Electronic Supplementary Material (ESI) for Sustainable Energy & Fuels.

Supporting information

Enhancing operational stability in perovskite solar cells by solvent-free encapsulation method

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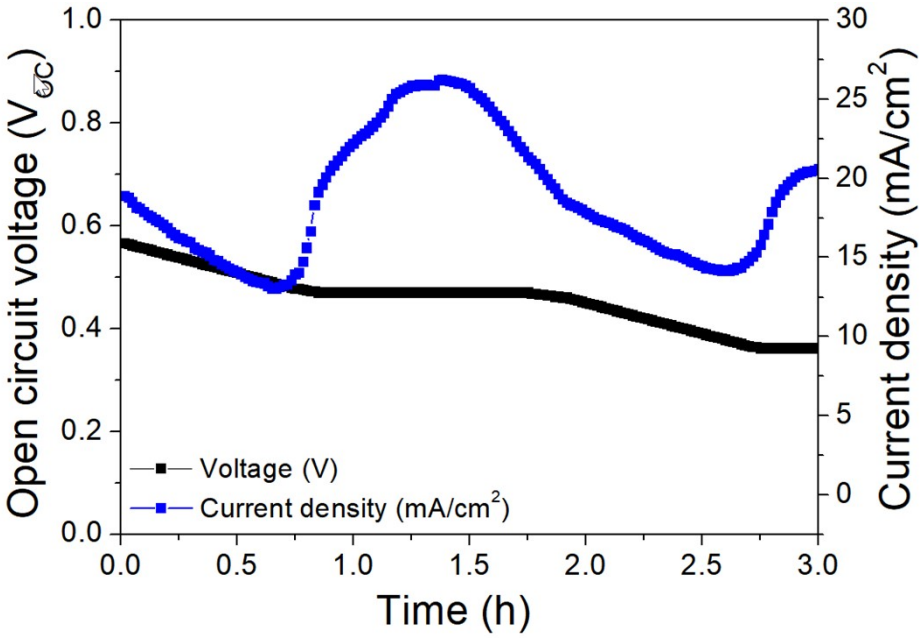


Figure S1. Open circuit voltage (V_{OC}) and current density evolution with a temperature cycle (320K to 360K) of un-encapsulated device.

Tabe S1. Statistics of the photovoltaic parameters of pristine $MAPbI_3$ (reference), after the encapsulation process and after different degradation tests.

Fresh devices				**Encapsulated devices**				**Tested devices**			
V_{OC} (V)	**J_{SC} (mA·cm^{-1})**	**FF (%)**	**PCE (%)**	**V_{OC} (V)**	**J_{SC} (mA·cm^{-1})**	**FF (%)**	**PCE (%)**	**V_{OC} (V)**	**J_{SC} (mA·cm^{-1})**	**FF (%)**	**PCE (%)**
Temperature test											
1.068	22.48	0.785	18.84	1.047	22.87	0.76	18.25	1.052	21.26	0.731	16.36
1.066	22.49	0.786	18.84	1.06	22.56	0.76	18.24	1.041	20.97	0.734	16.02
1.077	22.44	0.785	18.97	1.078	22.57	0.75	18.21	1.022	20.57	0.716	15.05
1.091	22.73	0.746	18.52	1.087	22.3	0.73	17.72	1.031	19.94	0.735	15.10
Humidity test								1.04±0.013	20.67±0.57	0.73±0.01	15.61±0.66
1.053	22.38	0.775	18.26	1.075	22.28	0.711	17.04	1.046	19.3	0.697	14.07
1.06	22.56	0.763	18.24	1.078	22.28	0.727	17.47	1.054	19.92	0.728	15.30
1.049	22.43	0.755	17.75	1.090	22.53	0.683	16.77	1.055	19.5	0.723	14.87
1.076	22.67	0.820	18.25	1.102	22.12	0.734	17.9	1.043	18	0.716	13.44
Long-term stability test								1.05±0.006	19.15±0.82	0.72±0.013	14.38±0.82
1.102	22.46	0.762	18.86	1.080	22.58	0.806	18.00	0.970	15.21	0.628	9.26
1.109	22.71	0.752	18.95	1.095	21.28	0.810	18.80	0.948	14.7	0.596	8.30
1.067	22.10	0.774	18.26	1.061	21.9	0.756	17.69	0.864	13.32	0.686	7.86
1.074	22.42	0.767	18.47	1.052	22.14	0.758	17.81	0.882	14.35	0.657	8.32
1.07±0.02	22.48±0.17	0.77±0.02	18.51±0.38	1.07±0.01	22.28±0.41	0.74±0.03	17.81±0.55	0.91±0.05	14.36±0.79	0.64±0.04	8.41±0.59

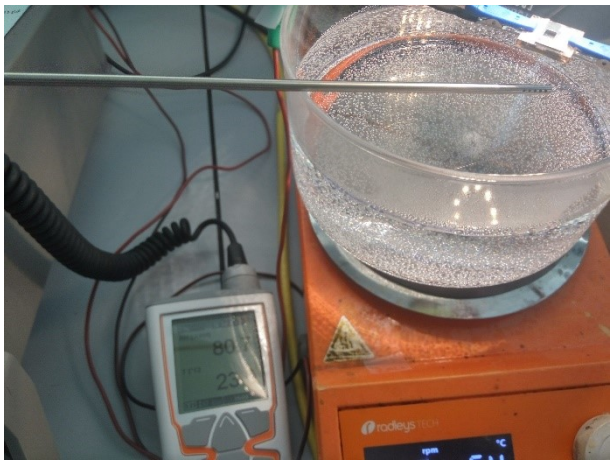


Figure S2. Temperature measurement of the samples in the vapour experiment.

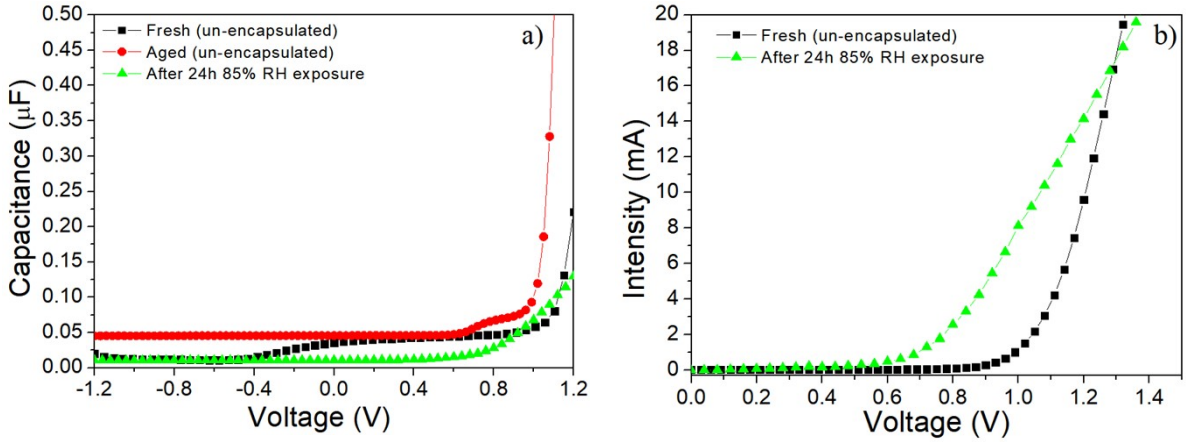
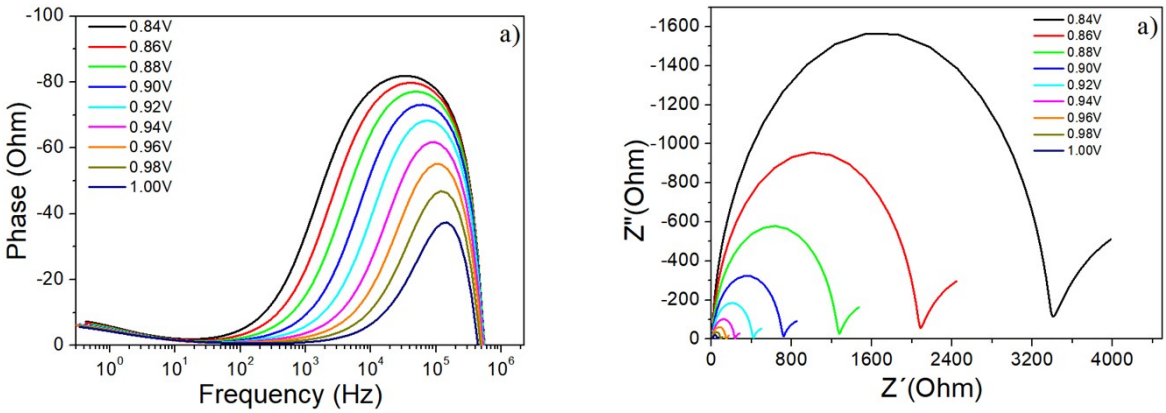


Figure S3. a) Capacitance versus voltage of fresh, aged (12 months) and encapsulated (after 24h at 85% RH exposure) samples. b) Dark I-V curve of a fresh and an encapsulated sample after 24h at 85% RH exposure.



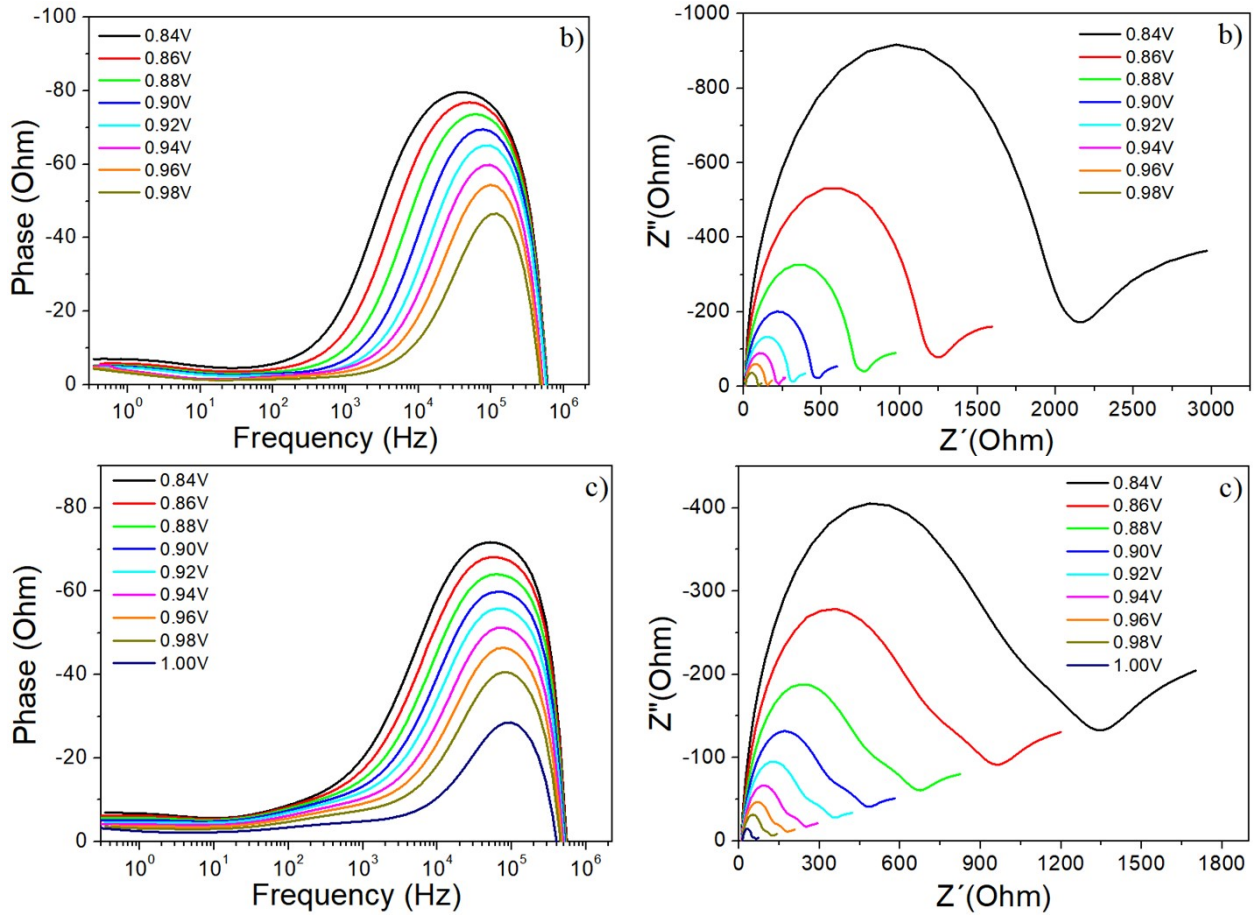


Figure S4. Bode plot (left) and Nyquist plot (right) of a) fresh, b) encapsulated and c) after 5 minutes immersed in water.

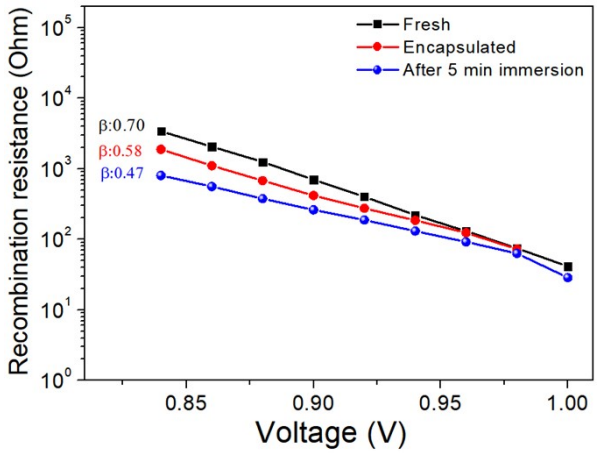


Figure S5. Recombination resistance vs voltage of fresh, encapsulated and after immersed in water for 5 minutes.

Device architecture	*Material*	*Method of encapsulation*	*Testing condition*	*Device efficiency with time*	Ref
Glass/FTO/TiO_2 (ZnO)/$MAPbI_3$/Spiro-OMeTAD/MoO_3/Al	UV Epoxy with desiccant and SiO_2 layer	UV curing With cover slip and 50 nm SiO_2 e-beam	Condition 1) under constant light soaking at 65 % relative humidity (RH) and 85 ◦C Condition 2) outdoor testing 432 h	Retained 85 % after 144 h in condition 1 Retained 90 % after 432 h in condition 2	[1]
Glass/FTO/TiO_2/$MAPbI_3$/Spiro-MeTAD/MoO_3/Al	UVC Epoxy with desiccant (180 µm)	UV curing With Cover slip	Condition1) alternating illumination 10 h/ dark in14 h cycles (65 %RH)Condition 2) under constant illumination at 85 ^oC	Retained 90 % in condition 1 Retained 80 % in condition 2	[2]
Glass/FTO/TiO_2/$MAPbI_3$/ZrO_2/Carbon	UVC Epoxy as side and over sealing	UV curing With Cover slip	Condition 1) 100 ^oC dark Condition 2) kept in dark	Retained 80 % after 300 h in condition 1 no loss after 1500 h in condition 2	[3]
Glass/ITO/SnO_2/$MAPbI_3$/Spiro-OMeTAD/Au	UVC Epoxy	UV curing With Cover slip	Stored in a glove box, and measured Under ambient condition (20 ^oC –25 ^oC; relative humidity of 25–40 %).	Retained 90 % of its initial PCE after 2500 h in Nitrogen	[4]
Glass/FTO/NiO/$MAPbI_3$/PCBM/Ag	UVC Epoxy	UV curing With Edge seal	Condition1) continuous AM 1.5 light soaking at 25 ^oC,<25 % RH Condition 2) kept in dark 85 ^oC (RH < 25 %)	Retained 90 % in condition 1 after 500 h Retained 80 % in condition 2 after 500 h in Nitrogen	[5]
Glass/ITO/C_{60}/$MAPbI_3$/P3HT/CNT	UVC Epoxy	UV curing With Cover slip	AM 1.5G one sun illumination including UV radiation in ambient air	Retained 80 % after 2200 h	[6]
ITO/poly-TPD/$MAPbI_3$/PC60BM/ BPhen/Ag	UVC Epoxy + PVP	UV curing With Cover slip	Continuous illumination by 1500 W Xenon lamp (42 ± 3) ^oC, (38 ± 6) % RH	Retained 80 % of its initial performance after 1500 h	[7]
Glass/FTO/TiO_2/$MAPbI_3$/Au	UVC Epoxy	UV curing With Cover slip	dark at 30 ^oC, 50 % humidity environment	Retained 80 % of its initial performance after 70 days	[8]
Glass/FTO/TiO_2/$MAPbI_3$/P3HT/Au	Epoxy + PEG	UV curing With Cover slip	Storage under ambient condition with a 28 % RH.	Retained 80 % of its initial performance after 830 day	[9]
Glass/FTO/TiO_2/$MAPbI_3$/Carbon	PDMS	Cover slip and curing at 80 ◦ C	Kept at room temperature in the dark (20 % RH) air exposure	No loss after 3000 h	[10]
Glass/FTO/TiO_2/$MAPbI_3$/Spiro-OMeTAD/Au	PMMA + Graphene oxide	Spin coating	Condition 1) room temperature (75 %RH) Condition 2)85 ^oC in Ambient condition (35 % RH)	retained 90 % its initial PCE after 500 h in condition 1 retained 80 % of the initial PCE after 100 h in condition 2	[11]
Glass/FTO/TiO_2/$MAPbI_3$/Spiro-OMeTAD/Au	PTFE	Spin coating	Ambient environment	Retained 95 % of its initial PCE after 30 days	[12]
Glass/FTO/TiO_2/$MAPbI_3$/Spiro-OMeTAD/Au	CF_4	Plasma coating	Under the continuous Xe lamp (AM 1.5G, 1 sun) illumination in ambient air	Retained 70 % of its initial PCE after 100 h	[13]
Glass/ITO/TiO_2/C_{60}/$MAPbI_3$/PTAA/ Au	Organosilicate barrier	Spray-plasma deposition	Condition 1) Kept at 85 ^oC in 85 % RH Condition 2) Kept at 85 ^oC, 25 % RH	Retained 60 % after 150 h in condition 1 retained 92 % after 3176 h in condition 2	[14]
Glass/FTO/TiO_2/$MAPbI_3$/Spiro-OMeTAD/Au	adamantane nanocomposite	plasma vacuum deposition	Kept in ambient environment (85 %RH)	Retained 70 % of its initial PCE after 216 h	[15]

Glass/ITO/NiO/$MAPbI_3$/$PC_{61}BM$/ ALD-TiO_2/Ag	ALD Al_2O_3 (10 nm) and Al (20 nm) and AL_2O_3 (30 nm).	ALD at 60 °C	Kept in ambient environment (25 °C,40–60 %RH)	97 % of the initial PCE after 1000 h	[16]
Glass/ITO/PEDOT.PSS/$MAPbI_3$/ ALD-ZnO/Ag NWs	50-nm ALD Al_2O_3 film-coated PET substrate with an edge seal of UV-curable epoxy	ALD at 100 °C for Al_2O_3	Kept in ambient atmosphere (30 °C, 65 %RH)	retained >95 % of its initial PCE after 40 days	[17]
Glass/FTO/bl-TiO_2/mp- TiO_2// $MAPbI_3$/PTAA/Au	Al_2O_3 and PV_3D_3 stack	iCVD coupled with ALD	Condition 1) Kept 50 °C and 50 % RH Condition 2) Kept 25 °C and 50 % RH	Retained 97 % after 300 h in condition 1 retained >95 % after 1500 h in condition 2	[18]
Glass/ITO/SnO_2/$MAPbI_3$/Spiro-OMeTAD/Au	(PEN)/ZTO/ORMOCER/ZTO/ORMOCER/ZTO/$SiO_xC_yH_z$	UV curing of adhesive coated Stack film on PVSC	Kept in dark	retained 77 % of initial PCE after 840 h	[19]
Glass/ITO/SnO_2/MAPbI3/Spiro-OMeTAD/Ag	Alucone and Al_2O_3 stack	MLD and PEALD	30 °C and 85 % RH	retained 96 % of initial PCE after 2000 h	[20]
Glass/ITO/NiO/$MAPbI_3$/PCBM/Ag	1H,1H,2H,2H-Perfluorodecyltrichlorosilane (FDTS) and Al_2O_3 stack	Thermal evaporation and ALD technique	Condition 1) AM 1.5G illumination stored in N_2 atmosphere Condition 2) Kept 25 °C and 50 % RH Condition 3) Kept 8 °C and 85 % RH	retained 90 % after 1000 h in condition 1 retained 90 % after 1400 h in condition 2 retained 90 % after 450 h in condition 3	[21]
PET/IZO/c-TiO_2/$MAPbI_3$/Spiro-MeOTAD/Au	View barrier	adhesion transfer tape	Kept at ambient condition	No loss in PCE after 500 h	[22]
Glass/ITO/TiO_2/$MAPbI_3$/Spiro-OMeTAD/Au	PUA	UV curing With Cover slip	Condition 1) 85 °C in air at MMP Condition 2) 85 %RH at MMP Condition 3) soak in water for 5 min Condition 4) immersed in water at MMP Condition 5) Aging after soaking into water	Retained 90% in condition 1 Retained 78% after 24 h in condition 2 Retained 95% in condition 3 Retained 98% after 16 h in condition 4 Retained 80% after 3800 h in condition 5	This work

Table S2. Comparison of the encapsulation approaches with same perovskite composition and similar device configuration.

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