Electronic Supplementary Material (ESI) for Journal of Materials Chemistry C.

Supplementary Information

Improved photovoltaic performance of triple cation mixed-halide perovskite solar cells with binary trivalent metals incorporated on titanium dioxide electron transport layer

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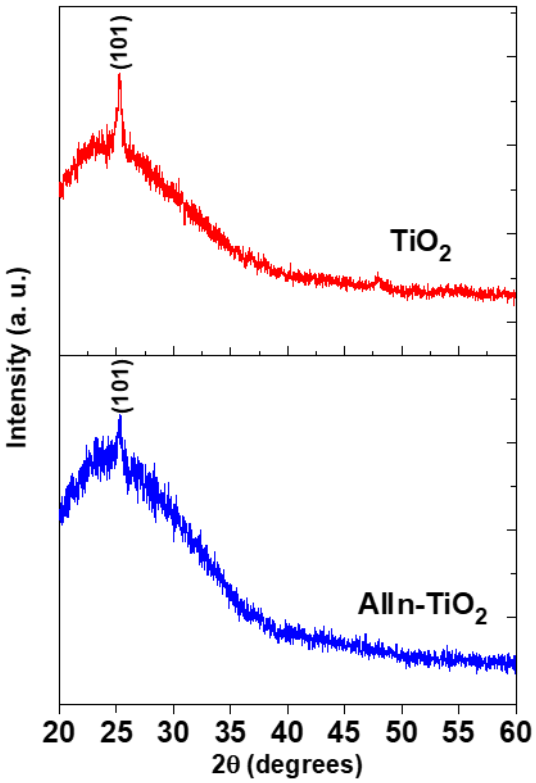

Figure S1. X-ray diffraction patterns of TiO_2 and AlIn-TiO_2 films.

From the cross sectional SEM images, there was negligible difference in thickness of both pristine TiO_2 and $AlInTiO_2$ films, whereby both films had similar thicknesses of 60 nm. Such low doping concentration in our doped film makes no impact on the film formation in our spin-casting technique. As such, the decrease in peak intensity is probably due to the presence of dopant in our film.

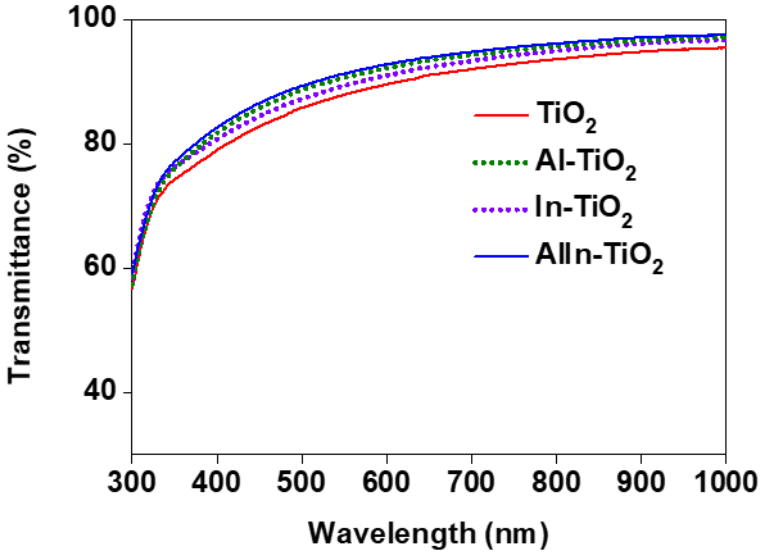

Figure S2. Transmittance spectra of TiO_2, Al- TiO_2. In- TiO_2 and AlIn-TiO_2 films.

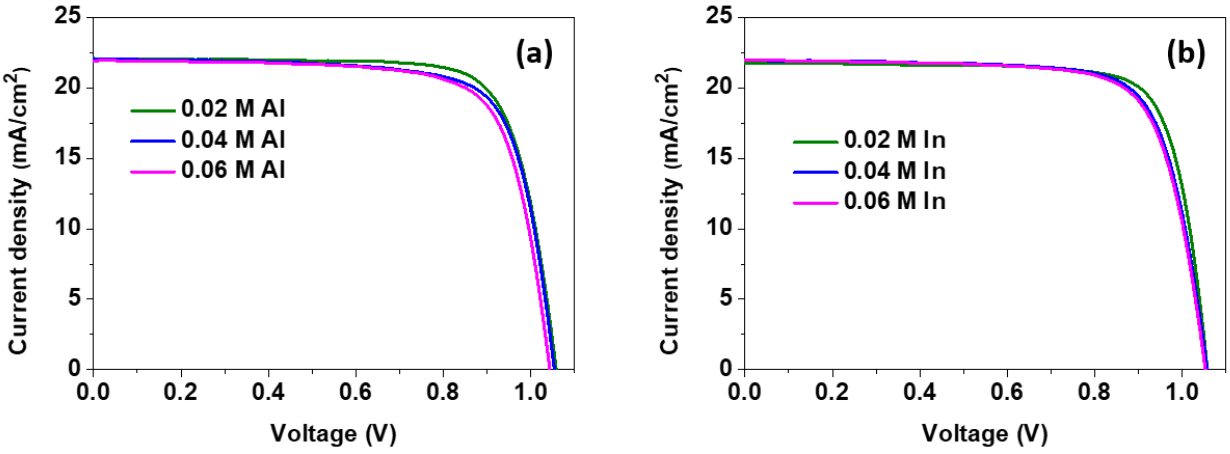

Figure S3. Current density-voltage (J-V) characteristics of perovskite solar cells with Al-TiO_2 and In-TiO_2 ETLs.

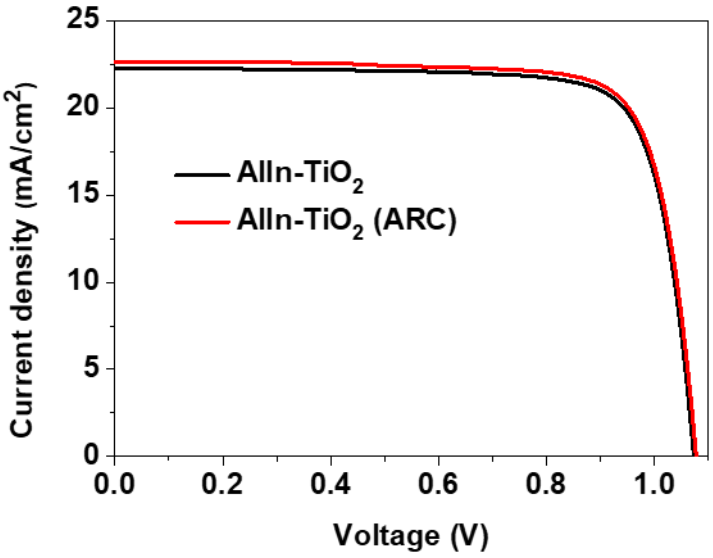

Figure S4. Current density-voltage (J-V) characteristics of AlIn-TiO_2 based perovskite solar cells with and without anti-reflection film (ARC).

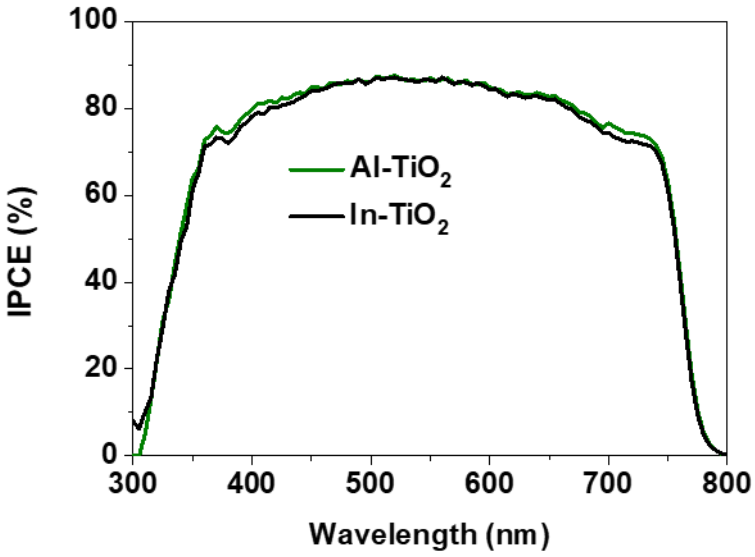

Figure S5. IPCE spectra of perovskite solar cells with Al-TiO_2 and In-TiO_2.

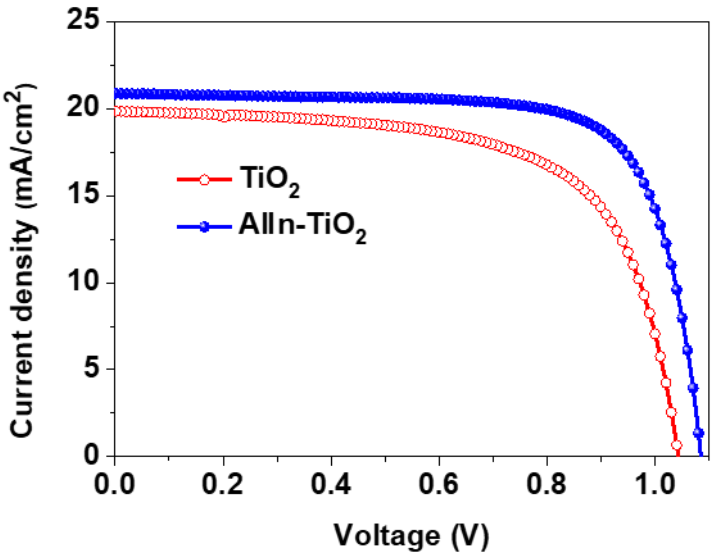

Figure S6. Current density-voltage (J-V) curves of the TiO_2 and AlIn-TiO_2 based perovskite solar cells after 25 days in ambient condition.

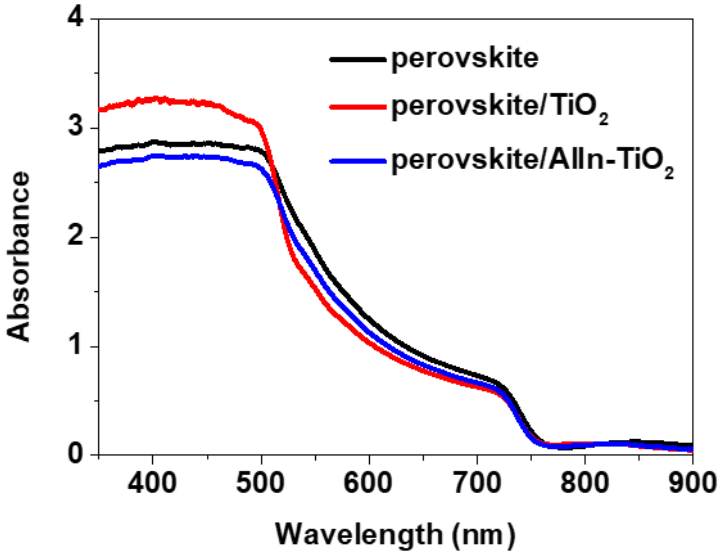

Figure S7. Absorption spectra of perovskite coated TiO_2 and AlIn-TiO_2 films.

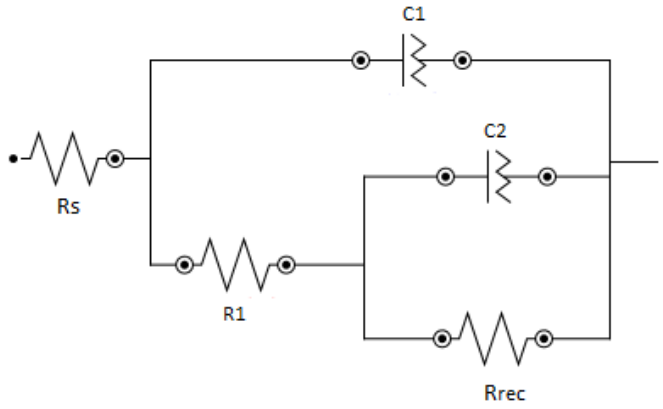

Figure S8. Equivalent circuit for the analysis of perovskite solar cells.

To gain more insight into the charge transport and recombination dynamics in the devices, EIS measurements were carried out for the TiO_2 and AlIn-TiO_2 based devices under dark in the Ar atmosphere (glove box). The impedance spectra exhibited two arcs in the complex impedance plot as reported widely in literature for devices with good charge extraction. The data was analysed using the commonly reported [1-2] equivalent circuit consisting of a series resistance (R_s), two capacitive (C_1 and C_2) and two resistive components (R_{rec} and R_1). The series resistance arises from the Ohmic contribution from wires and contacts. Capacitance C_1 related to the high frequency part of the spectra originates from the dielectric bulk capacitance of the device and the low frequency capacitance C_2 is generally associated with the trapping and detrapping of carriers. The origin of the resistances R_1 and R_{rec} are not clearly established but they are often associated with the bulk conductivity and recombination resistance of the device.

Table S1: Photovoltaic parameters of perovskite solar cells with Al-TiO_2 and In-TiO_2.

ETLs	Voc [V]	Jsc [mA cm^{-2}]	FF [%]	PCE [%]
0.04 M Al-doped TiO_2	1.05	22.04	75.26	17.43
0.06M Al-doped TiO_2	1.04	22.02	74.93	17.15
0.04 M In-doped TiO_2	1.05	21.94	75.89	17.57
0.06 M In-doped TiO_2	1.05	21.98	75.02	17.33

Table S2: The Hall effect parameters of TiO_2 and AlIn-TiO_2 devices, with structure of glass/TiO_2 (or AlIn-TiO_2)/Au.

ETLs	Type	Hall mobility ($cm\ V^{-1}S^{-1}$)	Carrier density ($1/cm^3$)	Resistivity (Ohm*cm)	Conductivity ($S\ cm^{-1}$)
TiO_2	N	1.03	2.14×10^{14}	28310	3.53×10^{-5}
AlIn-TiO_2	N	1.15	2.85×10^{14}	18926	5.28×10^{-5}

Table S3: Analysis of the TRPL with two-exponential decay characteristics for perovskite, perovskite/TiO_2 and perovskite/AlIn-TiO_2.

Samples	**A_1**	**τ_1 (ns)**	**A_2**	**τ_2 (ns)**	**$\tau_{average}$ (ns)**
Perovskite	0.25	8.47	0.75	309.1	233.9
Perovskite /TiO_2	0.20	9.10	0.80	258.4	208.5
Perovskite /AlIn- TiO_2	0.32	10.6	0.68	215.7	150.1

Table S4: The fitted parameters for EIS measurements acquired under dark condition.

ETLs	R_{series} (Ω)	R_{rec} (KΩ)
TiO_2	19.5	5.40
AlIn- TiO_2	18.7	56.9

References

[1] A. Guerrero, G. G.-Belmonte, I. M.-Sero, J. Bisquert, Y. S. Kang, T. J. Jacobsson‖, J.-P. C.-Baena, A. Hagfeldt, *J. Phys. Chem. C* **2016**, *120*, 8023.

[2] I. Zarazua, G. Han, P. P. Boix , S. Mhaisalkar, F. F.-Santiago, I. M.-Seró , J. Bisquert, G. G.-Belmonte, *J. Phys. Chem. Lett.* **2016**, *7*, 5105.