

Supporting information

High-Performance Perovskite Solar Cells and Modules  
Fabricated by Slot-Die Coating with Nontoxic  
Solvents

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**Table S1.** The thickness, resistance (R) and device performance of slot-die coated PSCs with different precursor concentration of NiO<sub>x</sub> film compared with spin coated PSCs.

Process	Precursor concentration (M)	Thickness (nm)	R (10 <sup>-1</sup> ohm)	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	PCE (%)
Slot-die (SD)	0.125	22.52 ±3.03	8.04	0.98 ±0.07	20.30±0.71	60.74 ±8.78	12.26 ±2.23
				(1.01)	(19.46)	(66.22)	(13.12)
	0.25	60.37 ±6.84	12.44	1.05 ±0.01	18.52 ±0.52	73.24 ±3.12	14.30 ±0.81
				(1.05)	(18.80)	(77.53)	(15.43)
	0.375	69.12±7.76	14.65	1.05 ±0.00	17.78 ±0.38	71.84 ±3.98	13.47 ±0.77
				(1.06)	(17.45)	(77.17)	(14.30)
	0.50	86.88±8.15	19.05	1.05 ±0.01	16.41 ±0.80	71.78 ±4.41	12.47 ±1.07
				(1.06)	(17.06)	(74.85)	(13.57)

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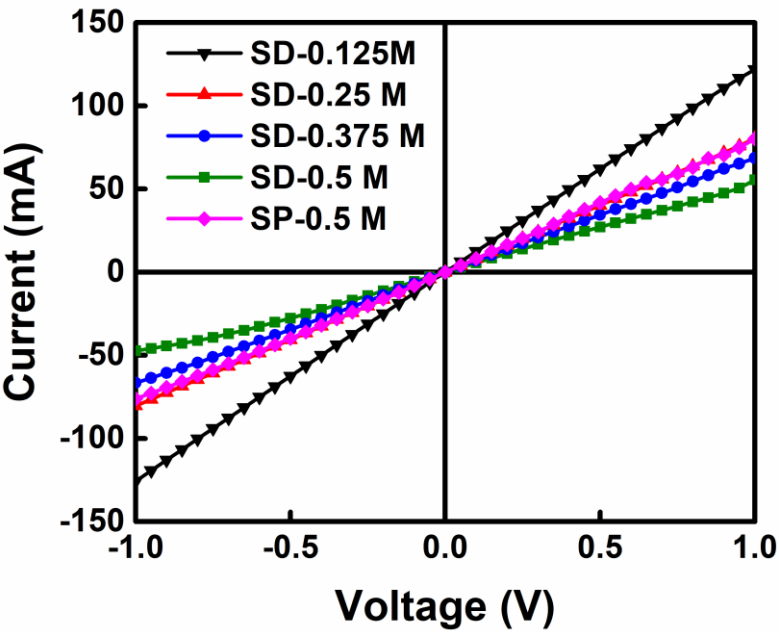
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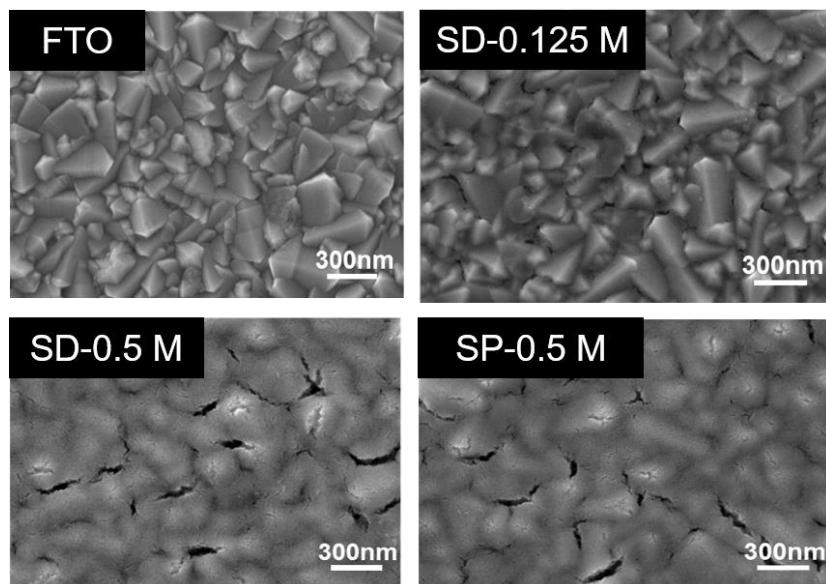
Spin	0.50	61.30 ±6.59	12.64	1.05 ±0.01	18.31 ±0.72	73.98 ±2.33	14.28 ±0.52
(SP)				(1.08)	(19.06)	(74.46)	(15.41)

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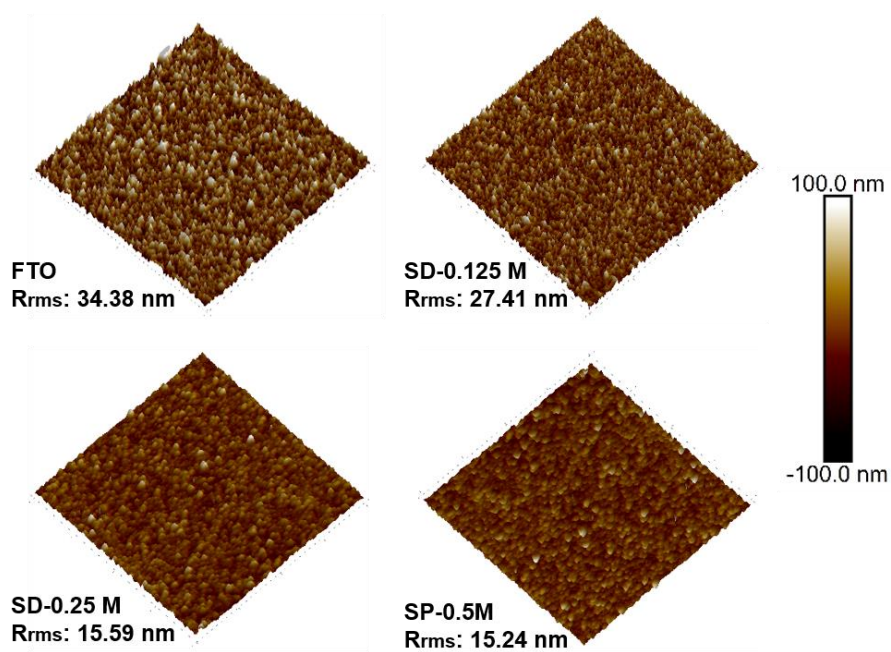


**Figure S1.** The I–V curve of slot-die coated NiO<sub>x</sub> film with precursor concentration and spin coated NiO<sub>x</sub>–NiO<sub>x</sub> film obtained by linear sweep voltammetry.

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**Figure S2.** Top view SEM image of FTO, 0.125 M and 0.25 M nm NiO<sub>x</sub> film by slot-die, 0.5 M NiO<sub>x</sub> film by spin coating.



**Figure S3.** AFM image of FTO, 0.125 M and 0.25 M NiO<sub>x</sub> film by slot-die, 0.5 M NiO<sub>x</sub> film by spin coating.

**Table S2.** Physical properties of solvents.

Solvent	Vapor pressure at R.T. (Pa)	Surface tension (mN m <sup>-1</sup> )	Boiling point (°C)
DMF	516	33.78	152
DMSO	56	37.81	189
2-MP	1292	26.23	135
DMSO+2-MP	-	29.65	-

**Table S3.** Fitting results of time-resolved photoluminescence characterization.

Solvent	$\tau_1$ (ns)	Fraction (%)	$\tau_2$ (ns)	Fraction (%)	$\tau_{\text{average}}$ (ns)
DMSO	21.54	75	2.27	25	16.73
DMSO:2-MP (30 vol%)	36.59	88	3.72	12	32.64

**Table S4.** Device performance of different thickness of perovskite film by slot-die coating.

Thickness (nm)	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	PCE (%)
218.47±29.21	1.03 ±0.02 (1.05)	14.26 ±1.87 (14.86)	67.16 ±5.32 (72.79)	9.86 ±1.76 (11.44)

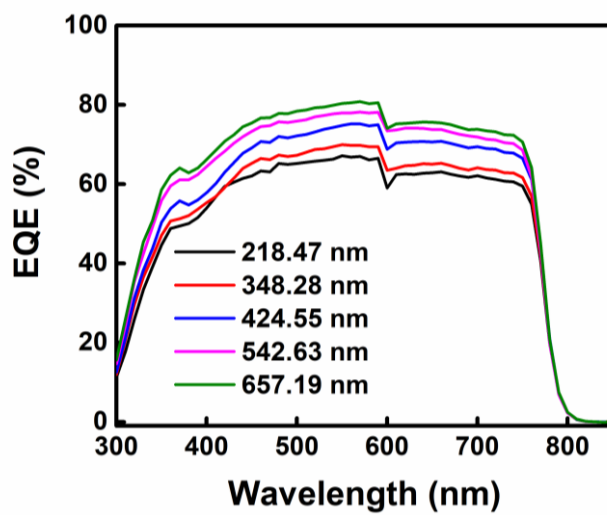
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348.28±34.86	1.01 ±0.01 (1.01)	16.34 ±1.03 (17.18)	67.58 ±4.48 (71.32)	11.15 ±1.32 (12.46)
424.55±36.56	1.02 ±0.02 (1.03)	17.63 ±1.33 (18.19)	69.73 ±3.83 (71.63)	12.58 ±1.50 (13.48)
542.63±28.25	1.03 ±0.02 (1.05)	18.54 ±1.02 (18.98)	68.13 ±5.23 (70.47)	13.11 ±1.50 (14.13)
657.19±62.36	1.03 ±0.04 (1.06)	19.05 ±2.95 (19.42)	59.53 ±7.69 (63.19)	11.77 ±2.24 (13.07)



**Figure S4.** EQE spectrum with different thickness of perovskite film by slot-die coating.

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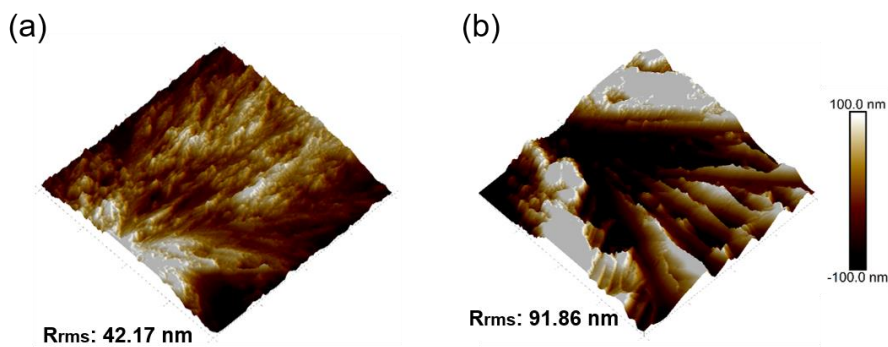
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**Figure S5.** Different thickness of slot-die perovskite film (a) 542.63 nm, (b) 657.19 nm.

**Table S5.** Device performance of slot-die coated PSCs with perovskite film fabricated at different substrate temperature.

Substrate temperature (°C)	$V_{oc}$ (V)	$J_{sc}$ (mA/cm <sup>2</sup> )	FF (%)	PCE (%)
130	1.03 ±0.05 (1.05)	17.48 ±2.69 (18.28)	59.82 ±7.34 (64.82)	10.87 ±3.98 (12.51)
150	1.04 ±0.01 (1.05)	18.14 ±1.07 (18.24)	71.22 ±4.08 (73.31)	13.49 ±1.17 (14.11)
170	1.05 ±0.02 (1.06)	19.25 ±0.73 (19.88)	73.05 ±3.65 (76.22)	14.84 ±1.14 (16.09)
190	1.03 ±0.02 (1.06)	17.53 ±1.54 (18.66)	60.71 ±5.17 (66.54)	11.06 ±1.88 (13.16)

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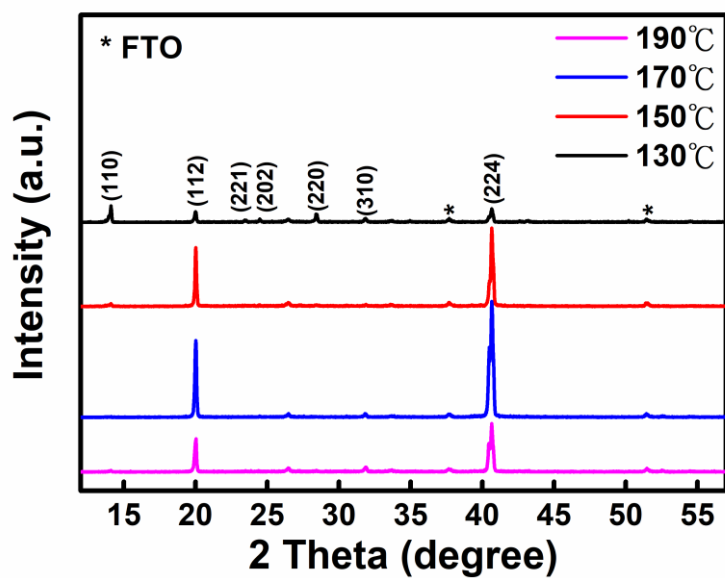
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**Figure S6.** XRD patterns of perovskite films fabricated at different substrate temperature.

**Table S6.** Device performance of slot-die coated PSCs using PC<sub>61</sub>BM films fabricated by different solvent compared with spin coated PSCs.

Process	PCBM solvent	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	PCE (%)
Slot-die (SD)	o-xylene	1.02 ±0.02 (1.06)	17.31 ±1.16 (19.35)	64.10 ±4.88 (66.65)	11.41 ±1.24 (13.64)
	anisole	0.95 ±0.05 (1.01)	17.08 ±1.83 (19.25)	51.62 ±8.45 (63.03)	8.64 ±2.37 (12.36)
	CB	1.02 ±0.01 (1.02)	17.49 ±0.88 (18.10)	64.50 ±5.10 (73.52)	11.52 ±1.01 (13.62)

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Spin (SP)	CB	1.03 ±0.02 (1.06)	18.66 ±0.63 (19.34)	71.88 ±3.67 (74.72)	13.86 ±0.92 (15.35)
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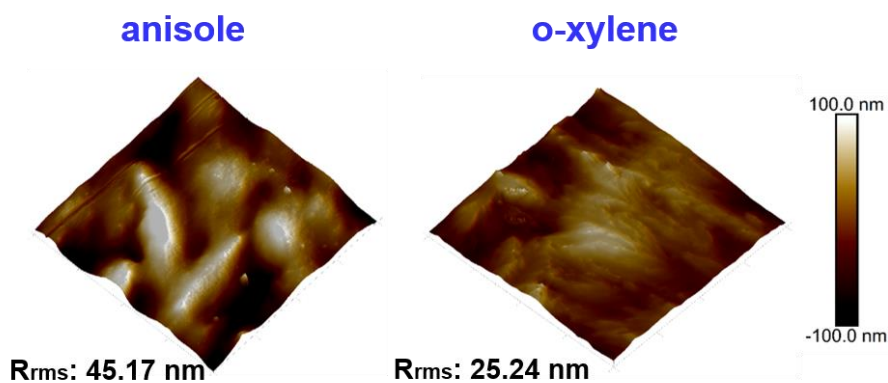
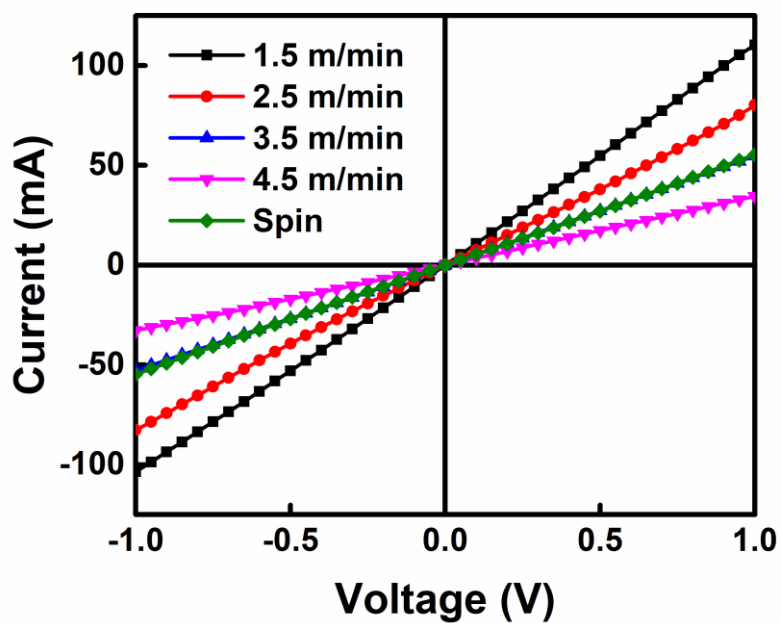
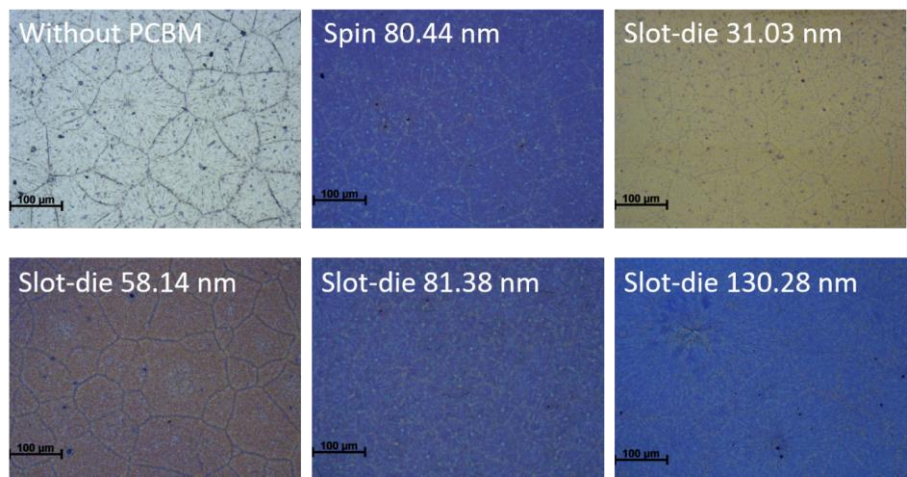


Figure S7. AFM image of PC<sub>61</sub>BM using anisole and o-Xylene solvent.





**Figure S8.** The  $I$ - $V$  curve of slot-die coated PC<sub>61</sub>BM film with different moving rate and spin coated PC<sub>61</sub>BM film obtained by linear sweep voltammetry.



**Figure S9.** OM images of slot-die coated PC<sub>61</sub>BM film with different thickness and spin coated PC<sub>61</sub>BM film.

**Table S7.** Device performance of slot-die coated PSCs with different WF materials compared with spin coated PSCs.

Process	Work function layer	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	PCE (%)
Slot-die (SD)	PEI	0.97 ±0.04 (1.03)	16.51 ±1.86 (17.40)	51.54 ±5.16 (61.14)	8.38 ±1.75 (11.03)
	TBAOH	1.02 ±0.02 (1.07)	16.47 ±0.84 (18.69)	68.48 ±3.75 (69.17)	11.62 ±0.97 (13.85)
Spin (SP)	PEI	1.03 ±0.02 (1.06)	18.69 ±1.18 (18.89)	67.03 ±5.30 (73.35)	13.03 ±1.73 (15.73)
	TBAOH	1.02 ±0.01 (1.04)	17.41 ±0.96 (18.89)	66.20 ±4.15 (70.46)	11.85 ±1.25 (13.95)

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**Table S8.** Device performance of standard perovskite solar cell and 4 cm<sup>2</sup> substrate area module. The J<sub>sc</sub> and PCE are performed under active area.

Device	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	PCE (%)
Standard cell (0.09 cm <sup>2</sup> )	1.03 ±0.02 (1.00)	18.51 ±0.90 (20.34)	62.86 ±4.91 (68.03)	12.03 ±1.08 (13.86)
Module (0.75 cm <sup>2</sup> )	1.99 ±0.06 (2.11)	8.92 ±0.87 (10.10)	56.69 ±2.58 (63.30)	10.03 ±1.35 (13.54)

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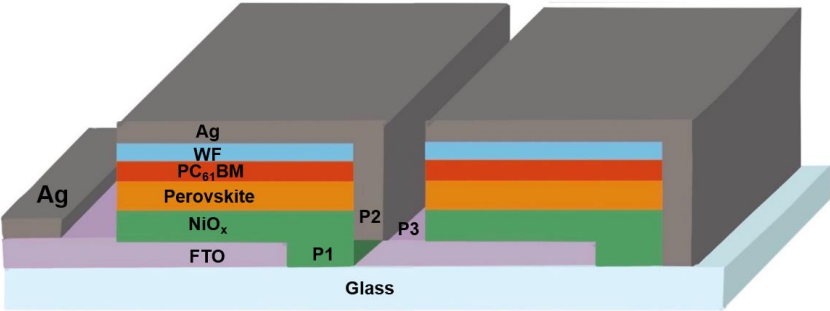
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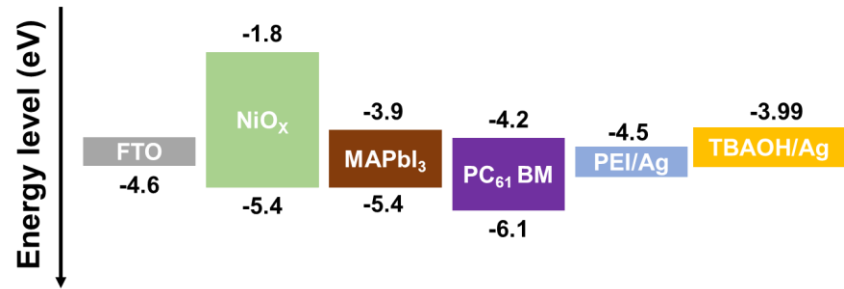
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**Figure S10.** The schematic diagram of the module. The line widths of P1, P2, and P3 were 50 μm, 100 μm, and 100 μm, respectively.



**Figure S11.** The energy band diagram of the perovskite device.

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