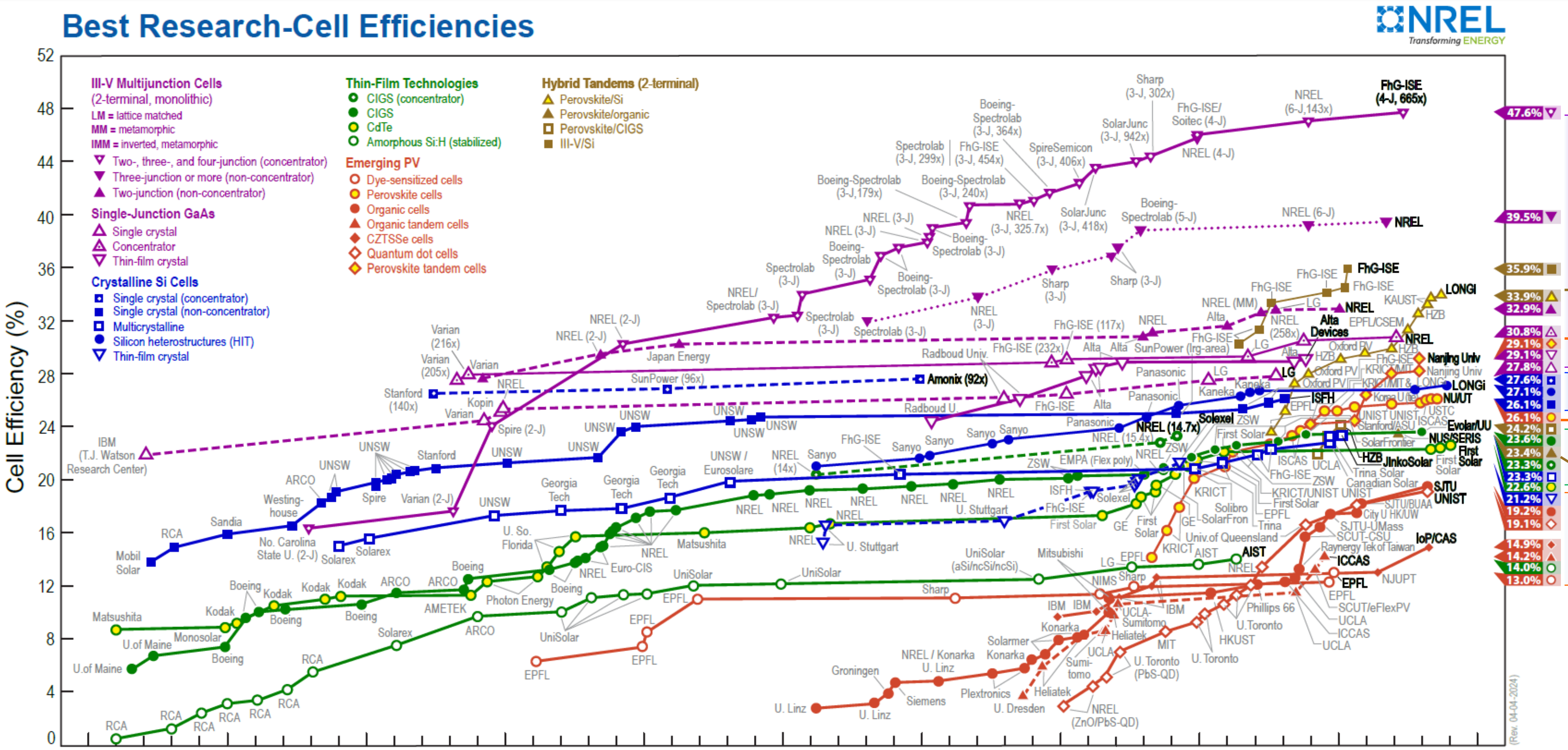
Fei Guo
Jinan University
21.05.2024

OUTLINE

- Introduction to scalable crystallization of perovskite films
- Our old / recent results

  Vacuum quenching / Perovskite-based tandems
- Summary
- Acknowledgement

Efficiency Evolution of Photovoltaics



Multi-junction & GaAs

Perovskite/Si tandem

Perovskite/PVK tandem

Crystalline Silicon

Perovskites

Thin-film: (CIGS, CdTe)

Perovskite/OPV tandem

Emerging PV:

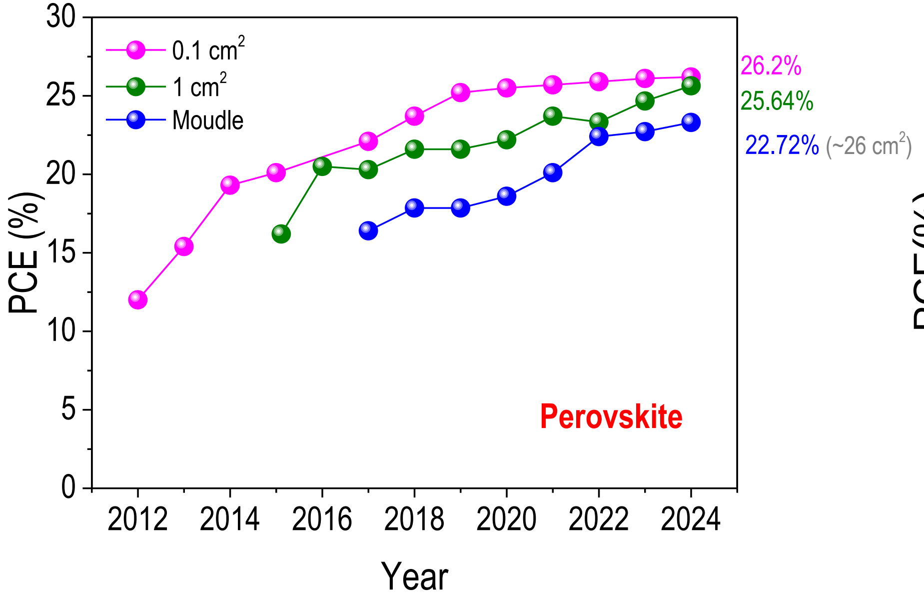
(Perovskites, OPV, QD, DSSC…)

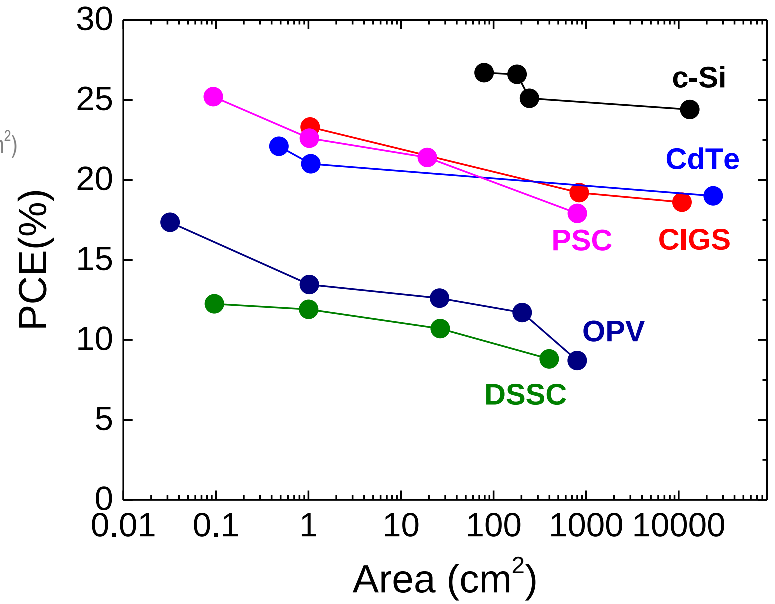
PV Type	Efficiency
C-Silicon	27.1%
Perovskite	26.1%
CIGS	23.6%
CdTe	22.6%
OPV	19.2%

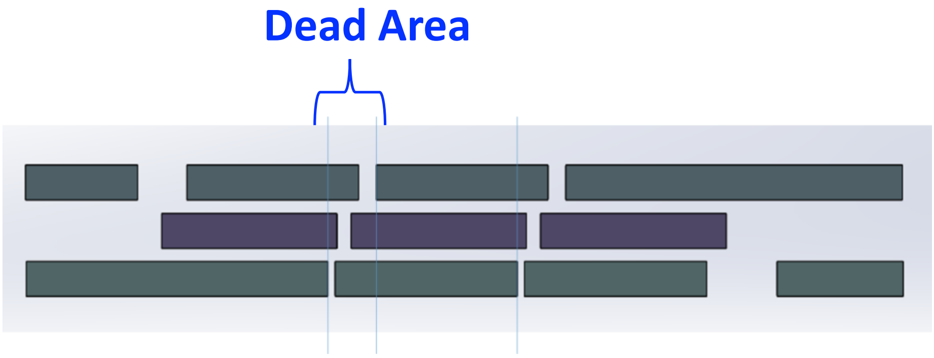
Emerging PV = Third generation PV = Solution Processable PV

Efficiency Losses During Upscaling

Large efficiency gap between small-size devices and large-area modules





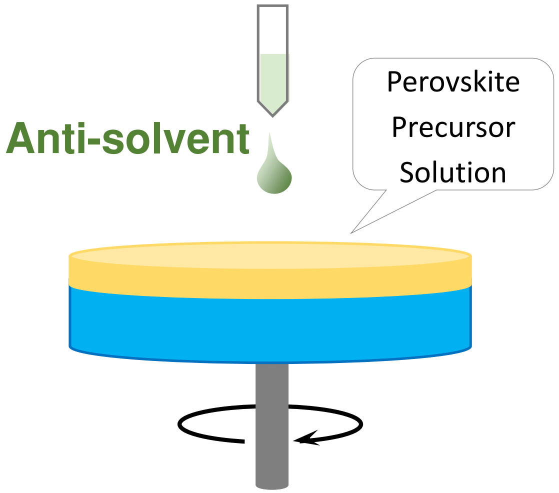


Solutions:

- ❑ Scalable coating of high-quality perovskite films
- ❑ Advanced module design and fabrication technology

Efficiency Losses During Upscaling

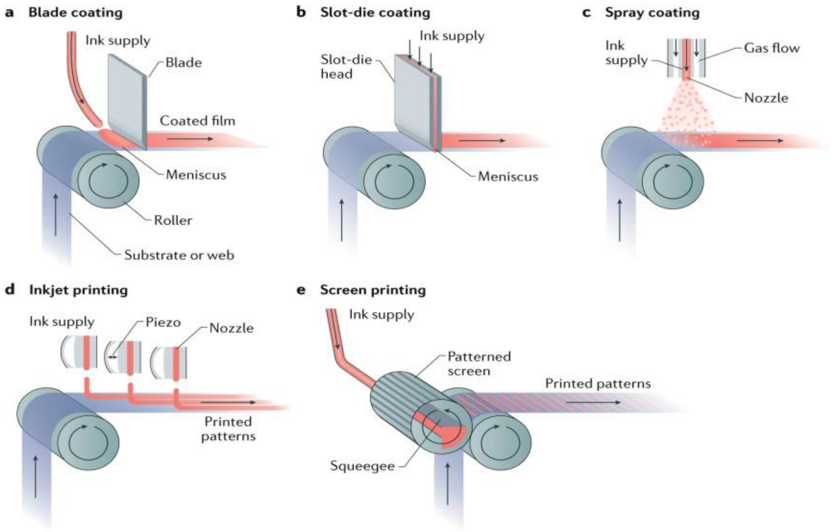
Spin coating



Pros & Cons:

- ✔ Easy to handle in lab
- ✔ Small amount of solution
- ✔ Good at producing uniform film
- ✗ High material waste (> 90%)
- ✗ Non scalable (< 5×5 cm^2)
- ✗ Unable to translate to scalable lines

Scalable coating



Crystallization protocols are difficult to be transferred to scalable coating lines

Challenges:

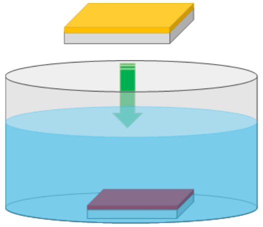
- ❑ **Film homogeneity (macro)**
  Solvent evaporation and solute migration/aggregation take place simultaneously
- ❑ **Crystal morphology (micro)**
  Control crystallization dynamics
- ❑ **Crystal structure**
  Phase purity, crystal orientation, phase segregation, defects ...

It is of essential importance to **control crystallization dynamics** to achieve large scale fabrication of perovskite thin-films

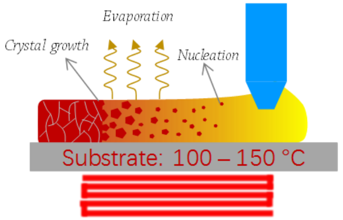
Nature Reviews Materials, ***2018***, *3*, *1-20.*

Established Crystallization Protocols

Nat Energy, 2017, 2, 17038.
ACS Energy Lett, 2018, 3, 322.
Sustain Energ Fuels, 2018, 2, 2442.
…



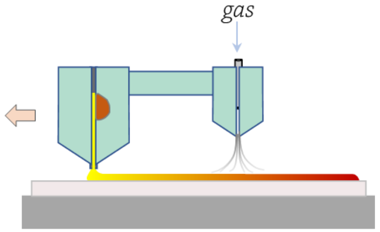
Antisolvent quenching



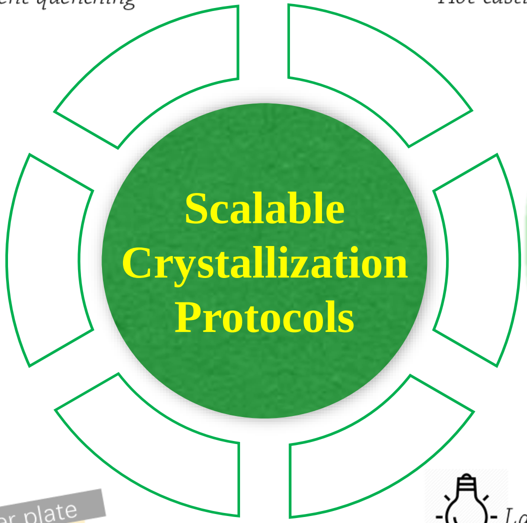
Hot-casting

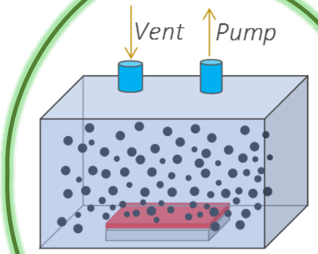
Energ Environ Sci, 2015, 8, 1544.
Adv Energy Mater, 2017, 7, 1700302.
Sci Adv, 2019, 5, eaav8925.
Adv Mater, 2020. 32, 2000995.
Nat Energy, 2018, 3, 560-566.
…

J Power Sources, 2015, 277, 286.
Joule, 2019, 3, 402.
Sci Adv, 2019, 5, eaax7537.
Adv Energy Mater, 2020, 10, 1903108.
ACS Energy Lett, 2019, 4, 2393.
…



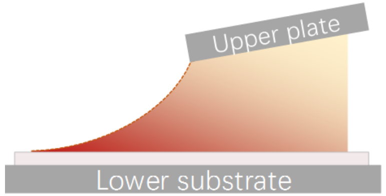
Gas quenching





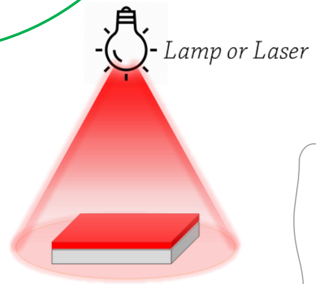
Vacuum quenching

Adv. Funct. Mater. **2019**, 29, 1900964.
Adv. Sci. **2019**, 6, 1901067.
Nano Energy, **2019**, 66, 104099.
Adv. Energy Mater., **2020**, 10, 2000173.
Adv. Funct. Mater., **2020**, 30, 2001240.
ACS Energy Lett., **2020**, 5, 1386-1395.
Adv. Funct. Mater., **2021**, 30, 2107644.
Energy Environ. Sci., **2020**, 13, 4666.
Adv. Funct. Mater., **2022**, 2112146.
ACS Energy Lett. ***2023***, *8*, *502*.



Meniscus assisted crystallization

Nat Commun, 2017, 8, 16045.
Energ Environ Sci, 2016, 9, 2295.
Adv Mater, 2017, 29, 1701440.
Nature, 2017, 550, 92..
…



Radiative annealing

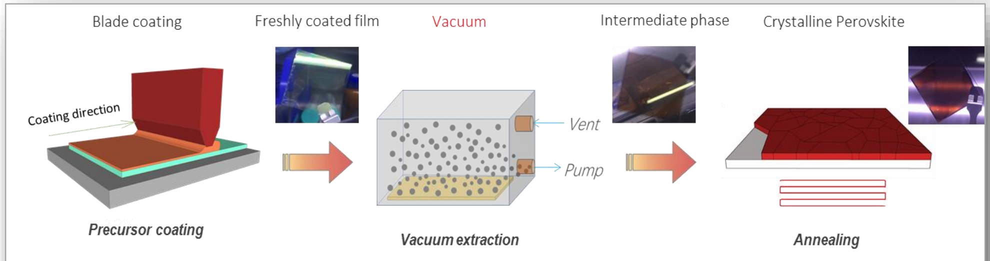
J Mater Chem A, 2015, 3, 9123
Adv Energy Mater, 2020, 10, 1902898.
Energ Environ Sci, 2020, 13, 1187.
Adv Energy Mater, 2018, 8, 1702915
…

Our Printed Perovskites

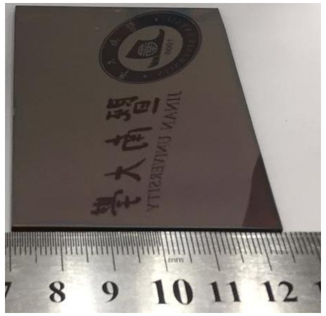
Since 2017 Jinan Uni

Scalable crystallization technique

Precursor ink

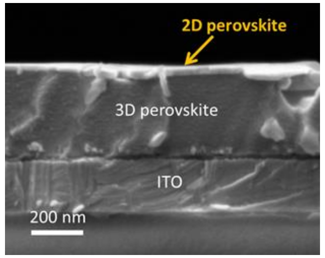


Adv. Funct. Mater., **2019**, 29, 1900964. *Adv. Sci.*, **2019**, 6, 1901067.



Large-area film

Dimensionality

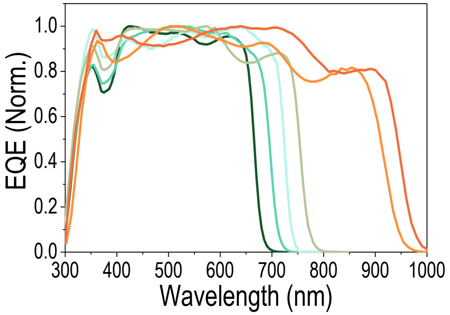


Energy Environ. Sci., **2020**, 13, 4666.

Nano Energy, **2022**, 91, 106658.

Adv. Funct. Mater., **2022**, 2112146

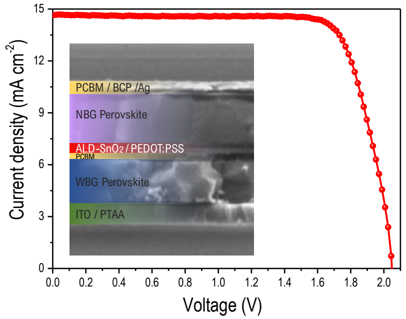
Wide/narrow bandgap



ACS Energy Lett., **2020**, 5, 1386-1395.

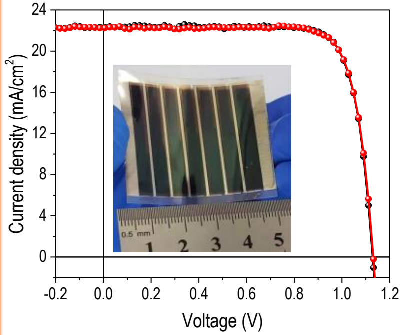
Nano Energy, **2019**, 66, 104099.

Tandems



ACS Energy Lett. 2023, 8, 502–512

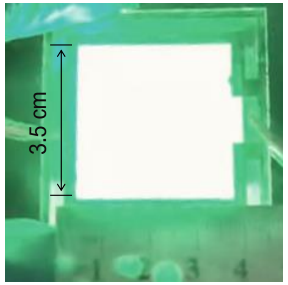
Flexible device



Adv. Funct. Mater., **2020**, 30, 2001240.

Adv. Sci., **2021**, 8, 2101856.

Perovskite LED



Adv. Funct. Mater., **2021**, 32, 2107644.

ACS Nano, **2023**, 17, 4483

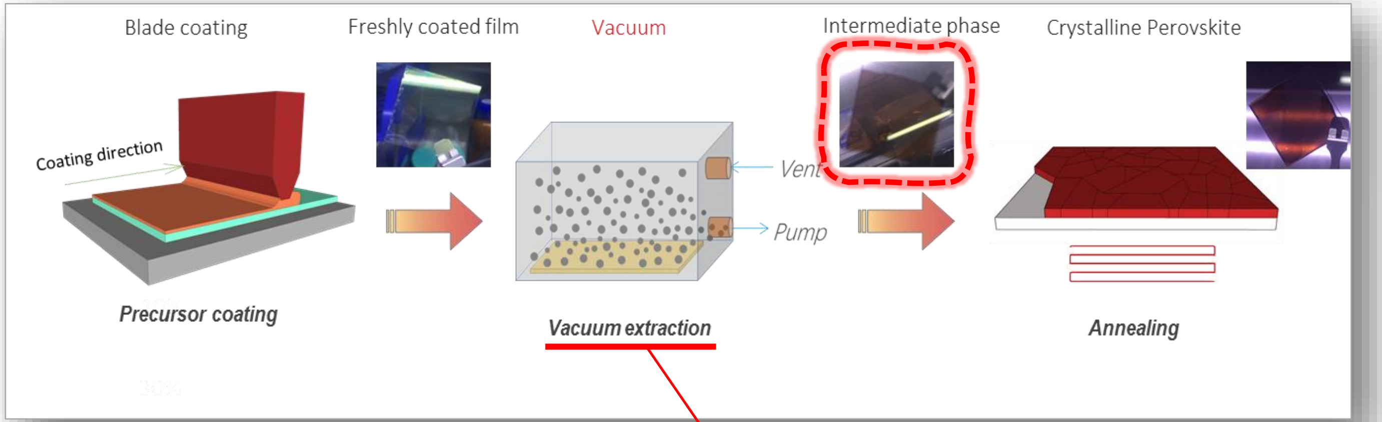
报告提纲

- ❑ Introduction to scalable crystallization of perovskite films
- ❑ Our old / recent results

  Vacuum quenching / Perovskite-based tandems

- ❑ Summary
- ❑ Acknowledgement

Our Method - Vacuum Quenching



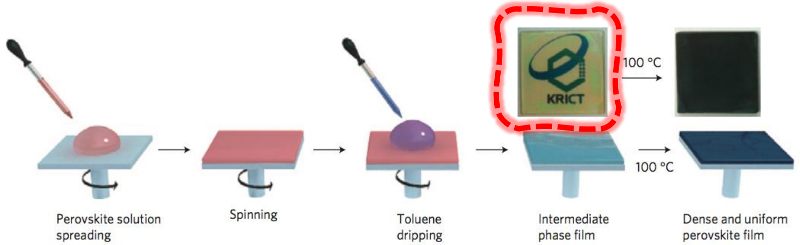

nature materials

ARTICLES

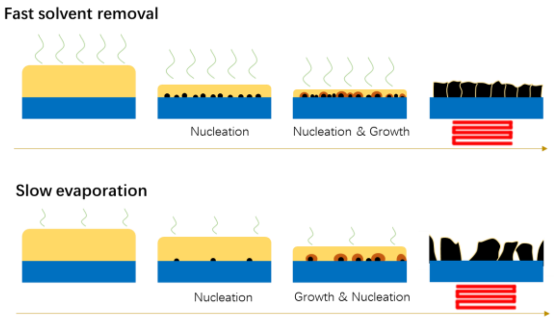
PUBLISHED ONLINE: 6 JULY 2014 | DOI: 10.1038/NMAT4014

Solvent engineering for high-performance inorganic–organic hybrid perovskite solar cells

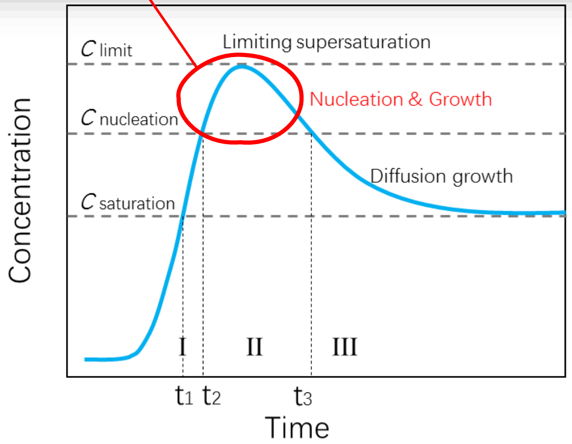
Nam Joong Jeon[1†], Jun Hong Noh[1†], Young Chan Kim[1], Woon Seok Yang[1], Seungchan Ryu[1] and Sang Il Seok[1,2*]

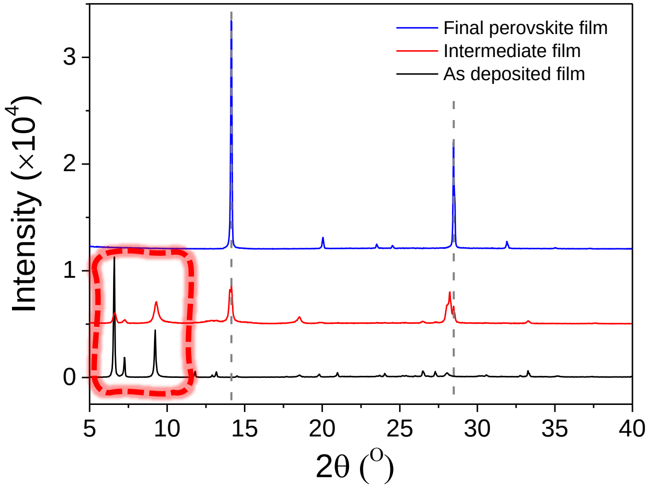


Nat. Mater. **2014**, 13, 897.

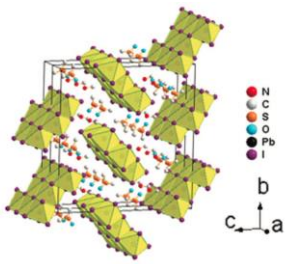


Energy Environ. Sci., **2020**, 13, 4666.





Adv. Sci., **2019**, 6, 1901067.



$MA_2Pb_3I_8{\cdot}2DMSO$

J. Am. Chem. Soc. **2016**, 138, 9919.

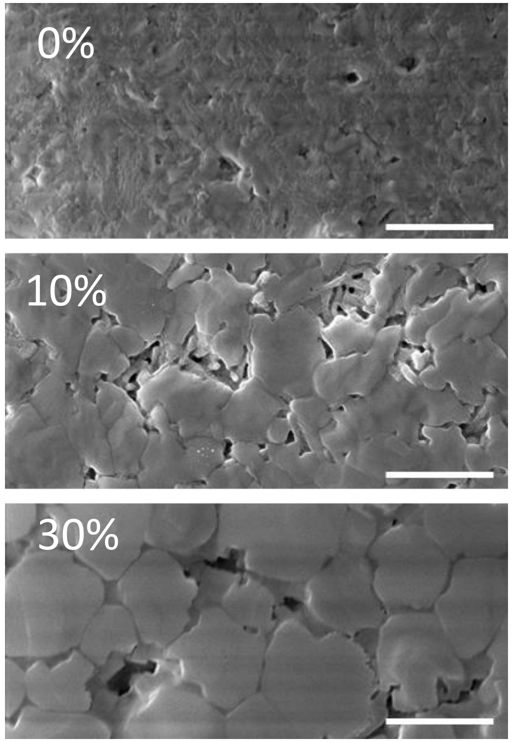
Vacuum: Fast nucleation and prevent solute migration/aggregation by fast solvent removal

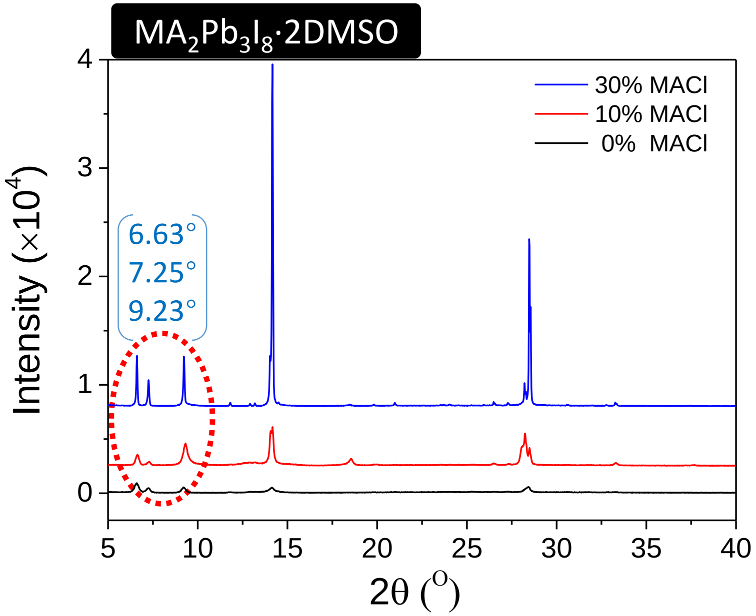
Our Method - Vacuum Quenching

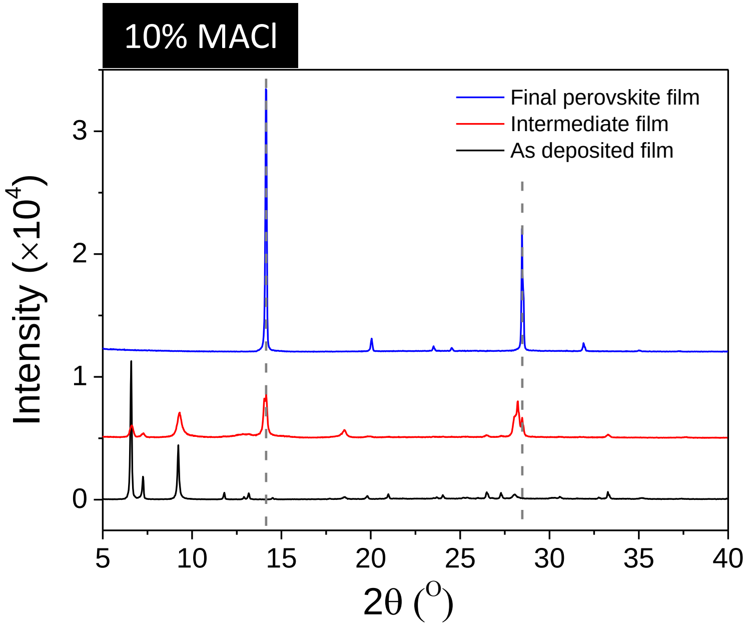
Crystallization dynamics

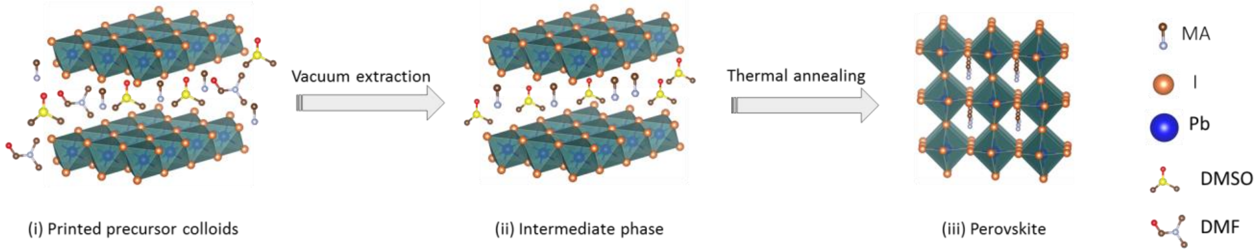
Additive MACl: Modulate crystal morphology and stabilize phases

Intermediate film





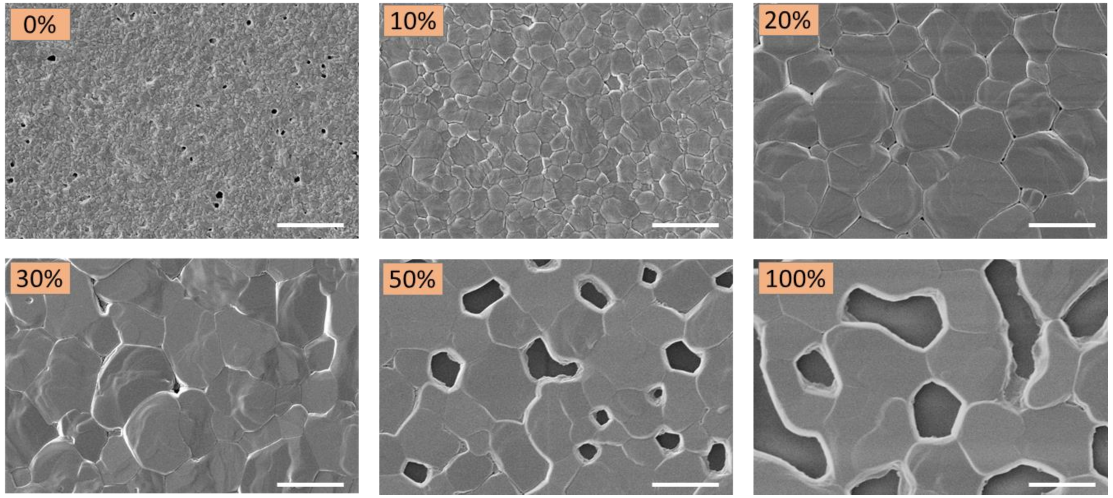


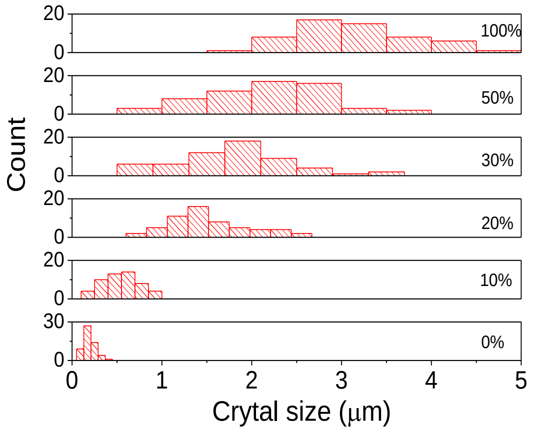


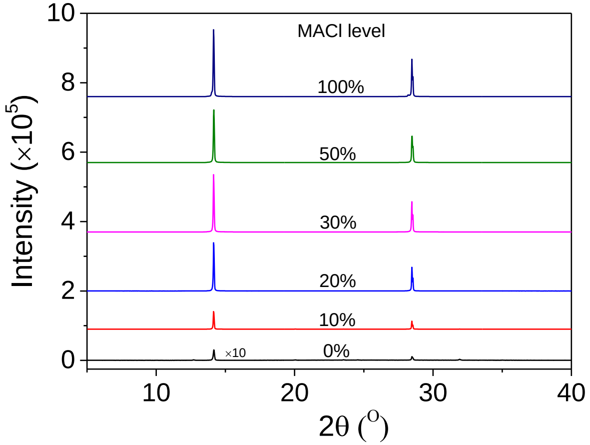
Guo F., Qiu S., et al. *Advanced Science* **2019**, 6, 1901067.

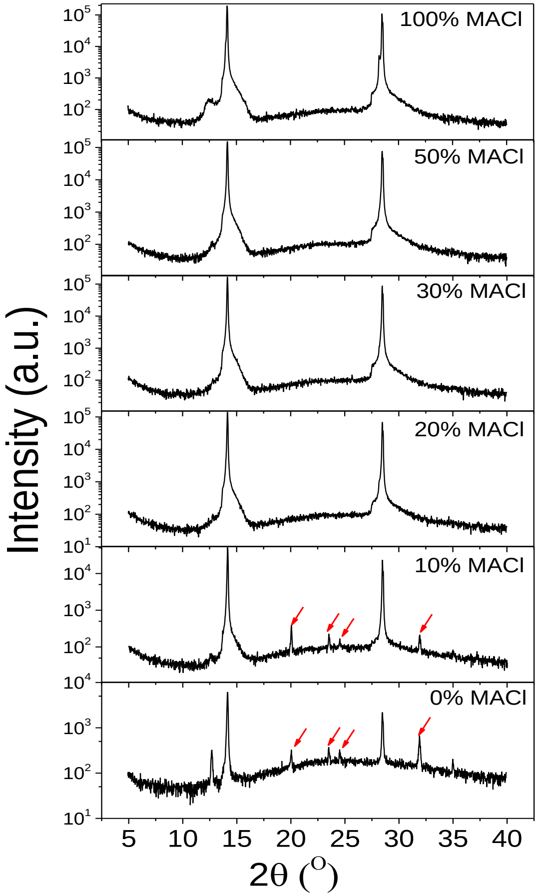
Our Method - Vacuum Quenching

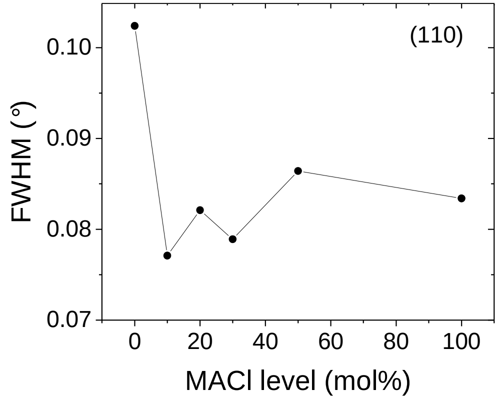
MAPbI$_3$ cystal quality

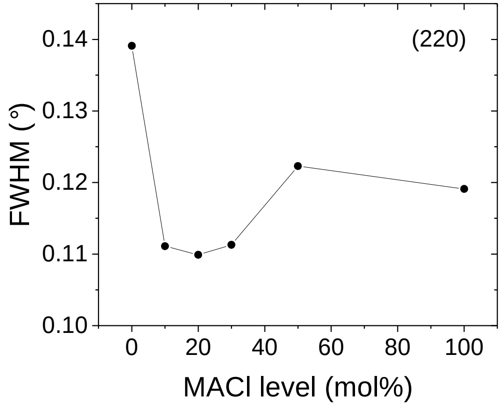










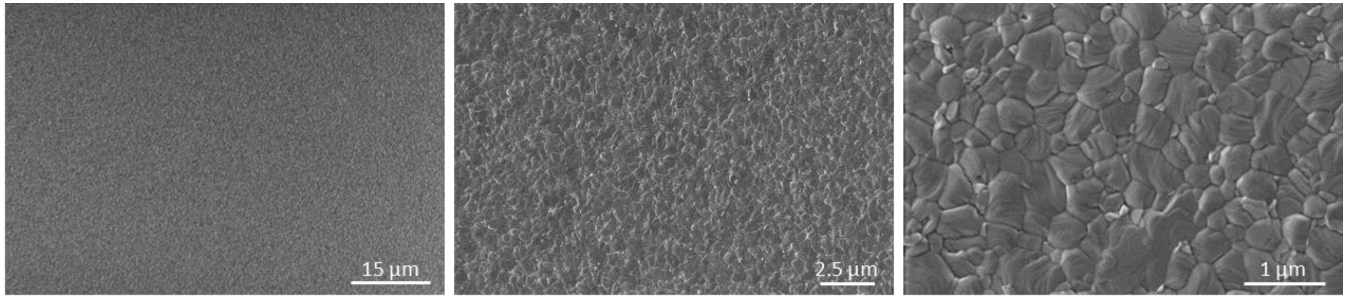


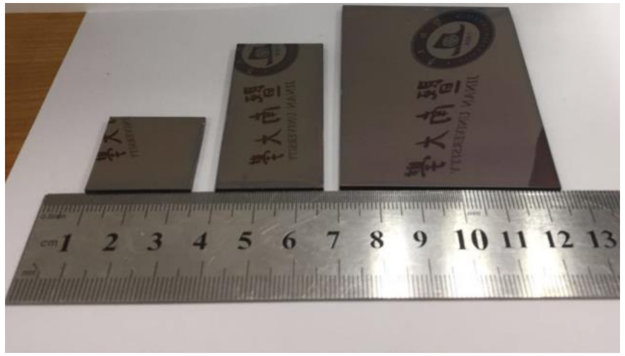
Our Method - Vacuum Quenching

Importance of vacuum

With vacuum

10% MACl



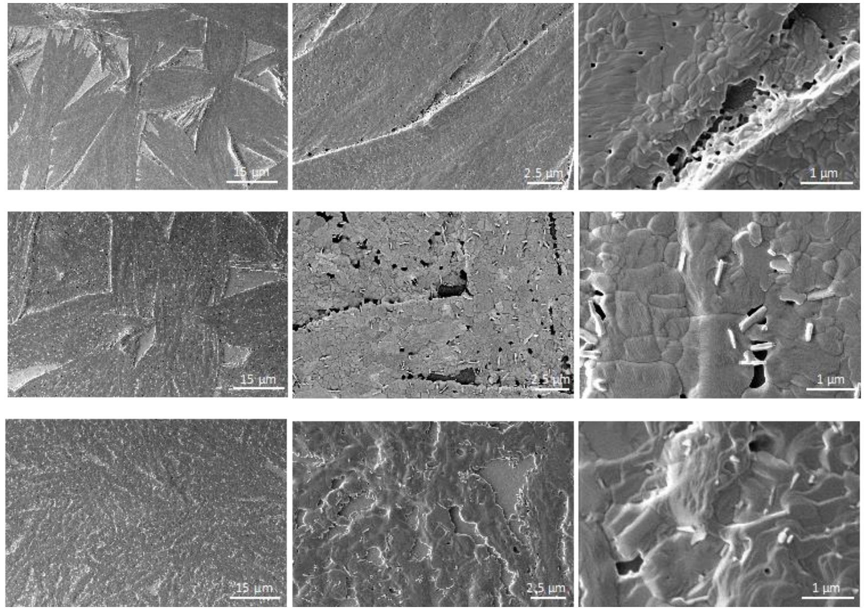


Without vacuum

0% MACl

10% MACl

30% MACl



Guo F., Qiu S., et al. *Advanced Science* **2019**, 6, 1901067.

报告提纲

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  Vacuum quenching / Perovskite-based tandems
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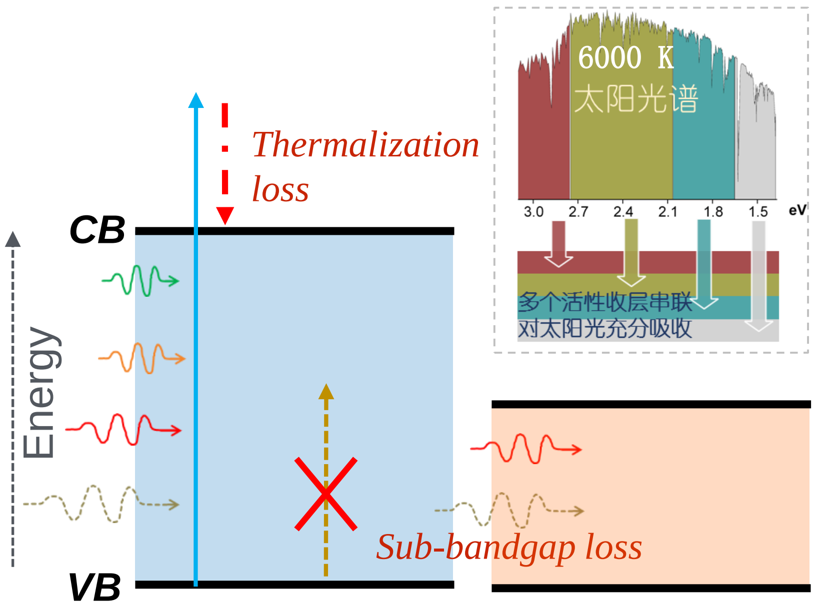
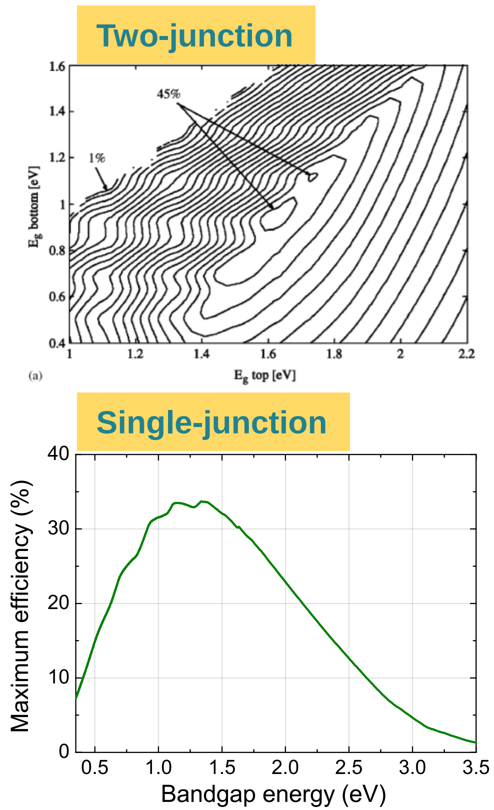
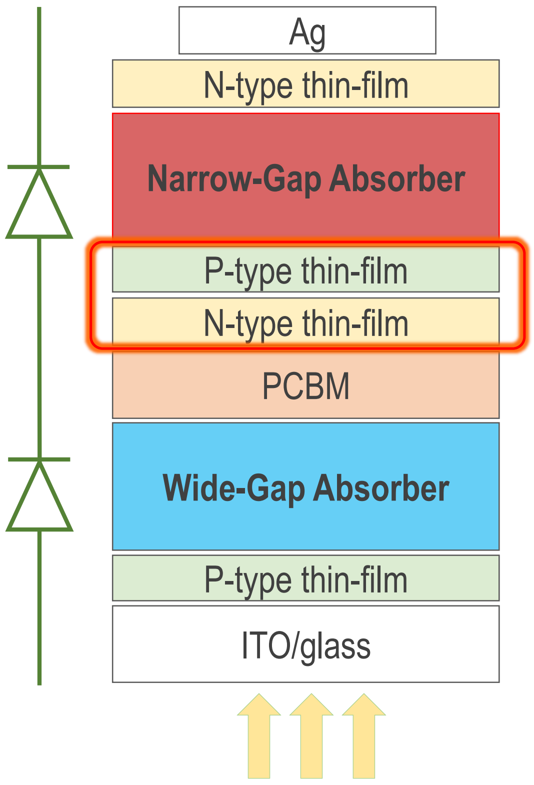
Why Tandem Architecture ?

Single-junction Multi-junction







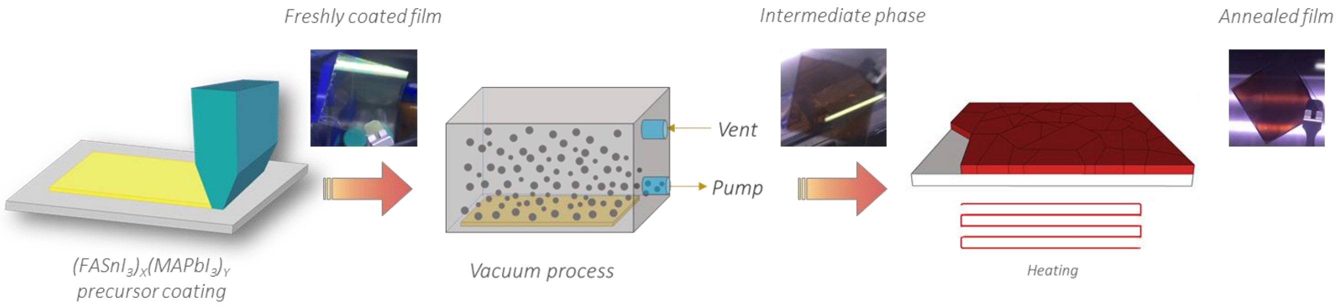
Narrow gap
- Thick enough to ...

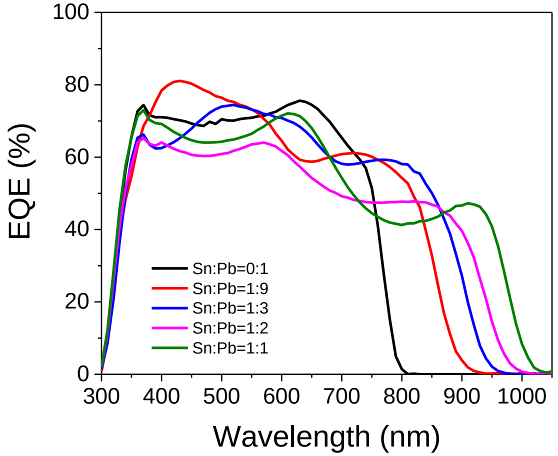
Charge recombination
- High transmittance
- Low ohmic resistance
- Prevent solvent penetration

Wide gap
- Low voltage loss

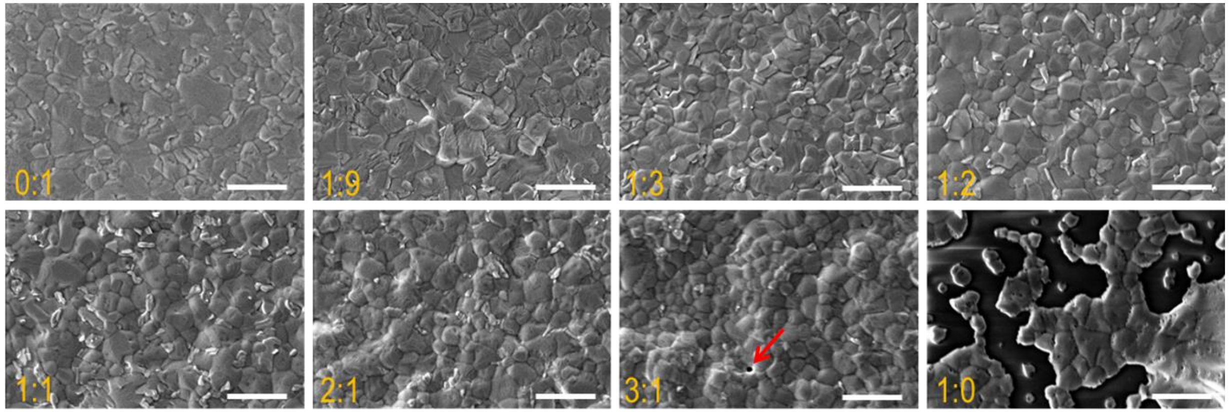
 Solar energy materials and solar cells, **2006**, 90, 2952.

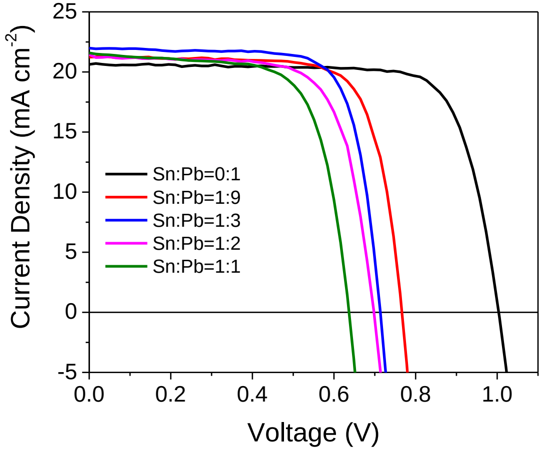
Printing Low-bandgap perovskites





Different Sn-Pb ratios





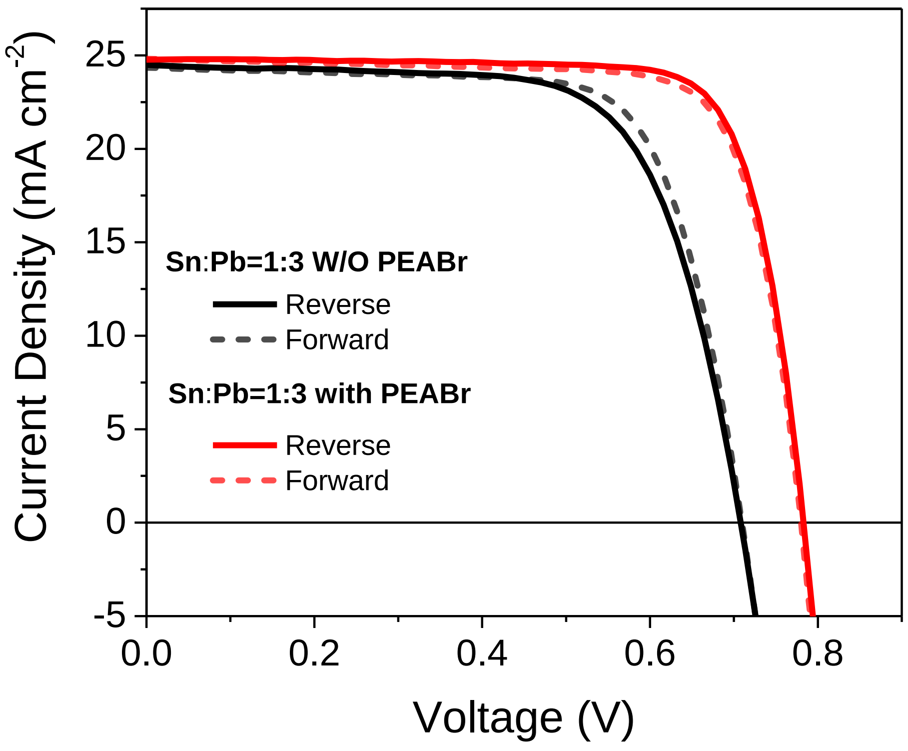
High FFs but high V_{OC} losses!

Passivation?

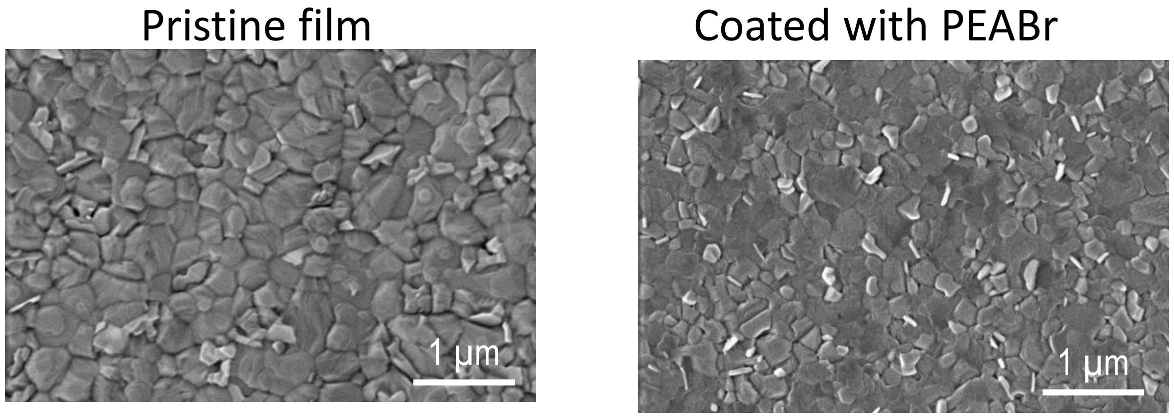
Zeng L., Chen Z., Qiu S., et al. *Nano Energy* **2019**, 66, 104099.

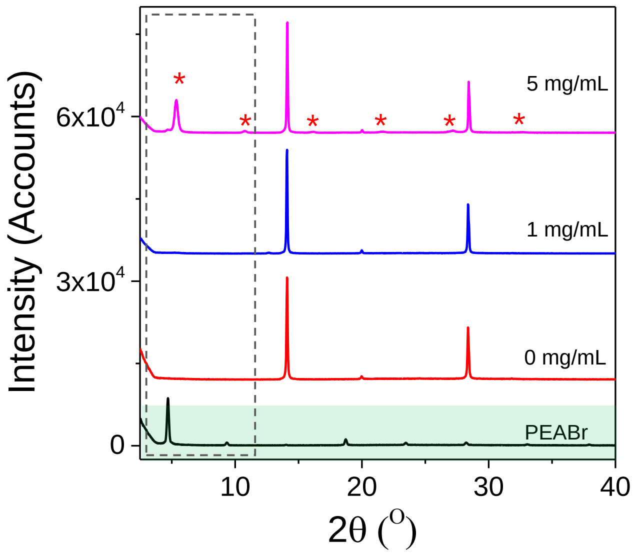
Printing Low-bandgap perovskites

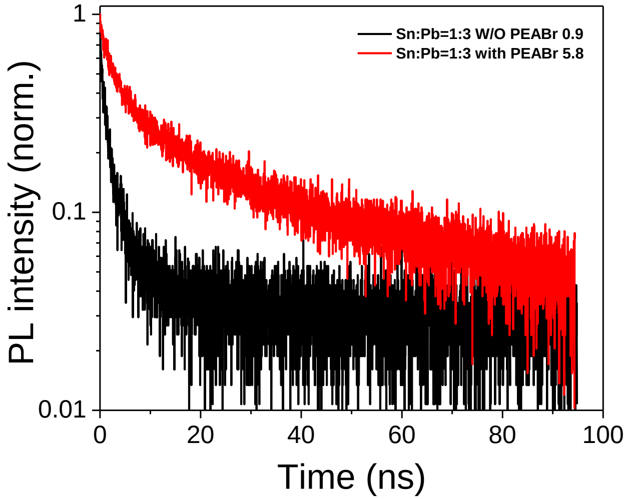
Passivation with PEABr (Two-step)



Jsc=24.9 Voc=0.78 FF=0.78 PCE=15.15%

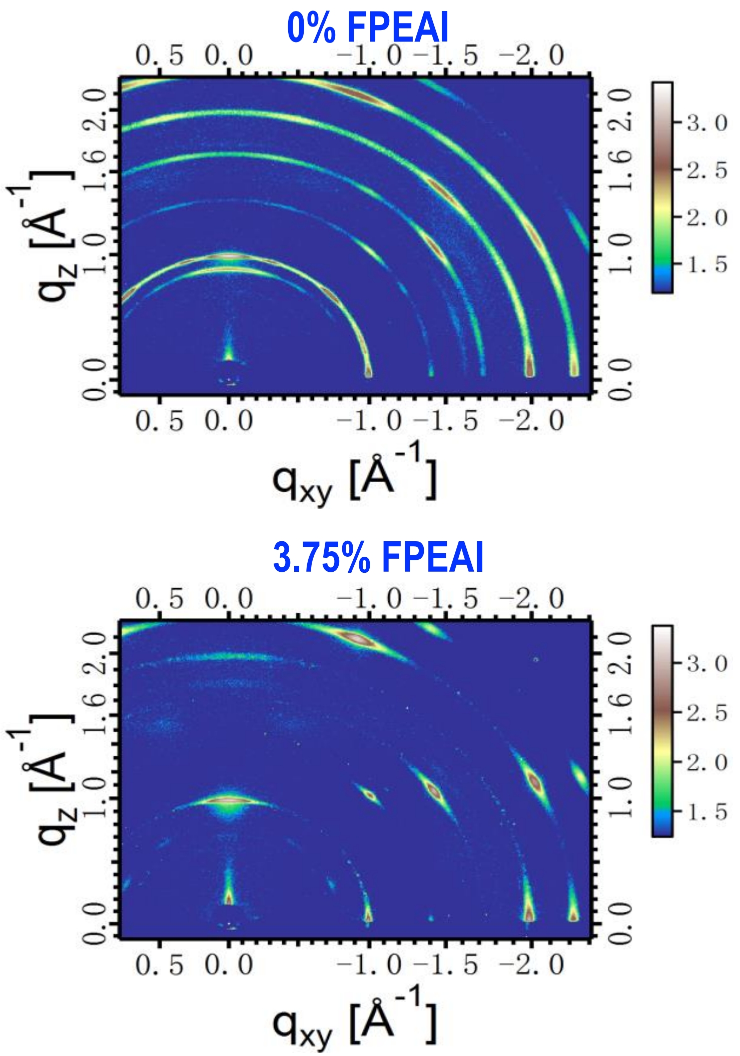


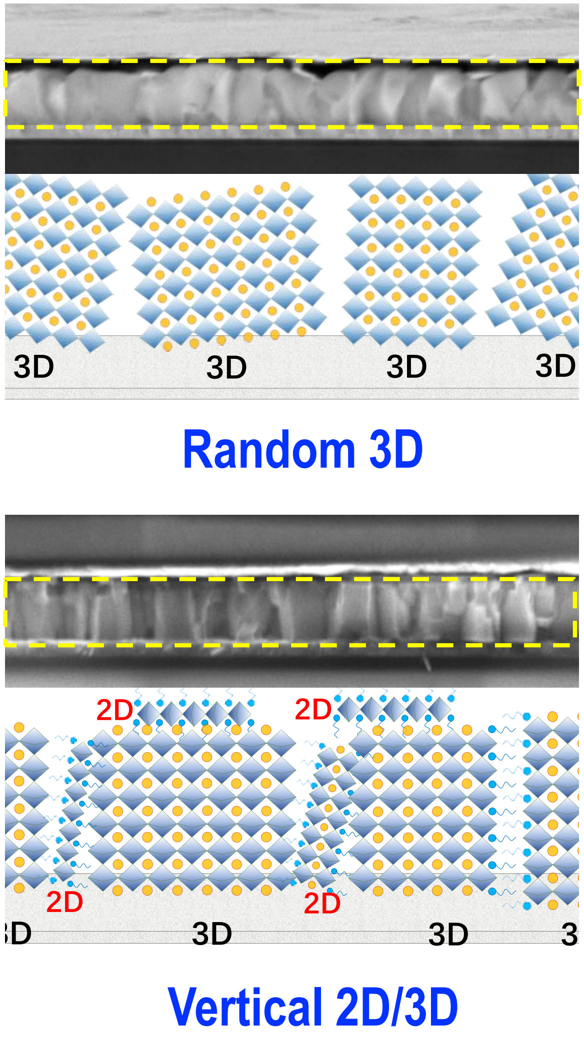


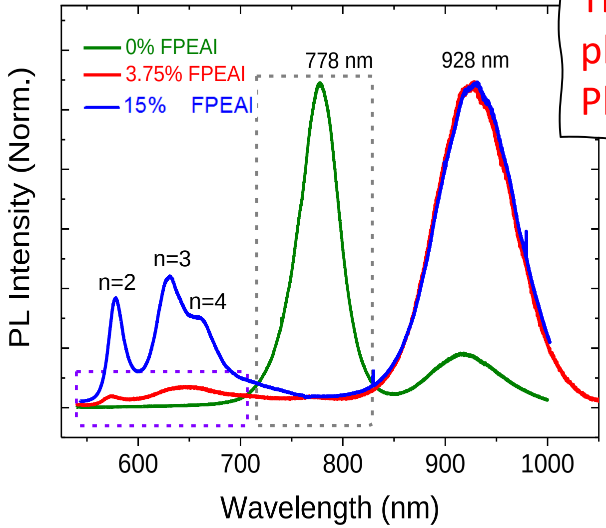


Zeng L., Chen Z., Qiu S., et al. *Nano Energy* **2019**, 66, 104099.

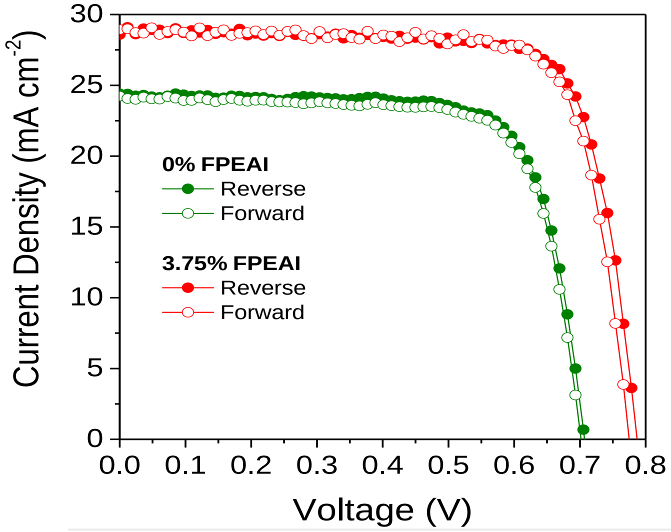
2D/3D Mixed Pb-Sn Perovskites







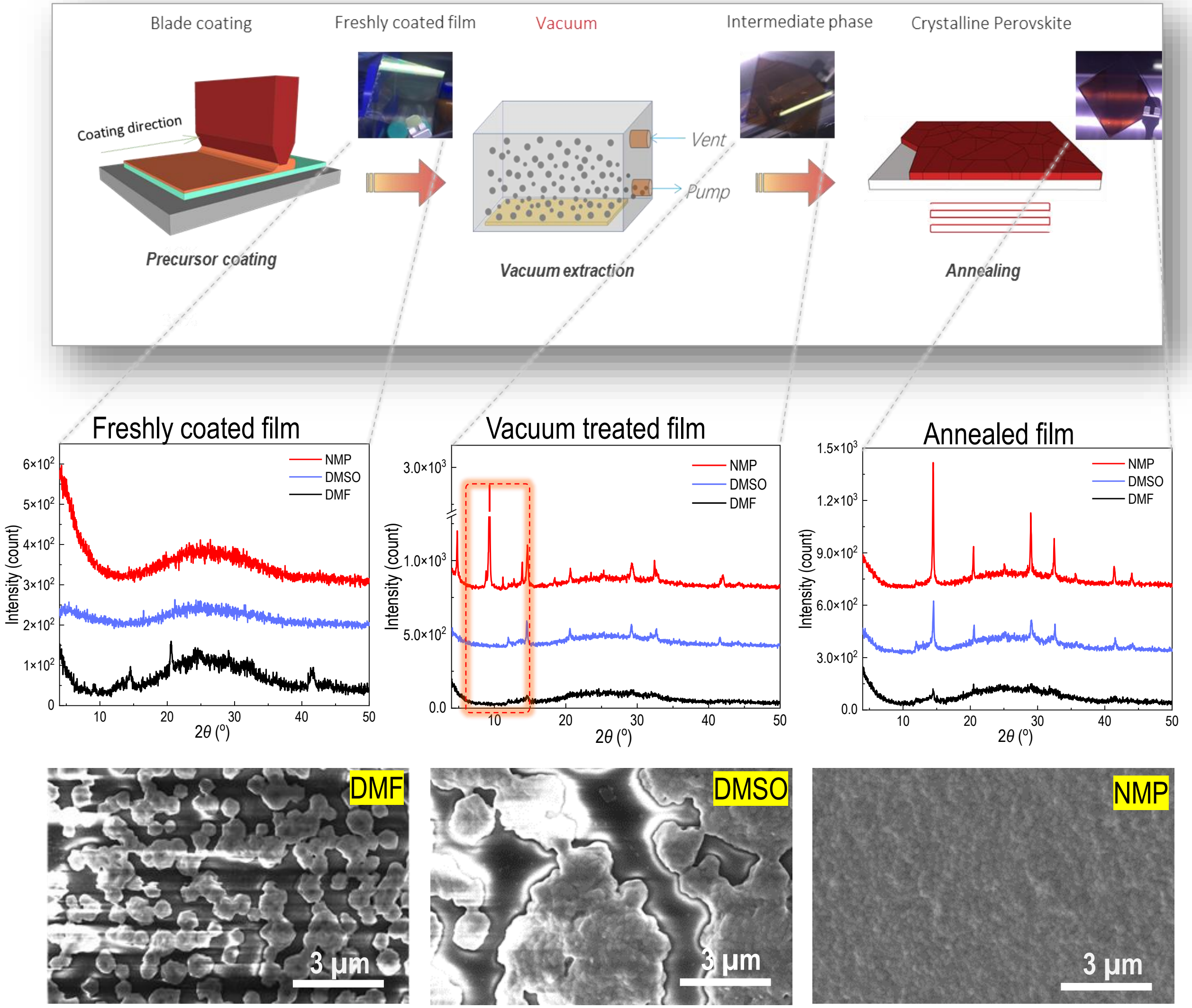
The 1st observation of phase segregation in Pb-Sn perovskites

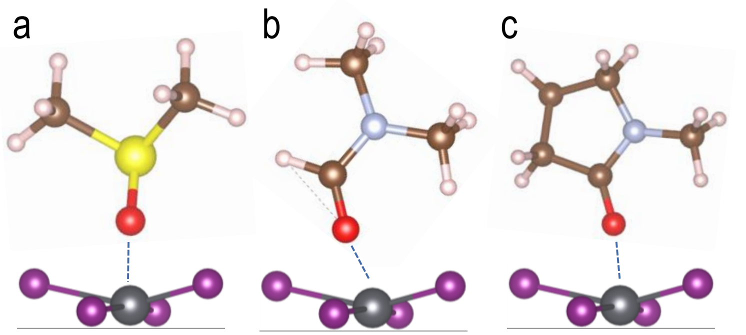


Jsc=28.4 Voc=0.79 FF=0.78 PCE=17.51%

C. Li, Y. Pan, *et al.*, *ACS Energy Lett.*, **2020**, 5, 1386.

Printing Wide-bandgap Perovskites



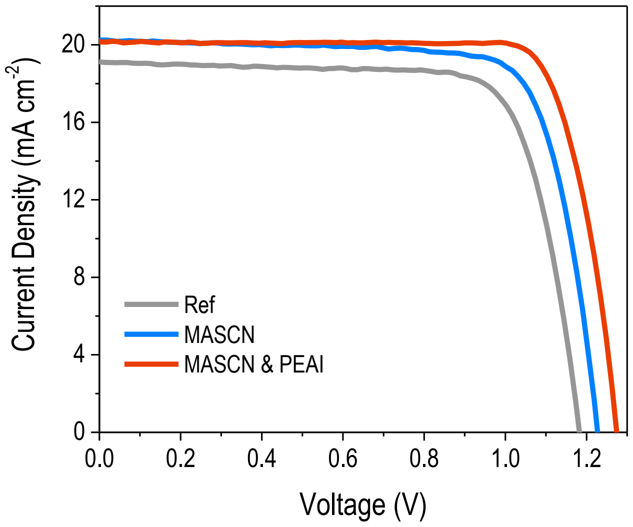


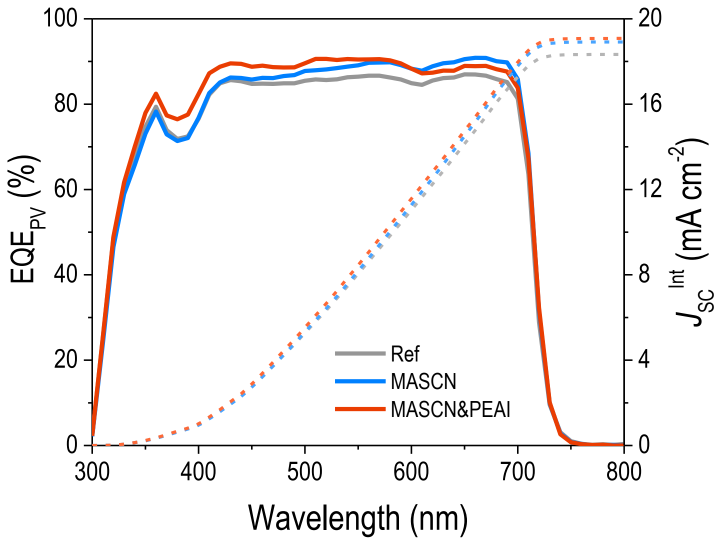
E_{PbI2}	E_{DMF}	E_{DMSO}	E_{NMP}	E_{Total}	ΔE
-7.735	-68.034	-	-	-76.65	-0.881
-7.735	-	-50.421	-	-59.094	-0.938
-7.735	-	-	-93.98	-102.798	-1.083

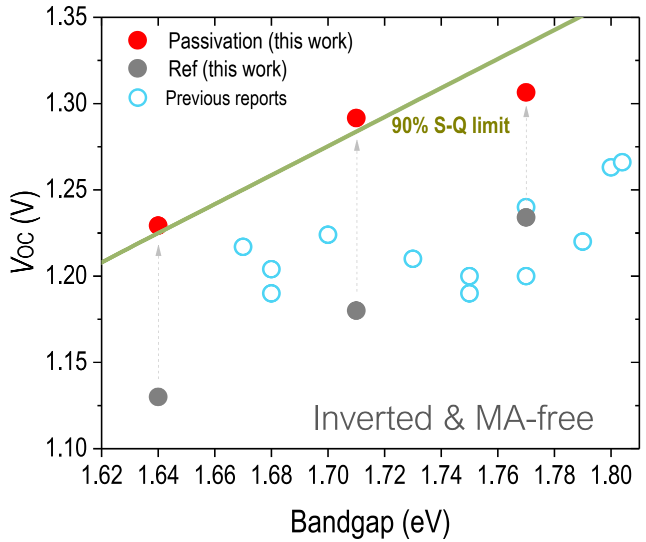
The **strongest binding strength** between NMP and PbI_2, enables to form an **intermediate adduct more stable** than DMSO and DMF, finally giving rise to **controllable crystallization kinetics**.

Printing Wide-bandgap Perovskites

$FA_{0.9}Cs_{0.1}Pb(Br_{0.3}I_{0.7})_3$ Eg=1.71 eV





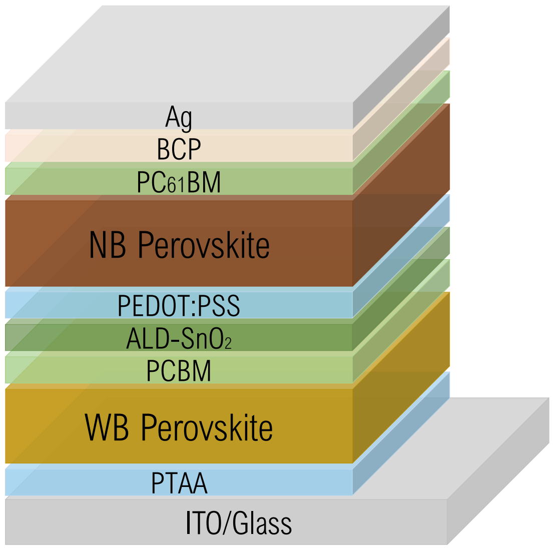


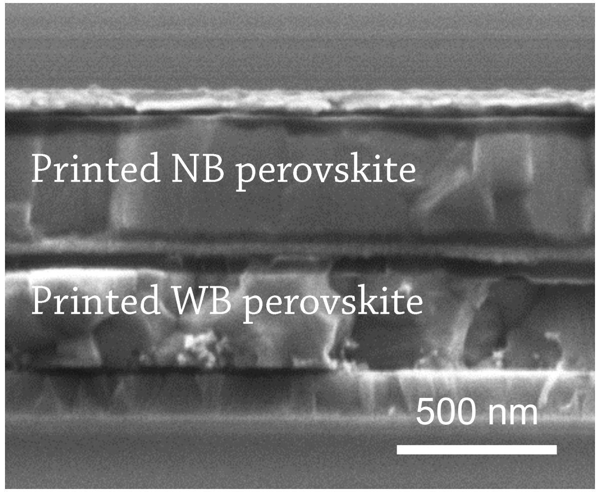
Wide-bandgap Perovskite	V_{OC} [V]	J_{SC} [mA cm^{-2}]	$J_{SC, EQE}$ [mA cm^{-2}]	FF [%]	PCE [%]
Ref	1.18	19.53	18.34	71.15	16.40
MASCN	1.23	20.24	18.92	76.04	18.99
MASCN&PEAI	1.27	20.32	19.09	81.22	20.84

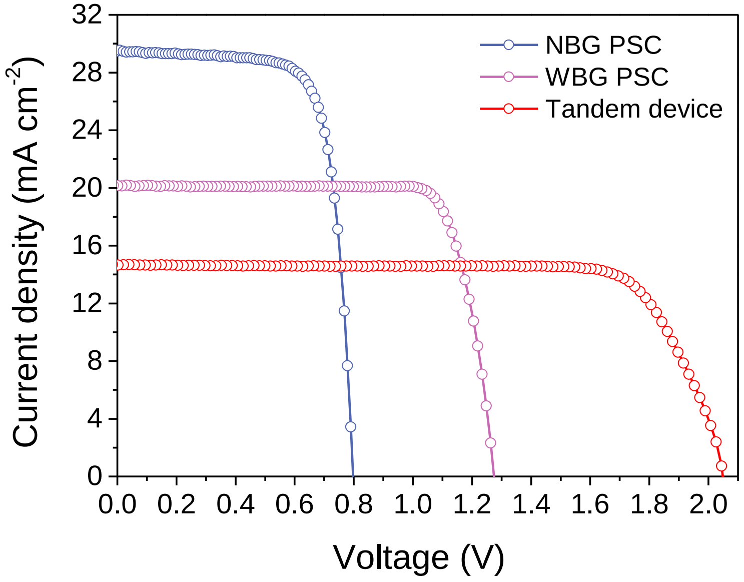
X.M. Zhou, *ACS Energy Lett.* **2023**, 8, 502–512.

Printed Perovskite Tandems

Perovskite - Perovskite





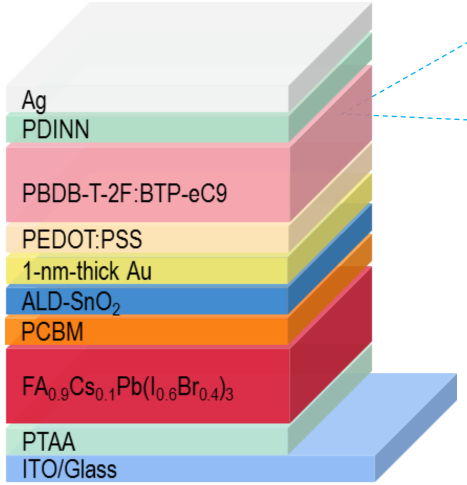


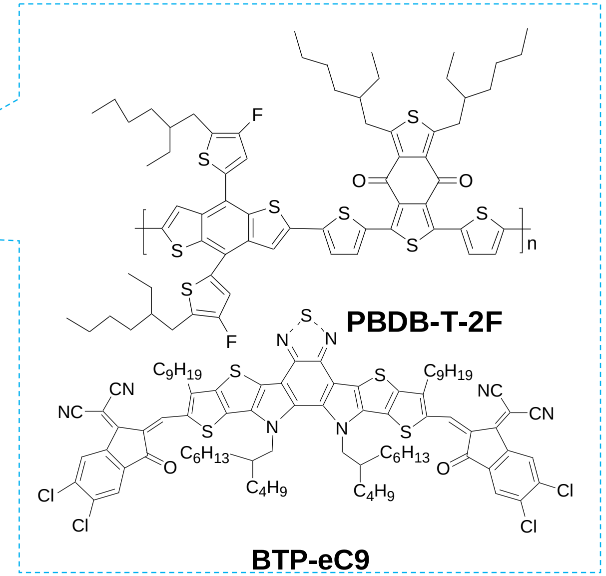
Wide-bandgap Perovskite	V_{OC} [V]	J_{SC} [mA cm^{-2}]	FF [%]	PCE [%]
Wide-bandgap	1.27	20.32	81.22	20.84
Narrow-bandgap	0.80	29.47	75	17.57
All-perovskite tandem	2.05	14.66	78.7	**23.65**

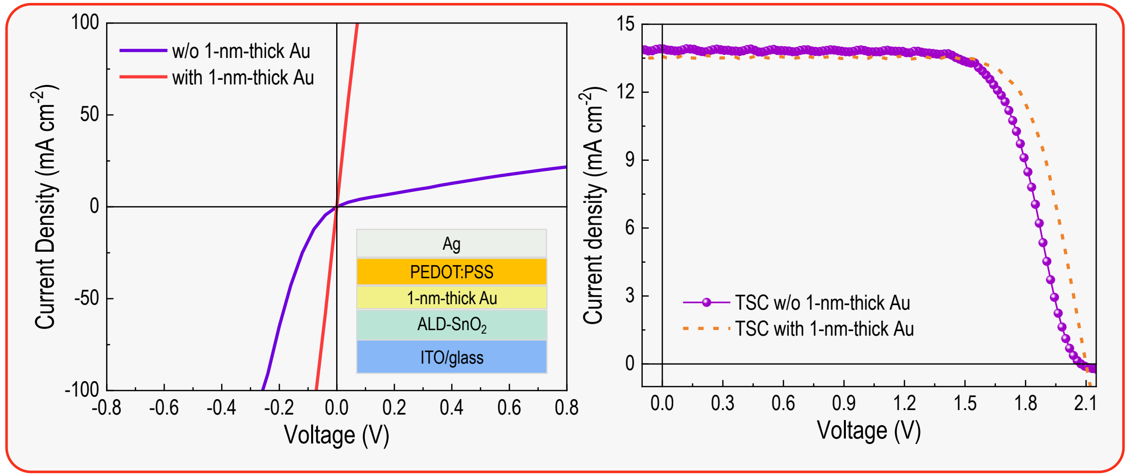
X.M. Zhou, *ACS Energy Lett.* **2023**, 8, 502–512.

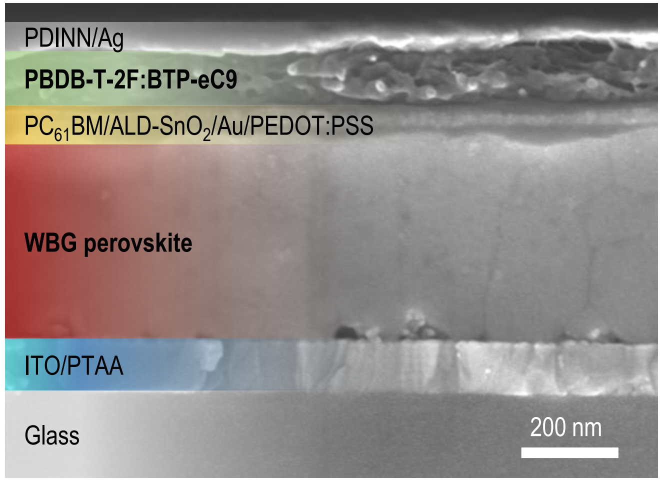
Printed Perovskite Tandems

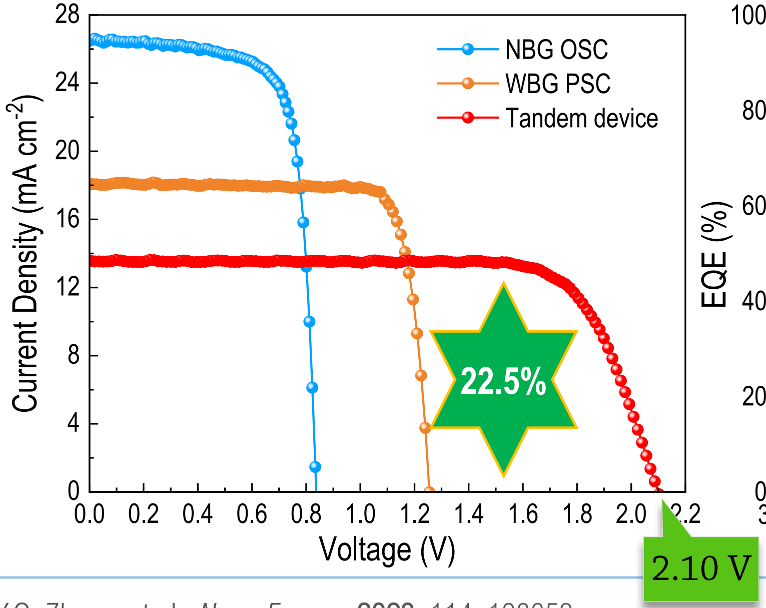
Perovskite - Organic

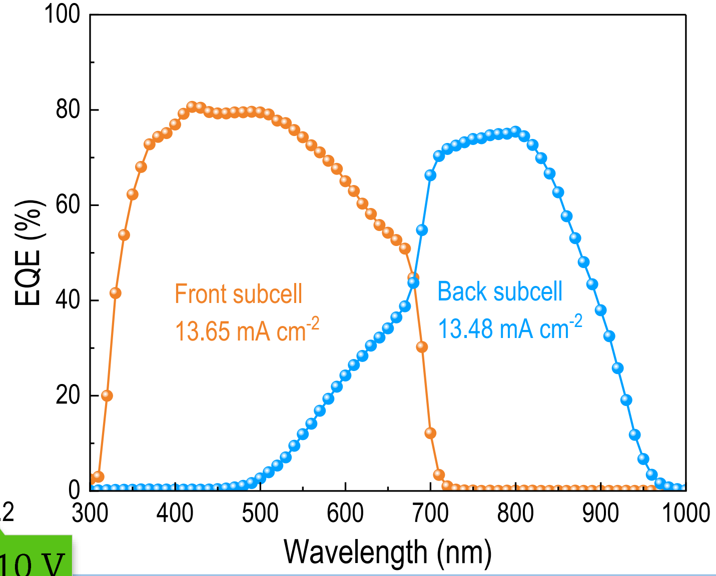






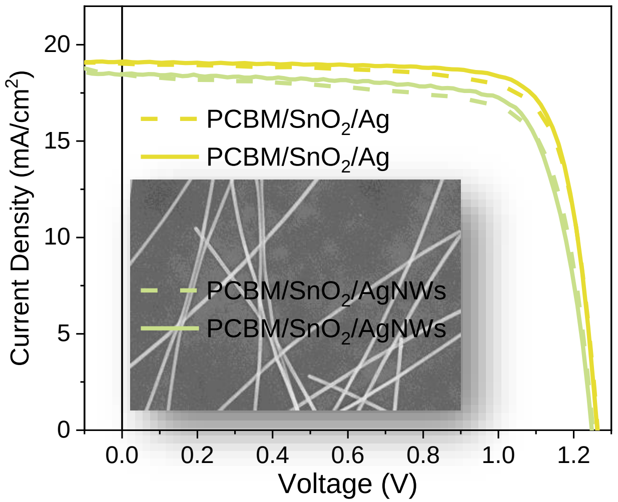


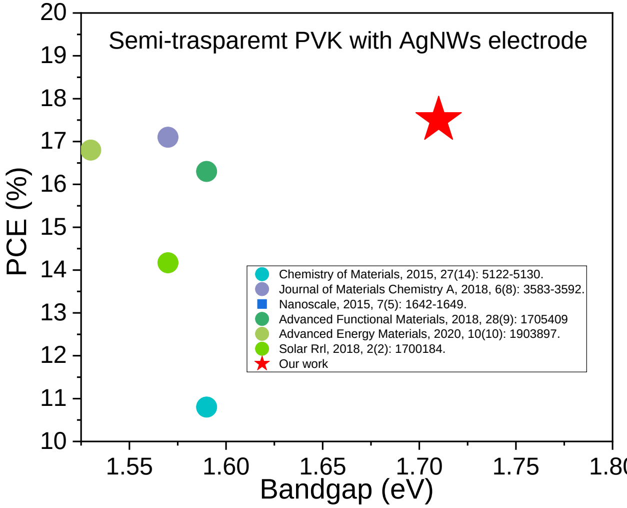


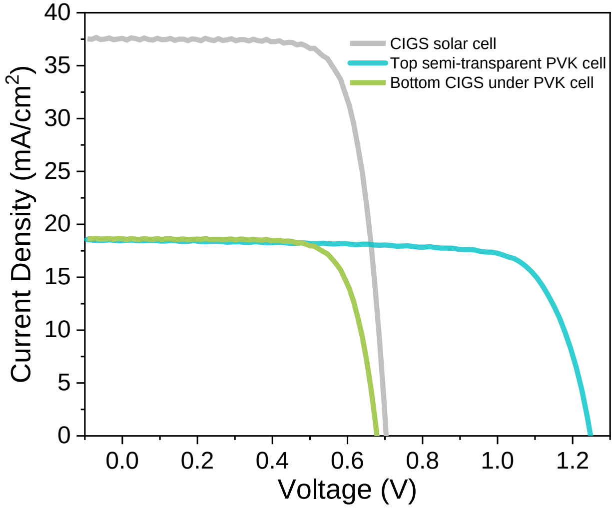


Y.C. Zhang, et al., *Nano Energy*, **2023**, 114, 108653.

Perovskite - CIGS







	PCE	V_{oc} (V)	I_{sc} (mA/cm^2)	FF
CIGS	19.61	0.702	37.52	74.38
Semi-transparent PVK cell	17.50	1.255	18.44	0.756
Bottom CIGS under PVK cell	9.35	0.678	18.58	74.24
4T tandem solar cell	26.85	-	-	-

Chen et al., Manuscript in preparation

报告提纲

- ❑ Introduction to scalable crystallization of perovskite films
- ❑ Our old / recent results
  - Vacuum quenching / Perovskite-based tandems
- ❑ Summary
- ❑ Acknowledgement

Summary

- Developed a generic **VACUUM-QUENCHING** crystallization method, which enables to scalable deposit high-quality large-area perovskite thin films of different bandgaps for versatile applications.
- Identified that **NMP is an ideal solvent** in controlling crystallization kinetics of scalable process wide-bandgap perovskite thin films.
- All-perovskite and perovskite-organic tandem devices are fabricated based impermeable **ALD-deposited SnO2** charge recombination layers.
- **Novel Cr-based** charge recombination layers without ALD procedure are developed to build perovskite-perovskite and perovskite-organic tandem devices.

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Chief Contributors:

Hongbing Li, Chaoran Chen, Ting Huang, Hongwei Lai, Xinming Zhou, Hongwei Lai, Shudi Qiu, Chaohui Li

Collaborator:

FAU: Dr. Karen Forberich, Prof. Christoph J. Brabec

EPFL: Prof. Mohammad K. Nazeeruddin

Zhengzhou Uni: Prof. Xianhu Liu

Henan Uni: Prof. Shi Chen

Wuhan Uni: Prof. Jianmin Li

Thank you for your kind attention

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