# Supporting Information

# A General Enlarging Shear Impulse Approach to Green Printing Large-area and Efficient Organic Photovoltaics

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## **Experimental Section**

#### **Materials**

PM6, Y6 BTP-eC9 and PDINO were purchased from Solarmer Materials Inc. PEDOT:PSS (Clevios P VP Al4083) was obtained from Heraeus.CF, o-Xylene (o-XY) and Chloronaphthalene were supplied by Sigma Aldrich.

#### **Device fabrication**

Organic solar cells (OSCs) adopt ITO/PEDOT:PSS/PM6:Y6/PDINO/Al traditional device structure. The glass substrate engraved with ITO and silicon wafer is washed with detergent, deionized water and isopropyl alcohol under ultrasonic for 30 minutes each time, and then dried with a nitrogen gun. After the Plasma treating for 3 min, PEDOT:PSS (poly (3,4ethylenedioxythiophene): poly (styrene-sulfonate)) was spin-coated at 4000 rpm (40 s) and generated at 150°C in ambient atmosphere for 20 minutes. For spin-coating process, the active layer solution of PM6:Y6 were dissolved in o-XY at a total concentration of 16 mg mL<sup>-1</sup> with the D/A ratio of 1:1.2 by weight. And the active layer solution was stirred at 70 °C overnight. Transfer the substrate coated with PEDOT:PSS layer to the high purity nitrogen glove box for the next step. The mixed solution is spin-coated onto preheated ITO/PEDOT:PSS at 1000 rpm for 40 s and annealed at 100 °C for 10 minutes. For MGC process, the active layer solution of PM6:Y6 were dissolved in o-XY at a total concentration of 17.6 mg mL<sup>-1</sup> with the D/A ratio of 1:1.2 by weight. And the active layer solution was stirred at 70 °C overnight. Then, an active layer was deposited by MGC at the ambient environment. The silicon wafers were first soaked in octadecyltrichlorosilane/toluene for 20 min, then annealed at 120°C for 20 min and finally UVO treated for 10 min. The gap between blade and substrate was 150 um and the temperature of substrate was ~100 °C. The active layers were performed after the dropping of active layer solution (10 uL) at the beginning of the substrate area in air. The final films were transferred in N<sub>2</sub>-filled glovebox with the followed thermal annealing at 100 °C for 10 min. Then, PDINO (perylene diimide functionalized with amino N-oxide) was coated on the active layer. Finally, Al (100 nm) was deposited by thermal evaporation.

#### Characterization

The current-voltage (*J-V*) characteristics were characterized by a Keithley 2400 source meter. Standard silicon solar cells were calibrated by NREL and current was detected under a solar simulator (Enli Tech, 100 mW cm<sup>-2</sup>, AM 1.5 G irradiation). The EQE spectra are recorded on a commercial EQE measurement system (Enlitech, QE-R3011) in nitrogen environment.

The ultraviolet-visible (UV) spectra were measured by a PerkinElmer Lambda 750 spectrophotometer and the films were illuminated by the light-emitting diode light which can radiate a circle cold light source (light intensity 1.3~1.5 sun), and the wavelength of the light can be controlled by optical filter in 600-700 nm, 560-700 nm, and 460-700 nm. The steady state photoluminescence (PL) spectrum was obtained using a Shamrock sr-303i-B spectrograph from Andor Tech. PL spectra were excited using a Xe flash lamp. And the time-resolved photoluminescence (TRPL) are measured by an Edinburgh Instruments FLS920 spectrometer. Atomic force microscopy (AFM) images were measured by MultiMode 8-HR (Bruker). Transmission electron microscope (TEM) images were taken on a JEOL-2100F transmission electron microscope and an internal charge-coupled device (CCD) camera. And the specimen for TEM measurement was fabricated same with the device structure without PDINO/Al (with the structure of ITO/PEDOT:PSS/active layer), then the film was divided into several pieces by a tweezer and floated on water surface, finally collected the active layer on a copper mesh. Grazing incidence wide-angle X-ray scattering (GIWAXS) measurements were performed at beamline BL14B1 of Shanghai Synchrotron Radiation Facility. The incident angle was 0. 16°, which maximized the scattering intensity from the samples, and the samples were radiated at the X-ray wavelegth of 0.124 nm. And the specimens using for GIWAXS measurements were prepared similar to the films for AFM analysis except that the substrate used for it is silicon wafer in a dimension of 1.5 cm×1.5 cm.

# Active layer film thickness control in the Meniscus-guided coating (MGC)

The active layer film thickness is strongly responsible for the device PCE. When the MGC is in the Landau-Levich state, the film thickness of the active layer increases as the MGC speed rises. To avoid the effect of the active layer film thickness on the device PCE, the film thickness is controlled by controlling the gap between the blade and the substrate during the MGC process. In the following film preparation process, the film thickness is controlled to be around 135 nm (**Supplementary figure 1-2 and Supplementary table 1**).



**Supplementary figure 1.** Under the condition of controlling the distance between the blade and the substrate, the film thickness at different speeds.



**Supplementary figure 2.** Under the condition of controlling the distance between the blade and the substrate, the film thickness at different speeds.

MGC speed	Film thickness
$(mm s^{-1})$	(nm)
15	132.5
25	135.4
35	134.3
45	136.2
55	134.6
65	138.3
75	140.9

**Supplementary table 1.** Under the condition of controlling the distance between the blade and the substrate, the film thickness at different speeds.

**Supplementary figure 3** illustrates the normalized UV-vis absorption spectra of the active layer films. In both spin-coating and MGC process, the absorption peak of Y6 appeared blue-shifted with the increase of shear impulse, indicating that the enhancement of shear impulse could inhibit the aggregation of Y6. Furthermore, the photoluminescence (PL) quenching efficiency of the blend films is studied to explore the charge transport and exciton dissociation behaviors. As shown in **Supplementary figure 4**, the PL intensity gradually diminishes with the increasing shear impulse in all process. And the fluorescence burst arrives maximum when the MGC speed is 75 mm s<sup>-1</sup>, indicating that the most effective charge transfer occurred in the sample. In addition, time-resolved photoluminescence (TRPL) decay spectra are tested in **Supplementary figure 5**, and the film lifetime decreases as the enhancement of shear impulse. The lifetime of the films conducts by spin-coating (minimal at a time of 40 s) is larger than that of the films prepared by MGC (minimal at a speed of 55 mm s<sup>-1</sup>), indicating that the MGC process is more favorable for the photoinduced charge transfer.

In addition, the difference of photovoltaic performance in the devices prepared by spincoating and MGC methods is further clarified through discovery the transport mechanics and composite characteristics. The charge recombination mechanism is studied through the relationship between  $V_{oc}$  and light intensity (Supplementary figure 6-7). The slope of  $V_{oc}$ versus the natural logarithm of the light intensity ( $P_{\text{light}}$ ) is close to 1 kT/q if the device only has a bimolecular recombination, and the slope equal to 2 kT/q means the trap-assisted recombination is significant (where T, k, and q are the temperature in Kelvin, Boltzmann constant, and the elementary charge, respectively).<sup>[1-2]</sup> For spin-coating process, the slope of fitting decreases gradually with the increase of shear impulse, and tends to be stable at 40 s. For MGC process, the slope of fitting decreases gradually as the shear impulse increases, and reaches lowest at 55 mm s<sup>-1</sup>. Compared with the spin-coating process, the minimum fitting slope of the films fabricated by MGC process is 1.315 kT/q, while the minimum fitting slope of the spin-coating films is 1.347 kT/q. This indicates that the trap-assisted recombination of the devices prepared by MGC is effectively suppressed when compared with the devices manufacture by spin-coating. Moreover, the power-law dependence of  $J_{sc}$  versus  $P_{light}$  ( $J_{sc}$  =  $\beta(P_{\text{light}})^{\alpha}$ , where  $\beta$  is a constant) is utilized to further explore the charge recombination process in OSCs.<sup>[3]</sup> The  $\alpha$  values approaching to 1 indicate that the devices possess weak bimolecular recombination. In the spin-coating process, the fitting slope gradually increases as the shear impulse increases, and it tends to be stable when the spin-coating time is 40s ( $\alpha = 0.968$ ). In the MGC process, the maximum fitting slope is arrived when the MGC speed is 55 mm s<sup>-1</sup> ( $\alpha$  = 0.997), and then decreases with the enhancement of shear impulse. This phenomenon shows that the MGC process has smaller bimolecular recombination than the spin-coating process. In short, the growth of shear impulse is beneficial to enhance the photovoltaic parameters of OSCs.



**Supplementary figure 3.** Normalized absorption of active layer flims under (a) different spincoating time and (b) different MGC speed.



**Supplementary figure 4.** PL spectra of active layer flims under (a) different spin-coating time and (b) different MGC speed.



**Supplementary figure 5.** TRPL spectra of active layer flims under (a) different spin-coating time and (b) different MGC speed.



**Supplementary figure 6.** (a) The  $J_{sc}$  and (b) the  $V_{oc}$  versus light intensity of PM6:Y6 films with the different spin-coating times.



**Supplementary figure 7.** (a) The  $J_{sc}$  and (b) the  $V_{oc}$  versus light intensity of PM6:Y6 films with the different MGC speed.

**Spin-coating process:** The following calculation takes into account the horizontal impulse. Based on PM6: Y6 organic solar cells, the shear impulse of OSCs prepared by spin-coating with rotation time of 40 s was calculated <sup>[4-6]</sup>

 $I_{\text{spin-coating}}^* = F_{\text{RCF}} \cdot t$ 

 $= \int_0^T (\int_0^R 11.18 \times (rpm/1000)^2 dr) dt$ 

 $= \int_0^T (\int_0^R 11.18 \times (1000/1000)^2 \, \mathrm{dr}) \mathrm{dt}$ 

 $=\int_{0}^{T} 0.08385 \, \mathrm{dt}$ 

 $=\int_{0}^{40} 0.08385 \, \mathrm{dt}$ 

 $= 3.354 \text{ N} \cdot \text{S}$ 

Where  $I_{spin-coating}^*$  represents the shear impulse,  $F_{RCF}$  is the size of centrifugal force, and *t* represents the acting time of force.

**MGC process:** Based on PM6: Y6 organic solar cells, the shear impulse of OSCs prepared by scraping was calculated at an MGC speed of 55 mm s<sup>-1</sup>.

 $I_{\rm MGC} = \Delta P = mv_2 \cdot mv_1$ 

 $= m \cdot v_2 - m \cdot 0$ 

 $= m \cdot v_2$ 

$$= (m_{\text{solute}} + m_{\text{solvent}}) \cdot v_2$$

$$= [(c_{\text{solute}} \cdot v) + (\rho_{\text{solvent}} \cdot v)] \cdot v_2$$

= [(16.5 mg mL<sup>-1.</sup>10  $\mu$ L) + (0.879 g mL<sup>-1.</sup>10  $\mu$ L)]·55 mm/s

= 0.00049313

 $I_{MGC}^* = T \cdot I_{MGC} = 1.10197 \times 10^4 \times 0.00049313 = 5.434 \text{ N} \cdot \text{S}$ 

Where  $I_{MGC}$  the shear impulse actually received in the MGC process;  $I_{MGC}^*$  is the shear impulse can be directly compared with  $I_{spin-coating}^*$ ; the *T* value was measured to be about 1.10197 × 10<sup>4</sup> in our previous work <sup>[5]</sup>. *m* is the mass of the solution, including  $m_{solute}$  (solute mass) and  $m_{solvent}$ (solvent mass). The  $m_{solute}$  can be obtained by multiplying the concentration of the solute in the solvent by the volume of the solution used in MGC. The  $m_{solvent}$  can be obtained by multiplying the density of the solvent by the volume of the solution used in MGC. It should be noted that in this experiment, the total concentration of donor and receptor in o-XY was 17.6 mg mL<sup>-1</sup>, the volume of single MGC solution was 10 uL, and the density of solvent o-XY was 0.879 mg mL<sup>-1</sup>. Since the MGC speed is 0 when the solution just drops to the substrate in the MGC process, *v* is 0, *v* is the speed received in the MGC process, so *v* is 55 mm s<sup>-1</sup>.

**Supplementary Figure 8** illustrates the normalized UV-vis absorption spectra of the pure films. During the MGC process, the absorption peaks of both PM6 and Y6 showed a blue shift with the increase of shear impulse, indicating that the enhancement of shear impulse could inhibit the aggregation of PM6 and Y6. **Supplementary Figures 9-10** and **Supplementary table 2** show the water contact angles of PM6 and Y6 pure films, respectively. For pure films based on PM6, the water contact angles diminish with the increase of shear impulse, which further implicate the inhibition of PM6 aggregation by shear impulse. For Y6 pure films, the trend of water contact angles variations indicates that the enlarged shear impulse promotes the crystallization of Y6, which is consistent with the test results of GIWAXS.



**Supplementary figure 8.** Normalized UV-vis absorption spectra of (a) PM6 (b) Y6 pure films under MGC speed.



Supplementary figure 9. Water contact angles of PM6 pure films at different MGC speeds.



Supplementary figure 10. Water contact angles of Y6 pure films at different MGC speeds.

**Supplementary table 2.** Water contact angles of PM6 and Y6 pure films at different MGC speeds.

Materials	MGC speed (mm s <sup>-1</sup> )	Contact angle (°)
	15	108.8
	25	108.5
	35	108.1
PM6	45	107.5
	55	107.3
	65	107.1
	75	106.8
	15	93.2
	25	98.3
	35	100.6
Y6	45	101.8
	55	102.0
	65	104.1
	75	104.3



Figure S1. Energy level alignments of PM6, Y6 and BTP-eC9.



Figure S2. Normalized UV-vis absorption spectra of PM6 and Y6.



**Figure S3.** *J-V* characteristics of PM6:Y6 system of organic solar cells under different spincoating times.



**Figure S4.** EQE spectra of PM6:Y6 system of organic solar cells under different spin-coating times.



**Figure S5.** *J-V* characteristics of PM6:Y6 system of organic solar cells under different MGC speed.



Figure S6. EQE spectra of PM6:Y6 system of organic solar cells under different MGC speed.



**Figure S7.** The peak position of Y6 UV-vis absorption peak in the mixed film under different spin-coating time.



**Figure S8.** (a-b) AFM height images and phase images of using CF solvent for spin-coating time of 40s.



Figure S9. (a-b) TEM image of using CF solvent for spin-coating time of 40s.



Figure S10. (a-k) AFM height images of blend films at different spin-coating time.



Figure S11. (a-k) AFM phase images of blend films at different spin-coating time.



**Figure S12.** (a-d) TEM images were prepared by o-XY solvent spin-coating method at different spin-coating times.



Figure S13. (a-g) AFM height images of blend films at different MGC speed.



Figure S14. (a-g) phase images of blend films at different MGC speed.



**Figure S15.** (a-d) TEM images were prepared by o-XY solvent MGC method at different MGC speed.



Figure S16. The 2D GIWAXS pattern of PM6:Y6 system in CF solvent.



**Figure S17.** The corresponding in-plane and out-of-plane line cuts from the GIWAXS patterns under different spin-coating times and different MGC speed.



Figure S18. (a-k) Water contact angles of the different spin-coating time conditions blend films.



Figure S19. (a-g) Water contact angles of the different MGC speed conditions blend films.



**Figure S20.** Optical microscope image of coffee ring effect in active layer films after film formation.



Figure S21. PCE changes of devices prepared by MGC and spin-coating in different areas.



Figure S22 Module connection diagram.

Spin-coating times	$V_{ m oc}$	$J_{ m sc}$	$J_{ m EQE}$	FF	PCE max	PCE <sup>a)</sup> avg
(s)	(V)	(mA cm <sup>-2</sup> )	(mA cm <sup>-2</sup> )	(%)	(%)	(%)
1	0.77	14.15	13.32	54.91	6.00	5.82
3	0.78	15.54	14.74	58.86	7.12	7.00
5	0.78	17.37	16.41	59.60	8.07	7.89
7	0.78	18.51	17.63	60.16	8.69	8.45
10	0.78	19.27	18.42	60.38	9.07	8.89
15	0.78	20.46	19.45	62.67	10.0	9.87
20	0.78	21.04	20.34	63.28	10.4	10.2
30	0.78	22.45	21.43	63.89	11.1	10.9
40	0.78	22.81	21.72	65.59	11.6	11.4
50	0.78	22.61	21.71	64.19	11.4	11.3
60	0.78	22.84	21.92	65.75	11.6	11.5

**Table S1.** Photovoltaic parameters of the optimized PM6:Y6 OSCs with different spin-coating times under simulated solar illumination (AM 1.5 G, 100 mW cm<sup>-2</sup>).

<sup>a)</sup>Average PCE of 20 devices.

MGC speed	$V_{ m oc}$	$J_{ m sc}$	$J_{ m EQE}$	FF	PCE max	PCE <sup>a)</sup> avg
(mm s <sup>-1</sup> )	(V)	(mA cm <sup>-2</sup> )	(mA cm <sup>-2</sup> )	(%)	(%)	(%)
15	0.77	23.93	22.92	70.70	13.0	12.8
25	0.79	24.16	23.22	71.10	13.5	13.2
35	0.80	24.27	23.55	71.30	13.8	13.6
45	0.80	24.46	23.74	71.98	14.0	13.8
55	0.80	25.02	24.05	74.76	15.1	14.9
65	0.79	24.48	23.57	72.56	14.0	13.7
75	0.77	23.36	22.12	72.20	13.0	12.7

**Table S2.** Photovoltaic parameters of the optimized PM6:Y6 OSCs with different MGC speeds under simulated solar illumination (AM 1.5 G, 100 mW cm<sup>-2</sup>).

<sup>a</sup>Average PCE of 20 devices.

Method	Preparation Condition	Value of Shear Impulse
	1 s	0.08385
	3 s	0.25155
	5 s	0.41925
	7 s	0.58695
Spin costing	10 s	0.8382
Spin-coating	20 s	1.6770
	30 s	2.5155
	40 s	3.3540
	50 s	4.1925
	60 s	5.0310
	15 mm s <sup>-1</sup>	1.482
	20 mm s <sup>-1</sup>	1.976
	25 mm s <sup>-1</sup>	2.470
	30 mm s <sup>-1</sup>	2.964
MGC	35 mm s <sup>-1</sup>	3.458
MOC	40 mm s <sup>-1</sup>	3.952
	45 mm s <sup>-1</sup>	4.446
	55 mm s <sup>-1</sup>	5.434
	65 mm s <sup>-1</sup>	6.422
	75 mm s <sup>-1</sup>	7.410

Table S3. The value of the shear impulse under different spin-coating times and MGC speed.

	π-π stack (010)						
Direction	Solvent	Method	Condition	Scattering vector (q) [Å <sup>-1</sup> ]	d- spacing [Å]	FWHM a)	CL (nm)
	CF	Spin-coating	40 s	1.78	3.53	0.19	30.14
Out-of-plane o-XY –		Spin coating	15 s	1.75	3.59	0.28	20.44
	Spin-coating	40 s	1.75	3.59	0.28	20.44	
	0-71	MGC	15 mm s <sup>-1</sup>	1.76	3.57	0.24	23.73
			55 mm s <sup>-1</sup>	1.78	3.54	0.19	29.65

**Table S4.** The location of (010) peaks, d-spacing, FWHM and CCL values in the out-of-plane direction.

<sup>a)</sup> FWHM is full width at half maximum of the scattering peak.

Spin-coating times (s)	Contact angle (°)	Surface energy (mN m <sup>-1</sup> )	Interaction parameter $(\chi_{ij})$
1	109.79	17.21	0.41376
3	109.10	17.61	0.40894
5	108.55	17.93	0.40520
7	108.12	18.18	0.40235
10	107.98	18.28	0.40123
15	107.33	18.65	0.39717
20	107.10	18.78	0.39578
30	106.82	18.94	0.39409
40	106.12	19.36	0.38977
50	105.60	19.67	0.38670
60	105.29	19.85	0.38496

**Table S5.** Contact Angle, surface energy and interaction  $parameters(\chi)$  of water under different conditions of spin-coating.

MGC speed (mm s <sup>-1</sup> )	Contact angle (°)	Surface energy (mN m <sup>-1</sup> )	Interaction parameter $(\chi_{ij})$
15	108.3	18.13	0.40292
25	107.3	18.65	0.39717
35	106.5	19.11	0.39232
45	105.7	19.61	0.38728
55	104.8	20.12	0.38241
65	104.2	20.53	0.37870
75	103.8	20.74	0.37690

**Table S6.** Contact Angle, surface energy and interaction parameters  $(\chi)$  of water under different conditions of MGC.

Materials	Method	Solvent	Device Area (cm <sup>2</sup> )	PCE <sub>max</sub> (%)	Ref.
PTB7-Th:ITIC	Spin-coating	o-XY	0.1	8.11	7
PBDT-TS1:PPDIODT	MGC	o-MA	0.069	5.6	8
PBTA-TF:IT-M	MGC	o-XY/PN	0.04	8.2	9
PBTA-TF:IT-M	MGC	THF/IPA	0.04	11.7	9
PM6:IT-4F	MGC	o-XY/n- butylalcohol	0.04	12.3	10
PTzBI-Si:N2200	Slot die	MeTHF	0.04	11.76	11
PTzBI-Si:N2200	Slot die	MeTHF	1	10.15	11
P2F-EHp:IT-4F:IT- 4Cl	MGC	Toluene/o-XY	0.104	10.10	12
PTB7-Th:F10IC2	MGC	o-XY	0.04	11.4	13
PTB7-Th:F10IC2	MGC	CB	0.04	12.5	13
PM6:Y6-2Cl	MGC	CB	0.04	11.44	14
PM6:Y6-2Cl	MGC	CB/CN(2%)	0.04	12.9	14
PM6:BTP-4Cl-8	MGC	CB/CN(0.5%)	0.81	11.5	15
PM6:BTP-4Cl-12	MGC	CB/DIO(0.1%)	0.81	15.5	15
PM6:BTP-4Cl-16	MGC	CB/DIO(0.1%)	0.81	10.8	15
PM6:BTP-eC7	MGC	CB/DIO(0.1%)	1	8.75	16
PM6:Y6	Slot die	CB	0.56	15.2	17
PM6:Y6	Slot die	o-XY	0.56	15.6	17
PM6:Y6	Slot die	TMB	0.56	15.4	17
PM6:Y6	MGC	o-XY	0.08	12.98	18
PM6:Y6	MGC	o-XY/DMN(0.5%)	0.08	15.51	18
PM6:Y6	MGC	o-XY	1	10.83	18
PM6:Y6	MGC	o-XY/DMN(0.5%)	1	13.87	18

**Table S7.** Photovoltaic parameters of non-CF solvent non-spin-coating method organic solar cells under simulated solar illumination (AM 1.5G, 100 mW cm<sup>-2</sup>).

Area (cm <sup>2</sup> )	Spin-coating	MGC
0.04	11.6%	15.1%
0.1	11.0%	14.7%
0.2	10.6%	14.5%
0.3	10.3%	14.4%
0.4	10.2%	14.3%
0.5	9.8%	14.3%
0.6	9.5%	14.2%
0.7	9.3%	14.1%
0.8	9.0%	14.0%
0.9	8.7%	13.8%
1	8.1%	13.6%

**Table S8.** The PCE of using spin-coating and MGC method at different areas under simulated solar illumination (AM 1.5 G, 100 mW cm<sup>-2</sup>).

#### References

[1] L. J. A. Koster, V. D. Mihailetchi, R. Ramaker, P. W. M. Blom, *Applied Physics Letters*, **2005**, *86*, 123509.

[2] J. Min, Y. N. Luponosov, N. Gasparini, M. Richter, A. V. Bakirov, M. A. Shcherbina, S. N.

Chvalun, L. Grodd, S. Grigorian, T. Ameri, S. A. Ponomarenko, C. J. Brabec, *Adv. Energy Mater.*, **2015**, *5*, 1500386.

[3] A. K. K. Kyaw, D. H. Wang, V. Gupta, W. L. Leong, L. Ke, G. C. Bazan and A. J. Heeger, *ACS nano*, **2013**, *7*, 4569.

[4] J. Xin, X. Meng, X. Xu, Q. Zhu, H. B. Naveed, W. Ma, *Matter*, 2019, 1, 1316-1330.

[5] X. Meng, L. Zhang, Y. Xie, X. Hu, Z. Xing, Z. Huang, C. Liu, L. Tan, W. Zhou, Y. Sun,

W. Ma, Y. Chen, Adv. Mater., 2019, 31, 1903649.

[6] M. J. Cooker, D. H. Peregrine, J. Fluid Mech., 1995, 297, 193.

[7] Y Yu, T Tsai, C Yang, and C Chen, J. Phys. Chem. C, 2017, 121, 21969.

[8] L Ye, Y Xiong, S Li, M Ghasemi, N Balar, J Turner, A Gadisa, J Hou, B. T. O'Connor, H Ade, *Adv. Funct. Mater.*, **2017**, *27*, 1702016.

[9] W Zhao, S Zhang, Y Zhang, S Li, X Liu, C He, Z Zheng, J Hou, *Adv. Mater.*, **2018**, *30*, 1704837.

[10] S Dong, K Zhang, B Xie, J Xiao, H Yip, H Yan, F Huang, Y Cao, *Adv. Energy Mater.*,**2018**, 1802832.

[11] L Zhu, W Zhong, C Qiu, B Lyu, Z Zhou, M Zhang, J Song, J Xu, J Wang, J Ali, W Feng,Z Shi, X Gu, L Ying, Y Zhang, F Liu, *Adv. Mater.*, **2019**, *31*, 1902899.

[12] K An, W Zhong , L Ying, P Zhu , B Fan, Z Li , N Li, F Huang, Y Cao, *J. Mater. Chem. C*, **2020**, *8*, 270.

[13] X Han, J Zhu, Y Xiao, H Jiang, Z Zhang, J Wang, Z Li, Y Lin, X Lu, X Zhan, *Sol. RRL*.,**2020**, *4*, 2000108.

[14] Y Yu, R Sun, T Wang, X Yuan, Y Wu, Q Wu, M Shi, W Yang, X Jiao, J Min, Adv.

Funct. Mater., 2020, 31, 2008767.

[15] Y Cui, H Yao, L Hong, T Zhang, Y Tang, B Lin, K Xian, B Gao, C An, P Bi, W Ma, J Hou, *Nat. Sci. Rev.*, **2020**, *7*, 1239.

[16] Y Cui, H Yao, J Zhang, K Xian, T Zhang, L Hong, Y Wang, Y Xu, K Ma, C An, C He, ZWei, F Gao, J Hou, *Adv. Mater.*, **2020**, 1908205

[17] H Zhao, H B Naveed, B Lin, X Zhou, J Yuan, K Zhou, H Wu, R Guo, M A. Scheel, A Chumakov, S V. Roth, Z Tang, P Müller-Buschbaum, W Ma, *Adv. Mater.*, **2020**, 2002302.

[18] Y Li, H Liu, J Wu, H Tang, H Wang, Q Yang, Y Fu, Z Xie, ACS Appl. Mater. Interfaces., **2021**, *13*, 10239.