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尚柔新能源

Scalable Printing of Perovskite Film for Efficient and Stable Photovoltaic Module in Ambient Atmosphere

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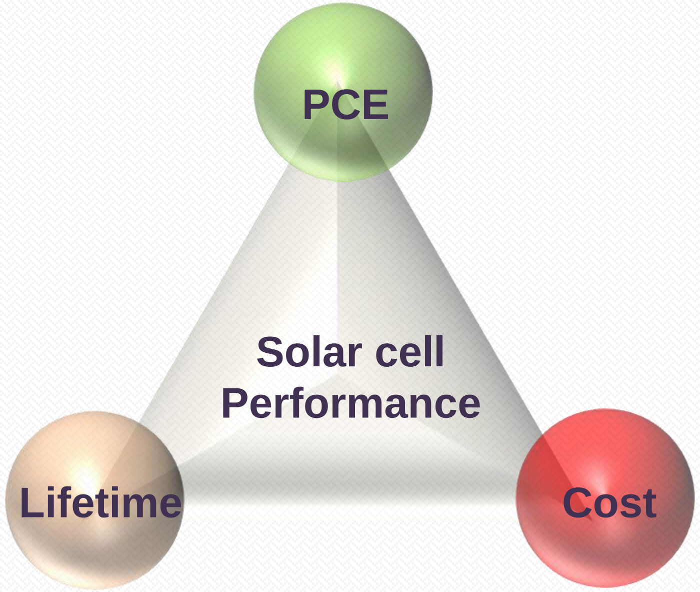
Sino-Germany Workshop on Printable Photovoltaics

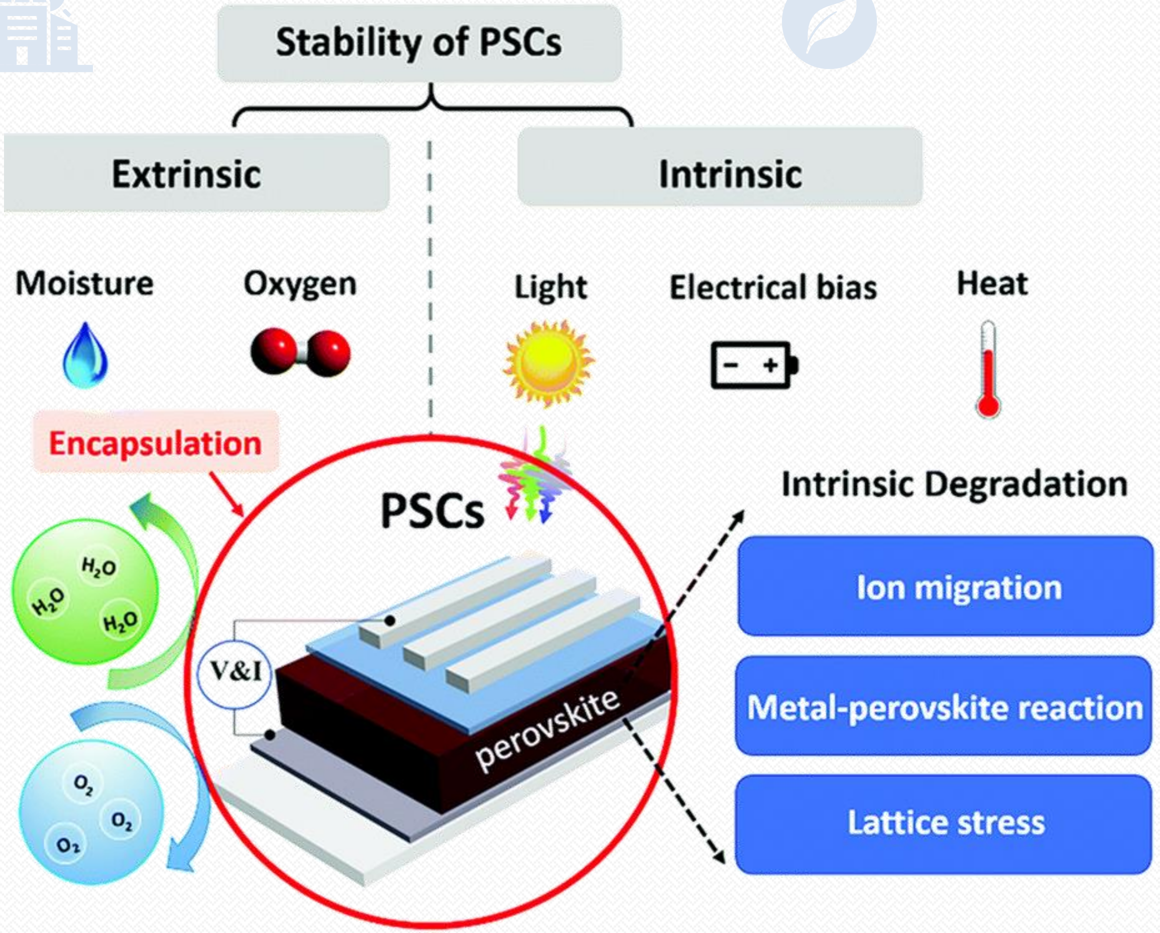
May 21st – 23rd, Erlangen, Germany

Date: May 28, 2024

Challenges to the commercialization of perovskite solar cells

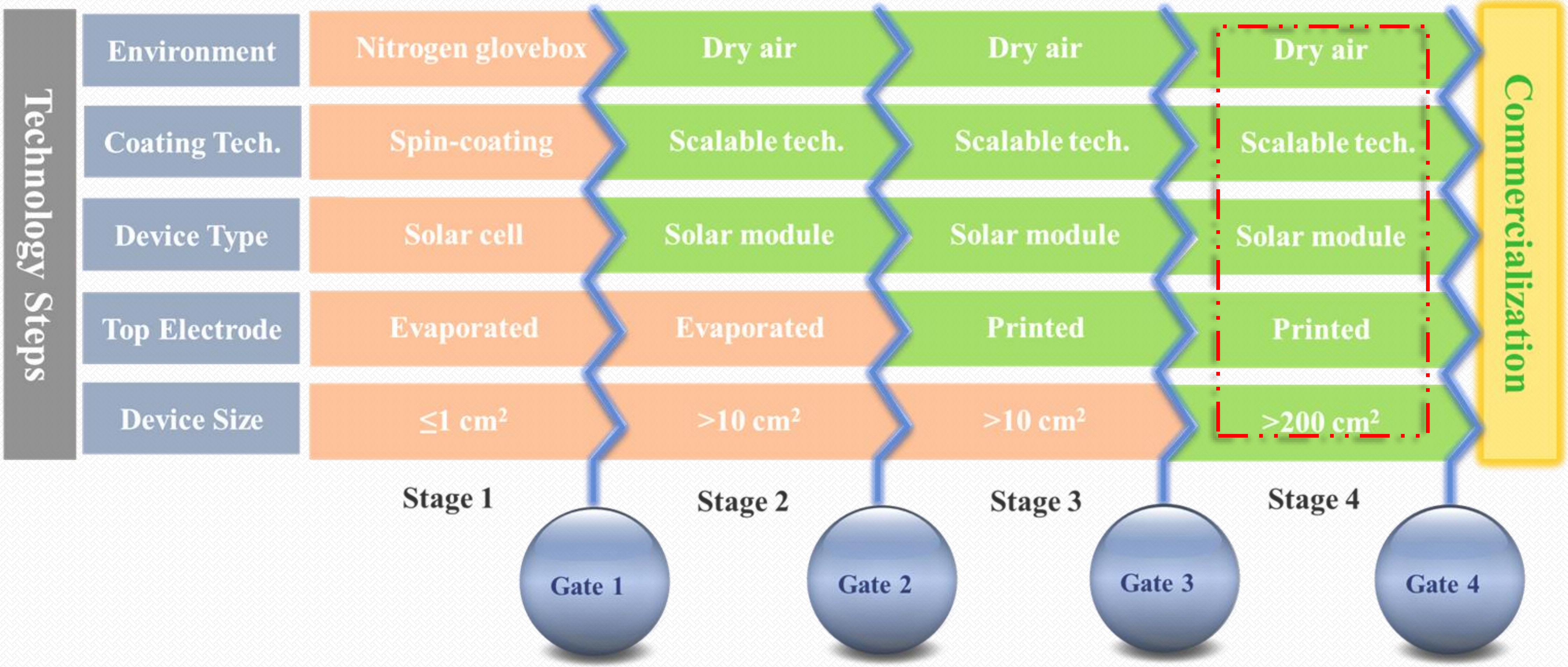
Golden triangle of solar cells





- Stability, Large-area fabrication

Stage-gate process for perovskite photovotics application



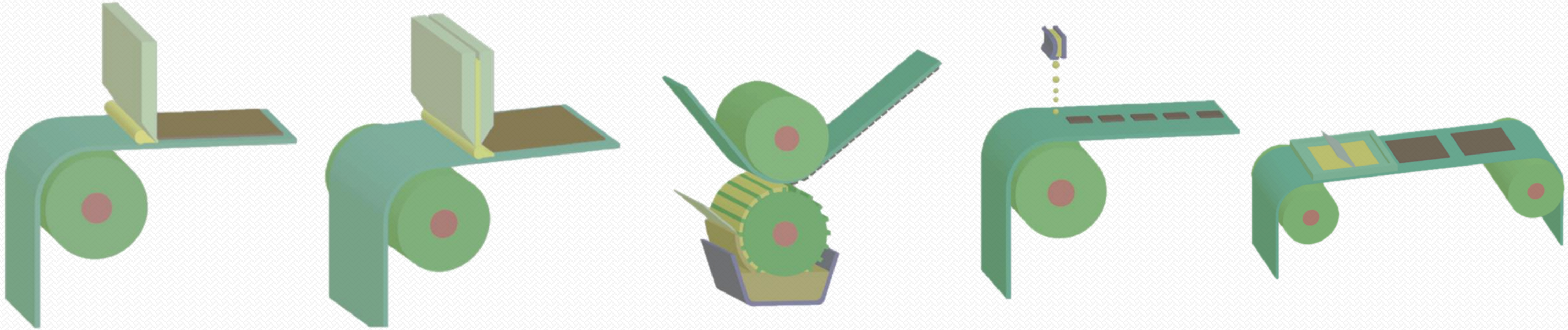
□ **PSCs, especially flexible PSCs, face a bright future**

F. Yang, N. Li, C. J. Brabec, H. J. Egelhaaf, *Adv. Energy Mater.* **2021**, *11*, 2101973.

Demand for high-throughput and cost-effective methods

Roll to Roll (R2R) fabrication

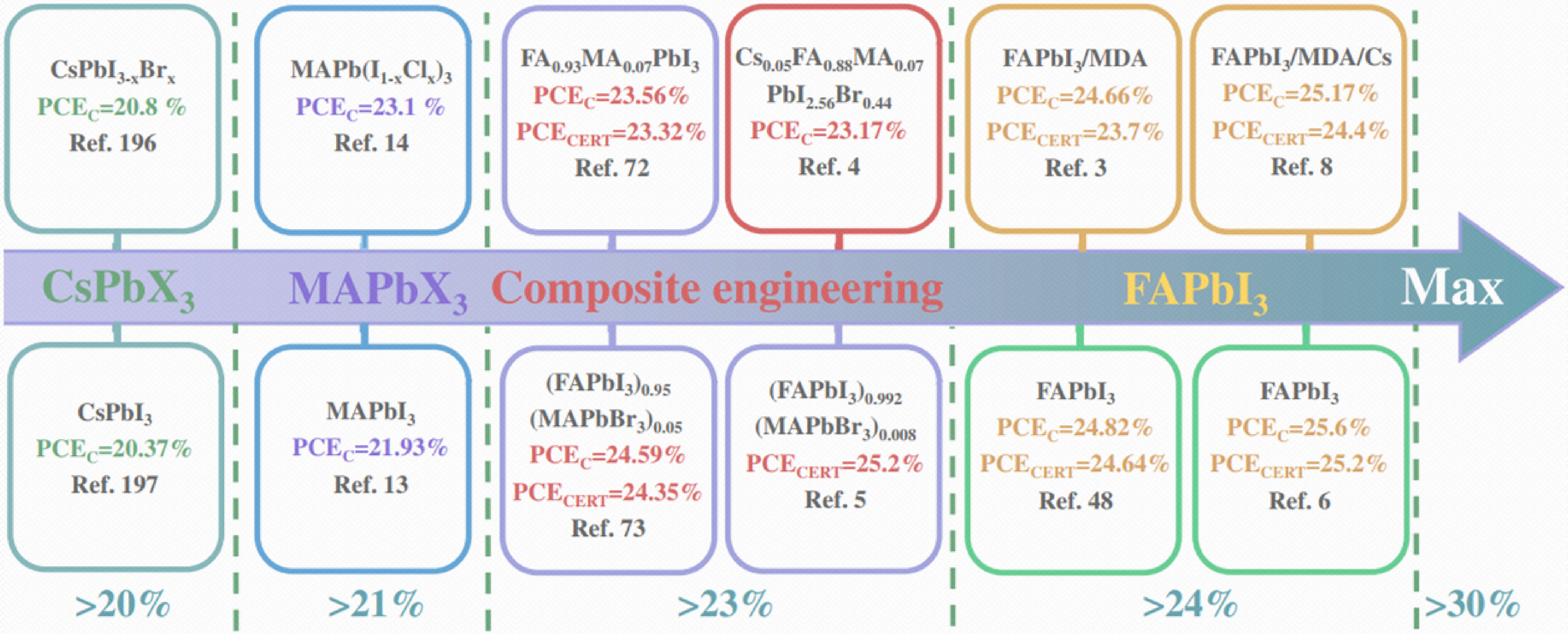
Nat. Commun. **2024**, 15, 1656.



F. Yang et al. npj Flex. Electron. **2021**, 5 , 1.

☐ **Developing scalable printing methods applicable to R2R fabrication process**

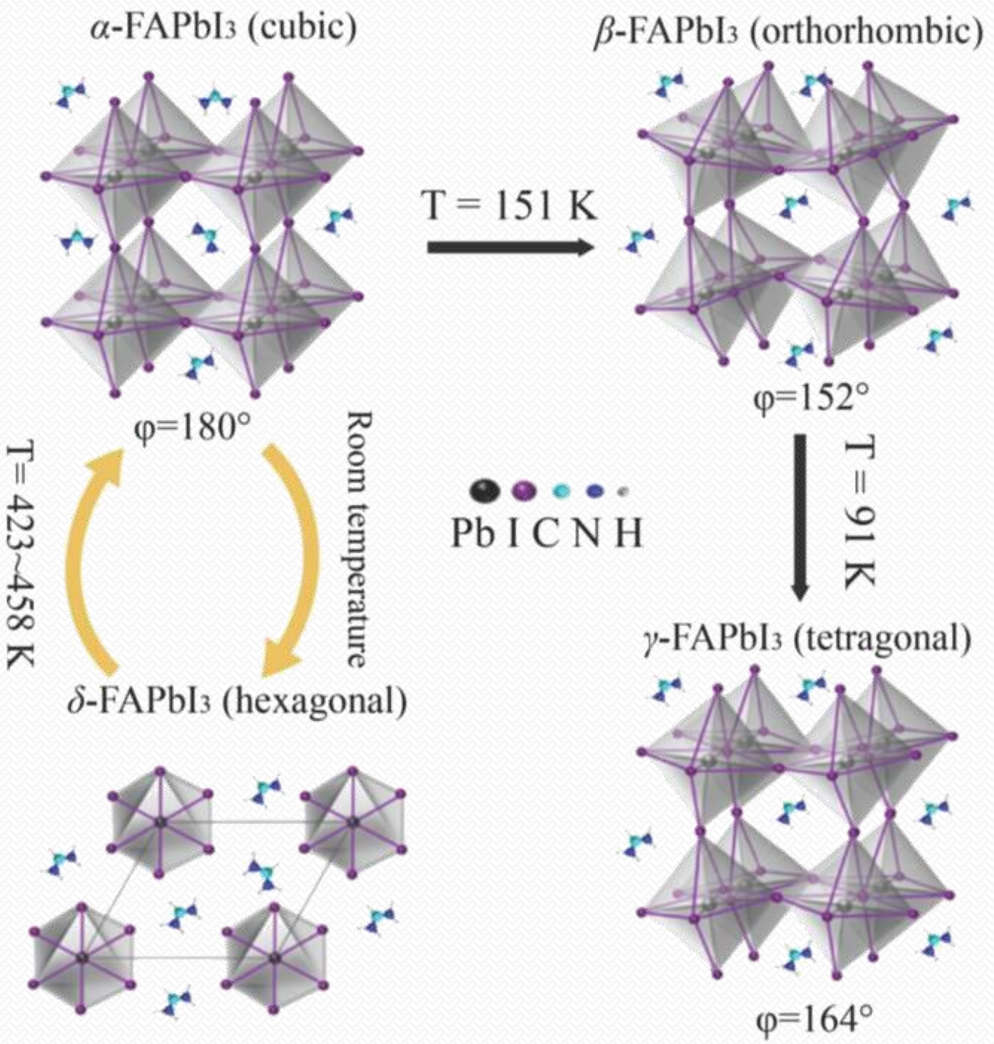
Promising perovskite composition: $FAPbI_3$

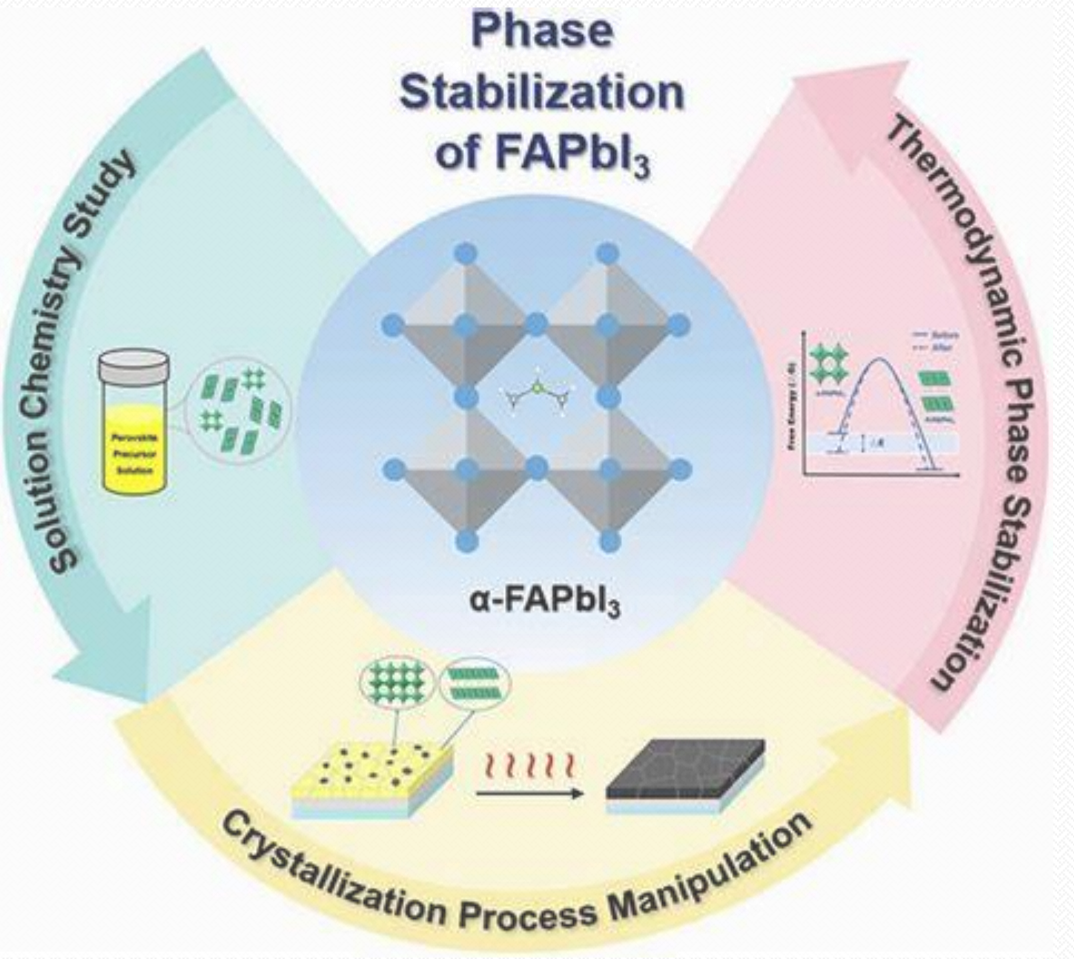


- ☐ **Superior thermal stability, suitable bandgap, high performance**

Sol. RRL, **2022,** 6, 2200060.

Unstable photoactive cubic phase (α-$FAPbI_3$)



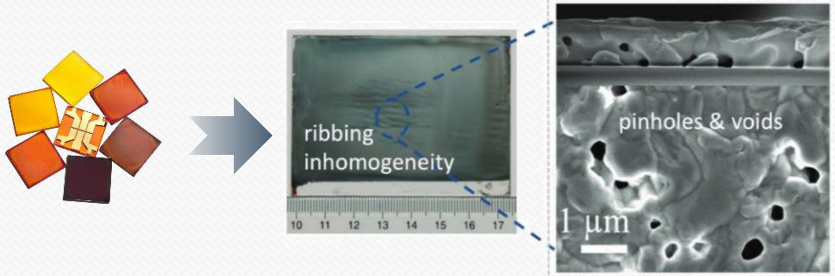


- Easily transformation into a non-photoactive δ-$FAPbI_3$ phase at room temperature, especially under the ambient atmosphere

Adv. Energy Mater. **2022**, 12, 2100690.

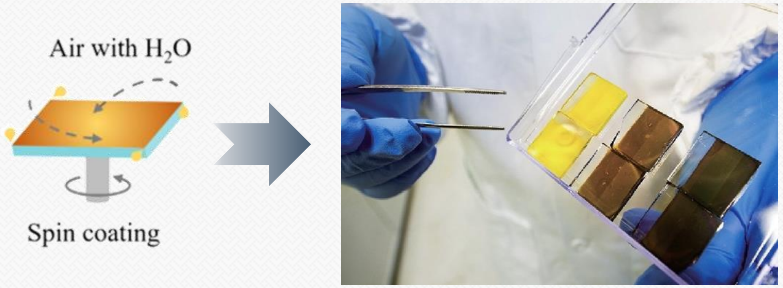
Issues of industrial producing $FAPbI_3$ perovskite

Large area film fabrication



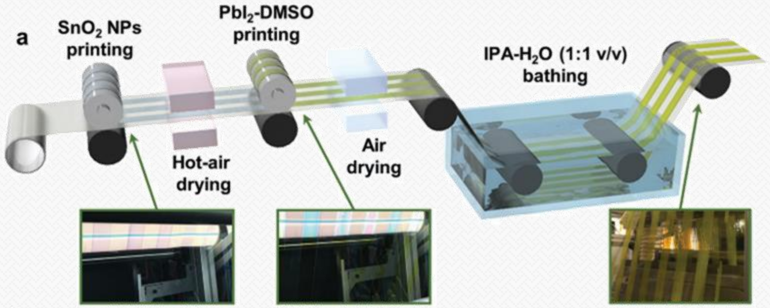
Adv. Energy Mater. **2023**, 13, 2203898

High humidity fabrication



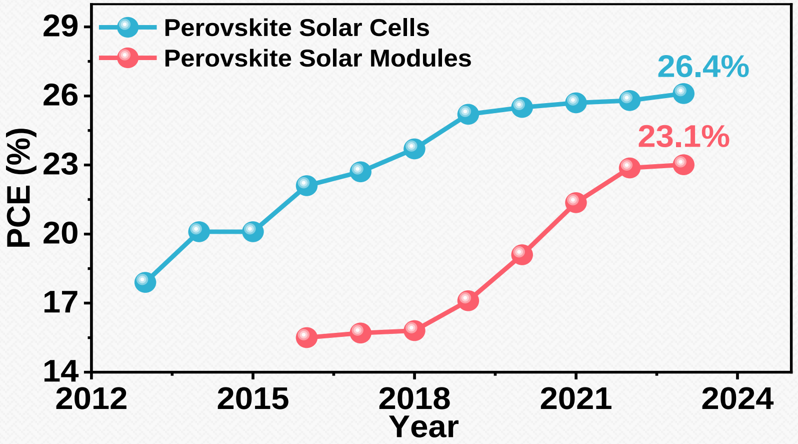
Angew. Chem. **2021**,133

High-throughput printing



Adv. Sci. **2019**, 6, 1802094

PCE gap



- ☐ **It is urgent to solve the key problems in the process of industrial fabrication of perovskite**

Our research interests

01

High humidity printing

Scalable Printing

$FAPbI_3$ Perovskite

Under Ambient

Atmosphere

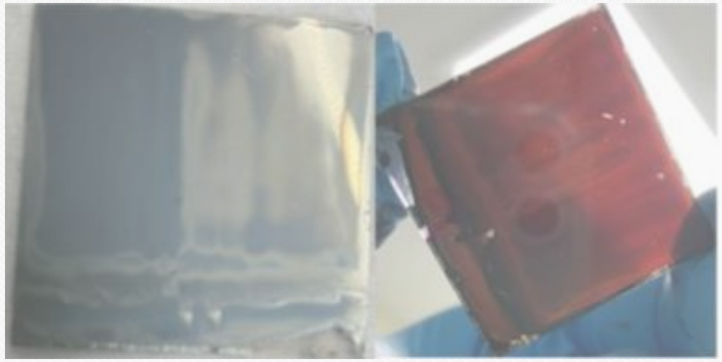
Joule, 2024, in press.
Angew. Chem.Int. Ed. 2024, 63, 16954.
Adv. Funct. Mater. 2024, 34, 2312250.
Sol. RRL 2024, 2301050.
Adv. Energy Mater. 2022, 12, 2202207.
Adv. Mater. 2021, 33, 2105170.
Adv. Energy Mater. 2021, 11, 2101219.
Adv. Energy Mater. 2021, 11, 2101973.
npj Flex. Electron. 2021, 5, 1.
Chin. Phys. B 2021, 30, 088803.
ACS Appl. Mater. Inter. 2021, 13, 61039.
Adv. Energy Mater. 2020, 10, 2001869.
Chem. Eng. J. 2019, 392, 123677.
ACS Sustain. Chem. Eng. 2020, 8, 8848.
Angew. Chem.Int. Ed. 2018, 57, 12745.
Adv. Funct. Mater. 2018, 28, 1804856.
ACS Appl. Mater. Inter. 2018, 10, 24543.
ACS Appl. Mater. Inter. 2018, 10, 16482.
ChemSusChem 2018, 11, 2348.
Sol. RRL 2018, 3, 1800275.

02

High-throughput printing

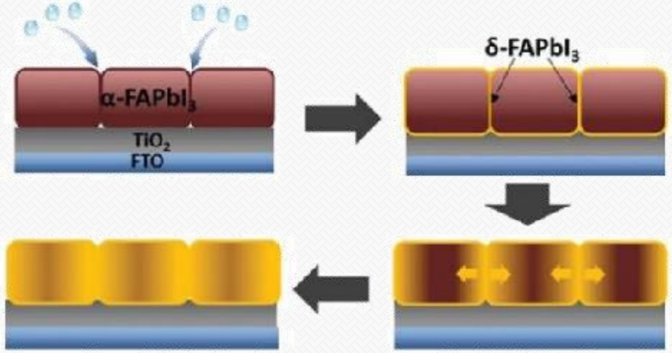
Topic 1

Printing perovskite film in humd atmosphere



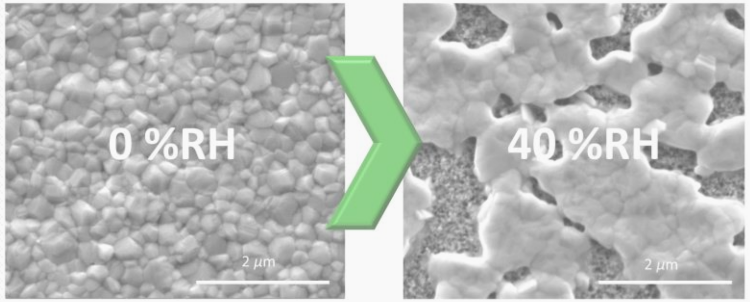
Adv. Mater. **2023**, 2307583

High phase transition and nucleation barrier

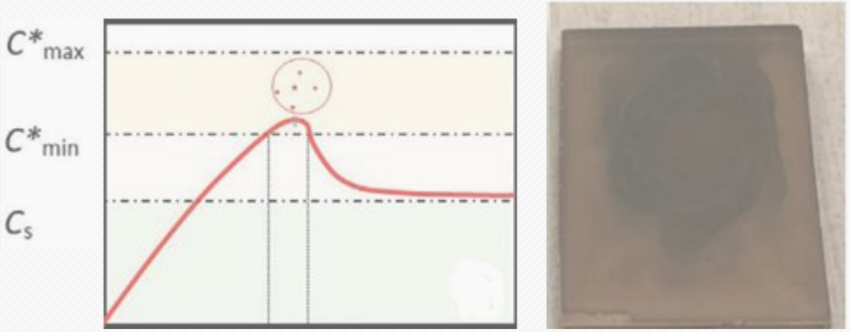


Adv. Funct. Mater. **2018**, 28 (11): 1705363.

Moisture can easily change α-phase to δ-phase perovskite

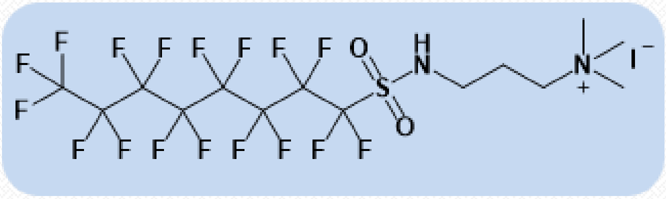


Poor film quality

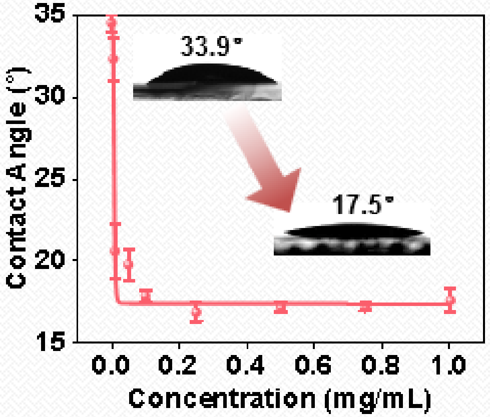


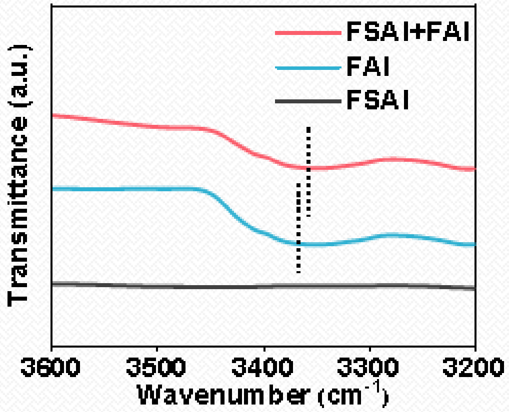
Low solvent volatile rate

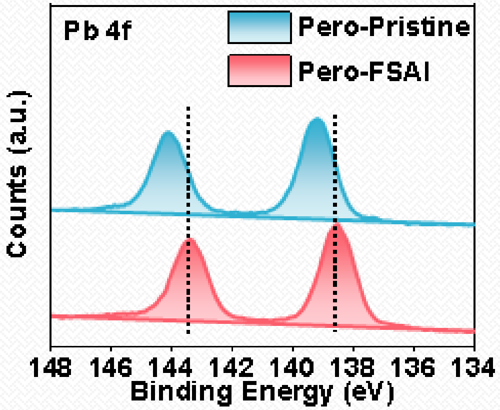
Perfluoroalkylsulfonyl ammonium in precursor ink



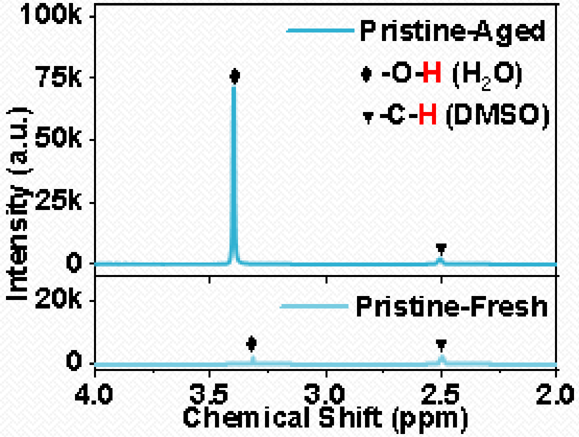
Structural formula of FSAI

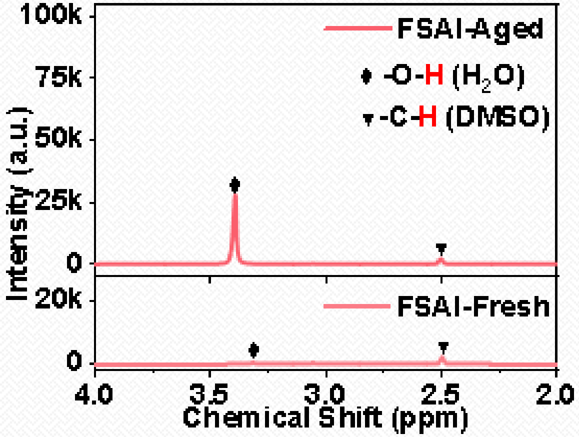


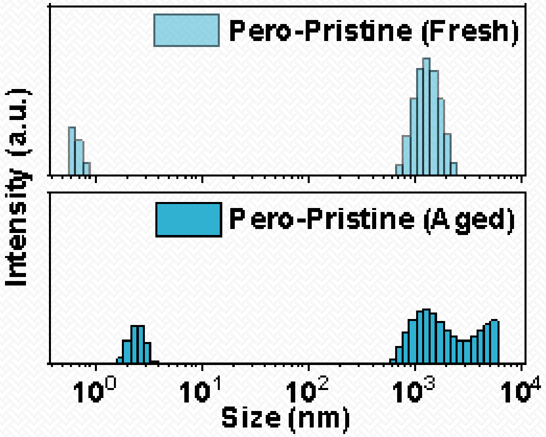


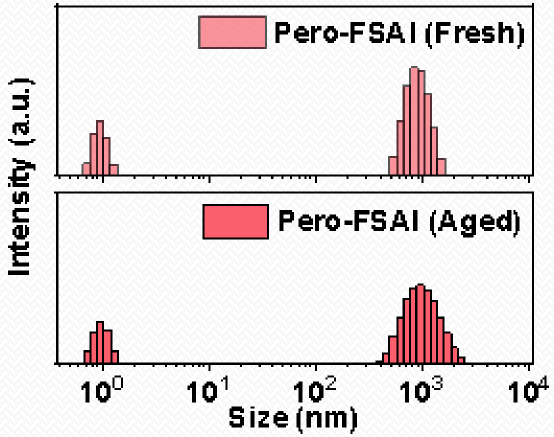


◆ FSAI interacted with both FAI and PbI_2 and reduced the perovskite heterogeneous nuclear barrier.









◆ Enhanced ink hydrophobicity and stability helped fabricate perovskite films at high humidity.

Humidity-resistant manufacturing

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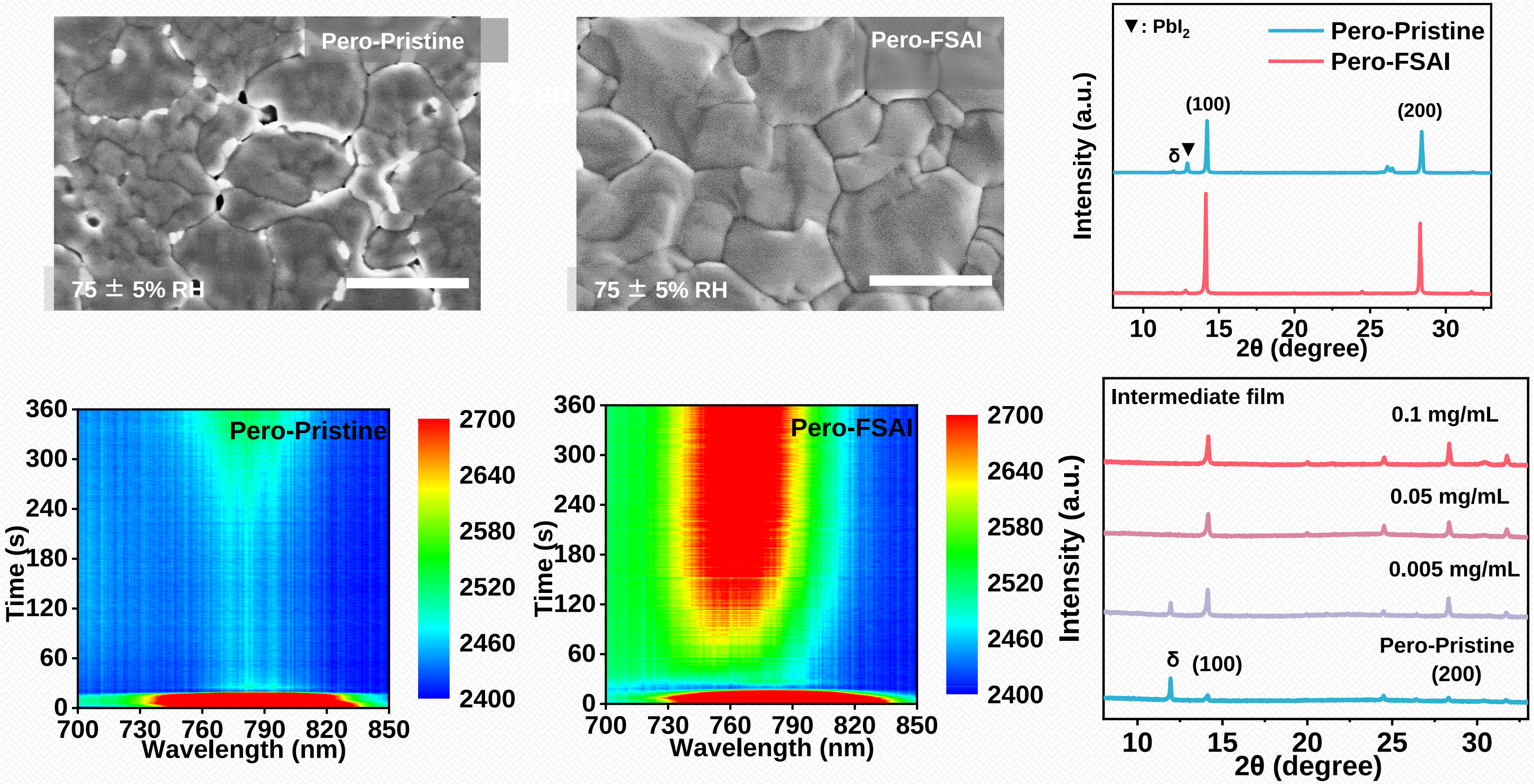
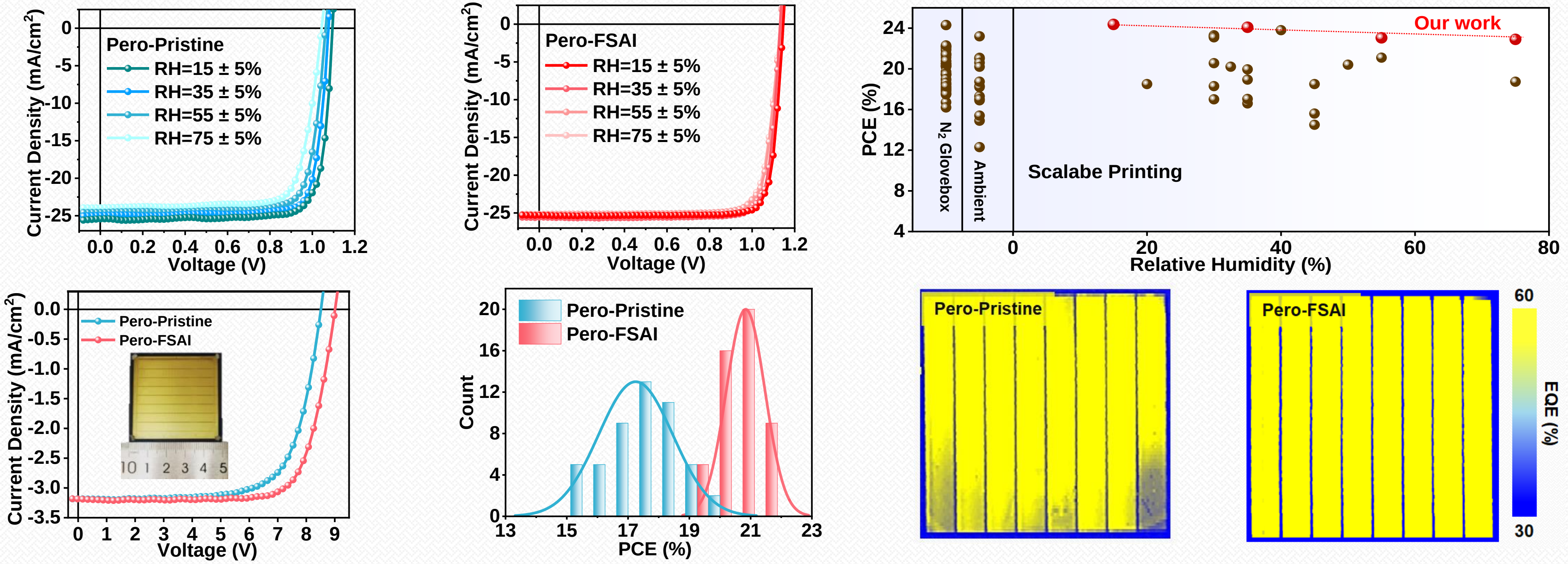


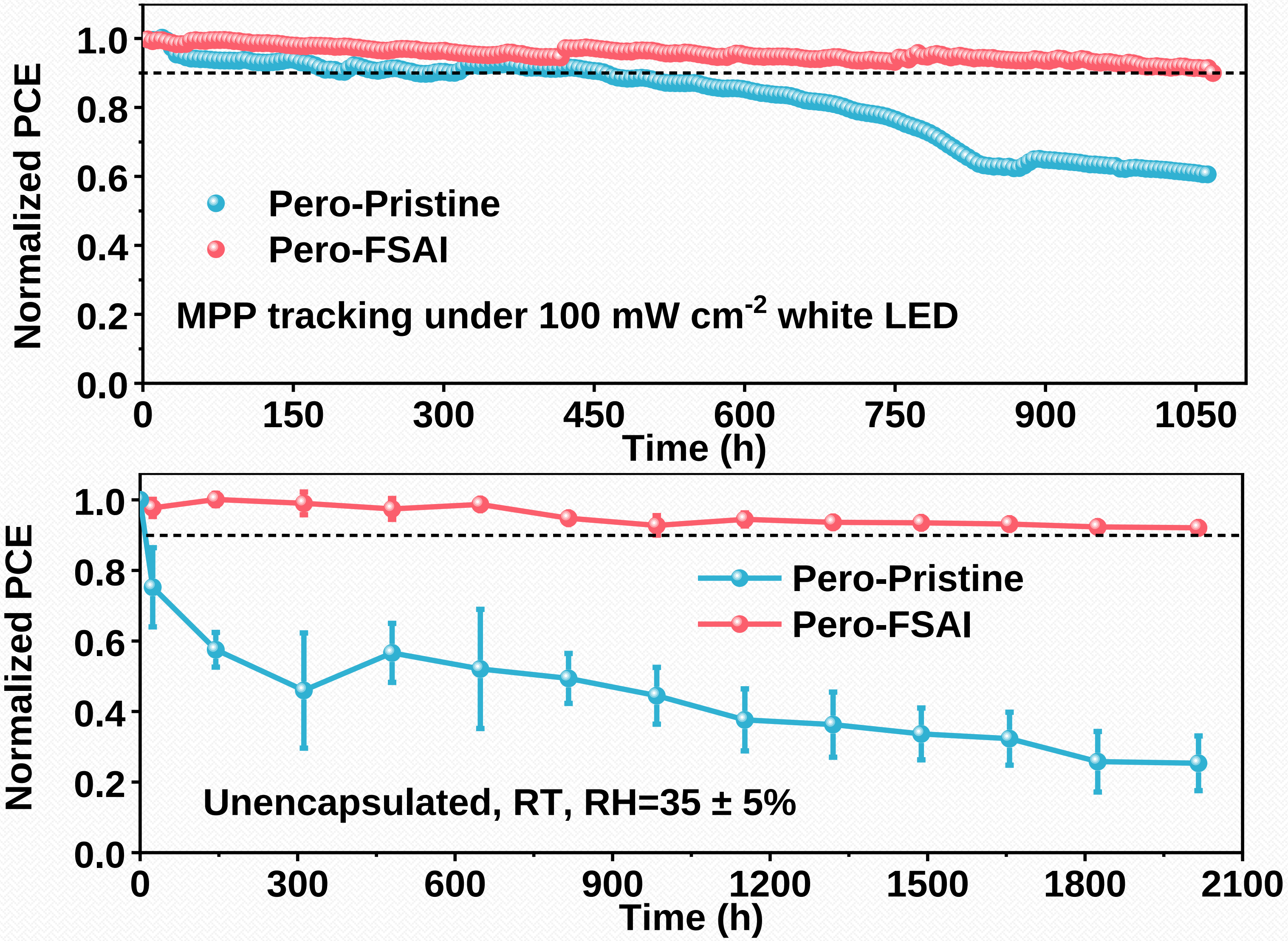
- ◆ The quality of perovskite films was well maintained under high humidity;
- ◆ FSAI incorporation can enhance the stability of the α-$FAPbI_3$ phase at room temperature.

Photovoltaic performance



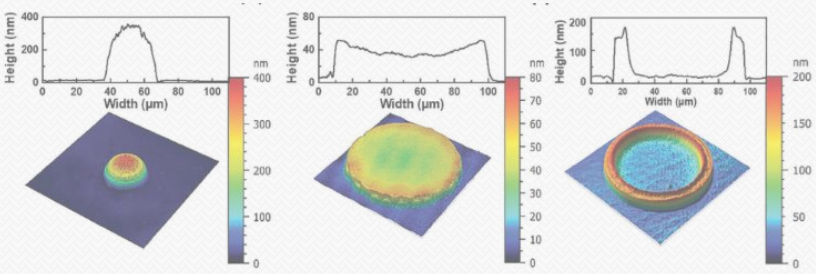
Active Area (cm^2)	RH (%)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	PCE (%)
0.062	15 ± 5	1.100	25.37	80.93	22.48
		1.149	25.30	84.00	24.37
	75 ± 5	1.045	23.93	76.89	19.24
		1.140	25.18	80.26	22.92
15.64	15 ± 5	8.515	3.187	71.44	19.38
		9.016	3.188	76.52	22.00

Devices stability



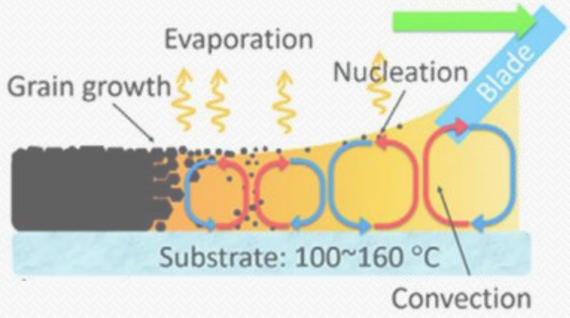
F. Yang, N. Li, C. J. Brabec, H. J. Egelhaaf, Y.W. Li, Y.F. Li, ***Joule***, 2024*, in press.*

High-throughput fabrication of perovskite photovoltaics



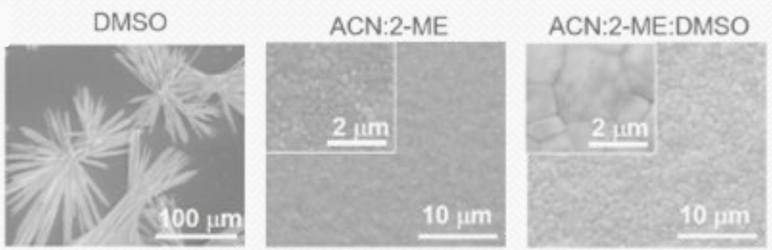
Coffee-ring effect induced pinholes and inhomogeneity

Adv. Optical Mater. **2021**, 9, 2100553



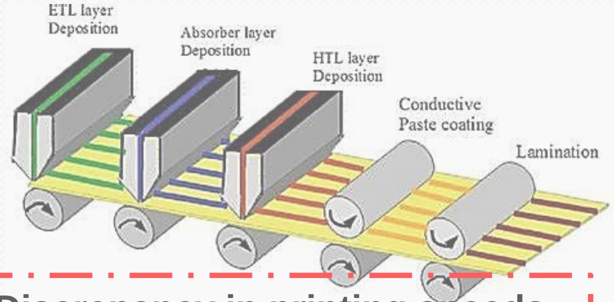
Uncontrolled volatilization and crystallization in large-area printing

Mater. Horiz. **2015**, *2*, 578-583



Decreased film quality for high speed printing

Sci. Adv. **2019**, 5 , 7537

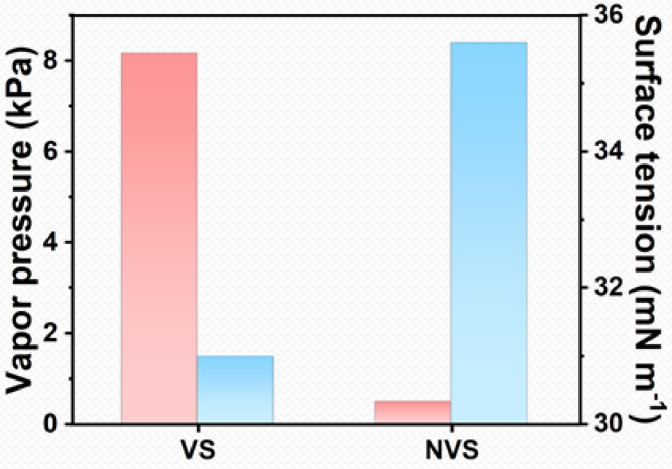


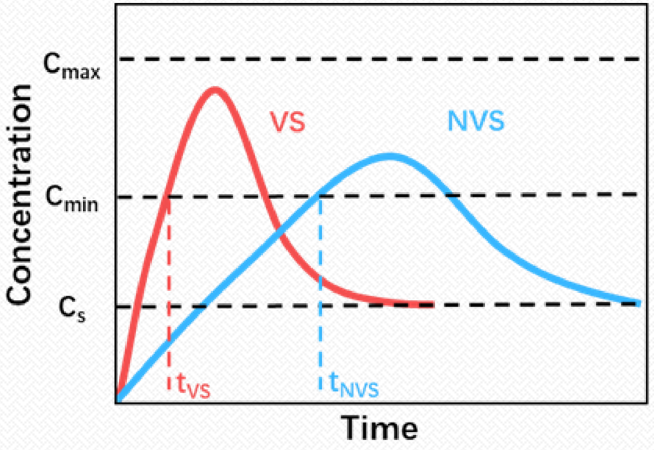
Discrepancy in printing speeds

Adv. Energy Mater. **2021**, 11, 2101973.

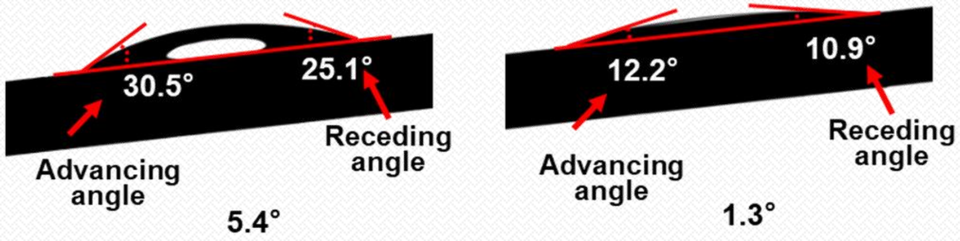
Current issues of Non-volatile DMF（NVS）precursor ink

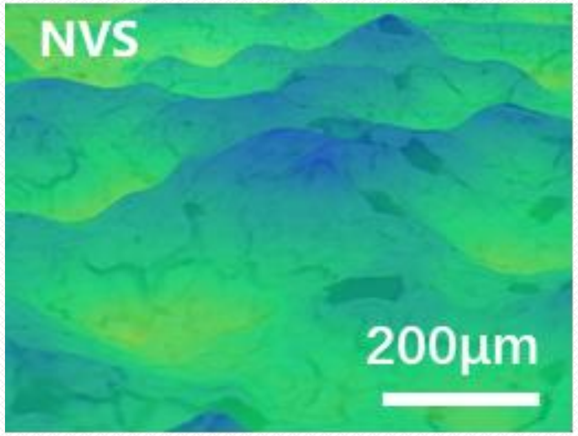
Control volatilization of solvent

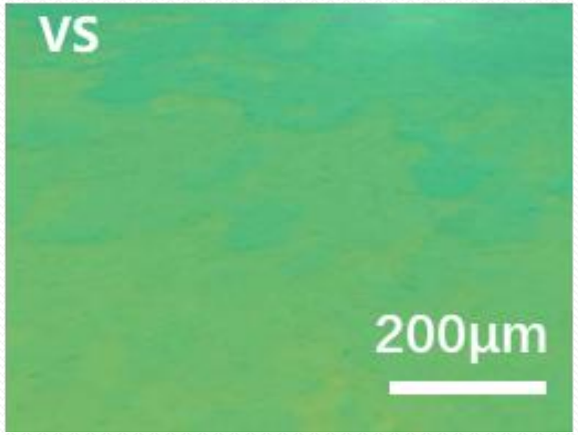




$$G_{Heterogeneous} = G_{Homogeneous} \times \frac{(2+\cos\theta)(1-\cos\theta)^2}{4}$$

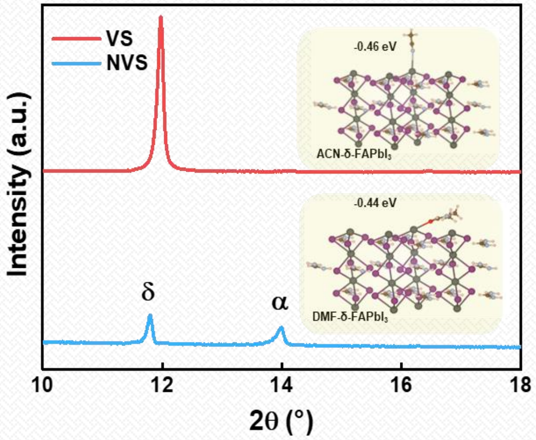


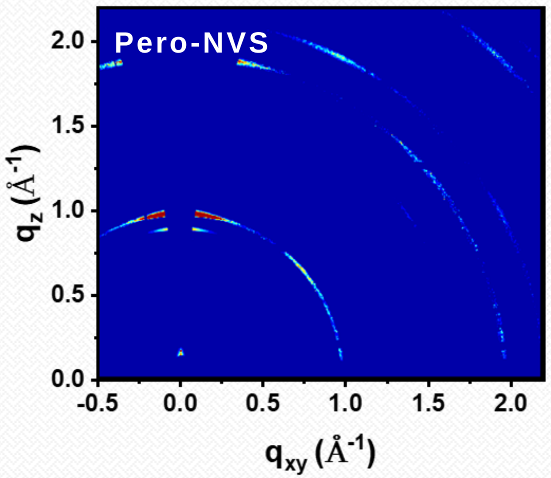


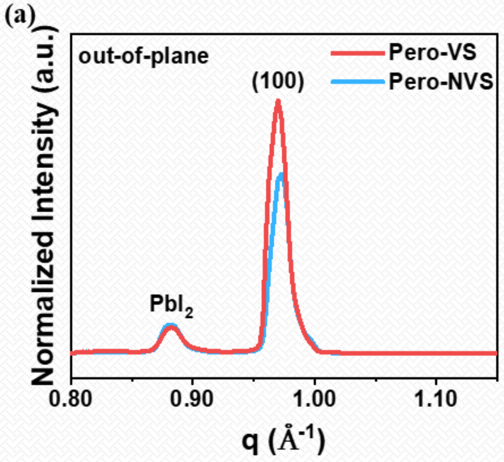


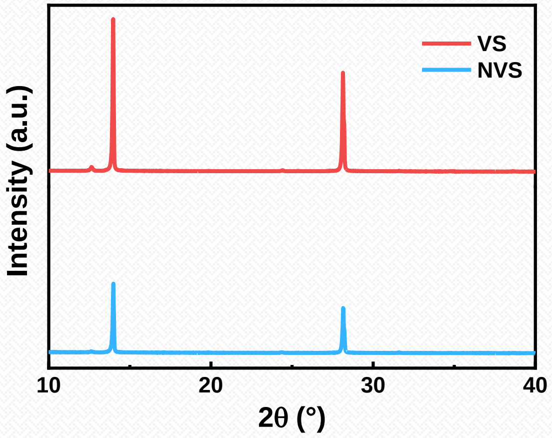
- VS: Using acetonitrile as the solvent with DMF/DMSO as the coordination additive.
- NVS: Commonly used DMF/DMSO solvents.
- Increased nucleation rate, reduced film porosity, and improved film quality.
- Reduces pinning effect and improves solution spread ability.

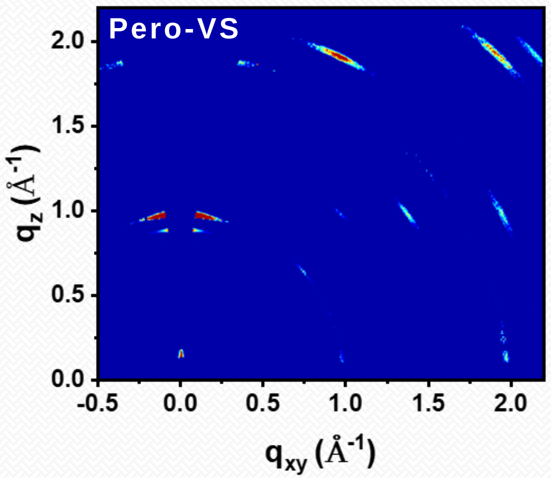
Optimization of perovskite phase transitions

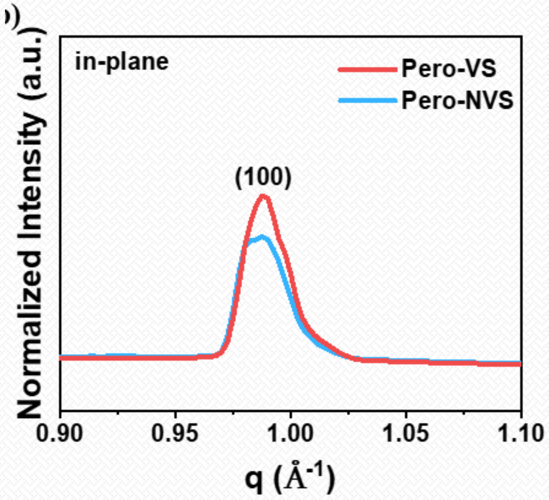






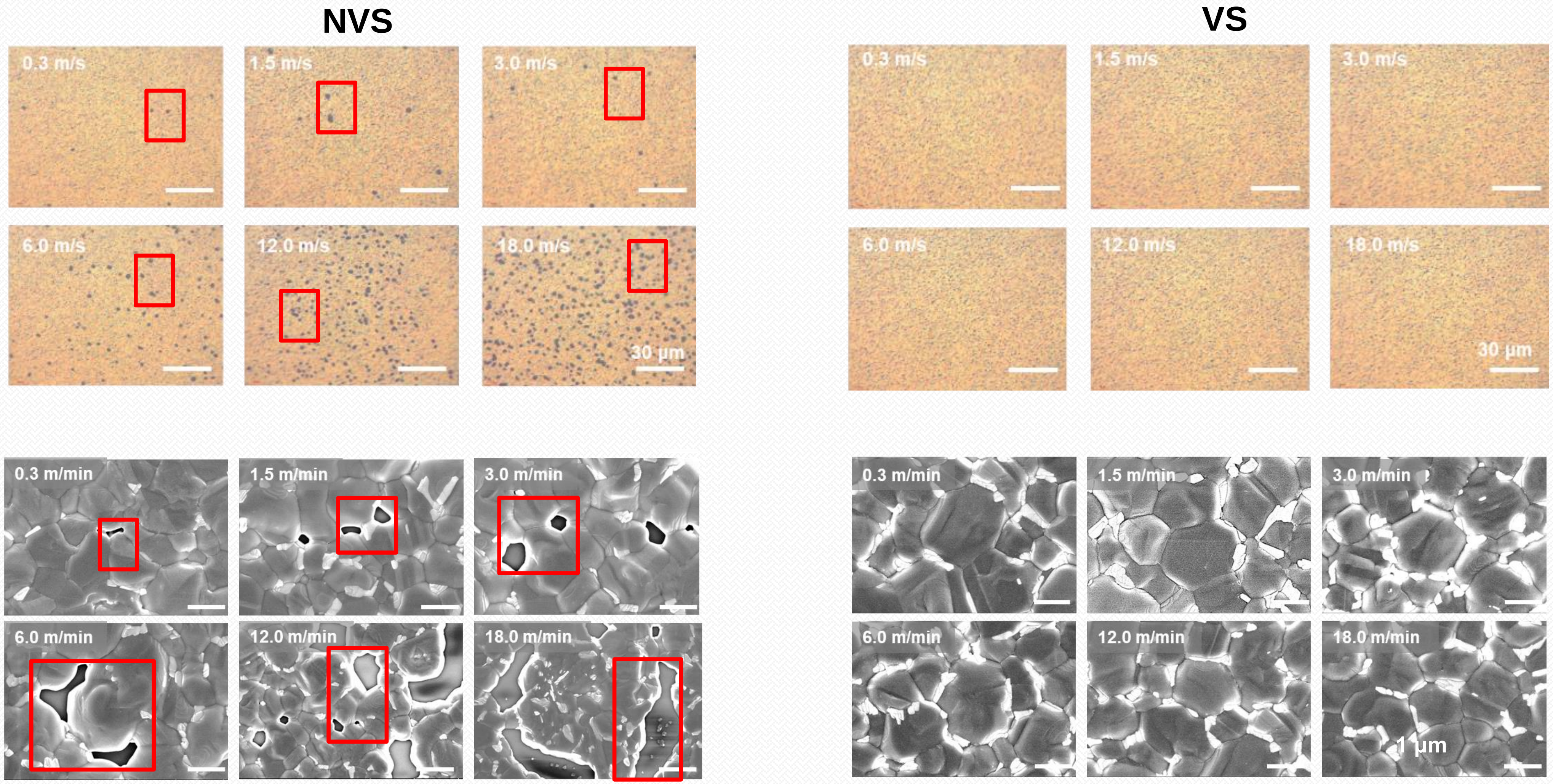






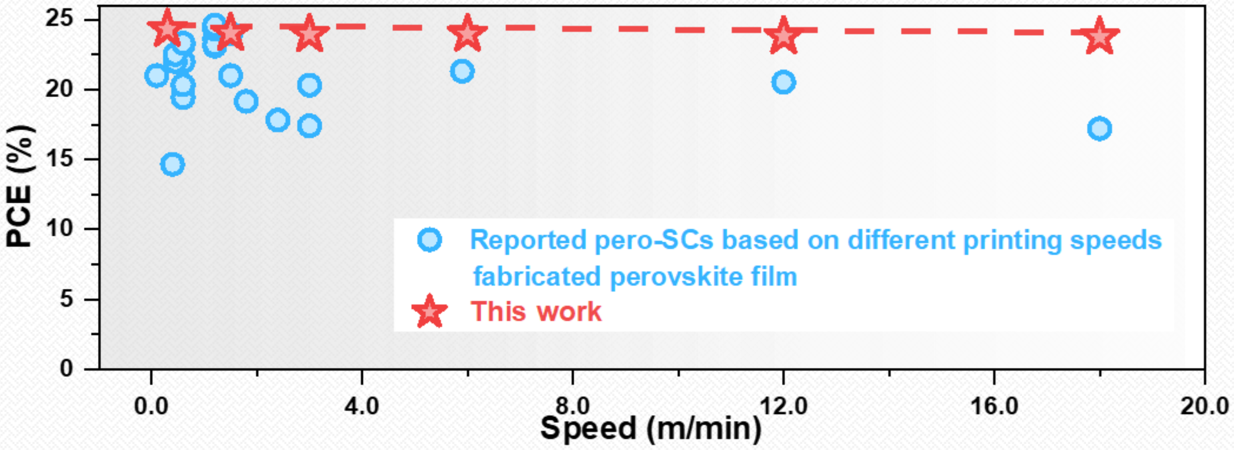
- **Generation of pure δ-$FAPbI_3$ phase in the intermediate film help for the restrained complicated pathways of crystal nucleation**

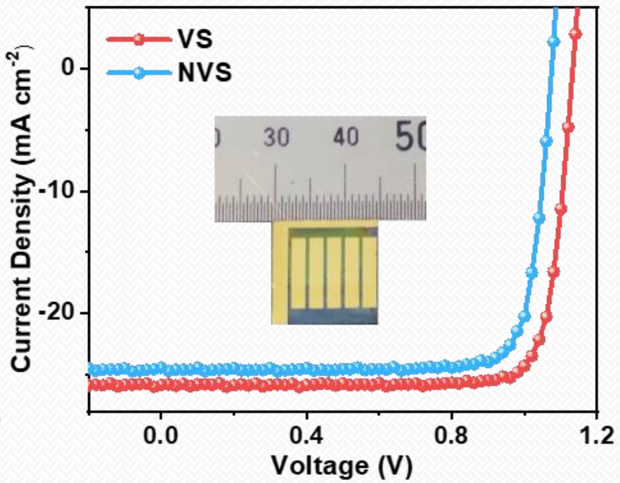
Wide speed window blade-coating



➢ **Remained high quality during the wide speed window printing (0.3 m/min to 18.0m/min)**

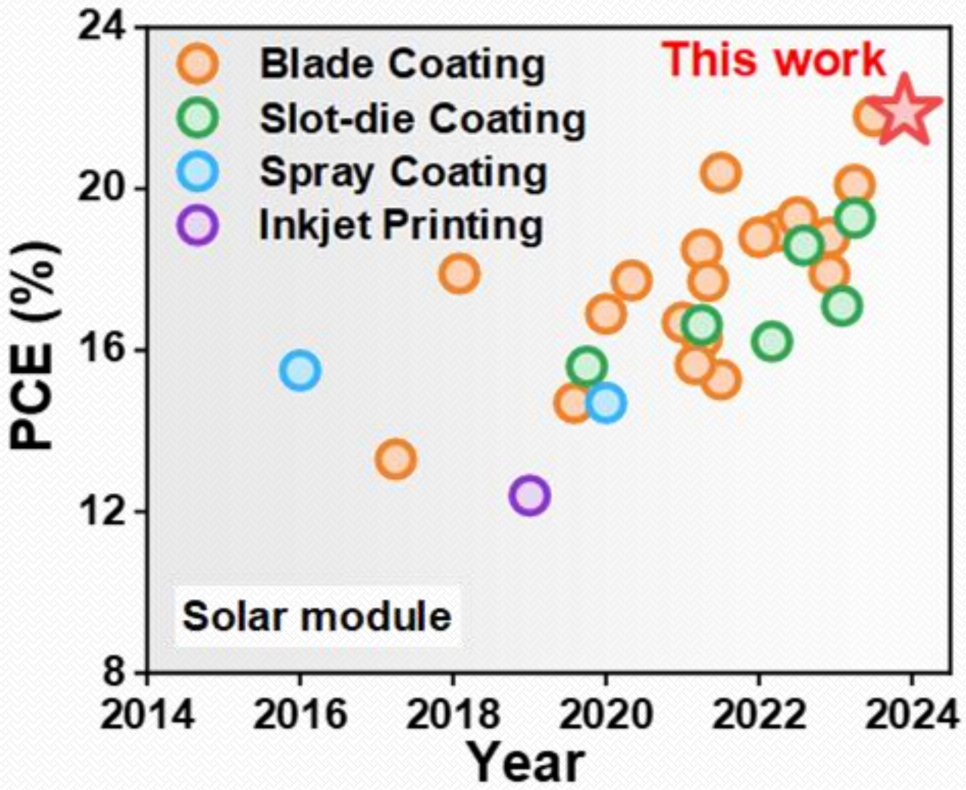
Photovoltaic performance

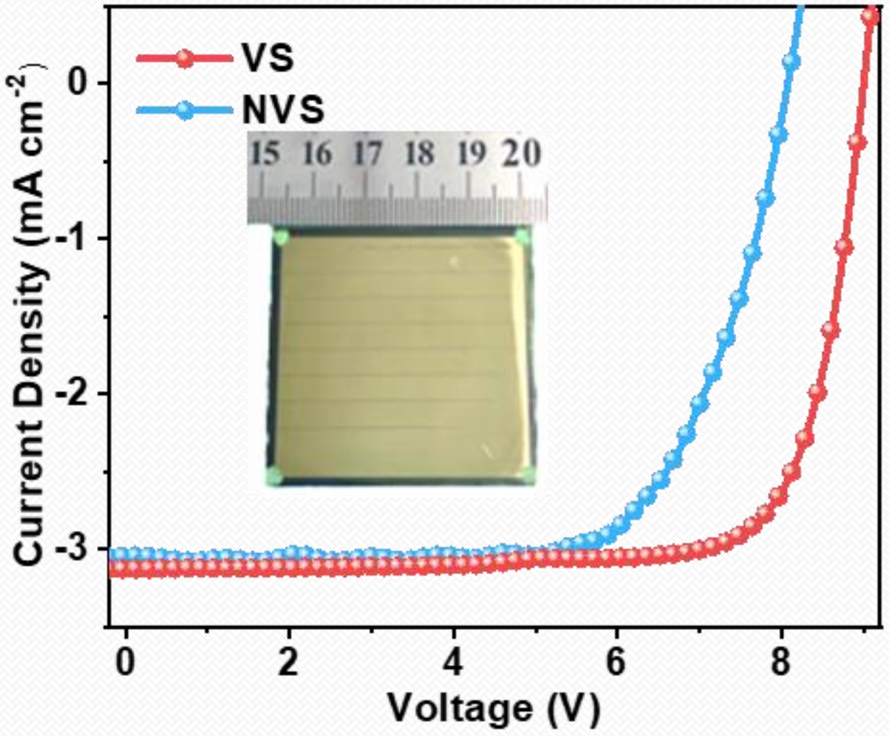




	Speed (m/min)	V_{OC} (V)	J_{SC} (mA/cm²)	FF (%)	PCE (%)
VS	0.3	1.15	25.73	82.18	**24.32**
	1.5	1.13	25.42	83.63	**24.04**
	3.0	1.13	25.70	82.67	**23.94**
	6.0	1.14	25.11	84.08	**23.98**
	12.0	1.12	25.50	83.16	**23.80**
	18.0	1.12	25.38	83.39	**23.76**
NVS	0.3	1.07	24.58	82.48	21.63
	1.5	1.04	24.72	72.74	18.69
	3.0	1.03	22.36	74.27	16.62

Photovoltaic performance





	Active area（cm²）	V_{oc} (V)	J_{sc} (mA/cm²)	FF (%)	PCE (%)
VS	15.64	9.00	3.14	77.55	**21.90**
NVS	15.64	8.07	3.05	70.10	17.27

F. Yang, C. J. Brabec, H. J. Egelhaaf, Y.W. Li, Y.F. Li, **Angew. Chem.**2024, 63 (7), e202316954.

Acknowledge

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Prof. Christoph J. Brabec, Prof. Egelhaaf, Hans-Joachim

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Thanks for your time!