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The aerosol-assisted chemical vapour deposition of Mo-doped BiVO₄ photoanodes for solar water splitting: an experimental and computational study†

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BiVO₄ is one of the most promising light absorbing materials for use in photoelectrochemical (PEC) water splitting devices. Although intrinsic BiVO₄ suffers from poor charge carrier mobility, this can be overcome by Mo-doping. However, for Mo-doped BiVO₄ to be applied in commercial PEC water splitting devices, scalable routes to high performance materials need to be developed. Herein, we propose a scalable aerosol-assisted chemical vapour deposition (AA-CVD) route to high performance Mo-doped BiVO₄. The materials were characterised using X-ray diffraction (XRD), Raman spectroscopy, X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM), atomic force microscopy (AFM), UV-visible absorption spectroscopy, and a range of PEC tests. By studying a range of Mo-precursor doping levels (0 to 12% Mo:V), an optimum precursor doping level was found (6% Mo:V); substituting V⁵⁺ sites in the host structure as Mo⁶⁺. In PEC water oxidation the highest performing material showed an onset of photocurrent (*J*_{on}) at ~0.6 V_{RHE} and a theoretical solar photocurrent (TSP) of ~1.79 mA cm⁻² at 1.23 V_{RHE} and 1 sun irradiance. Importantly, Mo-doping was found to induce a phase change from monoclinic clinobisvanite (m-BiVO₄), found in undoped BiVO₄, to tetragonal scheelite (t-BiVO₄). The effect of Mo-doping on the phase stability, structural and electronic properties was examined with all-electron hybrid exchange density functional theory (DFT) calculations. Doping into V and Bi sites at 6.25 and 12.5 at% was calculated for t-BiVO₄ and m-BiVO₄ phases. In accord with our observations, 6.25 at% Mo doping into the V sites in t-BiVO₄ is found to be energetically favoured over doping into m-BiVO₄ (by 2.33 meV per Mo atom inserted). The computed charge density is consistent with n-doping of the lattice as Mo⁶⁺ replaces V⁵⁺ generating an occupied mid-gap state ~0.4 eV below the conduction band minimum (CBM) which is primarily of Mo-4d character. Doubling this doping level to 12.5 at% in t-BiVO₄ resulted in the mid-gap state merging with the CBM and the formation of a degenerate semiconductor with electrons distributed over the 3d orbitals of V ions residing in the [001] plane. In conjunction with our experimental findings, this strongly suggests that it is the increased electron conductivity due to Mo doping of BiVO₄ that produces a more active photoanode for water splitting, and that this maximises between 6.25 to 12.5 at% doping.

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1 Introduction

Since the industrial revolution, societal dependence on fossil fuels has grown exponentially, which has caused CO₂ levels in

the atmosphere to rise from ~280 ppm in ~1750 to ~410 ppm today.^{1,2} This dramatic rise in CO₂ levels is the primary cause of climate change, which may have potentially catastrophic impacts if not curtailed.^{3,4} In order to reduce CO₂ emissions,

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$$\text{Mo}_V^{\times} \rightleftharpoons \text{Mo}_V^{\bullet} + e^{-} \quad (1)$$

All electron, hybrid exchange density functional theory calculations have been used to examine the phase change induced by Mo-doping and the associated changes in electronic structure. An accurate description of exchange and on-site electronic correlation is essential if the spatial delocalisation, spin polarisation and energy of the d-orbitals are to be reproduced.^{46,47} Electronic exchange and correlation were therefore approximated using the hybrid PBE0 functional.⁴⁸ This functional has demonstrated an improvement over local density functional theory (DFT) functionals in strongly correlated systems in both describing the character of electronic bands and in the prediction of band gaps, the latter of which are systematically underestimated with local DFT functionals due to their in-built self-interaction.⁴⁹ In this study, however, we have opted for a reduced 10% mixing of Hartree-Fock (HF) exchange (PBE0-10) as the band gaps in strongly correlated materials are observed to be overestimated at the standard 25% mixing of PBE0.^{50,51} To the authors knowledge, this is the first study to have applied this approach to Mo doping in both the t-

BiVO_4 and m-BiVO_4 structures. The calculations herein document the effects of Mo doping on the phase stability, local structure, projected density of states (PDOS) and bandgap, and the spin density distribution of the n-doped charge density.

2 Experimental

2.1. Synthesis

Phase pure BiVO_4 coatings were grown on FTO glass substrates (TEC 15; 2.5×2.7 cm) using a novel aerosol-assisted chemical vapour deposition (AA-CVD) method, inside a cold wall reactor (Fig. S1†). Substrates were heated from underneath using a graphite heating block. The inlet to the reactor was equipped with a cooling water jacket to prevent any prior decomposition of the precursor before reaching the reactor.

The precursor solution contained vanadyl acetylacetonate (0.056 g, 0.20 mmol), triphenyl bismuth (0.088 g, 0.20 mmol) in an acetone/methanol mixture (3 : 1; 40 ml). The solution was sonicated for 1 min to dissolve the precursors (VWR ultrasonic cleaner, 30 W, 45 kHz). The solution was then aerosolized using an ultrasonic humidifier (2 MHz, Liquifog, Johnson Matthey) and carried over the heated FTO substrate (400 °C) using compressed air at a flow rate of 5000 sccm (MFC, Brooks) over a period of ~20 min until the solution was fully transferred. To avoid unnecessary oxidation and change of the precursor solution, it was made fresh once the CVD reactor had reached temperature, and transferred immediately, with a total time from the making of the precursor solution to its transfer of less than 30 min.

A series of Mo-doped BiVO_4 coatings were made by adding molybdenum hexacarbonyl to the precursor solution before sonication. 1, 3, 6 and 12% Mo-doped BiVO_4 coatings were made by respectively adding 0.0005, 0.0015, 0.003 and 0.006 g (0.002, 0.006, 0.012, 0.024 mmol) to the precursor solution. The Mo-doping level represented the % Mo added with respect to the Bi (or V) precursor present in the precursor solution. All samples were subsequently annealed in an oven at 500 °C in air for 12 hours.

2.2. Physical characterisation

The speciation of the precursor solution was analysed using ^1H and ^{51}V NMR spectroscopy (Bruker Avance 600, 500 and 400 MHz instruments, with all chemical shifts reported in parts per million (ppm), ^{51}V NMR signals were reported against a VOCl_3 reference at 0 ppm). Chemical changes were monitored over time using visible absorption spectroscopy (Shimadzu UV-2600i). X-ray diffraction (XRD) patterns were measured with a Bruker D2 Phaser diffractometer with parallel beam optics equipped with a Lynx-Eye detector. X-rays were generated using a Cu source ($V = 30$ kV, $I = 10$ mA) with Cu $K_{\alpha 1}$ ($\lambda = 1.54056$ Å) and Cu $K_{\alpha 2}$ radiation ($\lambda = 1.54439$ Å) emitted with an intensity ratio of 2 : 1. Patterns were collected between $10^\circ \leq 2\theta \leq 60^\circ$ with a step size of 0.0243° . Patterns were compared to standards from the Physical Sciences Data-Science (PSDS) database.⁵² Lattice parameters and the average crystallite size of each sample was determined from a Le Bail model, which was fit to

each diffraction pattern using GSAS-EXPGUI software.⁵³ Raman spectra were obtained using a Horiba LabRam Infinity equipped a helium-neon laser (633 nm, 25 mW). The system was calibrated to a silicon reference, and samples were analysed over the 200–1200 cm^{-1} range. Standards were acquired from RRUFF project database.⁵⁴ For scanning electron microscopy (SEM), 15 nm of chromium was deposited on samples by sputtering to prevent charging. Images were taken using a Zeiss Auriga Cross Beam microscope with a Schottky field emission gun using a 5 keV electron beam. Atomic force microscopy was performed using an Agilent 5500AFM system in tapping-mode to investigate the surface morphology of the thin films deposited on FTO-coated float glass. The resonant frequency of the cantilever was approximately 270 kHz and the force constant was 40 N m^{-1} . The scanning probe microscopy control software PicoView was used to record film topography and phase changes of $1 \mu\text{m}^2$ and $10 \mu\text{m}^2$ regions. The images were processed and analysed using Gwyddion software. X-ray photoelectron spectroscopy (XPS) was performed using a Thermo Scientific™ K-Alpha™ instrument. The instrument uses monochromated and micro-focused Al- K_{α} ($h\nu = 1486.6$ eV) radiation to eject photoelectrons that are analysed using a 180° double-focusing hemispherical analyser with a 2D detector. A flood gun was used to minimize sample charging. Spectra were collected at 2×10^{-9} mbar base pressure. All samples were referenced to the C-C peak of adventitious carbon in the C 1s spectrum at a binding energy of 284.8 eV to correct for any charge that is not neutralised by the flood gun. After correction for the instrument transmission function using the Avantage software package, data was analysed using CASAXPS software.⁵⁵ Ultra-violet visible (UV-vis) transmission spectroscopy was performed on a Shimadzu UV-vis 2600 spectrophotometer equipped with an integrating sphere.

2.3. Photoelectrochemical water splitting

All photoelectrochemical analyses were carried out in a home-made PEEK cell with quartz windows. Analyses were carried out in 0.1 M phosphate buffer (0.05 M K_2HPO_4 , 0.05 M KH_2PO_4 ; pH = 7) in Milli-Q-water (Millipore Corp., $18.2 \text{ M}\Omega \text{ cm}$ at 25 °C). For all measurements, a three electrode configuration was used, with a Pt mesh counter electrode and a Ag/AgCl reference electrode in sat. $\text{KCl}_{(\text{aq})}$ (0.197 V_{NHE} at 25 °C; Metrohm). An Autolab potentiostat (PGSTAT12 with an FRA2 module) was used to apply voltage and measure currents. All applied voltages are reported *vs.* the reversible hydrogen electrode (V_{RHE}), converted using the Nernst equation:

$$V_{\text{RHE}} = V_{\text{Ag/AgCl}} + (0.0591 \times \text{pH}) + V_{\text{Ag/AgCl}}^\circ \quad (2)$$

where $V_{\text{Ag/AgCl}}$ is the applied potential *vs.* the reference electrode and $V_{\text{Ag/AgCl}}^\circ$ is the standard potential of the reference electrode.

The light source used to measure current–voltage (J) curves and incident photon to current efficiency (IPCE) curves was an ozone-free xenon lamp (75 W, Hamamatsu) coupled to a monochromator (OBB-2001, Photon Technology International). The IPCE was calculated using the following equation:⁵⁶



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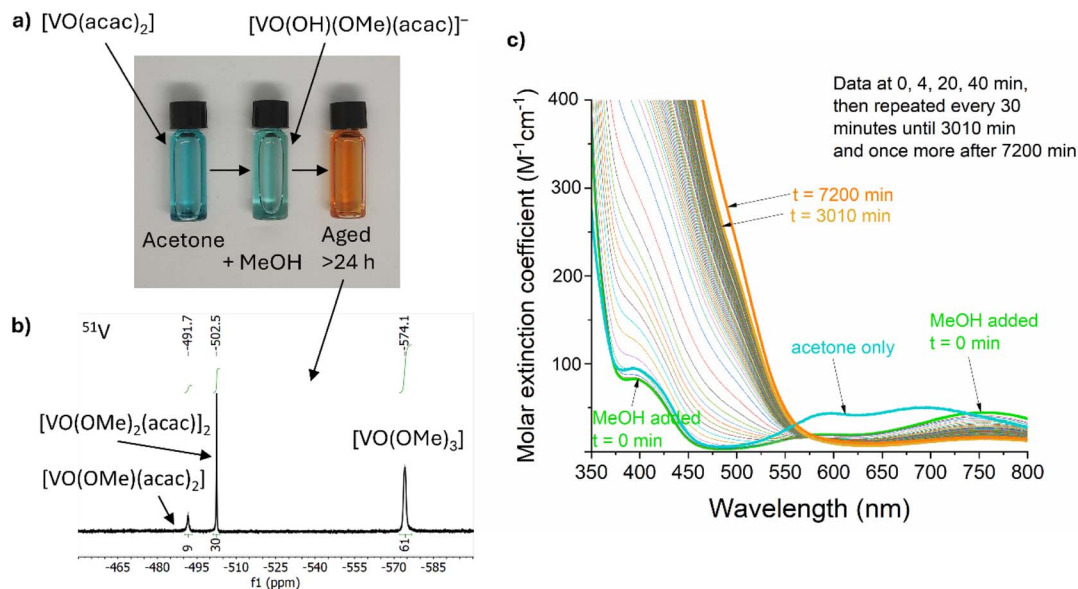


Fig. 1 (a) Photos (left to right) of $\text{VO}(\text{acac})_2$ dissolved in acetone, acetone/MeOH, and then after ageing under air. (b) ^{51}V NMR spectrum of a 5 mM solution of $\text{VO}(\text{acac})_2 + \text{BiPh}_3$ in deuterated acetone/MeOH (3 : 1) after oxidation for 30 h under air. (c) Visible absorption spectra of a 5 mM solution of $\text{VO}(\text{acac})_2$ in acetone (bold blue line) and 5 mM solution of $\text{VO}(\text{acac})_2$ in acetone/MeOH (3 : 1) over time (bold green line, $t = 0$ min; bold gold line, $t = 3010$ min; bold orange line, $t = 7200$ min). BiPh_3 was added at the end of the experiment but has no effect on the absorption spectrum.

(with minor chemical shift changes) but with different ratios. These favour acac-rich $\text{VO}(\text{OMe})(\text{acac})_2$ as the major component (Fig. S2b†). Recording the spectra at different time points after mixing indicated little change in the equilibrium position, however, at short time periods it is expected that solvolysis of the second acac ligand is much slower than the first.⁶⁹ The oxidation of the precursor solution under air (in a sealed cuvette) was monitored over time by visible absorption spectroscopy (Fig. 1c), 50% of the $\text{V}(\text{iv})$ signal has been lost after ~ 13 hours, which is consistent with loss of a broad paramagnetic signal for $\text{V}(\text{iv})$ species in the equivalent ^1H NMR data (Fig. S2c†). The oxidation of $\text{VO}(\text{acac})_2$ in MeOH has been reported to be first-order with respect to both $[\text{VO}(\text{acac})_2(\text{MeOH})]$ and O_2 ,⁶⁹ which was consistent with the conditions studied here, when followed by the loss of the d–d transition absorption signal centred around 750 nm (Fig. 1c and S2d†). The formation of oxidised species causes a change to an orange solution. The kinetics associated with the increase in absorption in the $\text{V}(\text{v})$ ligand to metal charge transfer region (<550 nm) are complex, indicating the formation of a shifting equilibrium of species during the transformation (Fig. S2e†). At early time points the LMCT absorptions increase linearly, e.g. with $\sim 0^{\text{th}}$ order kinetics, the LMCT band then increases at an elevated rate between 5–7 hours before dropping to a slower rate over prolonged time periods.

Whilst colourless $\text{Mo}(\text{CO})_6$ is poorly soluble in acetone/MeOH, slow partial dissolution to give a pale yellow solution occurs over 24 hours. Dissolution is accelerated in the presence of two equiv. acac-H, to give an orange solution. This solution shows a broad ^1H NMR signal at 15.5 ppm, suggesting a paramagnetic Mo compound with organic (acac) ligands.

$\text{Mo}^{6+}\text{O}_2(\text{acac})_2$ is a well-known compound, but would not give a paramagnetic signal, therefore a lower oxidation state of Mo is expected under these conditions. It is possible that reduced Mo compounds form in the precursor solution, especially if acac-H is released during the oxidation of V species. The exact Mo speciation is not easily probed due to the low solubility of $\text{Mo}(\text{CO})_6$. Acetone/MeOH solutions of BiPh_3 were examined by ^1H NMR spectroscopy, revealing the chemical inertness of BiPh_3 under air/moisture and in the presence of $\text{VO}(\text{acac})_2$, oxidised V^{5+} species (including excess acac-H) and $\text{Mo}(\text{CO})_6$ when studied by ^1H NMR (Fig. S2a†). It appears that BiPh_3 remains a well-defined complex under these conditions.

It is clear that the precursor solution is prone to ageing effects over time, driven by the oxidation of V^{4+} by air in the presence of MeOH, which in turn may release acac-H which could, in turn, ligate to oxidised Mo species. Ageing effects are known in the literature in related metal–organic decomposition processes to access BiVO_4 .⁷¹ Herein, to minimise the effect of ageing in our work, each precursor solution was made fresh for each CVD reaction and used within a period of ~ 30 min.

3.2. Physical characterisation

3.2.1. XRD and Raman spectroscopy. All coatings were characterised using XRD and Raman spectroscopy (Fig. 2). The XRD pattern of the BiVO_4 sample matched that of phase-pure monoclinic clinobisvanite ($I112/b$; $a = 5.1903(3)$ Å, $b = 5.0821(3)$ Å, $c = 11.6704(9)$ Å, $\alpha = \beta = 90^\circ$, $\gamma = 90.28(11)^\circ$) (Fig. 2a). This was analogous to previous work by Sagu *et al.* who grew BiVO_4 using an alternative AA-CVD route.¹⁴ However, the XRD patterns of all samples doped with Mo differed from BiVO_4 , with the dual peaks seen at $2\theta \sim 19$ and $\sim 29^\circ$ for BiVO_4

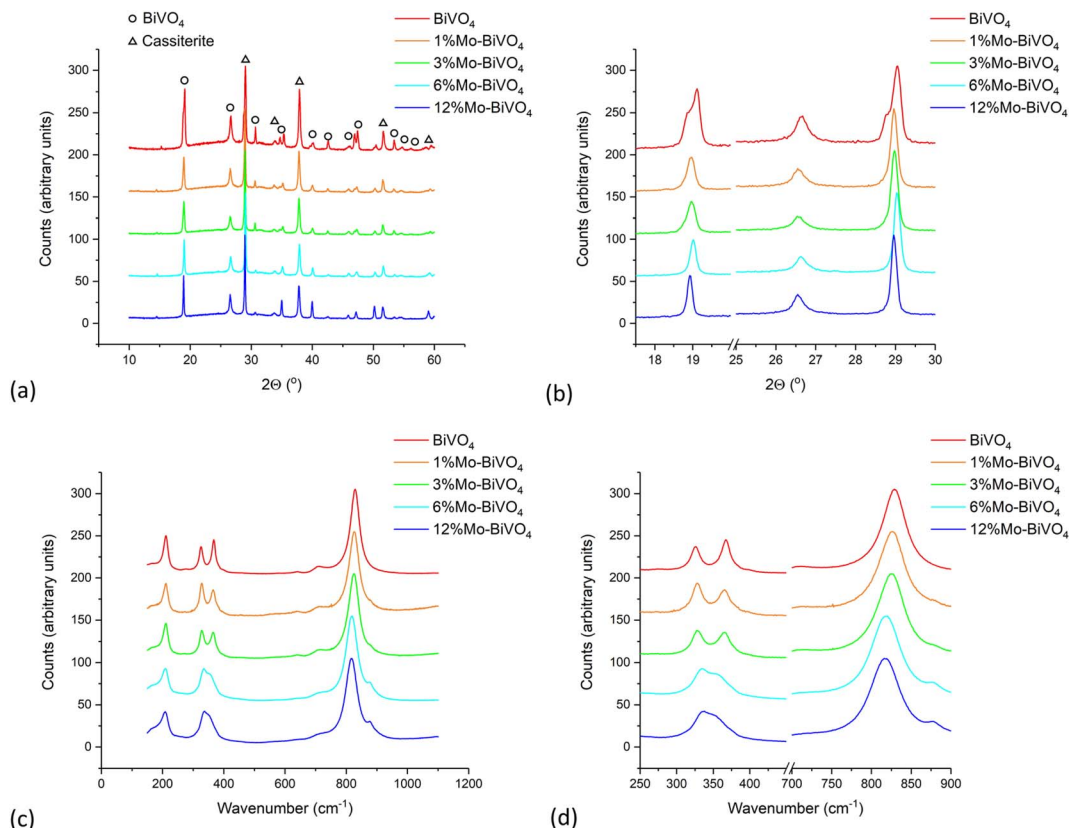


Fig. 2 (a) XRD patterns, (b) close-up view of select peaks in XRD patterns, (c) Raman spectra and (d) close-up view of select peaks in Raman patterns of BiVO₄ and all Mo-doped BiVO₄ samples.

merging to form single reflections in Mo-doped samples (Fig. 2b). This was attributed to a slight structural distortion, causing the monoclinic lattice to adopt the more symmetric tetragonal form. The XRD patterns of all Mo-doped BiVO₄ samples matched that of phase-pure tetragonal scheelite (*I*₄/a; *a* = *b* = 5.1206(5) Å, *c* = 5.0821(3) Å, *c* = 11.5755(10) Å, α = β = γ = 90° for the 1% Mo : BiVO₄ sample), with no additional phases observed. In undoped BiVO₄, the metastable tetragonal scheelite phase undergoes a phase change to the thermodynamic monoclinic clinobisvanite phase at ~255 °C.^{45,72} Herein, the addition of Mo-dopants were found to prevent this phase change, despite the coatings being grown at 400 °C and subsequently annealed in air at 500 °C. This effect was previously observed by Fischer *et al.* in their MOD grown Mo-doped BiVO₄ films, where they saw a continuous transition from the monoclinic clinobisvanite to tetragonal scheelite phase with increasing Mo-doping.³⁷ In their case, the full transition to tetragonal scheelite was observed with ~10.5% Mo-doping. This was also seen by Xiao *et al.* in their electrodeposited Mo-doped BiVO₄ films, where full transition to the tetragonal scheelite phase was found with ~10% Mo-doping.³⁴ Herein, our XRD results indicated a full transition to the tetragonal scheelite phase with only ~2% Mo-doping.

Le Bail models were fit to the XRD patterns, yielding the lattice parameters and average crystal sizes in our coatings. These parameters are plot in Fig. S3† and listed in Table 1.

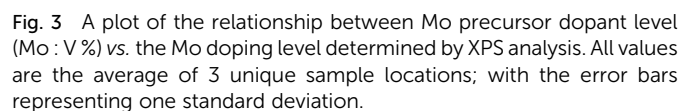
Comparing changes with Mo-doping to an undoped tetragonal scheelite standard (*I*₄/a; *a* = *b* = 5.105(1) Å, *c* = 5.0821(3) Å, *c* = 11.577(1) Å, α = β = γ = 90°),⁷³ we see that the *a* lattice parameter tended to increase as the Mo-doping level was increased; rising from 5.1903(3) Å in the undoped BiVO₄ standard to 5.1349(2) Å in 12% Mo : BiVO₄ (Fig. S3a†). However, the reverse trend was seen for the *c* lattice parameter; decreasing from 11.6705(9) Å in the undoped BiVO₄ standard to 11.5592(7) Å in 12% Mo : BiVO₄. Overall, there was a general trend for the unit cell volume to increase with Mo-doping; increasing from 301.7(1) Å³ in the undoped BiVO₄ standard to 304.8(2) Å³ in 12% Mo : BiVO₄. This trend is intuitive, as the Mo⁶⁺ dopants in a 4-coordinate environment have a higher ionic radius (*r* ~0.41 Å) than the V⁵⁺ sites they replace (*r* ~0.355 Å), causing the unit cell to expand to accommodate them. Correlating with this trend was the increase in average crystal size, increasing from ~25.2 nm in 1% Mo : BiVO₄ to ~44.5 nm in 12% Mo : BiVO₄.

Raman spectroscopy of the undoped BiVO₄ sample corroborated with XRD data, indicating the formation of the monoclinic form (Fig. 2c). The major peaks seen at ~213, ~328, ~368 and ~831 cm⁻¹ corresponded to the external lattice, A_g asymmetric V–O bending, B_g symmetric V–O bending and the A_g symmetric V–O stretching modes, respectively.⁷⁴ However, upon doping with increasing levels of Mo, a gradual merging of the A_g asymmetric and B_g symmetric V–O bending modes was observed, whereby at 12% Mo-doping the peaks had almost



^a Light power is $\sim 8.5 \text{ mW cm}^{-2}$. Numbers in brackets represent the standard error on the lowest significant figures.

The series of Mo-doped BiVO_4 showed broadly similar behaviour to undoped BiVO_4 , with some notable differences: (i) the binding energy of Bi^{3+} states tended to increase with Mo-doping and (ii) V^{4+} content tended to increase with Mo-doping. As expected, Mo-doped BiVO_4 samples showed the presence of Mo species. Across all Mo-doped samples, the average binding energy of the Mo $3d_{5/2}$ state was ~ 232.3 eV, in agreement with previous studies of Mo-doped BiVO_4 , and the assignment of a Mo^{6+} environment that substitutes V^{5+} sites.³⁰⁻³² Relating this binding energy with previous work on molybdenum oxides, we see that this shows a closer match to Mo_4O_{11} ($\text{Mo}^{5.5+}$; 232.1 eV)⁸² as compared with MoO_3 (Mo^{6+} ; 232.9 eV)⁸³ and Mo_2O_5 (Mo^{5+} ; 231.8 eV).⁸⁴ The Mo : V (%) was determined for all samples, and plot in Fig. 3. With increases in Mo precursor doping level, the amount of actual Mo-doping found in the coatings is supra-linear (*i.e.* Mo from the Mo precursor is



more effective in entering the BiVO_4 host lattice than V from the V precursor). However, at higher doping levels (from 6 to 12% Mo precursor doping level) a near linear relationship is seen, which may be due to a nearing of the solubility limit of Mo doping in BiVO_4 . Importantly, as the Mo-doping level was increased in BiVO_4 , the valence band maximum (VBM) energy did not significantly change (~ 1.9 to 2.0 eV; Table S1†). This strongly indicated that Mo doping does not alter the electronic states of the VBM region in BiVO_4 .

3.2.3. SEM and AFM analysis. Top-down SEM and AFM was carried out on our undoped BiVO_4 and series of Mo-doped

BiVO_4 coatings (Fig. 4). Top-down SEM imaging of our undoped BiVO_4 coating revealed densely packed cuboidal particles, that were predominantly ~ 200 nm wide (Fig. 4a). And top-down SEM imaging of a representative Mo-doped sample (6% Mo : BiVO_4) revealed densely packed irregular particles, that were predominantly between ~ 100 and 150 nm wide (Fig. 4b). XRD modelling showed that average crystal sizes ranged from ~ 25 to 45 nm in our coatings (Table 1). This indicated the particles seen in SEM were composed from a number of nanocrystals. The coating thickness of a representative 6% Mo : BiVO_4 coating was found to be ~ 180 nm by side-on SEM imaging (Fig. S6†).

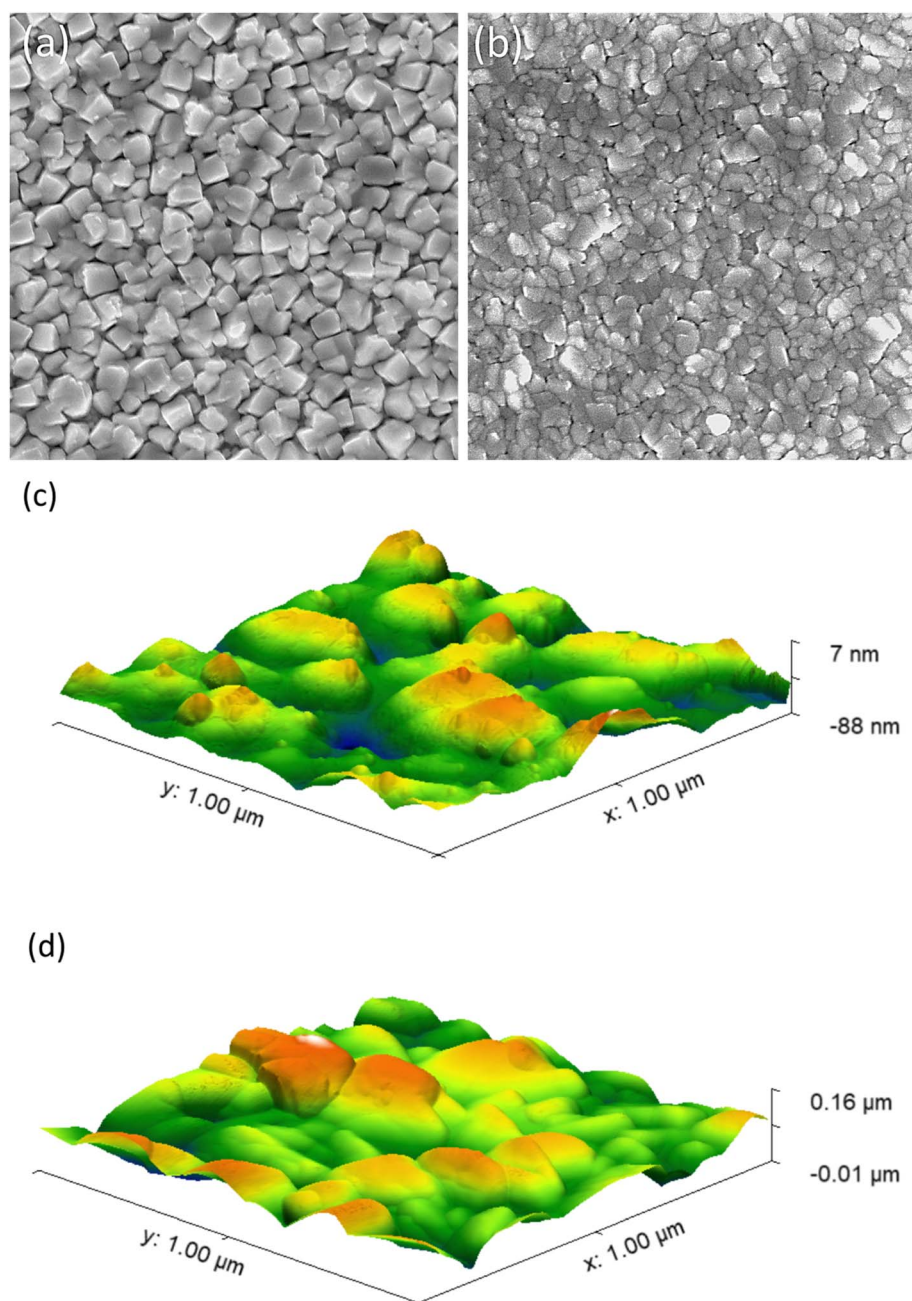


Fig. 4 SEM images of (a) BiVO_4 and (b) 6% Mo- BiVO_4 taken at 50k magnification [the width of each image represents a distance of $3.8 \mu\text{m}$]. AFM images, of (c) BiVO_4 and (d) 6% Mo- BiVO_4 measured over a $1 \mu\text{m} \times 1 \mu\text{m}$ square area.



Top-down AFM images revealed similar topographies to top-down SEM images for both the undoped BiVO_4 (Fig. 4c) and series of Mo-doped BiVO_4 coatings (Fig. 4d and S7†). From AFM images, the root mean square roughness (R_q) and surface area per square micron were determined for all samples (Table 1). The R_q ranged from ~ 17.2 to ~ 27.2 nm and the surface area per square micron ranged from 1.04 to 1.23 μm^2 . No observable trend between the level of Mo-doping and surface roughness or surface area was found. Broadly speaking, all coatings were highly smooth, and showed minimal differences in surface area (up to $\sim 15\%$).

3.2.4. UV-visible absorption spectroscopy. The UV-visible absorption spectrum was measured for all films (Fig. 5a). All samples, irrespective of their level of Mo-doping, showed broadly similar behaviour. They all showed a band edge at ~ 480 nm (~ 2.6 eV) and no additional absorbing states were seen up to 1200 nm. As all samples showed similar coloration by eye, this was to be expected. The indirect allowed and direct allowed transitions were determined through Tauc plots, with a representative example for undoped BiVO_4 shown in Fig. S8a.† No significant differences were seen in the range of indirect allowed and direct allowed bandgap energies that were determined (Table 1), with indirect allowed bandgaps ranging

between ~ 2.54 and ~ 2.56 eV and direct allowed bandgaps ranging between ~ 2.61 and ~ 2.65 eV. Notably, in all samples, the indirect allowed transition was consistently lower than the direct allowed transition; in agreement with computational studies.⁸⁵ Moreover, the similarity in bandgap energy found between the m- BiVO_4 and t- BiVO_4 samples was expected, as the monoclinic and tetragonal forms possess similar bandgap energies.⁸⁶

With knowledge of the coating thickness (Fig. S6†), the UV-visible absorption data was used to determine the penetration depth of light (Fig. S8b†).⁸⁷ This was used to calculate how different wavelengths of light are absorbed as they travel through our materials, and was done for the cases of UVA (325 nm), violet (400 nm) and blue (475 nm) light for the scenarios of front (Fig. 5b) and back (Fig. 5c) irradiation. Under front irradiation, most UVA ($\sim 99\%$) and violet ($\sim 85\%$) light is absorbed within 100 nm of entering the photoanode. However, only $\sim 43\%$ of blue light is absorbed within 100 nm of entering the photoanode, and only $\sim 64\%$ of blue light is absorbed across the entire 180 nm coating. Under back irradiation, light travels through the FTO layer before reaching the photoanode. Substantial parasitic light absorption is seen in the FTO layer, with this being most significant in the UVA region ($\sim 60\%$

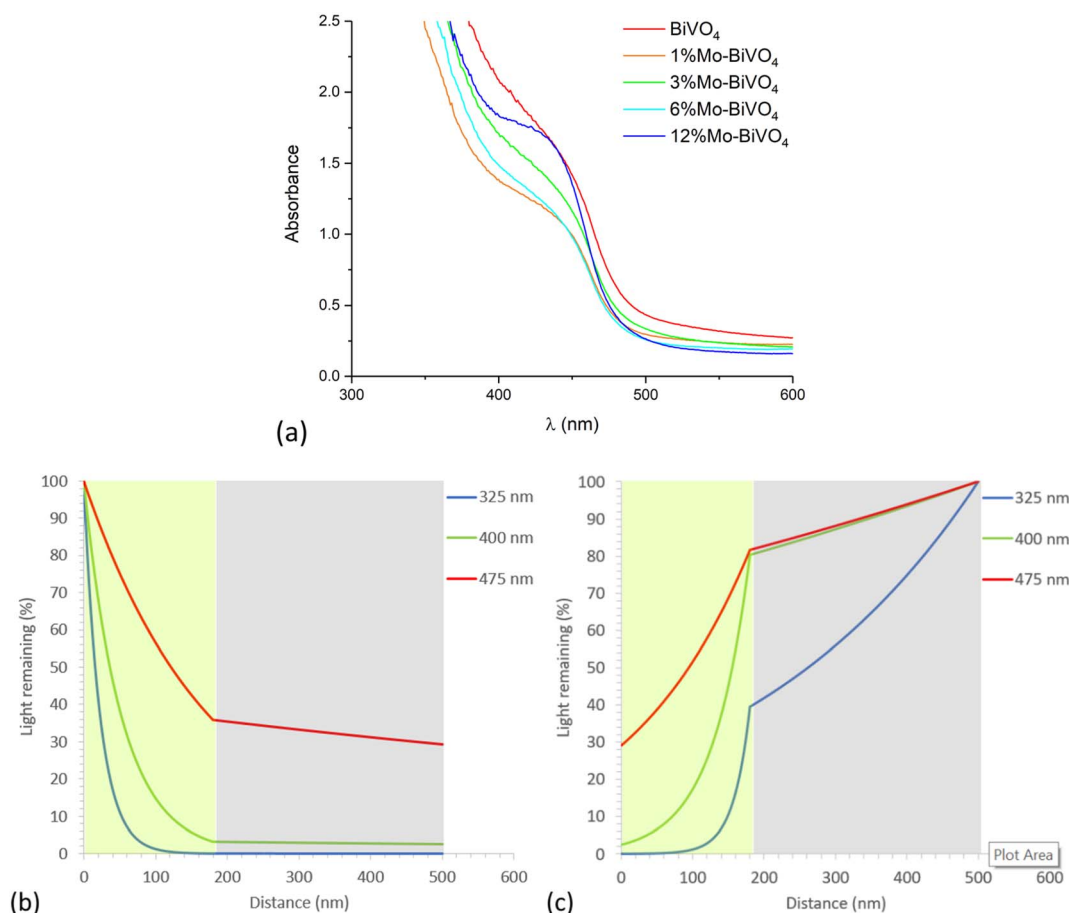


Fig. 5 (a) UV-visible absorption spectra of BiVO_4 and all Mo-doped BiVO_4 samples and light remaining (%) with distance travelled in 6% Mo- BiVO_4 for (b) front irradiation and (c) back irradiation (shaded green and grey areas represent BiVO_4 [180 nm thick] and FTO [320 nm thick] layers respectively).

absorbed across the 320 nm FTO coating). The remaining UVA is mostly absorbed ($\sim 39\%$) within the first 100 nm of entering the photoanode. For the cases of violet and blue light, only $\sim 20\%$ of light is parasitically absorbed by the FTO layer. Within 100 nm of entering the photoanode, $\sim 68\%$ and $\sim 35\%$ of the remaining violet and blue light is absorbed, respectively. Under back irradiation, across the entire photoanode, $\sim 39\%$, $\sim 78\%$ and $\sim 52\%$ of UVA, violet and blue light is absorbed, respectively. Whereas under front irradiation, $\sim 100\%$, $\sim 97\%$ and $\sim 64\%$ of UVA, violet and blue light is absorbed, respectively.

3.3. Photoelectrochemical water splitting

The PEC water oxidation performance of our undoped BiVO_4 and series of Mo-doped BiVO_4 was investigated using current-voltage (JV) curves in 0.1 M phosphate buffer under 400 nm excitation (Fig. 6). All samples showed similar dark electrocatalytic behaviour, with the onset for water oxidation seen at $\sim 2.0 \text{ V}_{\text{RHE}}$. Under illumination, all samples showed a similar onset to photocatalytic water oxidation at $\sim 0.6 \text{ V}_{\text{RHE}}$, and did not change for front or back irradiation.

Under front irradiation, the undoped BiVO_4 sample showed a slower rise in photocurrent density than the Mo-doped BiVO_4 samples, which was indicative of a higher barrier to electron carrier extraction in BiVO_4 (Fig. 6a). Although the highest

plateau photocurrent density is seen in the 3% Mo: BiVO_4 sample, reaching $\sim 1.5 \text{ mA cm}^{-2}$ at $2.1 \text{ V}_{\text{RHE}}$, the 6% Mo: BiVO_4 sample showed the highest photocurrent density at $1.23 \text{ V}_{\text{RHE}}$ of $\sim 0.82 \text{ mA cm}^{-2}$.

Under back irradiation, all samples showed similar PEC behaviour (Fig. 6b). There was a notable faster rise in photocurrent density in the undoped BiVO_4 sample than was seen under front irradiation, which was indicative of a comparatively lower barrier to hole carrier diffusion than electron carrier extraction in the material. Under back irradiation, the 6% Mo: BiVO_4 sample showed the highest plateau photocurrent density, reaching $\sim 0.75 \text{ mA cm}^{-2}$ at $2.1 \text{ V}_{\text{RHE}}$, and highest photocurrent density at $1.23 \text{ V}_{\text{RHE}}$ of $\sim 0.34 \text{ mA cm}^{-2}$.

Comparing front and back irradiation, the Mo-doped BiVO_4 samples showed notably higher photocurrent densities under front irradiation than back irradiation. A plot of the photocurrent density at $1.23 \text{ V}_{\text{RHE}}$ for front and back irradiation for all samples is shown in Fig. 6c. Similar trends were observed for front and back irradiation, with the photocurrent density consistently rising with increases in Mo precursor doping to 6% Mo:V, before falling at 12% Mo:V. With the exception of the undoped BiVO_4 sample, the photocurrent density at $1.23 \text{ V}_{\text{RHE}}$ was consistently higher for front irradiation than back irradiation. The 6% Mo: BiVO_4 sample showed the highest

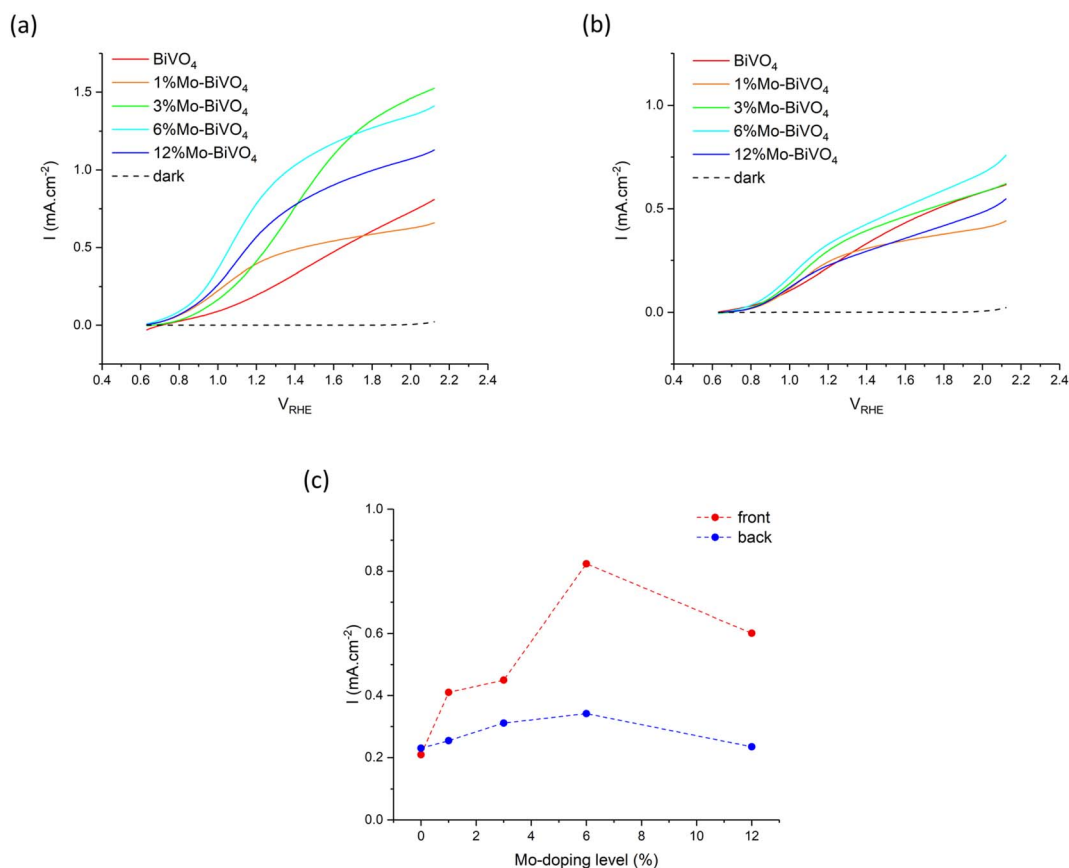


Fig. 6 Current voltage (JV) curves for BiVO_4 and all Mo-doped BiVO_4 samples measured with (a) front irradiation and (b) back irradiation. (c) The photocurrent densities observed at $1.23 \text{ V}_{\text{RHE}}$ for both front and back irradiation as a function of Mo precursor doping level (%) of BiVO_4 and all Mo-doped BiVO_4 samples. Samples were measured in 0.1 M phosphate buffer (pH = 7) using 400 nm light ($\sim 8.5 \text{ mW cm}^{-2}$).



performance in both cases, reaching photocurrent densities of ~ 0.82 and ~ 0.34 mA cm $^{-2}$ for front and back irradiation, respectively. Comparing the photocurrent densities seen at 1.23 V_{RHE}, the performance under front irradiation was up to 2.6 times better than under back irradiation (Table 1). These differences could not be rationalised from the subtle differences in light harvesting of the 400 nm light source, with $\sim 97\%$ absorbed under front irradiation and $\sim 78\%$ absorbed under back irradiation (Fig. 5). Rather, the increases in front irradiation performance, found with Mo-doping, were attributed to enhancements in electron carrier transport and extraction. As back irradiation performance was broadly the same across the series of samples, we conclude that this effect was predominantly limited to improving electron transport (*i.e.* hole carrier transport was largely unaffected by Mo-doping).

The incident photon-to-current efficiency (IPCE) was measured at 1.23 V_{RHE} in 0.1 M phosphate buffer under front and back irradiation for all samples (Fig. 7). Under front irradiation, the undoped BiVO₄ sample showed IPCEs of up to $\sim 10\%$ in the ultra-bandgap region. The 6% Mo : BiVO₄ sample showed the highest IPCEs, reaching $\sim 50\%$ at 325 nm. Similar to *JV* curve measurements, the IPCE performance consistently increased with Mo-doping from 0 to 6% Mo : V, and then decreased at 12% Mo : V. Under back irradiation, IPCEs were significantly lower than those measured under front irradiation. This, in part, was due to the parasitic absorption of light by the FTO substrate, which absorbed most strongly in the UV region. However, IPCEs in the visible region where the parasitic absorption of light was limited (to $\sim 20\%$) were substantially lower than those measured under front irradiation. Under back irradiation, the 6% Mo : BiVO₄ sample showed the highest IPCEs, reaching $\sim 14\%$ at 400 nm. This was less than half the value observed under front irradiation ($\sim 30\%$ at 400 nm). Importantly, under back irradiation, Mo-doping granted only marginal increases in performance compared with undoped BiVO₄, which is in line with the accepted hypothesis that Mo-doping primarily improves the conductivity of photo-generated electron carriers.

Under front irradiation, the highest IPCEs were seen in the UV region, where light is absorbed most prominently near the

surface of the material ($\sim 75\%$ of 325 nm light absorbed within 30 nm of entering the material). Under front irradiation, the 6% Mo : BiVO₄ sample showed IPCEs in the ultra-bandgap region between 4 and 5 times higher than undoped BiVO₄, whereas under back irradiation, the 6% Mo : BiVO₄ sample showed IPCEs in the ultra-bandgap region between 1 and 1.5 times higher than undoped BiVO₄. As the optical properties of both materials were similar, overall, these trends indicated that electron carrier transport and extraction was enhanced by a factor of between 4 and 5 with Mo doping, and that hole carrier transport was largely unaffected.

The theoretical solar photocurrent (TSP) was determined by multiplying the IPCE measured at 1.23 V_{RHE} with the solar spectrum (AM1.5) and integrating the photon-to-current flux (eqn (4); Fig. 8). Undoped BiVO₄ showed TSPs of ~ 0.48 and ~ 0.55 mA cm $^{-2}$ for front and back irradiation, respectively. In all cases, Mo-doping increased the TSP, with 6% Mo : BiVO₄ showing the highest TSPs of ~ 1.79 and ~ 0.78 mA cm $^{-2}$ for front and back irradiation, respectively. Similar to *JV* and IPCE curves, TSPs were significantly higher (up to a factor of ~ 2.3) for front irradiation than back irradiation. This, as mentioned above, is attributed to the improvement in electron carrier transport and extraction with Mo-doping.

The photoelectrochemical water oxidation performance of the samples produced herein is now compared with the literature; summarised in Table 2. Herein, we compare BiVO₄ produced by CVD routes (akin to this work) and Mo-doped BiVO₄ produced by any synthetic route. It should be noted, for fair comparisons to be made, more complex BiVO₄-based structures are not included in this table (*e.g.* surface modified BiVO₄ with a co-catalyst to improve surface reaction kinetics, or the formation of a BiVO₄-based heterojunction to improve charge carrier separation, *etc.*).

Sagu *et al.* used an AA-CVD method to produce m-BiVO₄ photoanodes.^{14,15} Porous irregular particles (~ 500 nm wide) of BiVO₄ were formed when ethylene glycol was used to dissolve their bismuth precursor, which when examined in 0.5 M Na₂SO₄(aq.), showed an onset potential of ~ 1.0 V_{RHE} and a photocurrent density of ~ 0.15 mA cm $^{-2}$ at 1.23 V_{RHE} and 1 sun irradiance.¹⁵ Smaller porous irregular particles (~ 75 nm wide)

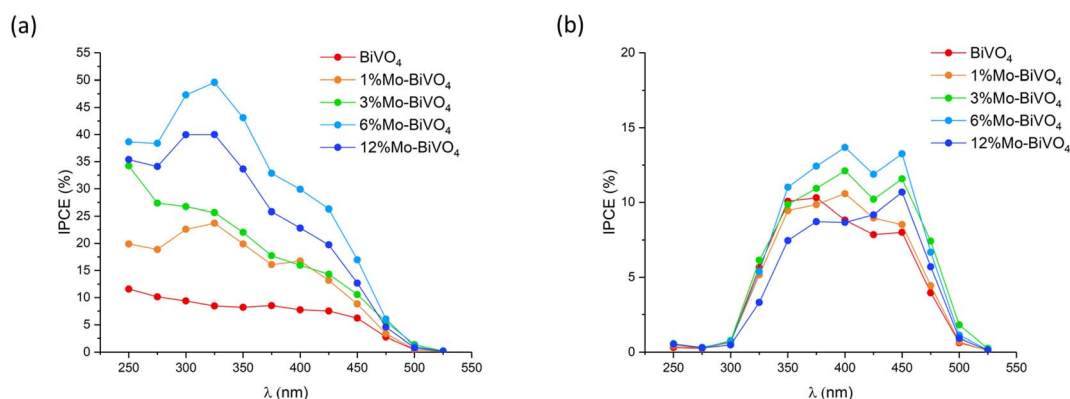
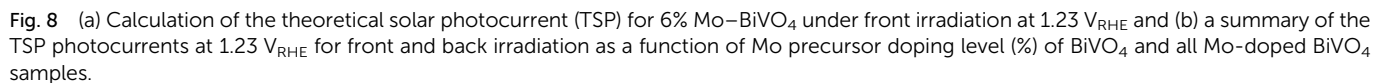


Fig. 7 Incident photon to current efficiency (IPCE) curves for BiVO₄ and all Mo-doped BiVO₄ samples measured with (a) front irradiation and (b) back irradiation. Samples were measured in 0.1 M phosphate buffer (pH = 7) at 1.23 V_{RHE}.





to 1 μm wide) of BiVO_4 were formed, which when examined in 0.5 M $\text{KOH}_{(\text{aq.})}$, showed an onset potential of $\sim 0.23 \text{ V}_{\text{RHE}}$ and a photocurrent density of $\sim 2.10 \text{ mA cm}^{-2}$ at $1.23 \text{ V}_{\text{RHE}}$ and 1 sun irradiance (although it should be noted that the photocurrent density decreased rapidly in this high pH electrolyte). Ager *et al.* used a VT-CVD method to produce m- BiVO_4 photoanodes.¹⁶

Photoanode	Synthesis method	^a Mo : V doping level (%)	Material structure	^b <i>J</i> _{on} (V _{RHE})	^c <i>J</i> (mA cm ⁻²)	Reference
BiVO ₄	AA-CVD	na	Porous irregular particles (~500 nm wide)	~1.0	~0.15	Sagu <i>et al.</i> ¹⁵
		na	Porous irregular particles (~75 nm wide)	~0.6	~0.40	Sagu <i>et al.</i> ¹⁴
	DLI-CVD	na	Densely packed rounded particles (~0.2 to 1 μm wide)	~0.23	~2.10	Gupta <i>et al.</i> ¹⁷
		na	Densely packed rounded particles (~200 nm)	~0.3 ^d	~0.95 ^d	Ager <i>et al.</i> ¹⁶
	AA-CVD	na	Densely packed cuboidal particles (~200 nm wide)	~0.6	~0.55	herein
Mo-BiVO ₄	Electro-deposition	1.25 (1.8)	Open nanoporous structure	~0.5	~0.85	Choi <i>et al.</i> ⁸⁸
		ns (ns)	Wormlike nanostructure (~100 nm wide)	~0.4	~1.4	Ao <i>et al.</i> ³⁵
		3 (3)	Wormlike nanostructure (~100 nm wide)	~0.55	~1.9	Xiao <i>et al.</i> ³⁴
	Electro-spinning	ns (ns)	1D nanofibres	~0.7	~0.15	Hwang <i>et al.</i> ³¹
		2.0 (3.0)	Irregular mesoporous network	~0.5	~0.77	Wong <i>et al.</i> ³⁰
		0.15 (ns)	Nanotextured pillars (~10 μm tall)	~0.7	~0.7	Yoon <i>et al.</i> ³²
	ESD	2.0 (4.5)	Mesoporous structure	~0.4	~0.4	Herring <i>et al.</i> ⁴¹
	MOD	0.5 (ns)	Dense, irregularly particles (~50 nm wide)	ns	~1.1 ^{d,f}	Kudo <i>et al.</i> ³⁸
		10 (6)	Dense, wormlike particles (~50 nm wide)	~0.5	~1.9	Fischer <i>et al.</i> ³⁷
		ns (3.0)	Nanoporous (~100 nm wide particles)	~0.4	~2.1	Cui <i>et al.</i> ³⁹
	PVD	3.0 (6.5)	Compact nanoporous structure (~150 nm wide particles)	~0.4	~2.2 ^e	Zou <i>et al.</i> ⁴⁰
		1.0 (1.0)	Nanostructured wormlike arrays (~100 nm in diameter)	~0.3 ^d	~2.1 ^d	Zhang <i>et al.</i> ⁴³
		ns (3.0)	Porous irregular particles (~200–400 nm wide)	~0.3 ^d	~3.5 ^d	Ager <i>et al.</i> ⁴²
		6.0 (9.6)	Densely packed irregular particles (~100 to 150 nm wide)	~0.6	~1.79	herein
	AA-CVD					

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Densely packed rounded particles (~ 200 nm) of BiVO_4 were formed, which when examined in a hole scavenger solution of $0.5 \text{ M Na}_2\text{SO}_{3(\text{aq})}$, showed an onset potential of $\sim 0.3 \text{ V}_{\text{RHE}}$ and a photocurrent density of $\sim 0.95 \text{ mA cm}^{-2}$ at $1.23 \text{ V}_{\text{RHE}}$ and 1 sun irradiance. Herein, an AA-CVD method was used to produce m- BiVO_4 photoanodes. Films with densely packed cuboidal particles (~ 200 nm wide) of BiVO_4 were formed, which when examined in 0.1 M phosphate buffer, showed an onset potential of $\sim 0.6 \text{ V}_{\text{RHE}}$ and a TSP of $\sim 0.55 \text{ mA cm}^{-2}$ when irradiated from the back. The PEC performance of the BiVO_4 photoanodes grown herein, using AA-CVD, compared favourably with previous work where alternative CVD routes were also used; displaying median onset potentials and photocurrent densities (Table 2).

Mo-doped BiVO_4 has been synthesised using a range of methods.^{30–32,34–43} Choi *et al.* used an electrodeposition method to produce Mo-doped BiVO_4 with open nanoporous structures.⁸⁸ They studied range of precursor doping levels from 0.5 to 3%, and found that the most photoelectrochemically active sample contained 1.8% Mo : V. They studied the activity of this sample in $1 \text{ M NaH}_2\text{PO}_4$ buffer, which showed an onset potential of $\sim 0.5 \text{ V}_{\text{RHE}}$ and a photocurrent density of $\sim 0.85 \text{ mA cm}^{-2}$ at $1.23 \text{ V}_{\text{RHE}}$ and 1 sun irradiance. Ao *et al.* also used an electrodeposition method to produce Mo-doped BiVO_4 .³⁵ The films possessed worm-like nanostructure (~ 100 nm wide). Their samples were tested in $0.1 \text{ M Na}_2\text{SO}_{4(\text{aq})}$, with the most active sample showing an onset potential of $\sim 0.4 \text{ V}_{\text{RHE}}$ and a photocurrent density of $\sim 1.4 \text{ mA cm}^{-2}$ at $1.23 \text{ V}_{\text{RHE}}$ and 1 sun irradiance. To our knowledge, the Mo-doping level was not stated for these samples (despite XPS analysis being carried out). And Xiao *et al.* produced Mo-doped BiVO_4 by electrodeposition.³⁴ Similar to Ao *et al.*,³⁵ worm-like nanostructures were formed. A range of doping concentrations were examined (from ~ 1 to $\sim 10\%$), with the most active sample containing $\sim 3\%$ Mo : V. In 0.5 M phosphate buffer, the best performing sample showed an onset potential of $\sim 0.55 \text{ V}_{\text{RHE}}$ and a photocurrent density of $\sim 1.9 \text{ mA cm}^{-2}$ at $1.23 \text{ V}_{\text{RHE}}$ and 1 sun irradiance.

Hwang *et al.* grew Mo-doped BiVO_4 using an electrospinning method, producing 1D nanofibers.³¹ The best performing sample, when examined in 0.1 M phosphate buffer, showed an onset potential of $\sim 0.7 \text{ V}_{\text{RHE}}$ and a photocurrent density of $\sim 0.15 \text{ mA cm}^{-2}$ at $1.23 \text{ V}_{\text{RHE}}$ and 1 sun irradiance. The Mo-doping level added or achieved was not stated. Wong *et al.* also used electrospinning route, producing Mo-doped BiVO_4 films formed from irregular mesoporous networks.³⁰ Their best performing sample contained 3% Mo : V, and when examined in $0.5 \text{ M Na}_2\text{SO}_{4(\text{aq})}$, showed an onset potential of $\sim 0.5 \text{ V}_{\text{RHE}}$ and a photocurrent density of $\sim 0.77 \text{ mA cm}^{-2}$ at $1.23 \text{ V}_{\text{RHE}}$ and 1 sun irradiance.

Yoon *et al.* grew Mo-doped BiVO_4 using an ESD method, forming nanotextured pillars that were $\sim 10 \mu\text{m}$ tall.³² They studied a range of Mo-doping levels from 0.05 to 0.20%, and found that the highest performance was seen in films with a 0.15% precursor doping level. The photoelectrochemical activity was investigated in $1 \text{ M Na}_2\text{SO}_4$, showing an onset potential of $\sim 0.7 \text{ V}_{\text{RHE}}$ and a photocurrent density of $\sim 0.7 \text{ mA cm}^{-2}$ at $1.23 \text{ V}_{\text{RHE}}$ and 1 sun irradiance.

Using a surfactant-assisted MOD route, Herring *et al.* produced mesoporous Mo-doped BiVO_4 films.⁴¹ Their optimal sample was produced from a 2.0% Mo : V precursor ratio, producing a film with 4.5% Mo : V doping. This was examined in $0.5 \text{ M Na}_2\text{SO}_{4(\text{aq})}$ phosphate buffer, and showed an onset potential of $\sim 0.4 \text{ V}_{\text{RHE}}$ and a photocurrent density of $\sim 0.4 \text{ mA cm}^{-2}$ at $1.23 \text{ V}_{\text{RHE}}$ and 1 sun irradiance. Kudo *et al.* produced densely packed, irregularly shaped particles (~ 50 nm wide) using MOD.³⁸ A range of Mo precursor doping levels were studied (from 0.25 to 1.5%). The optimum Mo precursor doping level was found to be 0.5%; however, the doping level achieved in the sample was not stated. The photoanode was studied in $0.1 \text{ M K}_2\text{SO}_{4(\text{aq})}$ in the presence of a hole scavenger $0.01 \text{ M K}_2\text{SO}_{3(\text{aq})}$, and achieved a photocurrent density of $\sim 1.1 \text{ mA cm}^{-2}$ at $\sim 1.13 \text{ V}_{\text{RHE}}$ at 1 sun irradiance. Fischer *et al.* also used MOD to synthesise Mo-doped BiVO_4 .³⁷ Their coatings were made of dense, wormlike particles (~ 50 nm wide). A wide range of Mo precursor doping levels were studied (0 to 20%). The sample containing 6% Mo : Bi doping showed the highest photoelectrochemical performance, where when examined in 0.1 M potassium phosphate buffer, showed an onset potential of $\sim 0.5 \text{ V}_{\text{RHE}}$ and a photocurrent density of $\sim 1.9 \text{ mA cm}^{-2}$ at $1.23 \text{ V}_{\text{RHE}}$ and 1 sun irradiance. Nanoporous (~ 100 nm wide particles) Mo-doped BiVO_4 was produced using MOD by Cui *et al.*³⁹ Their best performing sample contained a 3% Mo : V doping level, and when examined in $0.5 \text{ M KH}_2\text{PO}_4$ buffer, showed an onset potential of $\sim 0.4 \text{ V}_{\text{RHE}}$ and a photocurrent density of $\sim 2.1 \text{ mA cm}^{-2}$ at $1.23 \text{ V}_{\text{RHE}}$ and 1 sun irradiance. And Zou *et al.* used MOD to synthesise compact nanoporous films of Mo-doped BiVO_4 .⁴⁰ Their most active sample was contained 6.5% Mo : V, which when examined in $0.5 \text{ M Na}_2\text{SO}_{4(\text{aq})}$, showed an onset potential of $\sim 0.4 \text{ V}_{\text{RHE}}$ and a photocurrent density of $\sim 2.2 \text{ mA cm}^{-2}$ at $1.23 \text{ V}_{\text{RHE}}$ (Xe lamp; irradiance power not stated).

Zhang *et al.* grew Mo-doped BiVO_4 using a pulsed laser PVD route.⁴³ Nanostructured wormlike structures were formed, which were ~ 100 nm in diameter. A range of Mo-doping levels were studied (from 0.5 to 5.0%), where it was found that 1.0% Mo : V doping resulted in the highest performing photoanodes. When examined in a 0.1 M phosphate buffer solution with a $0.1 \text{ M Na}_2\text{SO}_{3(\text{aq})}$ hole scavenger, the optimal sample showed an onset potential of $\sim 0.3 \text{ V}_{\text{RHE}}$ and a photocurrent density of $\sim 2.1 \text{ mA cm}^{-2}$ at $1.23 \text{ V}_{\text{RHE}}$ and 1 sun irradiance. Ager *et al.* grew Mo-doped BiVO_4 using a reactive co-sputtering PVD method, forming porous irregular particles (~ 200 – 400 nm wide).⁴² A range of Mo-doping levels were studied (from 1.0 to 5.5%). It was found that 3% Mo : V doping resulted in the highest performing films. The photoelectrochemical performance was examined in 1 M phosphate buffer with $0.1 \text{ M Na}_2\text{SO}_{3(\text{aq})}$ hole scavenger, showing an onset potential of $\sim 0.3 \text{ V}_{\text{RHE}}$ and a photocurrent density of $\sim 3.5 \text{ mA cm}^{-2}$ at $1.23 \text{ V}_{\text{RHE}}$ and 1 sun irradiance.

Herein, an AA-CVD method was used to produce Mo-doped t- BiVO_4 photoanodes, forming densely packed irregular particles (~ 100 to 150 nm wide). A range of Mo-doping levels were investigated (from ~ 2.0 to $\sim 12.7\%$ doping level achieved), where the highest performance was observed (for both front



and back irradiation) was a 9.6% Mo-doped sample. This sample, when examined in 0.1 M phosphate buffer, showed an onset potential of ~ 0.6 V_{RHE} and a TSP of ~ 1.79 mA cm⁻² when irradiated from the front. Despite there being a wide range of Mo-doping levels studied to date, there is no consensus on what the optimum Mo-doping level; ranging from ~ 1.0 to 9.6% Mo : V%. This we attribute to the range of methods used to produce Mo-doped BiVO₄, resulting in a wide range of topographies, average crystal sizes and defect densities. However, what can be said is that the photoelectrochemical performance of the best performing Mo-doped BiVO₄ photoanode produced herein using AA-CVD showed photocurrent densities (TSP up to 1.79 mA cm⁻²) at the higher end of what has previously been achieved for this material (up to 2.1 mA cm⁻² at 1.23 V_{RHE} and 1 sun irradiance⁴²) (Table 2).

3.4. Computational studies

Hybrid exchange DFT calculations studies were carried out on the BiVO₄ system to determine the effect of Mo doping substituting for Bi or V sites, at 6.25 or 12.5 at%, with respect to the metal being replaced, in both the m-BiVO₄ and t-BiVO₄ host structures. Herein we describe the effect of Mo doping on the thermodynamically most stable structure computed and report computed PDOS and the spin density.

3.4.1. Structure. The structures of undoped t-BiVO₄ and m-BiVO₄ are shown in Fig. S9,[†] and their lattice parameters are shown in Tables 3 and 4, respectively. For t-BiVO₄, the calculated unit cell parameters in the *a*, *b* and *c* directions were marginally higher than those deduced from room temperature XRD, and resulted in a comparatively expanded unit cell volume ($\sim 1.0\%$ expansion *vs.* experimental observations). Conversely, for m-BiVO₄, the calculated unit cell parameters in the *a* and *b* directions were marginally lower than XRD measurements, and resulted in a comparatively contracted unit cell volume ($\sim 1.4\%$ contraction *vs.* experimental observations). Overall, these differences are small and typical of fully converged hybrid exchange DFT calculations for strongly correlated systems.

Experimental studies conducted herein showed that our 6% Mo-BiVO₄ sample produced the most active photoanode for water splitting under both front and back irradiation (Fig. 8b), which XPS, XRD and Raman spectroscopy analysis showed contained a Mo doping level of ~ 9.6 at% in V sites in a t-BiVO₄

structure. The calculated analogous t-BiVO₄ structure, at a similar level of Mo doping (6.25 at% in V sites) is shown in Fig. 9. A comparison of the unit cell lattice parameters shows that Mo doping in V sites results in an expansion in the unit cell volume of $\sim 0.79\%$ compared to the undoped structure, with the biggest change in lattice parameter seen in the *a* direction ($\sim 0.48\%$ increase). A similar level of unit cell expansion of $\sim 0.46\%$ was seen experimentally in the 6% Mo-BiVO₄ sample (Table 1). Our calculations showed that a higher level of Mo doping of 12.5 at% in V sites resulted in a further increase in the unit cell expansion of $\sim 1.72\%$ compared to the undoped structure.

In both t-BiVO₄ and m-BiVO₄, V⁵⁺ ions are coordinated by four O atoms in tetrahedral sites and Bi⁵⁺ ions are coordinated by eight oxygen atoms in cubic hole sites. Comparing the Shannon crystal radii for Mo replacing such sites, one would expect an expansion in the unit cell with Mo replacing V sites and a contraction with Mo replacing Bi sites.⁸⁹ In the undoped t-BiVO₄ structure, the average calculated V–O bond distance in the VO₄ tetrahedral units is 1.734 Å. Where the Mo dopant replaced V, the resulting MoO₄ tetrahedral unit formed had an average Mo–O bond distance of 1.839 Å. This indicated that doped Mo ions have an effective radius of ~ 0.11 Å larger than vanadium; this corresponds well with the Shannon ionic radii, where V and Mo ions in the 5+ state in a 4-coordinate environment show crystal radii of 0.495 Å and 0.60 Å, respectively.⁸⁹

As detailed above, Mo dopants at V sites retain a single electron in a 4d derived orbital, which acts as a n-dopant and is likely to contribute to increased conductivity. The computed spin density at a Mo doping of 6.25 at% at a V site in t-BiVO₄ is shown in Fig. 11b. It is clear that at this level of doping, the electron remains mostly localised to the local 4d orbital of Mo, with only some donation seen with neighbouring O ions in the MoO₄ unit, and a small donation seen to nearby V ions.

The calculated structures for m-BiVO₄ with 6.25 at% Mo doping of a V site is shown in Fig. S10,[†] t-BiVO₄ and m-BiVO₄ with 6.25 at% Mo doping of a Bi site are shown in Fig. S11 and S12,[†] respectively, t-BiVO₄ and m-BiVO₄ with 12.5 at% Mo doping of a V site are shown in Fig. 10 and S13,[†] respectively, and t-BiVO₄ and m-BiVO₄ with 12.5 at% Mo doping of a Bi site are shown in Fig. S14 and S15,[†] respectively. The lattice

Table 3 Table listing and comparing the calculated lattice parameters (*a*, *b*, *c*, α , β , γ), unit cell volumes (Å³) and change in unit cell volume *vs.* the undoped structure for the undoped and Mo-doped t-BiVO₄ structures studied herein

Mo-doped t-BiVO ₄					
Dopant site	n/a	V		Bi	
Doping level (at%)	0	6.25	12.5	6.25	12.5
<i>a</i> (Å)	5.1195	5.1442	5.1522	5.1091	5.0919
<i>b</i> (Å)	5.1195	5.1307	5.1522	5.1093	5.0916
<i>c</i> (Å)	11.6278	11.6387	11.6785	11.6409	11.6409
α (°)	90	90	90	89.5445	90.1624
β (°)	90	90	90	90.0542	90.6944
γ (°)	90	90.7870	90	89.6033	90.2061
Vol. (Å ³)	304.756	307.154	310.011	303.858	301.771
Vol. change <i>vs.</i> undoped (%)	n/a	0.79	1.72	−0.29	−0.98



Mo-doped m-BiVO ₄					
Dopant site	n/a	V		Bi	
Doping level (at%)	0	6.25	12.5	6.25	12.5
a (Å)	5.1217	5.1299	5.1293	5.1090	5.0929
b (Å)	5.1249	5.1447	5.1749	5.1093	5.0929
c (Å)	11.6549	11.6360	11.6208	11.6407	11.6419
α (°)	89.9985	90.0004	90.0032	90.4560	90.7593
β (°)	89.9989	89.9930	90.0022	90.0549	90.1496
γ (°)	90.6845	90.7784	91.1004	90.3914	90.2804
Vol. (Å ³)	305.899	307.070	308.402	303.848	301.928
Vol. change vs. undoped (%)	n/a	0.38	0.82	−0.67	−1.30

coordinating O ions), the average bond length decreased by ~ 0.35 Å, which are both in agreement with the expected outcomes from Shannon crystal radii.⁸⁹

As expected from the localised nature of the doped electron and the effect of ionic radius on the local tetrahedral environment the overall effect on the lattice is homogeneous in the level of doping. Relatively consistent changes in the unit cell lattice parameters were seen with Mo doping in V and Bi sites for the t-BiVO₄ and m-BiVO₄ host structures, with expansions/contractions in volume seen with Mo doping of V/Bi sites (Fig. S16a†). This was also consistent with what was seen in our experiments, where Mo doping of V sites in a t-BiVO₄ structure resulted in an expansion of the unit cell volume (Fig. S16b†), and therefore, validated our calculations. Regarding average metal oxygen bond lengths in both m-BiVO₄ and t-BiVO₄ structures, for the case of Mo dopants replacing V sites (*i.e.* tetrahedral hole sites with 4-coordinating O ions), the average bond length increased by ~ 0.1 Å, and for the case of Mo dopants replacing Bi sites (*i.e.* cubic hole sites with 8-

The total energy of each calculated structure was compared (values are per unit of the largest doped supercell – 16 formula units). In line with our experiments, it was energetically more favourable, by ~ 2.37 meV per cell, for undoped m-BiVO₄ to form compared with undoped t-BiVO₄. Again, in line with our experiments, this changed with Mo doping at 6.25 at% in V sites, with t-BiVO₄ becoming more favourable by ~ 2.33 meV per cell. At 12.5 at% Mo doping in V sites, the difference was negligible, with m-BiVO₄ being more favourable by only ~ 0.13 meV. Regarding Mo doping Bi sites, the difference was negligible at 6.25 at% doping, with t-BiVO₄ being more favourable by only ~ 0.19 meV, and more significant at 12.5 at% doping, with m-BiVO₄ being more favourable by ~ 3.05 meV. These are relatively small energetic differences and thermal fluctuations at

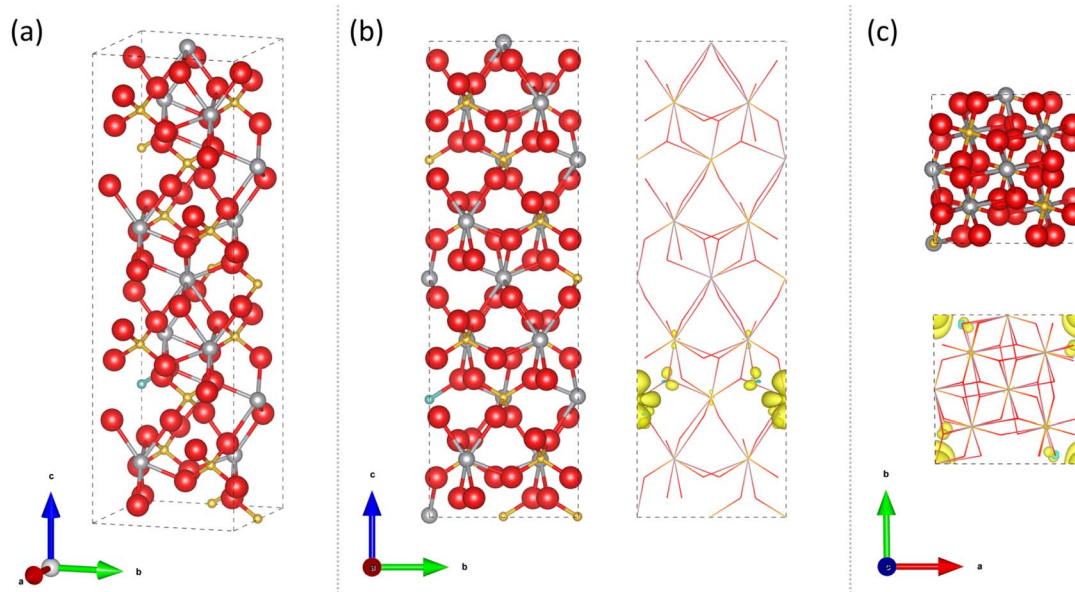


Fig. 9 Calculated structure for 6.25 at% Mo doping of a V site in t-BiVO₄ for a $2 \times 1 \times 1$ supercell showing atomic positions and spin density [Bi = silver, V = gold, O = red, Mo = light blue; ionic radii proportions scaled down for visibility]. (a) Angled view, (b) *a*-axis view and (c) *c*-axis view.

Fig. 10 Calculated structure for 12.5 at% Mo doping of a V site in tetragonal scheelite BiVO_4 for a single unit cell showing atomic positions and spin density [Bi = silver, V = gold, O = red, Mo = light blue; ionic radii proportions scaled down for visibility]. (a) Angled view, (b) a -axis view and (c) c -axis view.

room temperature would be expected to produce a somewhat disordered distribution of dopants amongst the available sites.

Assessing our spin density calculations, we will first discuss the effect of Mo doping in V sites. At 6.25 at% doping, the effect is similar in both t-BiVO₄ (Fig. 9) and m-BiVO₄ (Fig. S10[†]), with the 4d¹ electron of Mo localising primarily on the Mo dopant site, within a single d-orbital with a distinct distribution of charge. At 12.5 at% doping in m-BiVO₄, the situation is similar, with the 4d¹ electron remaining quite localised to Mo (Fig. S13[†]). However, at 12.5 at% doping in t-BiVO₄, a significant change is seen, with the 4d¹ electron being completely transferred from Mo to V 3d orbitals that lie in the [001] Miller plane (Fig. 10). The exact concentration at which the delocalisation occurs will be sensitive to the treatment of electronic self-interaction and to the particular distribution of dopants in the structure. Nevertheless, it is not unreasonable to conclude that as the dopant concentration approaches 12.5 at% there is a transition from a strongly correlated insulating state to a delocalised semiconductor. This inference is further supported by our XRD data (Fig. 2), in which the peak at $\sim 31^\circ 2\theta$, which corresponds to diffraction in the [004] plane, increases in intensity with Mo doping, and is significantly more pronounced in the 6% Mo-BiVO₄ sample. This is likely to be a result of the increased electron density in the [001] plane with Mo doping, as X-ray diffraction correlates with electron density.

Regarding the effect of Mo doping in Bi sites, at both 6.25 and 12.5 at% doping in both t-BiVO₄ and m-BiVO₄, the 4d³ electrons of Mo remain localised to Mo dopant sites, filling several d-orbitals to achieve a near even distribution of charge around the ion, with some spill-over seen onto neighbouring O and nearby V sites. With increased levels of Mo doping, the spillover onto neighbouring O and nearby V sites increases, however, we do not observe a transition to a delocalised state and charge remains primarily localised to Mo dopant sites.

3.4.2. Density of states. Full scale PDOS calculations are shown in Fig. S17 and S18† for all Mo doped t-BiVO₄ and m-BiVO₄ structures, respectively. Included in these figures are atom projections for all the doped structures and the projections of the specific orbitals that form the valence and conduction band in t-BiVO₄ and m-BiVO₄.^{90,91} As seen in previous work,⁹² in both t-BiVO₄ and m-BiVO₄, there are notable contributions from the Bi 6s and O 2p atomic orbitals that form the VBM and V 3d atomic orbitals that form the CBM. Of particular importance to the function of photoelectrodes is the bandgap energy and material conductivity. The PDOS in the bandgap region for all Mo doped t-BiVO₄ and m-BiVO₄ structures is shown in Fig. 11, with the computed energy gaps summarised in Table 5. In line with previous studies, the valence band maximum (VBM) region of all structures was primarily composed of O 2p orbitals, partially hybridised with Bi 6s orbitals, and the conduction band minimum (CBM) region of all structures was primarily composed of V 3d orbitals. This is consistent with a simple ionic picture of Bi³⁺ d¹⁰s⁻² and V⁵⁺ d⁰. The calculated band structures of t-BiVO₄ and m-BiVO₄ show that the lowest bandgap energy transitions are both indirect (Fig. S19†). The calculated bandgap energies of the undoped t-BiVO₄ and m-BiVO₄ structures were ~2.66 and ~2.69 eV, respectively (Fig. 11a). The calculated bandgap is determined to be indirect in both cases as the top of the valence band and bottom of the conduction band were located at different points in reciprocal space, as demonstrated by the band structures (Fig. S19†). This agrees with recent articles which consistently show the bandgap in BiVO₄ to be indirect.^{93,94} Also, our experimentally determined value for the indirect bandgap transition in m-BiVO₄ (Table 1) was close in value (~2.55 eV) to that we calculated (~2.69 eV), and was in line with previous experimental observations for BiVO₄.⁹⁵ The computed band gaps are sensitive to the electronic self-interaction which we emphasise

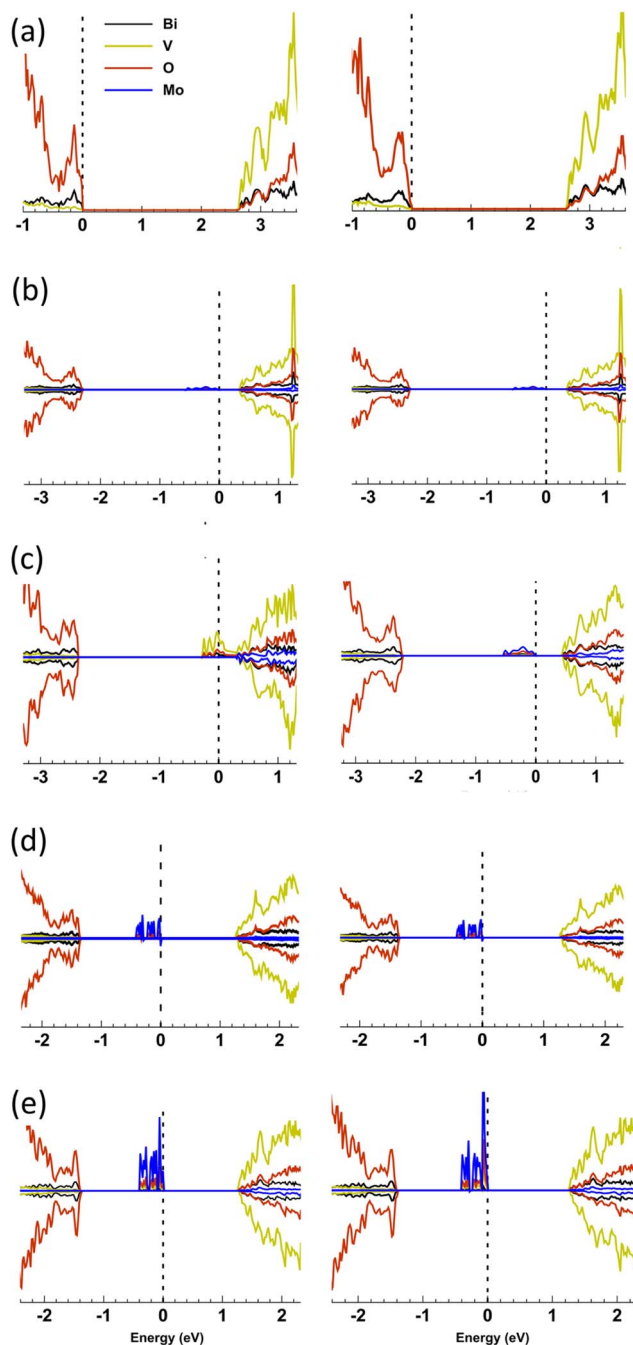


Fig. 11 Comparison of the PDOS for (left) t-BiVO₄ and (right) m-BiVO₄ host structures for (a) undoped, (b) 6.25 at% Mo in a V site, (c) 12.5 at% Mo in a V site, (d) 6.25 at% Mo in a Bi site, and (e) 12.5 at% Mo in a Bi site. For each host structure, the VBM, formed primarily by O orbitals, are plot at the same position to one another. The PDOS are drawn for energies ~ 1 eV below the VBM up to ~ 1 eV above the CBM, which is formed primarily by V orbitals. The dashed line represents the highest occupied state in each structure.

is here determined by the 10% admixture of Fock exchange in the PBE0 functional.⁹⁶

When the t-BiVO₄ and m-BiVO₄ structures were doped with Mo at either V or Bi sites (with the exception of 12.5 at% doping in V sites in t-BiVO₄) there is no substantial change in the

bandgap energy. The electronic structure of the doped state, however, does depend critically on the doping concentration. At 6.25 at% Mo doping on the V⁵⁺-site an upper band gap state of predominantly Mo character is formed ~ 0.6 eV below the CBM with a width of ~ 0.4 eV is formed (Fig. 11b). The state is of pure spin character and makes carriers available for thermally activated or hopping conductivity. The state may be characterised as a semi-localised Mo⁵⁺ 4d¹ orbital with the localisation attributable to strong on-site correlation. At 12.5 at% Mo doping in t-BiVO₄ this state is ionised to Mo⁶⁺ d⁰ and a band of V-derived states at the CBM are occupied producing a half metallic phase, as the kinetic energy of delocalisation in the V-d-band becomes the dominant energy scale (Fig. 11c). Analysis of the resultant spin density reveals that the charge is distributed over several neighbouring V sites, and is therefore likely to produce band-like electron conductivity. This delocalisation does not occur in m-BiVO₄ at 12.5 at% Mo doping, but is highly likely to do so at higher dopant concentrations. Doping at the Bi³⁺ site produces a localised Mo³⁺ 4d³ pure spin band centred some 1.4 eV below the CBM for both structures and concentrations considered.

Some consistent themes were seen with Mo dopants replacing V and Bi sites. Mo doping in V sites resulted in a more significant shift in the highest occupied state (HOS) energy from the VBM to ~ 2.2 – 2.3 eV above the VBM, whereas Mo doping in Bi sites resulted in a less significant shift in HOS energy from the VBM to ~ 1.1 – 1.3 eV above the VBM. This indicated that Mo doping in V sites will result in a more conductive material at room temperature than Mo doping in Bi sites. Also, Mo doping in both V and Bi sites resulted in the formation of mid-gap states, which were primarily composed of Mo 4d orbitals. These mid-gap states were closer to the CBM where Mo replaced V (~ 0.3 – 0.4 eV) than where Mo replaced Bi (~ 1.2 eV). Where Mo replaced Bi sites, the higher level of associated electrons on Mo (*i.e.* 4d³) resulted in a larger contribution of Mo 4d orbitals to the mid-gap state as compared with cases where Mo replaced V sites, which possessed a lower level of associated electrons on Mo (*i.e.* 4d¹). An exception was seen where Mo dopants replaced V sites at a concentration of 12.5 at%, where the mid-gap Mo 4d states merged with the CBM, resulting in the formation of a degenerate semiconductor where the HOS level resided in the conduction band (CB). Interestingly, electronic charge previously associated with Mo 4d orbitals was transferred onto V 3d orbitals that formed the CBM.

Our experimental findings indicated that Mo dopants replaced V sites, and at a doping level of ~ 9.6 at% of Mo in V sites, we saw our most active photoanode, where the performance under front irradiation was the most markedly improved. This was evidence that the transport of photo-generated electron carriers in BiVO₄ was improved upon Mo doping, reaching an optimum value at ~ 9.6 at%. This was in line with our computational studies, which indicated conductivity would significantly increase in Mo doped systems, due to a raising of the highest occupied state from the VBM to a filled mid-gap state (by ~ 2.27 eV where V was replaced by Mo at a doping level of 6.25 at%). Importantly, our computational studies also showed that high levels of Mo doping results in the



Structure	Dopant site	Doping level (at%)	Energy gaps (eV)		
			VBM to HOS	HOS to CBM	VBM to CBM
t-BiVO ₄	n/a	0	0	2.6639	2.6639
	V	6.25	~2.27	0.3483	2.6717
		12.5	~2.28	No gap ^a	2.1451 ^b
		6.25	~1.27	1.244	2.6609
	Bi	12.5	~1.28	1.2523	2.6873
m-BiVO ₄	n/a	0	0	2.6943	2.6943
	V	6.25	~2.24	0.3672	2.6770
		12.5	~2.20	0.4275	2.6626
		6.25	~1.17	1.2431	2.6610
	Bi	12.5	~1.18	1.2473	2.6879

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to study Mo doping of V sites in m-BiVO₄ (*U* correction for V, Mo and W = 2.7, 2.3 and 2.1 eV, respectively).¹⁰⁶ In their study they observed a mid-gap state ~1 eV above the VBM, where excess charge was primarily transferred from Mo to V sites. Li *et al.* applied a GGA + *U* functional to study Mo-doped BiVO₄ (*U* correction for V = 3.0 eV and Mo = 2.7 eV).¹⁰⁷ They observed bandgaps of 2.08 and 2.01 eV for the undoped and Mo-doped BiVO₄, respectively. With Mo-doping, they also observed an increase in n-type character and the formation of a shallow, filled mid-gap state beneath the CBM. And Ahmed *et al.* applied a GGA + *U* functional to study Mo-doping in m-BiVO₄ at 6.25 at% (*U* corrections for Bi, V, O and M of 4.8, 3.1, 2.0 and 2.3 eV, respectively).¹⁰⁸ Like several previous studies highlighted above, they found that Mo doping introduces a shallow filled spin-up impurity state near the CBM. They also found that the bandgap of the undoped material (2.51 eV) did not alter significantly upon Mo doping (2.52 eV).

Similar to our calculations herein, the hybrid HSE exchange-correlation functional was used by Laraib *et al.* to study the effect of doping in t-BiVO₄ and m-BiVO₄.¹⁰⁹ In their work, they simulated an n-doping of up to 0.25 electrons per formula unit by adding electrons and a homogeneous charge compensating background. They found that the resultant electron addition states localised on V sites in both structures, and that the t-BiVO₄ structure was less stable than the m-BiVO₄ structure. In contrast to the current work, they reported a computed electronic bandgap ~0.9 eV higher than that calculated herein. Ding *et al.* also applied the hybrid HSE exchange-correlation functional in their study of Mo-doping in m-BiVO₄.⁹⁶ Similar to our work, they investigated Mo dopants substituting either V or Bi sites at a concentration of 6.25 at%. They found that the formation energy of Mo-doped m-BiVO₄ was lower when Mo substituted V sites as opposed to Bi sites. For the case of Mo doping in tetrahedral V sites, the average Mo–O bond length was ~1.79 Å (~0.05 Å lower than our calculations) and for the case of Mo doping in cubic Bi sites the average Mo–O bond length was ~2.16 Å (~0.29 Å lower than our calculations). They used these bond lengths as a measure of the Mo valency with the implication of Mo⁶⁺ at V sites and Mo³⁺ at Bi sites. Ding *et al.*⁹⁶ also reported that optimisation with the GGA functional produces no mid-gap state when Mo replaces V sites, however, a mid-gap state is formed when Mo replaced Bi sites. Upon recalculating the electronic structure using the HSE functional, a mid-gap state is formed upon doping into V sites. They reported that the bandgap of m-BiVO₄ increased from ~2.08 eV to ~2.14 eV upon Mo doping V sites. Again these gaps are significantly lower than those reported here (~2.69 to ~2.68 eV, respectively) which can be attributed to the differing treatments of the Fock exchange contribution.

Using the hybrid PBE0 functional (with 10% Fock exchange mixing) our calculations provide a more consistent description of the electronic structure, which corresponds more closely to the observed optical bands gaps and transport properties seen experimentally. In addition, by considering both the m-BiVO₄ and t-BiVO₄ structures at 6.25 and 12.5 at% Mo doping, insights into the effect of doping induced changes in phase stability were also obtained, providing computational support for the

observed phase change from m-BiVO₄ seen with no doping to t-BiVO₄ upon doping with Mo.

4 Conclusions

Herein, a new AA-CVD route to Mo-doped BiVO₄ photoanodes is developed. By studying a range of Mo precursor doping levels (0 to 12% Mo: V), an optimum photoanode for driving photocatalytic water oxidation was found at 6% Mo precursor doping, which corresponded to an actual Mo : V doping level of $9.6 \pm 0.4\%$. XPS indicated that these Mo dopants inserted the host structure as Mo⁶⁺ states, replacing V⁵⁺ sites. The PEC water oxidation performance was favourable compared to leading Mo-doped BiVO₄ materials; with the 6% Mo : BiVO₄ sample showing a *J*_{on} of ~0.6 V_{RHE} and TSP of ~1.79 mA cm⁻² at 1.23 V_{RHE} and 1 sun irradiance under front irradiation. By comparing differences in PEC water oxidation performance under front and back irradiation, it was concluded that Mo-doping herein improved electron carrier transport and extraction in the host material by a factor of between 4 and 5, but did not significantly impact hole carrier behaviour. Importantly, Mo-doping was found to induce a phase change from monoclinic clinobisvanite (m-BiVO₄), in undoped BiVO₄, to tetragonal scheelite (t-BiVO₄). Using DFT, the effect of Mo-doping on the structural and electronic properties was studied using a global hybrid exchange-correlation functional PBE0-10. Both t-BiVO₄ and m-BiVO₄ structures were investigated, with Mo dopants replacing V or Bi sites at 6.25 and 12.5 at%, with respect to the metal site being replaced. Mo doping of V sites led to an expansion of the lattice, whereas Mo doping of Bi sites led to a contraction, and supported our conclusion from experimental work that Mo dopants substituted V sites. In agreement with our observations, Mo doping of V sites in t-BiVO₄ at 6.25 at% produced a lower energy than in m-BiVO₄ (~2.33 meV lower per dopant). At 12.5 at% the energy difference is negligible. Doping at both Bi and V sites resulted in the formation of localised mid-gap states primarily composed of Mo 4d orbitals, with the exception of 12.5 at% Mo doping of V sites in t-BiVO₄, where the states merge with the conduction band minimum, forming a degenerate semiconductor with electrons distributed over multiple V 3d ion sites. All cases of doping raised the highest occupied state and likely increased the conductivity of the system.

The findings herein not only support current understanding surrounding the effect of Mo-doping on the electron conductivity in BiVO₄, but provide further insight on the subtle structural changes that can occur and how this impacts the density of states. Moreover, the development of a new, scalable synthetic route to high performance Mo-doped BiVO₄ photoanodes may influence the future commercialisation of this technology.

Data availability

The data supporting this article have been included as part of the ESI.†



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