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26 **Inverted perovskite solar cells (PSCs) promise enhanced operating stability compared to**

27 **their normal-structure counterparts[1–3]. To improve efficiency further, it is crucial to**

28 **combine effective light management with low interfacial losses[4,5]. Here we develop a**

29 **conformal self-assembled monolayer (SAM) as the hole-selective contact on light-managing**

30 **textured substrates. Molecular dynamics simulations indicate cluster formation during**

31 **phosphonic acid adsorption leads to incomplete SAM coverage. We devise a co-adsorbent**

32 **strategy that disassembles high-order clusters, thus homogenizing the distribution of**

33 **phosphonic acid molecules, thereby minimizing interfacial recombination and improving**

34 **electronic structures. We report a lab-measured power-conversion efficiency (PCE) of 25.3%**

35 **and a certified quasi-steady-state PCE of 24.8% for inverted PSCs, with a photocurrent**

36 **approaching 95% of the Shockley-Queisser maximum. An encapsulated device having a PCE**

37 **of 24.6% at room temperature retains 95% of its peak performance when stressed at 65°C**

38 **and 50% relative humidity following >1000 hours of maximum power point tracking under**

39 **1-sun illumination. This represents one of the most stable PSCs subjected to accelerated**

40 **ageing – achieved with a PCE surpassing 24%. The engineering of phosphonic acid**

41 **adsorption on textured substrates offers a promising avenue for efficient and stable PSCs. It**

42 **is also anticipated to benefit other optoelectronic devices that require light management.**

43   Perovskite solar cells (PSCs) have recently attained a certified efficiency of 26.1%[6]; however, the

44   very highest PCE devices have yet to meet operating stability under accelerated ageing tests[5]. The

45   limited device stability is attributed to the presence of mobile and hygroscopic p-type dopants in

46   hole-transporting layers, which undermine moisture and thermal stability[7]. Inverted PSCs present

47   a solution by utilizing undoped hole-selective contacts[8]. Recent studies have shown PCEs

48   surpassing 25% for inverted PSCs[2]. However, when adhering to the stringent quasi-steady-state

49   (QSS) protocol, their certified efficiency (~24%) requires further improvement[3,9].

50   Efforts to improve inverted PSC efficiency have focused on interface passivation[2,9,10]. This

51   approach suppresses non-radiative recombination and thus improves fill factors and

52   photovoltages[11]. Nevertheless, higher photocurrents are needed for efficiency gains. In normal-

53   structure PSCs, this has been realized using textured fluorine-doped tin oxides (FTO) as the

54   transparent conductive oxides (TCO)[4,5]. The pyramidal grains on FTO minimize reflection losses

55   and extend the length of the average optical path[4]. By contrast, inverted PSCs, often built on

56   smooth indium tin oxides (ITO)[9,10], face substantial optical losses due to the lack of light

57   management.

58   The discrepancy is ascribed to differences in transporting materials and deposition techniques. In

59   normal-structure PSCs, inorganic hole-blocking layers are conformally deposited on textured

60   substrates using spray pyrolysis and chemical bath deposition[4,5]. However, inverted PSCs typically

61   employ ultra-thin (<5 nm) organic hole-selective contacts on substrates[2,3], which can be

62   challenging to deposit uniformly using solution processing[12]. Inhomogeneity leads to energy losses

63   and insufficient carrier extraction[13].

64   Self-assembled monolayers (SAMs), particularly those composed of phosphonic acid molecules

65   with hole-selective tail groups, have shown promise in addressing this issue[14]. Phosphonic acids

66   establish coordinative/covalent bonds with TCOs, allowing for sufficient SAM coverage on rough

67   surfaces[15]. This could provide a low-loss interface, uniting light management with interface

68   passivation. Indeed, photocurrent improvements have been observed when replacing SAM-

69   modified ITO with FTO substrates in inverted PSCs[16].

70   Despite the promise, achieving a high-density, closely packed SAM remains challenging, which

71   leads to erratic interfacial properties[17]. For example, M. Liu et al. revealed that phosphonic acids

72   failed to fully cover textured wafers, which affected the performance of tandem solar cells[18]. Even

73 on flat substrates, the formation of SAMs tends to be non-uniform, a problem usually attributed to

74 the limited solubility of phosphonic acids[19] and their insufficient chemical bond formation with

75 metal oxides[20].

76 Several strategies have been proposed to ensure conformal SAM coverage, such as utilizing more

77 reactive oxide surfaces (e.g., nickel oxides) to promote hetero condensation[18], employing thermal

78 evaporation for SAM deposition[21], and designing highly soluble phosphonic acid molecules[19].

79 However, these methods can be laborious, requiring time-intensive molecule design, synthesis,

80 and vacuum-based layer deposition. Additionally, the use of highly reactive oxides could

81 compromise device stability due to redox reactions with ammonium halides[22].

82 **Molecular dynamics simulations**

83 We sought to deepen understanding of how phosphonic acids interact with textured TCOs. We

84 began by looking at the case of 2-(9H-carbazol-9-yl)ethyl)phosphonic acid (2PACz), an organic

85 molecule (Fig. 1a) capable of forming SAMs on TCOs[14], and investigated its interactions with

86 FTO. 2PACz has found extensive applications as a hole-selective contact in PSCs in view of its

87 excellent defect passivation and deep highest occupied molecular orbital (HOMO) level[21]. The

88 surface properties of FTO were approximated using tin oxides (SnO_2), given that commercial FTO

89 has a fluorine-doping level under 0.5% (atomic percentage)[23]. Flat vs. corrugated SnO_2 were

90 analysed to understand the effects of surface morphology (Supplementary Fig. 1).

91 Molecular dynamics (MD) simulations suggest that 2PACz molecules can agglomerate, forming

92 dimers, trimers, and tetramers (Fig. 1b and Supplementary Fig. 2). Within the initial 1 nanoseconds

93 of simulations, 90% of the final number of clusters has been reached (Fig. 1b), and dimers were

94 the most prevalent among clusters (Fig. 1c). Compared to flat surfaces, textured surfaces led to

95 more clusters (e.g., 7 vs. 0 for 20 2PACz molecules on 6-nm-wide SnO_2) (Supplementary Note 1;

96 Supplementary Figs. 3 and 4). The cluster formation is closely linked to the inhomogeneity of

97 SAMs on FTO. For instance, when 162 2PACz molecules are positioned on top of textured SnO_2

98 surfaces, despite their initial random distribution (Supplementary Video 1), the finial equilibrated

99 structures exhibit clear phase segregation (Fig. 1d), where almost 85% of the SnO_2 surface remains

100 uncovered by any 2PACz molecules (Supplementary Fig. 5). These observations were also verified

101 in a larger system (22-nm width; 1134 2PACz molecules) (Supplementary Fig. 6).

102 Reasoning that a thiol group (−SH) could interact with phosphonic acids, and a carboxyl group
103 (−COOH) attached to FTO, we introduced 3-mercaptopropionic acid (3-MPA) (Fig. 1a) in
104 simulations to break apart 2PACz clusters particularly on textured substrates. The approach is akin
105 to the co-adsorbent strategy used in dye-sensitized solar cells to reduce dye aggregation on
106 titanium oxides[24]. Similar strategies have been employed to improve the quality of hole-selective
107 SAMs[25,26]. With 3-MPA at a molar ratio of 1:9 with 2PACz, we saw a relative 15% decrease in
108 the number of clusters on textured surfaces (Fig. 1b), and a slower formation rate (20 ns^{-1} vs. 28
109 ns^{-1}) (Supplementary Fig. 7). In particular, the higher-order clusters (trimers and tetramers)
110 decreased by 53% (Fig. 1c). As a result, the mixed system shows less phase segregation (Fig. 1e
111 and Supplementary Video 2), leading to extended surface coverage (67% vs. 15%) by 2PACz
112 molecules (Supplementary Fig. 5). Ab initio MD (AIMD) simulations (Supplementary Note 2 and
113 Supplementary Fig. 8) indicate that the presence of 3-MPA hinders the free movement of
114 individual 2PACz molecules by forming a supramolecular structure (Fig. 1f). This reduces
115 agglomeration with already-formed dimers, suppressing the formation of higher-order clusters
116 (Supplementary Video 3). Density functional theory (DFT) calculations revealed surface binding
117 energies of −3.2 eV and −2.6 eV for 2PACz and 3-MPA, respectively, which are much stronger
118 than the interaction energies of 2PACz clusters (−0.3 to −0.1 eV per molecule). This indicates
119 robust anchoring of 2PACz and 3-MPA molecules upon contact with substrate surfaces.

120 **Characterization of organic contacts**

121 We deposited both 2PACz and a mixture of 2PACz:3-MPA on FTO substrates using solution
122 processing, followed by annealing the film at 100°C and solvent washing (Methods). Micelles
123 were detected in the processing solutions through dynamic light scattering (DLS) (Supplementary
124 Fig. 9). However, due to their limited proportion in the volume distribution compared to 2PACz
125 monomers, film formation primarily resulted from molecular diffusion rather than direct micellar
126 adsorption[27].

127 The film composition and its interaction with FTO substrates were investigated using X-ray
128 photoelectron spectroscopy (XPS) and attenuated total reflectance Fourier transform infrared
129 spectroscopy (ATR-FTIR), respectively. For the film comprising solely 2PACz molecules (the
130 control), the presence of 2PACz was evidenced by the appearance of the phosphine (P) doublet
131 peak (Fig. 2a) and the characteristic C-N peak and C-C/C-H peak (Supplementary Fig. 10) in the

132   XPS spectra[21]. In the case of mixed film, 3-MPA was indicated by the sulfur (S) 2p doublet peak

133   at around 163.8 eV (i.e., the thiol group) (Fig. 2a)[28]. From ATR-FTIR, bidentate or tridentate

134   binding was identified as the mode of 2PACz-FTO interactions, given the appearance of the

135   symmetric PO_3^{2-} stretching (at 996 cm^{-1} for the control sample)[29,30] and the disappearance of P–

136   OH vibrations[14]. These also indicated that solvent washing removed unbound molecules[14]. With

137   3-MPA addition, a redshift of approximately 5 cm^{-1} was observed for the PO_3^{2-} vibrational mode,

138   indicating the enhanced surface binding of 2PACz – as confirmed by AIMD simulations

139   (Supplementary Note 3; Supplementary Figs. 11 and 12). ATR-FTIR of the FTO/3-MPA sample

140   (Fig. 2b) further showed carboxylate-related peaks and a reduction in the intensity of the C=O

141   peak, which correspond to the bidentate chelation of 3-MPA with FTO surfaces[31]. Combining the

142   results from XPS and ATR-FTIR, we reasoned that 3-MPA functioned as a co-adsorbent,

143   modulating the interaction of 2PACz with FTO substrates.

144   The resultant SAM uniformity was characterized by Kelvin probe force microscopy (KPFM).

145   Topography images revealed that, despite varying SAM modifications, the surface morphology of

146   FTO substrates was retained due to the ultra-thin nature of SAMs (Supplementary Fig. 13). From

147   the respective contact potential difference (CPD) maps (Fig. 2c), we recorded surface potential

148   variations on 2PACz-modified surfaces within a range of 120 mV. A Gaussian fit of the single

149   peak in the CPD distribution yielded the full-width half-maximum (FWHM) of 37 mV

150   (Supplementary Fig. 14). Introducing 3-MPA enhanced the homogeneity of electronic properties

151   on SAM-modified surfaces, as reflected by a narrower CPD distribution with the FWHM of 22

152   mV.

153   To directly visualize the distribution of SAMs on FTO substrates, we performed high-angle

154   annular dark-field (HAADF) scanning transmission electron microscopy (STEM) measurements.

155   Fig. 2d shows cross-sectional HAADF-STEM images of both control and mixed samples. Because

156   of the contrast in the atomic number[2], SAM was discernible as a dark layer sandwiched between

157   the brighter FTO and protective molybdenum oxide (MoO_x) layers. For the control SAM, we

158   observed thickness variations across the same FTO facet, with certain regions showing thicknesses

159   less than 1 nm. This suggests a low-density coverage and inhomogeneous distribution of 2PACz

160   molecules[32]. The mixed sample exhibited significant improvements in terms of SAM uniformity

161   and coverage: A consistent thickness was recorded for the mixed SAM on the same facet, albeit

162 with variations between 1 and 2 nm across different facets. Correspondingly, mixed SAM-

163 modified FTO substrates exhibited higher hydrophobicity than control SAM-modified

164 counterparts (Supplementary Fig. 15). Cyclic voltammetry (CV) measurements further determined

165 the areal density of 2PACz in the mixed SAM to be 3.9×10^{13} molecules cm^{-2}, a 70% increase

166 from the 2.3×10^{13} molecules cm^{-2} in the control SAM (Supplementary Fig. 16)[16,27].

Characterization of perovskite films

168 To investigate the impact of SAMs on the structural and optoelectronic properties of perovskites,

169 we fabricated triple-cation $Cs_{0.05}MA_{0.10}FA_{0.85}PbI_3$ perovskite thin films on different FTO/SAM

170 substrates. From scanning electron microscopy (SEM), we observed no notable change in the

171 perovskite surface morphology when 3-MPA was incorporated into the SAM (Fig. 3a, b). Grazing

172 incidence wide-angle x-ray scattering (GIWAXS) measurements showed nearly identical crystal

173 structures for perovskites deposited on both the control and mixed SAMs (Fig. 3c). Here, the main

174 constituent was photoactive α-phase perovskites, with traces of the 4H hexagonal phase detected

175 at $q = 0.82 \text{ Å}^{-1}$ and 0.92 Å^{-1} as well as PbI_2 at $q = 0.90 \text{ Å}^{-1}$, respectively (Supplementary Fig. 14)[33].

176 Time-of-flight secondary ion mass spectrometry (TOF-SIMS) further confirmed that both 3-MPA

177 and 2PACz molecules, due to their chemisorption on FTO surfaces, remained localized at the

178 perovskite/FTO interfaces (Fig. 3d, e). These findings suggest that 3-MPA is not likely to change

179 the perovskite formation process or contribute to the grain boundary or top surface passivation.

180 We conducted photoluminescence (PL) characterization by exciting perovskite thin films at a 1-

181 sun-equivalent photon flux. We saw an average photoluminescence quantum yield (PLQY) of 0.13%

182 ± 0.02% for perovskites directly deposited onto FTO substrates, corresponding to a quasi-Fermi

183 level splitting (QFLS) of 1.105 eV (Supplementary Table 1)[34]. 2PACz can passivate defects on

184 metal oxide surfaces and effectively block electron injection[35], resulting in an approximately 50-

185 fold increase in the PL intensity (Fig. 3f). We noted an average PLQY of 7% ± 2% for the

186 perovskite/2PACz/FTO stacks (Fig. 3g), corresponding to a QFLS of 1.207 eV. The incorporation

187 of 3-MPA further improved the average PLQY to 10% ± 1%. This we ascribed to better SAM

188 coverage rather than 3-MPA passivation since the thiol group of 3-MPA was embedded within the

189 SAM (Fig. 1f).

190 We used ultraviolet and inverse photoelectron spectroscopy (UPS and IPES) to determine the work

191 function and transport energy levels of perovskites and SAMs. The secondary electron cutoff in

192 the UPS spectra indicated an increase in the work function (WF) from 4.56 to 4.93 eV upon

193 depositing the control SAM on the FTO substrate (Supplementary Fig. 18). 3-MPA led to an

194 additional WF shift of +100 meV. The ionization energy (IE) was 5.51 and 5.64 eV for the control

195 and mixed SAMs, respectively. In contrast, perovskites exhibited similar conduction band

196 minimum (CBM) and valance band maximum (VBM) on different substrates (Fig. 3h). The

197 resultant energy level diagrams of perovskites and SAMs are depicted in Fig. 3i, j. A vacuum level

198 (VL) shift of 0.17 eV was recorded between the perovskite and the 2PACz bilayer, which further

199 increased to 0.32 eV for the perovskite/mixed-SAM bilayer[36]. A higher VL shift indicates an

200 enlarged built-in field[37], which in PSCs can lead to enhanced carrier extraction[38]. Meanwhile, the

201 IE offset between the bilayer remained consistent for the control and mixed SAMs (referenced to

202 the Fermi level (E_F)).

Solar cell efficiency and stability

204 We fabricated PSCs having the inverted structure: FTO/SAM/perovskites/3,4,5-trifluoroanilinium

205 (345FAn)/fullerene (C_{60})/bathocuproine (BCP)/Ag (Fig. 4a and Supplementary Fig. 19). 345FAn

206 was selected for interface engineering due to its thermal stability[1]. 2PACz (control) and 2PACz:3-

207 MPA (mixed) were employed as the SAMs for hole-selective contact. The corresponding solar

208 cell parameters are summarized in Fig. 4b. We found that compared to control devices, the mixed

209 SAM led to improved performance (average PCE 25.0% compared with 24.1%). This came from

210 open-circuit voltage (V_{oc}, from 1.141 V to 1.159 V) and fill factor (FF, from 82.3% to 84.1%)

211 (Supplementary Note 4). We noted that device reproducibility was comparable for both control

212 and mixed SAMs, likely due to SAM inhomogeneity occurring at the nanoscale[18,27]. The champion

213 device with the mixed SAM exhibited a PCE of 25.3% from the reverse J-V scan, which agrees

214 with the PCE obtained from the steady-state power output (Supplementary Fig. 20). The integrated

215 short-circuit current density (J_{sc}) of 25.8 mA cm^{-2} derived from the external quantum efficiency

216 (EQE) measurement matches well with that from the J-V sweep (Fig. 4c).

217 One mixed-SAM-based FTO device was characterized at Newport (Montana, USA); and produced

218 a QSS-certified PCE of 24.8%, with a V_{oc} of 1.150 V, a J_{sc} of 25.5 mA cm^{-2}, and an FF of 84.5%

219 (Fig. 4d and Supplementary Fig. 21). Although there have been reports of inverted PSCs with

220 efficiencies surpassing 25%[2,3], the certified PCEs measured under stabilized conditions (including

221 maximum power point (MPP) and QSS tracking) have yet to reach the same level (Supplementary

222 Table 2). The QSS efficiency reported herein represents a new record for inverted PSCs, improving

223 upon the previous record QSS efficiency of 24.09% in literature (Fig. 4e).

224 For comparison, inverted PSCs were fabricated on smooth ITO substrates. We obtained an average

225 PCE of 23.4% for control ITO devices, which was lower than that of control FTO devices, despite

226 their higher average V_{oc} and FF (Supplementary Fig. 22). This emphasizes the need to augment J_{sc}

227 for inverted PSCs. The limited J_{sc} is ascribed to the smoothness of ITO substrates (Supplementary

228 Fig. 23), leading to reduced light-scattering and thus insufficient light absorption in the full device

229 (Supplementary Fig. 24). Interestingly, the performance of mixed-SAM-based ITO devices was

230 only slightly improved, possibly due to the weak interactions of 3-MPA with ITO surfaces

231 (Supplementary Note 5; Supplementary Fig. 25).

232 We evaluated the operating stability of PSCs using International Summit on Organic Photovoltaic

233 Stability (ISOS)-L-3 protocols, in which the encapsulated device was subjected to continuous 1-

234 sun equivalent, white-LED illumination (Supplementary Fig. 26) at 50% relative humidity and

235 heatsink temperature of 65°C. To impede ion and moisture diffusion, we replaced BCP with

236 atomic-layer-deposited SnO_2 as a buffer layer[9]. The resultant device delivered a PCE of 24.6% at

237 room temperature (Supplementary Fig. 27). During the ISOS-L-3 testing, the device initially

238 demonstrated a PCE of 22.6%, which increased to 23.1% after 1.6 hours of MPP tracking (Fig. 4f).

239 The lower PCE at 65°C, compared to room temperature, is ascribed to the negative temperature

240 coefficient of PSCs (–0.15% /°C)[39]. The PCE stabilized at 21.9% (95% of the peak PCE) until the

241 end of the test (1075 h), with the main degradation in the photocurrent (Supplementary Fig. 28).

242 The initial performance and operating stability reported herein are compared with other PSCs

243 subjected to ISOS-L-3 tests (Supplementary Table 3).

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Figure Legends

Fig.1|MD simulations of phosphonic acid adsorption with and without molecular additives.
a, Chemical structures of the phosphonic acid 2PACz and the bifunctional compound 3-MPA. **b**, Total number of 2PACz clusters formed over a set period, in the absence (control) and presence (mixed) of 3-MPA. **c**, Types of 2PACz clusters formed at equilibrium. **d, e**, Top views of equilibrated molecular representations of control (**d**) and mixed (**e**) systems. 2PACz and 3-MPA (where applicable) are shown in pink and blue, respectively; Sn and O atoms, shown in the background, are depicted in yellow and red, respectively. **f**, Successive steps along an AIMD trajectory showcasing the role of 3-MPA as a co-adsorbent. Large, encircled areas are magnifications of small ones.

Fig.2|Homogeneity of self-assembled monolayers formed on FTO substrates. a, XPS P $2p$ (left) and S $2p$ (right) spectra for the control and mixed samples. The peaks were fitted using one S $2p$ or P $2p$ doublet with a 2:1 peak area ratio. **b**, 2PACz (left) and 3-MPA (right) transmission FTIR spectra, compared with ATR-FTIR spectra for the SAM (left) and 3-MPA (right) coated FTO substrates. The FTIR peaks identified at 947 and 1021 cm^{-1} for 2PACz powders correspond to the symmetric and asymmetric stretching of P–OH, respectively. Cz = carbazole. **c**, KPFM images of control (left) and mixed (right) SAM-coated FTO substrates. **d**, Cross-sectional HAADF-STEM images of control (top) and mixed (bottom) SAMs sandwiched between MoO_x and FTO.

Fig.3|Materials properties of perovskite films on different FTO/SAM substrates. a, b, Top-view SEM images of perovskite films deposited on control (**a**) and mixed (**b**) SAMs. **c**, GIWAXS images for perovskite films on control (left) and mixed (right) SAMs. The color bar shows the diffraction intensity collected from the GIWAXS detector. q_{xy} and q_z represent in-plane and near out-of-plane scattering vectors, respectively. **d, e**, TOF-SIMS profiles of perovskites on FTO/control SAM (**d**) and FTO/mixed SAM (**e**) substrates measured in negative polarity. Traces of SH^- were identified at the perovskite/control SAM interface, possibly due to contamination of precursor materials. **f**, Absolute intensity PL spectra of perovskite films on bare FTO (no SAM) and control and mixed SAMs. **g**, PLQYs of perovskite films on control and mixed SAMs (5 samples for each condition). Statistical distribution represented in box plots (line within the box: mean, box limit: standard deviation). **h**, UPS and IPES spectra of perovskite films on control and mixed SAMs. Gaussian fit (grey line) was used to determine the conduction and valence bands. **i, j**, Schematic energy level diagrams of the perovskite/control SAM (**i**) and perovskite/mixed SAM bilayer (**j**), respectively.

Fig.4|Photovoltaic performance of perovskites solar cells. a, Schematic illustration of the device architecture with textured FTO substrate. **b,** Solar cell parameters for the control (16 devices) and mixed (32 devices) SAM devices. Statistical distribution represented in box-and-whisker plots (line within box: median, box limit: standard deviation, whiskers: 1.5 outliers). **c,** EQE and integrated J_{sc} (grey dashed line) curves of the mixed SAM device. **d,** QSS J-V curve of one representative mixed SAM device certified at Newport. Inset: PV parameters of the device. **e,** Certified performance of inverted PSCs measured under the QSS condition. **f,** MPP tracking of the encapsulated mixed SAM device at heatsink temperature of 65°C with a relative humidity of ~50% under 1-sun illumination. The device configuration is FTO/SAM/Perovskite/345FAn/C_{60}/ALD-SnO_2/Ag, having a PCE of 24.6% at room temperature.

Methods

Molecular dynamics simulations

Static DFT calculation and AIMD were performed with the CP2K[40] package utilizing a mixed Gaussian/plane wave (GPW) basis. The PBE exchange-correlation functional[41], DFT-D3 dispersion corrections[42], and dipole corrections[43] necessary for periodic boundary conditions along the perpendicular direction to the surface were included. Valence electron wave functions were expanded in a double-ζ Gaussian basis set with polarization functions (DZVP)[44]. The energy cut-off for the electron density expansion in the GPW method was 400 Ry. Born-Oppenheimer AIMD simulations were run with an integration time step of 0.5 fs and the system was kept at 300 K using the thermostat of Bussi et al.[45] in a canonical isothermal-isochoric (NVT) ensemble, where the total number of atoms N, the volume V and the temperature T of the system were held constant. All AIMD simulations were performed at Γ point. Being the most stable surface, the SnO_2 (110) was chosen as the substrate surface. The systems were equilibrated over 5 ps in the NVT ensemble and the remaining 40 ps were used for the production run. To investigate the interactions between the 2PACz and 3-MPA molecules, as well as molecules and the SnO_2 substrate, 5 scenarios were simulated: (1) a single molecule (2PCAz or 3-MPA) on SnO_2 (110), (2) one 2PACz and one 3-MPA concurrently on SnO_2 (110), (3) two 2PACz and one 3-MPA on SnO_2(110), (4) four 2PACz and one 3-MPA on SnO_2(110), and (5) six 2PACz and one 3-MPA on SnO_2 (110). In all the scenarios, an in-plane SnO_2 (110) simulation cell of 22.690 Å × 27.756 Å with 45 Å of vacuum between the slab repetitions was used. AIMD was also used to estimate the interaction energy of 2PACz and 3-MPA with the SnO_2 (110) surface. The final AIMD configurations were relaxed with DFT to extract the interaction energies of the molecules. Binding energies were calculated as $\Delta E_b = E_{tot} - E_S - E_{mol}$, where E_{tot} is the energy of the final relaxed configuration (molecule on SnO_2 (110)); E_S is the energy of the final configuration of the slab; E_{mol} is the energy of the final configuration of the isolated molecule. The interaction energies of 2PACz clusters were computed after DFT relaxations of isolated clusters. Dimers, trimers, and tetramers were considered. Interaction energies per molecule were calculated as $\Delta E_i = (E_{tot} - nE_{mol})/n$, where E_{tot} is the energy of the final relaxed cluster; n is the number of molecules forming the cluster; E_{mol} is the energy of a single relaxed molecule assumed isolated. Vibrational power spectra were computed as the Fourier transform of the autocorrelation function of the atomic velocities.

Classical MD simulations with full atomic resolution were realized with the help of the LAMMPS MD simulator[46]. The equations of motion were integrated using the Velocity-Verlet method[47], with a 1 fs time step, while bond stretching was not constrained for any bonds. To maintain isothermal conditions, the deterministic Nosé – Hoover thermostat[48,49], with a time constant equal to 0.1 ps, was utilized. This ensured that thermostating was applied to both translational and rotational degrees of freedom, crucial for the asymmetric 2PACz and 3-MPA molecules. All classical MD simulations were realized in the canonical NVT ensemble at T = 300K comprising a V-shaped SnO_2 (110) model system with dimensions 60 Å × 105 Å × 40 Å. Periodic boundary conditions were used in x- and y-directions, whereas reflective boundary conditions were employed in the z-direction. The two considered systems, control and mixed, comprised a total of 18498 and 18714 atoms, respectively, whereas the experimental molar ratio (2PACz/3-MPA= 9/1) was retained in the simulated mixed system. The systems were equilibrated for 1 ns followed by a 10ns production simulation, where sampling took place every 500 fs for the calculation of ensemble averages. A snapshot of the system was taken every 1000 fs for visualization purposes. The calculation of the number distributions of formed 2PACz clusters was performed through an in-house code utilizing

418 a threshold distance of 8 Å among the centre of masses of adjacent 2PACz molecules in accordance
419 with the nearest neighbour shell of the corresponding radial distribution function as clustering
420 criterion.

421 To accurately capture the interactions of SnO_2, the thoroughly validated classical force field
422 developed by Bandura et al.[50] was used. The all-atom OPLS force field was utilized for 3-MPA,
423 wherein the corresponding interaction parameters were obtained with the help of the LigParGen
424 server[51]. For 2PACz, containing the phosphonic functional group, the specially designed force field
425 developed by Meltzer et al.[52] based on the Generalized Amber Force Field[53] was utilized. The van
426 der Waals and electrostatic non-bonded interactions were calculated using a real-space cutoff
427 radius of 10 Å and 8 Å, respectively, whereas the particle-particle-particle-mesh (PPPM) scheme[54]
428 with an accuracy of 0.0001 (kcal/mol)/Å was used for the consideration of long-range electrostatic
429 interactions. Because the SnO_2 force field uses a Buckingham potential for the van der Waals
430 interactions, its combination with the Lennard-Jones potential used for the compounds was
431 realized by fitting the Buckingham parameters of SnO_2 to a suitable set of Lennard-Jones
432 parameters[55] and geometric mixing rules were applied for all dissimilar non-bonded interactions.

433 **Materials**

434 All materials were used as received without further purification. Organic halide salts, including
435 methylammonium iodide (MAI), formamidinium iodide (FAI), methylammonium chloride
436 (MACl), were purchased from Great Cell Solar. Cesium iodide (CsI), 3-mercaptopropionic acid
437 (3-MPA), 3,4,5-trifluoroaniline (98%), and guanidinium thiocyanate (GuaSCN) were purchased
438 from Sigma-Aldrich. 3,4,5-trifluoroaniline was converted to its ammonium form following the
439 published procedure. [2-(9H-Carbazol-9-yl)ethyl]phosphonic Acid (2PACz), lead iodide (PbI_2,
440 99.99%), and bathocuproine (BCP) were purchased from TCI. Anhydrous solvents including N,
441 N-dimethylformamide (DMF, 99.8%), dimethyl sulfoxide (DMSO, 99.9%), 2-propanol (IPA,
442 99.5%), chloroform (CF, 99.8%), and anisole (99.7%) were purchased from Sigma-Aldrich. C_{60}
443 was purchased from Xi'an Polymer Light Technology Corp. ITO and FTO (TEC 10) substrates
444 were purchased from Thin Film Devices Inc. and Ossila, respectively.

445 **Perovskite film fabrication**

446 1.5 M of $Cs_{0.05}MA_{0.1}FA_{0.85}PbI_3$ perovskite precursor was fully dissolved in mixed solvents of DMF
447 and DMSO (4:1, v/v) with the molar ratio for FAI/MAI/CsI was 0.85:0.1:0.05. 10 mg mL^{-1} MACl
448 and 8 mg mL^{-1} GuaSCN were added in the solution to improve the film morphology. The precursor
449 solution was filtered through a 0.22 μm polytetrafluoroethylene (PTFE) membrane before use. 60
450 μL of perovskite solution was deposited on the substrate and spun cast at 1000 rpm for 10 s
451 followed by 6000 rpm for 30 s. 150 μL anisole was dropped onto the substrate during the last 5 s
452 of the spinning, resulting in the formation of dark brown films that were then annealed on a hot
453 plate at 100°C for ITO and 120°C for FTO for 20 min.

454 **Device fabrication**

455 FTO glasses were sequentially sonicated in aqueous detergent, deionized water, acetone, and IPA
456 each for 10 min. After drying with nitrogen, the substrates were exposed to UV-ozone treatment
457 for 15 min to remove organic contaminants and then transferred into a nitrogen-filled glovebox
458 maintaining less than 0.1 ppm of O_2 and H_2O. 100 μL of 2PACz or a mixture of 2PACz:3-MPA (in
459 a molar ratio of either 9:1 in characterization and device fabrication, or 8:2 in XPS measurements)

460 in anhydrous ethanol (1 mM) solution was uniformly spread on the substrates and allowed to rest
461 for 15 s, followed by spinning the films at 3000 rpm for 30s. The films were then annealed at
462 100°C for 10 min and washed by dropping 500 μL ethanol during the film spinning at 3000 rpm.
463 Perovskites solution was deposited on the SAM-modified substrate as detailed above. 200 μL of
464 345FAn solution (1 mg/mL) in CF with an additional 3% of IPA was then drop cast within 2-3 s
465 on the perovskite film spinning at 4000 rpm (i.e., dynamic spinning) and annealed at 100°C for 5
466 min. Both control and mixed SAM films were then transferred to the thermal evaporator
467 (Angstrom engineering). C_{60} (30 nm) and BCP (7 nm) were deposited sequentially with a rate of
468 0.3 Å s^{-1} and 0.5 Å s^{-1}, respectively, at a pressure of ca. 2 x 10^{-6} mbar. Finally, Ag contact (140
469 nm) was deposited on top of BCP through a shadow mask with the desired aperture area. For the
470 stability testing, ALD-SnO$_2$ were used as the barrier layer. The deposition of ALD-SnO$_2$ was
471 carried out in the PICOSUN R-200 Advanced ALD system. H_2O and TDMASn were used as
472 oxygen and tin precursors. Precursor and substrate temperature were set to 75°C and 85°C,
473 respectively. 90 SCCM N_2 was used as carrier gas. Pulse and purge times for H_2O were 1 s and 5
474 s, and 1.6 s and 5 s for TDMASn. The total deposition cycle is 120, corresponding to 20 nm of
475 SnO$_2$.

Solar cell characterization

477 The current-voltage (*I-V*) characteristics of solar cells were measured using a Keithley 2400
478 sourcemeter under the illumination of solar simulator (Newport, Class AAA) at the light intensity
479 of 100 mW cm^{-2} as checked with a calibrated reference solar cell (Newport). The stabilized PCE
480 was measured by setting the bias voltage to the V_{MPP} and then tracing the current density. The V_{MPP}
481 was determined from the reverse *I-V* curve. The active area was determined by the aperture shade
482 mask (0.049 cm^2) placed in front of the solar cell to avoid overestimation of the photocurrent
483 density. EQE spectra were recorded with a commercial system (Arkeo-Ariadne, Cicci Research
484 s.r.l.) based on a 300 W xenon light source and a holographic grating monochromator (Cornerstone,
485 Newport).

Stability tests of solar cells

487 Devices were placed in a homemade stability tracking station. The illumination source is a white
488 light LED with intensity calibrated to match the 1-sun condition. For the ISOS-L-3 ageing protocol
489 (65 or 85°C; 50% relative humidity; MPP)[56], the device chamber was left open in a room with
490 50±10% humidity and solar cell was mounted on a metal plate kept at 65°C by a heating element.
491 A thermal couple attached to the metal plate was used to monitor and provide feedback control to
492 the heating element to ensure temperature consistency. MPP was tracked using a home-build
493 MATLAB-based MPP tracking system using a 'perturb and observe' method. The MPP was
494 updated every 1000 minutes. Encapsulation was done by capping the device with a glass slide,
495 using UV-adhesive (Lumtec LT-U001) as a sealant.

XPS measurements

497 XPS measurements were performed with a Thermo Scientific K-Alpha system with 180° double-
498 focusing, hemispherical analyser. The system is equipped with a 128-channel detector and
499 monochromatic small spot XPS. An Al Kα source (1486.6 eV) was used for excitation and a pass
500 energy of 50 eV was used for XPS acquisition. Samples mounted on a metal specimen holder. All
501 data were analysed with CasaXPS and Thermo Avantage software.

KPFM measurements

KPFM measurements were performed using an Asylum Research Cypher S atomic force microscope (Oxford Instruments, Santa Barbara, USA) with an ASYELEC.01-R2 Ti-Ir coated cantilever (Asylum Research). Scans were performed over 2 µm at 512 pixels and 0.5 Hz using a two-pass method where the first pass is a tapping mode topography scan and the second in KPFM mode with a tip potential of 3 V and a surface clearance of 5 nm. Cantilever calibration was performed using the Thermal method from the Asylum Research GetReal database.

HAADF-TEM measurements

HAADF-TEM images were acquired at an aberration corrected FEI (Titan Cubed Themis G2) operated at 300 kV equipped with an XFEG gun and Bruker Super-X EDS detectors. The SAM samples had a structure of glass/FTO/SAM/MoO_x (50 nm), where the MoO_x layer was deposited through thermal evaporation with a low rate of 0.1 Å s^{-1} at a pressure below 2 x 10^{-4} Pa. The cross-sectional samples were prepared by using a focused ion beam system (FIB, Helios G4 UX). Another protective layer of carbon was thermally evaporated before ion-beam cutting and etching.

CV measurements

CV measurements were conducted using a three-electrode configuration with a potentiostat (PGSTAT204, Autolab). The working electrodes were prepared using a spin coating method on an FTO electrode. The exposed area of the working electrode to the electrolyte measures 8 mm × 21.4 mm. A platinum plate and an Ag/AgCl electrode (in a 3.0 M KCl solution) were employed as the counter and reference electrodes, respectively. The measurements were performed in an Ar-saturated solution of 1,2-dichlorobenzene (o-DCB) with 0.1 M tetrabutylammonium hexafluorophosphate ($TBA^+PF_6^-$) serving as the supporting electrolyte. All potentials are referenced against the ferrocene redox couple, serving as an internal standard. The effective coverage of the self-assembled monolayers on the FTO surface is measured by the slope of a linear dependency of the oxidative peak intensity against the scan rate as follows:

$$i_{p,o} = \frac{n^2 F^2}{4RTN_A} A\Gamma^* v$$

$i_{p,o}$ is the oxidative peak current, v is the voltage scan rate, n is the number of electrons transferred, F is the Faraday constant (96,485 C mol^{-1}), R is the universal gas constant (8.314 J K^{-1} mol^{-1}), T is the temperature, N_A is the Avogadro constant, A is the electrode area, and Γ^* is the areal density.

UPS and IPES measurements

UPS measurements were taken with an Excitech H Lyman-α photon source (10.2 eV) with a nitrogen-filled beam path coupled with a PHI 5600 UHV and analyser system. A sample bias of -5 V was applied and a pass energy of 5.85 eV was used for UPS acquisition. IPES measurements were performed in the Bremsstrahlung isochromatic mode with electron kinetic energies below 5 eV and an electron gun emission current of 2 µA was used to minimize sample damage. A Kimball Physics ELG-2 electron gun with a BaO cathode was used to generate the electron beam. Emitted photons were collected with a bandpass photon detector consisting of an optical bandpass filter (254 nm, Semrock) and a photomultiplier tube (R585, Hamamatsu Photonics). Samples were held at a -20 V bias during all IPES measurements and the UHV chamber was completely dark.

Other characterizations

Particle size distributions in solutions were determined by the DLS technique using a Malvern Zetasizer Nano ZS. Contact angles were measured using VCA-Optima XE. The image was taken with CCD camera within 1 s after water droplet. GIWAXS measurements were performed at CMS beamline, NSLS II. The monochromatic X-ray with the energy of 13.5 keV shone upon the samples at different grazing incident angles of 1°, 0.5°, and 0.08° with an exposure time of 10 s. A Pilatus800K detector was placed 259 mm away from the sample to capture the 2D diffraction pattern. Absolute intensity photoluminescence spectra were measured using an integrating sphere, and Andor Kymera 193i spectrograph, and a 660 nm continuous-wave laser set at 1-sun equivalent photon flux (1.1 μm beam full-width half-maximum, 632 μW); photoluminescence was collected at normal incidence using a 0.1 NA, 110 μm-diameter optical fiber. TOF-SIMS was conducted on the IONTOF M6 instrument with a Bi^{3+} (30 keV) primary ion beam for analysis and an Cs-cluster gun (2 keV) for sputtering. Data was acquired in positive mode with an analysis area of 49×49 μm^2 centred and a raster area of 200×200 μm^2. IR spectra were obtained in the attenuated total reflectance mode using a Fourier-transform IR spectrometer (Thermo Scientific iS50). Samples were prepared on the FTO substrate and scanned in the spectral range of 4000 to 550 cm^{-1} with a minimum number of 500 scans and a resolution of 4 cm^{-1}. The triangular apodization function was used to improve the signal-to-noise ratio. High-resolution SEM images were obtained using the Hitachi S5200 microscope with an accelerating voltage of 1.5 kV. A low accelerating voltage and a low beam current were deployed to reduce surface damage of perovskite films under electron beam bombardment. The diffuse and specular light reflected from the substrate surface was measured using a Cary 5000 UV-Vis-NIR double-beam spectrophotometer in diffuse reflectance mode. Pure $BaSO_4$ was used for the baseline collection.

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Acknowledgements

Author contributions

S.M.P., M.W., M.G., and E.H.S. conceived the idea and proposed the experimental and modelling design. N.L., L.A., V.C., and U.R. carried out the MD simulation. S.M.P. fabricated all the devices and conducted the characterization. T.H., H.R.A and K.R.G performed XPS, UPS, and IPES characterization and data analysis. W.Y. and L.X. carried out the HAADF-STEM measurements. F.T.E., M.W., S.M.Z., and M.G. conducted the PL and EQE characterization and data analysis. M.W. measured DLS. H.S. conducted CV measurements and data analysis. D.C. performed UV-Vis spectroscopy characterization. Y.Y. and M.G.K. measured TOF-SIMS. K.D. and A.A. performed the GIWAXS measurements. M.V., E.D.J. and D.B.K. helped with the device fabrication and material characterization. P.S. and T.F. performed the KPFM measurements. M.W., S.M.P., N.L., M.G., and E.H.S. co-wrote the manuscript. All authors contributed to data analysis, read, and commented on the manuscript.

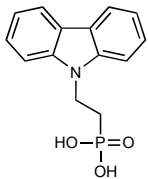**Competing interests**

The authors declare no competing interests.

Data availability

All data are available in the main text or the supplementary materials. Further data are available from the corresponding author on reasonable request.
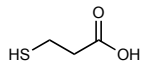
Code availability

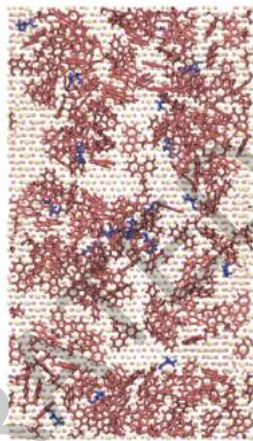The codes and post-analysis tools for MD simulations are available in the following repository: https://doi.org/10.5281/zenodo.8393081.
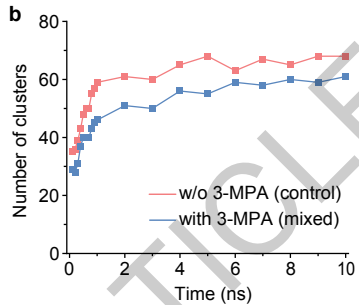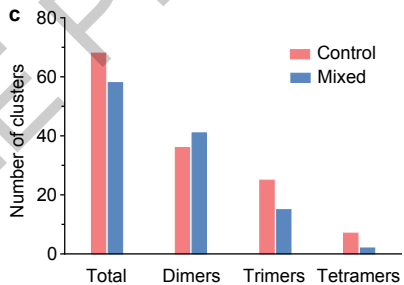
Correspondence and requests for materials should be addressed to M.G. or E.H.S.

a

Control P 2*p* / Control S 2*p* / Mixed P 2*p* / Mixed S 2*p*

Binding energy (eV)

Intensity (a.u.)

b

$v_{as}(PO_3^{2-})$ v(Cz) Mixed
$v_{as}(PO_3^{2-})$ v(Cz) Control
v(P–O–(H)) 2PACz

v(COO$^-$) v(C=O) FTO/3-MPA
3-MPA

Wavenumber (cm^{-1})

Intensity (a.u.)

c

Control Mixed

60 mV
30
0
–30
–60

500 nm 500 nm

d

Control Low coverage 100 nm — MoO$_x$ — 2PACz — FTO 20 nm

Mixed High coverage 100 nm — MoO$_x$ — Mixed — FTO 20 nm

a Control

b Mixed

c

q_z ($Å^{-1}$)

4H   α (100)   Control

4H   α (100)   Mixed

q_{xy} ($Å^{-1}$) q_{xy} ($Å^{-1}$)

2×10^4 Counts 10^2

d

Counts

Control

PbI^-
Sn^-
P^-
SH^-

Sputter time (s)

e

Counts

Mixed

PbI^-
Sn^-
P^-
SH^-

Sputter time (s)

h

Intensity (a.u.)

UPS   IPES

Mixed

Control

Fit

Energy w.r.t. vaccum (eV)

f

Photon flux (s^{-1} m^{-2} nm^{-1})

Mixed
Control

No HTL

Wavelength (nm)

g

PLQY (%)

Control   Mixed

i Control

E_{vac} ΔE_{vac}
0.17 eV

4.93 eV   5.51 eV   4.04 eV

E_F 4.76 eV

IE   HTL   5.59 eV
                    PVSK

j Mixed

E_{vac} ΔE_{vac}
0.32 eV

5.03 eV   5.64 eV   4.04 eV

E_F 4.71 eV

IE   HTL   5.58 eV
                    PVSK

a (diagram layers, top to bottom): Ag, BCP, C$_{60}$, Perovskite, HTL (mixed), FTO, Glass

b PCE (%), V_{oc} (V), J_{sc} (mA cm^{-2}), FF — Control, Mixed

c EQE (%), Integrated J_{sc} (mA cm^{-2}) vs Wavelength (nm)

d Current density (mA cm^{-2}) vs Voltage (V)

- - - Reverse
● QSS
MPP

mks Newton®

J_{sc} (mA cm^{-2})	V_{oc} (V)	FF (%)	PCE (%)
25.5	1.150	84.5	24.8

e PCE (%) vs Year

QSS certification — This work

22.34% 22.62% 23.91% 24.05% 24.09%

f PCE (%) vs MPP tracking time (h)

95% of the peak PCE

ISOS-L-3
Light illumination; 65°C; 50% RH

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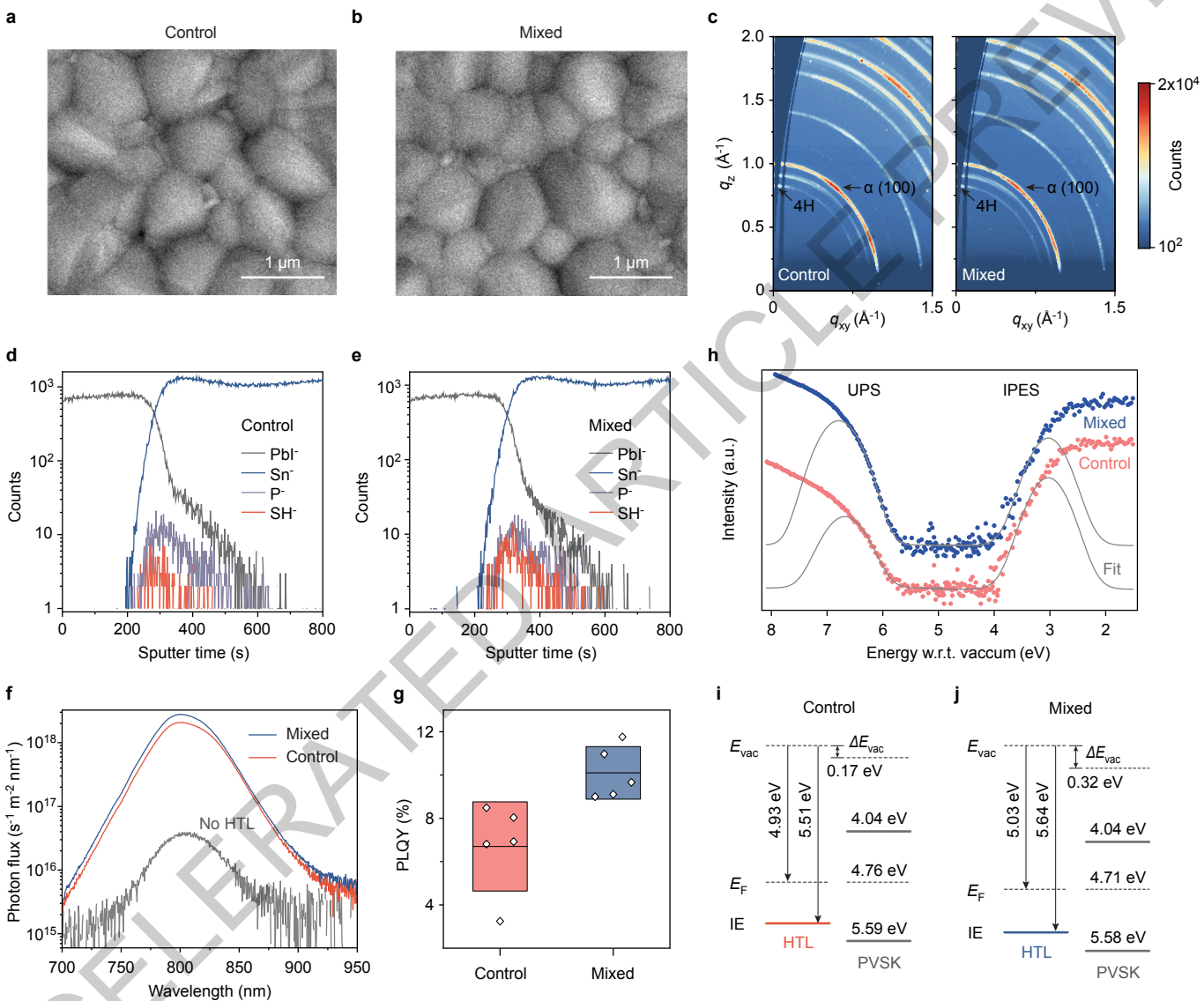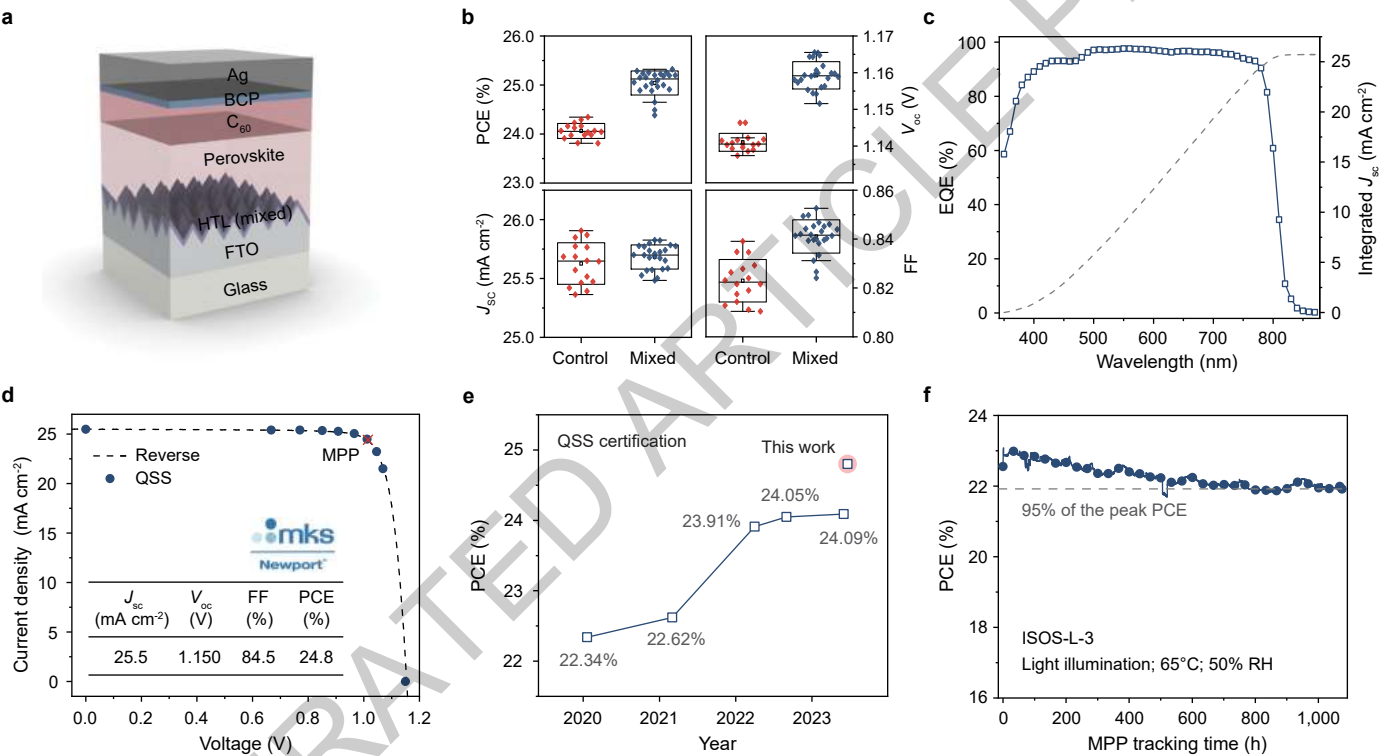## Solar Cells Reporting Summary

Nature Research wishes to improve the reproducibility of the work that we publish. This form is intended for publication with all accepted papers reporting the characterization of photovoltaic devices and provides structure for consistency and transparency in reporting. Some list items might not apply to an individual manuscript, but all fields must be completed for clarity.

For further information on Nature Research policies, including our data availability policy, see Authors & Referees.

▶ Experimental design

Please check: are the following details reported in the manuscript?

1. **Dimensions**

   Area of the tested solar cells
   ☒ Yes ☐ No
   0.049 cm2

   Method used to determine the device area
   ☒ Yes ☐ No
   The active area was determined by the aperture shade mask (0.049 cm2) placed in front of the solar cell

2. **Current-voltage characterization**

   Current density-voltage (J-V) plots in both forward and backward direction
   ☒ Yes ☐ No
   Figure 4d (reverse and quasi-steady-state scans)

   Voltage scan conditions
   For instance: scan direction, speed, dwell times
   ☒ Yes ☐ No
   Supplementary Figure 21

   Test environment
   For instance: characterization temperature, in air or in glove box
   ☒ Yes ☐ No
   Supplementary Figure 21

   Protocol for preconditioning of the device before its characterization
   ☐ Yes ☒ No
   No preconditioning is needed

   Stability of the J-V characteristic
   Verified with time evolution of the maximum power point or with the photocurrent at maximum power point; see ref. 7 for details.
   ☒ Yes ☐ No
   Supplementary Fig. 20b

3. **Hysteresis or any other unusual behaviour**

   Description of the unusual behaviour observed during the characterization
   ☐ Yes ☒ No
   PCE from reverse scan matches well with those from the quasi-steady-state scan and steady-state measurements.

   Related experimental data
   ☒ Yes ☐ No
   Figure 4d and Supplementary Fig. 20

4. **Efficiency**

   External quantum efficiency (EQE) or incident photons to current efficiency (IPCE)
   ☒ Yes ☐ No
   Figure 4c

   A comparison between the integrated response under the standard reference spectrum and the response measure under the simulator
   ☒ Yes ☐ No
   The difference was found to be less than 1.5% (Main text - Solar cell efficiency and stability)

   For tandem solar cells, the bias illumination and bias voltage used for each subcell
   ☐ Yes ☒ No
   Not relevant

5. **Calibration**

   Light source and reference cell or sensor used for the characterization
   ☒ Yes ☐ No
   Methods - Solar cell characterization

   Confirmation that the reference cell was calibrated and certified
   ☒ Yes ☐ No
   Methods - Solar cell characterization

Calculation of spectral mismatch between the reference cell and the devices under test

☒ Yes   M = 1.019 for the certified device
☐ No

6. Mask/aperture

Size of the mask/aperture used during testing

☒ Yes   0.049 cm2
☐ No

Variation of the measured short-circuit current density with the mask/aperture area

☐ Yes   The accuracy of short-circuit current density was confirmed from EQE measurements.
☒ No

7. Performance certification

Identity of the independent certification laboratory that confirmed the photovoltaic performance

☒ Yes   Newport
☐ No

A copy of any certificate(s)
Provide in Supplementary Information

☒ Yes   Supplementary Figure 21
☐ No

8. Statistics

Number of solar cells tested

☒ Yes   Figure 4b and Supplementary Figure 22
☐ No

Statistical analysis of the device performance

☒ Yes   Figure 4b and Supplementary Figure 22
☐ No

9. Long-term stability analysis

Type of analysis, bias conditions and environmental conditions
For instance: illumination type, temperature, atmosphere humidity, encapsulation method, preconditioning temperature

☒ Yes   Figure 4f, Supplementary Figure 26 and Supplementary Figure 28
☐ No