The role of ultra-thin \( \text{MnO}_x \) co-catalysts on the photoelectrochemical properties of \( \text{BiVO}_4 \) photoanodes†

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Metal oxide semiconductors are promising as photoanodes for solar water splitting, but they typically suffer from poor charge transfer properties due to the slow surface reaction kinetics for oxygen evolution. To overcome this, their surfaces are usually modified by depositing earth-abundant, efficient, and inexpensive water oxidation co-catalysts. While this effort has been successful in enhancing the photoelectrochemical performance, a true understanding of the nature of the improvement is still under discussion. This is due to the fact that the co-catalyst can have multiple functionalities, e.g., accelerating charge transfer, passivating surface states, or modifying band bending. Disentangling these factors is challenging, but necessary to obtain a full understanding of the enhancement mechanism and better design the semiconductor/co-catalyst interface. In this study, we investigate the role of atomic layer deposited (ALD) \( \text{MnO}_x \) co-catalysts and their thickness in the photoelectrochemical performance of \( \text{BiVO}_4 \) photoanodes. Modified \( \text{MnO}_x/\text{BiVO}_4 \) samples with an optimum thickness of \(~4\, \text{nm}\) show higher photocurrent (a factor of \(~3\)) as well as lower onset potential (by \(~100\, \text{mV}\)) compared to the bare \( \text{BiVO}_4 \). We combine spectroscopic and photoelectrochemical measurements to unravel the different roles of \( \text{MnO}_x \) and explain the photocurrent trend as a function of the thickness of \( \text{MnO}_x \). X-ray photoelectron spectroscopy (XPS) studies reveal that the surface band bending of \( \text{BiVO}_4 \) is modified after the addition of \( \text{MnO}_x \), therefore reducing surface recombination. At the same time, increasing the thickness of \( \text{MnO}_x \) beyond the optimal \(4\, \text{nm}\) provides shunting pathways, as shown by energy dispersive X-ray scanning transmission electron microscopy (EDX-STEM) and redox electrochemistry. This cancels out the band bending effect, which explains the observed photocurrent trend. Therewith, this study provides additional insights into the understanding of the charge transfer processes occurring at the semiconductor–catalyst interface.

Introduction

Photoelectrochemical (PEC) water splitting is an attractive method to harvest solar energy and store it in the form of chemical bonds (i.e., \( \text{H}_2 \) and \( \text{O}_2 \)).†–‡ Among the two half-reactions, oxygen evolution is typically the limiting one due to the more kinetically demanding nature of the reaction.‡ Therefore, significant efforts have been dedicated to the development of efficient photoanodes to drive this reaction. Metal oxides are widely used as photoanode materials due to their low costs, general stability and scalable preparation techniques. However, their performance is often limited by poor surface charge transfer properties due to low catalytic activity and/or high surface recombination.§–¶ To overcome this, various co-catalysts, e.g., \( \text{RuO}_2, \text{NiFeOOH}, \text{NiFeO}_4, \text{CoPi}, \text{MnO}_x \), etc. have been applied in order to modify the surface of metal oxide semiconductors,§–† which resulted in an improvement of the photocurrent.¹⁴,¹⁷–²⁵ Indeed, most metal oxide photoanodes showing high photocurrent (>5 mA cm\(^{-2}\)) are decorated with additional co-catalysts.¹⁶,²⁶,²⁷

One of the key parameters in the optimization of a semiconductor/co-catalyst interface is the thickness of the co-catalyst. Various reports have shown that there exists an optimal thickness at which the photocurrent of the semiconductor/co-catalyst photoanode is maximized.²⁸,²⁹ This behavior has been attributed to a few factors, e.g., trade-off between higher catalytic activity and parasitic absorption or resistivity in thicker co-catalysts, but no clear evidence was provided up to now. In addition, despite the improvement observed with co-catalyst deposition on metal oxide photoanodes, the true role of the co-catalysts is still under debate. Already, in 2012, Gamelin pointed out conflicting proposed
mechanisms for photocurrent enhancement in CoPi/hematite photoanode systems. More recently, differing mechanisms were also reported for CoPi/BiVO₄ photoanode systems. Photoinduced absorption spectroscopy (PIA) and intensity modulated photocurrent spectroscopy (IMPS) studies concluded that CoPi passivates surface states on BiVO₄, but dual working-electrode voltammetry measurements showed that CoPi also has a true catalytic role on BiVO₄. The considerations above, therefore, clearly illustrate that we still need additional well-designed studies in order to fully unravel the role of co-catalysts on semiconductor photoanodes for water oxidation. In this work, we investigate the role of ultra-thin MnO₂ co-catalysts on spray-deposited BiVO₄ photoanodes. Spray-deposited BiVO₄ is among the best performing non-nanostructured BiVO₄ photoelectrodes, and the scalability of the process has been demonstrated. Earth-abundant and inexpensive MnO₂ has been shown to demonstrate a particularly promising behavior and low overpotential when deposited on BiVO₄. Here, by using atomic layer deposition (ALD), we carefully control the thickness of the MnO₂ co-catalysts and examine the PEC properties of the resulting MnO₂/BiVO₄ photoanodes. The photocurrent is maximized when the thickness of MnO₂ is 4 nm. By examining the interface properties between MnO₂ and BiVO₄ using a combination of spectroscopy, (photo)electrochemical and microscopy techniques, we are able to show that increasing the thickness of MnO₂ results in decreasing surface recombination due to higher band bending, but also in the creation of shunting pathways due to direct contact between the MnO₂ and the conducting substrates (FTO) at pinholes. These two competing effects, therefore, result in a trade-off, which fully explains the observed photocurrent trend.

**Experimental**

**Deposition of BiVO₄ thin film photoanodes**

BiVO₄ thin films were deposited using spray pyrolysis. Commercial FTO-coated glass slides (fluorine-doped tin dioxide, 15 Ω·cm⁻¹, TEC-15, Pilkington) were used as the substrates. Prior to the deposition, a three-step cleaning procedure of ultrasonication in 10 vol% Triton™ X-100 solution (Sigma Aldrich), acetone, and ethanol, each for 15 minutes, was followed. A thin interfacial layer of SnO₂ was deposited using spray pyrolysis as the hole blocking layer on the FTO substrates using 5 mL solution of 0.1 M SnCl₄ (98%, Aldrich) in ethyl acetate (99.8%, VWR Chemical). The solution was sprayed onto the substrates using a Quickmist air atomizing spray nozzle (1/4QMJAU-NC + SUQR-200). The distance between the spray nozzle and the substrate, which was placed on a hot plate, was 20 cm. To ensure adequate solvent evaporation a pulsed spray mode was used; 5 s of spraying was followed by a 53 s delay. The BiVO₄ precursor solution was prepared by dissolving 4 mmol Bi(NO₃)₃·5H₂O (98%, Alfa Aesar) in acetic acid (99.8%, Sigma Aldrich), while 4 mmol VO(AcAc)₂ (99%, Acros Organics) was dissolved separately in absolute ethanol (VWR Chemicals). Each solution was ultrasonicated for 15 minutes, then mixed, and finally ultrasonicated again for 15 minutes. The ratio of the acetic acid and absolute ethanol was 1 : 9 in the final 100 mL solution. The hot plate temperature was kept constant at 425 °C for the SnO₂ deposition and then increased to 450 °C for the BiVO₄ deposition. In order to improve the crystallinity, following the deposition, all samples were annealed in air at 460 °C for 2 hours.

**Deposition of MnO₂ co-catalysts**

Manganese oxide (MnO₂) thin films were deposited using a home-built, hot-wall atomic layer deposition (ALD) reactor. The ALD reactor was constantly pumped by using a turbo molecular pump, backed-up with a roughing pump. The BiVO₄ substrates were mounted on a sample carrier, which is directly placed on the substrate heater in the ALD reactor. Bis(cyclopentadienyl)manganese ((EtCp₂)Mn, Strem Chemicals, 98%), kept at 85 °C was used as the Mn precursor, and water (Millipore, 18.2 MQ) as the oxygen source. The reactor wall was heated to 125 °C, while the substrate temperature was kept at 150 °C. The Mn precursor and the water dosing steps were performed each for 1.5 s. After each of these dosing steps, a pump/purge/pump step was carried out, consisting of 30 s pumping/0.1 s Ar dose/30 s pumping. This led to a growth per cycle (GPC) of 1.3 Å. The film thicknesses were determined by ex situ spectroscopic ellipsometry (J.A. Woollam Co. spectroscopic ellipsometer, M-2000D, 193–1000 nm) on a silicon reference sample placed next to the BiVO₄ substrates during the deposition. The dielectric function of the MnO₂ film was modeled with a Tauc–Lorentz dispersion equation.

**Materials characterization**

X-ray diffraction (XRD) measurements were done using a Bruker D8 diffractometer with Cu Kα radiation at 40 kV and 40 mA. UV-Vis spectra were measured using a PerkinElmer Lambda 950 spectrophotometer equipped with an integrating sphere. The films were placed inside the integrating sphere with a center mount sample holder (positioned at ~7.5° offset from the incident light) to measure transmittance (T), which is the sum of transmittance (T) and reflectance (R). Scanning helium ion microscopy (HIM) images were obtained with a Zeiss Orion Nanofab equipped with a secondary electron detector. HIM allows for high-resolution imaging of weakly or non-conductive nanosized features requiring a large depth of focus. The He gas pressure was set to 2 × 10⁻⁶ Torr for an acceleration voltage of 30 kV, probe currents ranging from 0.1 to 0.3 pA and a high spot control number to minimize the beam divergence. Monochromatic Al Kα radiation (hv = 1486.74 eV, SPECS FOCUS 500 monochromator) was used for X-ray photoelectron spectroscopy (XPS, SPECS PHOIBOS 100 analyzer) measurements. The pass energy was set to 30 and 10 eV with step sizes of 0.5 and 0.05 eV for the survey and fine spectra, respectively. The peaks were fitted in XPSPEAK software, using Voigt profiles and a Shirley background subtraction. All spectra were calibrated with respect to the adventitious carbon C 1s peak at 284.5 eV. Samples for observation in the cross section were prepared by using a Zeiss Crossbeam 340 focused ion beam system. Elemental distribution maps were obtained using a Zeiss LIBRA 200 FE transmission electron microscope operated at 200 kV.
accelerating voltage in scanning mode using a Thermo Fisher energy dispersive X-ray (EDX) spectrometer. The data shown here represent the net count signal after spectral deconvolution with an averaging kernel of $3 \times 3$ pixels.

**Photoelectrochemical characterization**

A three-electrode configuration using a custom Teflon cell (sample area $= 0.283 \text{ cm}^2$) was applied for photoelectrochemical measurements. The photoelectrochemical experiments were performed in a $0.1 \text{ M}$ potassium phosphate buffer (KPi, pH $\sim 7$) electrolyte. The buffer solution was prepared by mixing 4.625 g of potassium phosphate monobasic ($\text{KH}_2\text{PO}_4$, 99.5%, Merck) and 15.05 g of potassium hydrogen phosphate trihydrate ($\text{K}_2\text{HPO}_4\cdot3\text{H}_2\text{O}$, 99%, Merck) in 1 L of Milli-Q water ($18.2 \text{ M}\Omega$ cm). A Solartron SI 1286 potentiostat was used to control the potential of the working electrode. The reference electrode was an Ag/AgCl electrode (XR300, saturated KCl) used to control the potential of the working electrode. The solution was stirred in a frequency range of 100 mHz to 100 kHz. A high-speed Si photodiode (Thorlabs PDA10A-EC), the current monitor output of the as-mentioned potentiostat and the voltage signal of the high-speed Si photodiode were connected to the two channels of the FRA. The real and imaginary components of the electrochemical impedance were obtained using a calibrated photodiode ($0.015 \text{ V cm}^{-2}$) and the voltage of the Si photodiode were obtained using the FRA. The absolute (dimensionless) complex gain of the photo-electrode was converted by multiplying with a conversion factor ($0.015 \text{ V cm}^{-2}$), which was determined by measuring the absolute light intensity using a calibrated photodiode ($3.08 \text{ mW cm}^{-2}$) and the voltage of the high-speed Si photodiode. The absolute light intensity was calculated using the equation:

$$
\eta_{\text{CT}} = \frac{k_{\text{tr}}}{k_{\text{tr}} + k_{\text{rec}}}
$$

Electrochemical impedance spectroscopy (EIS) measurements were conducted under the same blue LED illumination between 0.6 and 1.6 $V_{\text{RHE}}$. The frequency was swept from 100 kHz to 100 mHz with a modulation amplitude of $10 \text{ mV}$.

**Results and discussion**

The X-ray diffractograms of the BiVO$_4$ samples with MnO$_x$ co-catalysts (2 and 6 nm) are shown in Fig. 1a. All peaks can be assigned to the BiVO$_4$ film (monoclinic, PDF 00-014-0688) and the FTO substrate. No change in the XRD patterns was observed for thicker MnO$_x$ films (up to 10 nm) on BiVO$_4$, which suggests that the MnO$_x$ co-catalyst layers are amorphous. However, some degree of crystallinity may be present, since the XRD pattern of a 20 nm MnO$_x$ film on quartz shows one small peak belonging to the MnO crystal structure (PDF 01-075-1090) (Fig. S1a, ESI†). Deposition of MnO$_x$ on BiVO$_4$ films also results in a slight increase of the absorption at wavelengths lower than $\sim 700$ nm, as shown in Fig. 1b. This increase can be assigned to the additional absorption in the MnO$_x$ layers, as shown by the systematic increase of the absorbance of MnO$_x$ films on quartz with increasing thickness (Fig. S1b, ESI†). Also, the presence of different oxidation states of manganese in the MnO$_x$ layer is studied by XPS and is shown in Fig. S2.† Mn$^{2+}$, Mn$^{3+}$, and Mn$^{4+}$ are present in all of the samples with similar values regardless of the thickness. The average oxidation state of manganese in our films is 2.7 and does not depend on the thickness of the MnO$_x$ layer.
Fig. 2a shows the current–voltage curves of BiVO$_4$ with different thicknesses of MnO$_x$ co-catalysts under 455 nm LED illumination. Up to a MnO$_x$ thickness of 4 nm, the photocurrent of the BiVO$_4$ samples at 1 V$_{RHE}$ increases by a factor of $\frac{3}{2}$. This photocurrent increase is not due to changes in specific surface area, since the electrochemically active surface area of the BiVO$_4$/MnO$_x$ (4 nm) sample is actually 25% smaller than that of the bare BiVO$_4$ (Fig. S3†). A small 100 mV cathodic shift of the onset potential of BiVO$_4$ can also be observed. Beyond this thickness (i.e., >4 nm), the photocurrent, however, starts to decrease. We confirm the reproducibility of this trend by measuring the photocurrent of at least four samples that were deposited with the same parameters but made in different spray pyrolysis and ALD batches. The production of oxygen from our films was confirmed by performing electrochemical mass spectrometry (EMS) measurements, as shown in Fig. S4†, for the BiVO$_4$/MnO$_x$ (4 nm) sample. With a calculated faradaic efficiency of 94 ± 1% at 0.7 V$_{RHE}$, almost all photocurrent is due to oxygen evolution. A comparison of the photocurrent of these samples with various thicknesses of MnO$_x$ co-catalysts at 1 V$_{RHE}$ is shown in Fig. 2b (black curve); the same photocurrent trend as described earlier for the other batch of samples is maintained, which confirms the reproducibility of our samples.

To reveal the underlying reason behind the observed trend, we performed intensity modulated photocurrent spectroscopy (IMPS) measurements and determined the charge transfer efficiency ($\eta_{CT}$). The complex IMPS plot at an applied potential of 1 V$_{RHE}$ was evaluated for bare BiVO$_4$ and different thicknesses of MnO$_x$ co-catalysts (2, 4, and 6 nm) deposited on BiVO$_4$ films (Fig. S5, ESI†). The resulting charge transfer efficiency, $\eta_{CT}$, for the bare BiVO$_4$ thin films and after addition of MnO$_x$ co-catalysts with different thicknesses is plotted in Fig. 2b (red circles); a correlation between $\eta_{CT}$ and the photocurrent is clearly present. The obtained charge transfer and surface recombination rate constants ($k_{tr}$ and $k_{rec}$, respectively) are shown in Fig. S6, ESI† While $k_{tr}$ remains more or less constant with varying thicknesses of the MnO$_x$ co-catalyst, $k_{rec}$ is minimized at the same optimal thickness of 4 nm. This suggests that the main role of MnO$_x$ on BiVO$_4$ is to suppress the surface recombination.

The photocurrent trend described above cannot be simply explained by the dark electrocatalytic activity trend of the MnO$_x$ catalyst. Fig. S7, ESI† shows the current–voltage curves of MnO$_x$ films with different thicknesses. The plot shows that increasing
the thickness resulted in a monotonous decrease of the current densities. It is therefore clear that MnO\textsubscript{x} possesses a different role other than improving the catalytic activity when deposited as a co-catalyst on BiVO\textsubscript{4}. This typical response was also reported by Strandwitz et al.;\textsuperscript{39} they attributed this to the ohmic loss within the MnO\textsubscript{x} layers.

In order to elucidate the influence of the MnO\textsubscript{x} layer on the surface recombination of BiVO\textsubscript{4}, the chemical nature of the films (and interface) was investigated by XPS. The spectra of the Bi 4f and V 2p core levels are shown in Fig. 3a and b, respectively. With increasing the thickness of the MnO\textsubscript{x} co-catalyst, it can be clearly seen that the peaks shift towards lower binding energies. In contrast, Fig. 3c shows that the peak position of the Mn 2p core level does not shift with the increasing MnO\textsubscript{x} thickness. The peak shifts for all these core levels are summarized in Fig. 3d.

The above-mentioned observation can be explained by the increase of band bending upon the addition of the MnO\textsubscript{x} co-catalyst. As illustrated in Scheme 1, with increasing band bending in the BiVO\textsubscript{4} film, X-ray excitation with the same photon energy (i.e., 1486.7 eV from our Al K\textalpha\textsubscript{1} radiation) will result in detected photoelectrons with increasing kinetic energy. This translates to a shift of the core level peaks to lower binding energies, which is indeed observed in our experimental results. To further confirm this explanation, we calculated the extent of band bending in our BiVO\textsubscript{4} films, assuming the core level peak position values of the BiVO\textsubscript{4} single crystal as those of the bulk (159.3 eV for Bi 4f\textsubscript{7/2} and 516.9 eV for V 2p\textsubscript{3/2}).\textsuperscript{48} The values for BiVO\textsubscript{4} films with various MnO\textsubscript{x} thicknesses are listed in Table S1;\textsuperscript{†} the values calculated using the Bi 4f\textsubscript{7/2} peak position agree very well with those calculated using V 2p\textsubscript{3/2}. Indeed, the extent of band bending increases with the increasing film thickness.

The additional band bending explains the improvement of the PEC performance (Fig. 2a) with the increasing thickness of MnO\textsubscript{x} (up to 4 nm). The increase of band bending has two implications: (i) increase of the space charge width; and (ii) lower surface recombination. The space charge region width can be calculated from eqn (3).

$$W = \sqrt{\frac{2e\phi_{Sc}}{\varepsilon \varepsilon_0 N_D} + \frac{kT}{e} - \frac{\Delta E}{e}}$$

$\varepsilon_0$ is the vacuum permittivity and $\varepsilon_r$ is the dielectric constant, $e$ is the elementary charge, $N_D$ is the donor density, $\phi_{Sc}$ is the potential drop across the space charge layer for bare BiVO\textsubscript{4}, $\Delta E$ is the shift of the core-level peak position (represents the additional potential drop with the presence of MnO\textsubscript{x}), $k$ is the Boltzmann constant, and $T$ is the temperature. Increasing the thickness of the co-catalyst results in an increase of the space charge region width from 47 to 63 nm. However, assuming that all carriers generated in the space charge can be collected (Gärtner model),\textsuperscript{49} such an increase of $W$ only corresponds to
13% increase of the photocurrent generated in the space charge region. This is much smaller than the three-fold increase of the observed photocurrent (Fig. 2b), suggesting that the extension of the space charge width is a minor factor influencing the photoelectrochemical performance.

Alternatively, larger band bending may also result in a lower surface majority carrier concentration \((n_{\text{surf}})\) as shown in the following equation:

\[
\frac{n_{\text{surf}1}}{n_{\text{surf}2}} = \exp \left( \frac{\Delta E}{kT} \right) \tag{4}
\]

Since surface recombination is a function of \(n_{\text{surf}}\), the overall surface recombination is decreased with decreasing \(n_{\text{surf}}\) and the photocurrent is improved. Based on the \(~0.1\) eV additional band bending observed for the optimum 4 nm MnO\(_x\)/BiVO\(_4\) sample (see Fig. 3d), we estimate that \(n_{\text{surf}}\) is lowered by a factor of \(~40\), which is in good agreement with the observed \(k_{\text{rec}}\) decrease from IMPS (Fig. 6, ESI†).

We note that the photocurrent enhancement can also be a result of the surface passivating effect of the MnO\(_x\) layer, which would also decrease surface recombination. Such an effect has been reported for other overlayers, such as amorphous TiO\(_2\), Al\(_2\)O\(_3\) and CoPi. However, while we cannot completely rule out this explanation, the good quantitative agreement between the decrease of \(k_{\text{rec}}\) and \(n_{\text{surf}}\) in our films suggests that surface passivation does not play a major role.

Although the above-mentioned band bending observation can satisfactorily explain the increase of the photocurrent of BiVO\(_4\) after deposition of MnO\(_x\) films, it cannot account for the overall photocurrent trend; the band bending continues to increase with the increasing MnO\(_x\) thickness, yet the photocurrent decreases when the MnO\(_x\) films are thicker than 4 nm. A competing mechanism therefore exists, which compensates for

**Scheme 1** Schematic illustration of the band diagram of BiVO\(_4\) and BiVO\(_4\) with the increasing MnO\(_x\) thickness. Since the energy of the X-ray is constant, increasing the band bending at the interface results in photo-emitted electrons with a larger kinetic energy \((E_{k,1} < E_{k,2} < E_{k,3})\). This translates to a shift in the binding energy towards lower values, which explains our observed XPS results (Fig. 3).
the increasing band bending at the BiVO₄/MnOₓ interface. One possibility is simply the lower (dark) electrochemical activity of MnOₓ with the increasing thicknesses (Fig. S7, ESI†), which has been shown to be related to the poor conductivity of the MnOₓ layer.† To confirm if this is also the case when MnOₓ is deposited on BiVO₄, electrochemical impedance spectroscopy (EIS) was conducted for BiVO₄ samples with different thicknesses of MnOₓ. We focus on two thicknesses of the MnOₓ layer on BiVO₄: 4 nm as the optimum thickness and 6 nm as the thickness at which a decrease in photocurrent already occurs. The Nyquist plot for the BiVO₄ coated with 4 nm of MnOₓ is shown in Fig. S8a.† Two semicircles can be clearly observed. We apply a resistance-based analysis method on the resistances in the films, as recently established by Moehl et al. for multilayer water splitting photocathodes.† In order to assign the identity of each semicircle, the measurements were also conducted at different applied potentials. As shown in Fig. S8a,† increasing the potential does not change the first semicircle, but a systematic decrease of the radius of the second semicircle can be observed. We therefore, attributed the first semicircle to the resistance to the MnOₓ layer (R_MnOₓ) and the second semicircle to the charge transfer resistance (R_C). Fig. S8b† shows the Nyquist plot of the BiVO₄ films with 4 and 6 nm of MnOₓ measured at ~1.23 V_{RHE}. R_C decreases with the increasing MnOₓ thickness, while R_MnOₓ remains relatively constant (62.3 ± 9.3 vs. 64 ± 14 Ω for the 4 and 6 nm MnOₓ films, respectively). These results therefore cannot explain the decrease of photocurrent for BiVO₄ with MnOₓ films thicker than 4 nm.

Another plausible explanation for the decrease of photocurrent beyond 4 nm thickness of MnOₓ is the presence of shunting pathways. For example, Boettcher and co-workers showed that in the case of NiFeOₓ co-catalysts on a hematite photoanode, direct contact between NiFeOₓ and the underlying FTO substrate—due to the porosity or the existence of pinholes in the hematite photoanode—provides a pathway for electron-hole recombination (i.e., shunting).† To determine whether this may be the case for our films, dark cyclic voltammetry measurements were performed for FTO and bare BiVO₄ in 50 mM ferri/ferrocyanide with 0.1 M supporting KCl electrolyte (Fig. 4a). The dark current for the FTO shows clear peaks corresponding to the oxidation and reduction of the [Fe(CN)₆]₃⁻/[Fe(CN)₆]⁴⁺ redox couple. For a dense BiVO₄ film (i.e., no pinholes and the FTO is therefore not exposed to the electrolyte), these redox peaks should not be visible and only negligible dark currents are measured.† However, the same dark cyclic voltammetry measurements on our BiVO₄ film show the [Fe(CN)₆]₃⁻/[Fe(CN)₆]⁴⁺ redox peaks, albeit being smaller and shifted to higher/lower potentials. This suggests that pinholes are indeed present on our spray-pyrolysed BiVO₄. For the MnOₓ/BiVO₄ samples, these pinholes represent the area where direct contact between MnOₓ and FTO can occur. In addition, we measured the dark current for the BiVO₄ samples with different thicknesses of MnOₓ in 0.1 M KPi electrolyte. Indeed, the dark current increases for samples with MnOₓ films thicker than 4 nm (Fig. 4b), confirming the presence of MnOₓ/FTO contact. These observations, therefore, suggest that a shunting effect is the reason behind the decreasing photocurrent for thicker MnOₓ films.

The presence of the pinholes, and therefore the shunting pathways, is further confirmed with additional microscopy measurements. The scanning helium ion microscopy top view image of the BiVO₄ film shows that it is not fully compact, i.e., some parts of the FTO substrate are not covered (Fig. 5). Fig. 6 shows the scanning transmission electron microscopy (STEM) cross-section image of a BiVO₄ sample with 10 nm-thick MnOₓ layers. The EDX-STEM mapping (Fig. 6b–f) shows the pinholes on BiVO₄ quite clearly. From the composite map (Fig. 6f), the areas in which MnOₓ is in direct contact with FTO are marked with the red arrows.

We can now summarize our findings on the role of MnOₓ films on BiVO₄ and the correlation with the observed photocurrent trend. The deposition of MnOₓ co-catalysts on BiVO₄ films with increasing MnOₓ thickness results in additional band bending at the interface. This leads to lower surface majority
carrier concentration, reduced surface recombination, and higher photocurrent. When the films become too thick, they can make direct contact with the underlying FTO. This causes a shunt between the surface of the BiVO₄ and the FTO substrate that causes recombination. These two competing effects (illustrated in Scheme 2) explain the photocurrent being maximized for the BiVO₄ films with 4 nm MnOₓ co-catalysts.

Conclusions

In summary, we have investigated the role of ultra-thin ALD MnOₓ co-catalyst layers on BiVO₄ photoanodes. Upon the deposition of MnOₓ, the PEC performance of BiVO₄ is enhanced. The photocurrent reaches its maximum for a MnOₓ thickness of 4 nm (~3-fold improvement as compared to the bare BiVO₄); beyond this thickness the photocurrent decreases. We showed that the MnOₓ dark catalytic activity and conductivity trends cannot explain this photocurrent trend. IMPS analysis showed that the charge transfer efficiency and surface recombination rate constant follow the same trend with MnOₓ thickness as the photocurrent. We found that MnOₓ introduces additional band bending (up to ~0.2 eV) at the BiVO₄/MnOₓ interface, as shown from the XPS analysis, which reduces surface recombination. However, at the same time, due to the morphological nature of our spray-pyrolysed BiVO₄ films, increasing the MnOₓ thickness also increases the possibility of MnOₓ filling the pinholes and creating direct contact with the underlying FTO substrate. We showed that this is indeed the case using electrochemical and TEM analysis. This results in shunting, which increases the electron-hole recombination and cancels out the favorable effect of band bending for thicker MnOₓ films. Overall, this study sheds light on the main role of MnOₓ co-catalysts on BiVO₄ and the underlying reason behind the co-catalyst thickness optimization. It is expected that the phenomena observed in our system can be extended to other semiconductors and co-catalysts, especially those with a similar morphology.

Conflicts of interest

There are no conflicts to declare.

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