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A Nanostructured Chromium (III) Oxide/ Tungsten (VI) Oxide p-n Junction Photoanode toward Enhanced Efficiency for Water Oxidation

Zhuofeng Hu, Mingkun Xu, Zhurui Shen, Jimmy C. Yu

A nanostructured chromium(III) oxide/ tungsten(VI) oxide (Cr$_2$O$_3$/WO$_3$) p-n junction photoanode is established here. It is prepared by depositing Cr$_2$O$_3$ nanoparticles on to WO$_3$ nanosheet array. The formation of p-n junction is confirmed by Mott-Schottky plot and photocurrent measurement. Electrochemical and spectroscopic methods indicate that the recombination rate of photogenerated charges becomes lower in this photoanode. Consequently, its onset potential shifts negatively by about 0.1 V and photocurrent density increases from 0.7 to 1.8 mA cm$^{-2}$ at 1.8 V vs. RHE. The incident photon-to-current efficiency (IPCE) also shows a one-fold improvement. In addition, the construction of p-n junction leads to an increase of faradaic efficiency (holes to oxygen) from 73.9% to 92.0%, which is attributed to the suppression of side reactions in the water oxidation. This work will bring new inspirations for improving the performance of WO$_3$ and other photoanodes.

Introduction

Metal oxide semiconductors are often used to convert solar energy into electricity and chemical fuels in photoelectrochemical cells (PECs). With a band gap of 2.7 eV, WO$_3$ can utilize the solar spectrum up to ~460 nm. Moreover, its positive valence band edge (3.0 eV vs. RHE) is sufficient to overcome the overpotential of water oxidation. Therefore, WO$_3$ has been widely studied as a promising photoanode in photoelectrochemical water oxidation.

The performance of WO$_3$ photoanodes mainly depends on the separation efficiency of photogenerated electron/hole pairs. So far, several routes have been developed for the improvement: (i) deposition of water oxidation cocatalyst; (ii) introduction of hole sacrifice agents; (iii) doping heteroatoms into the lattice and (iv) shortening the diffusion-length of photogenerated charges.

Apart from the aforementioned methods, building a nanostructured p-n junction photoanode is a promising approach to reduce the charge recombination. The p-n junction can facilitate the charge separation by the internal electric field in its depletion region. For example, n-type BiVO$_4$ exhibited lower charge recombination rate at the surface trapping states when loaded with p-type NiO. N-type TaON/p-type Cu$_2$O showed a maximum IPCE of 59% at a wavelength of 400 nm, and reached 3.06 mA cm$^{-2}$ under AM 1.5G simulated sunlight at 1.0 V vs. RHE. However, there are few reports about the enhancement of WO$_3$ photoanode by constructing a p-n junction.

Scheme 1 A diagram of the nanostructured Cr$_2$O$_3$/WO$_3$ p-n junction photoanode toward high faradaic efficiency in water oxidation.

Cr$_2$O$_3$, an p-type semiconductor with a bandgap of 3.4 eV, has been extensively studied in the fields of heterogeneous catalysis, photocatalysis and hydrogen absorption. Herein, we use nanostructured Cr$_2$O$_3$/WO$_3$ p-n junction as an example to suppress the charge recombination in water oxidation. P-type Cr$_2$O$_3$ nanocrystals are decorated on the surface of n-type WO$_3$ nanosheets by electrophoresis. Characterization by SEM, TEM and XRD etc. show that the two types of materials contact intimately with each other.
other. Results from photoelectrochemical measurements confirm that the as-prepared \( \text{Cr}_2\text{O}_3/\text{WO}_3 \) photoanode exhibits higher photocurrent density and incident photon-to-current efficiency (IPCE) than those of \( \text{WO}_3 \) photoanode. Besides, the faradaic efficiency for water oxidation is increased from 73.9% (\( \text{WO}_3 \) photoanode) to 92.0% (\( \text{Cr}_2\text{O}_3/\text{WO}_3 \) photoanode). Based on the electrochemical and spectroscopic measurements, a possible mechanism is proposed to explain the superior performance of the \( \text{Cr}_2\text{O}_3/\text{WO}_3 \) photoanode.

**Experimental Section**

All chemical reagents are commercially available and used as received.

**Preparation of \( \text{WO}_3 \) nanosheets on FTO glasses (\( \text{WO}_3 \) electrode).** 70 mg of sodium tungsten (\( \text{Na}_2\text{WO}_4 \)) was firstly dissolved in 10 mL of deionized (DI) water. Then, 5 mL of 10 M hydrochloric acid (HCl) was added dropwise. Once the solution became light yellow, 70 mg of ammonium oxalate (\( \text{NH}_4\text{C}_2\text{O}_4 \)) was added. After 10 minutes of stirring, the solution was transferred into a 20 mL Teflon-lined stainless steel autoclave, sealed and heated at 120 °C for 12 hours. Thereafter, the FTO glass was taken out and washed with ethanol and water. A film of yellow \( \text{WO}_3 \) was observed on the surface of the FTO glass. The film was then calcination at 550 °C for 3 hours to transform \( \text{WO}_3 \) into \( \text{WO}_3 \) and improve the contact to FTO.

**Preparation of \( \text{Cr}_2\text{O}_3 \) nanocrystals.** 340 mg of sodium dichromate (\( \text{Na}_2\text{Cr}_2\text{O}_7 \)) was firstly dissolved in 19 mL of DI water. Then, 1 mL of 6M HCl was added dropwise. The mixed solution was transferred into a 20 mL Teflon-lined stainless steel autoclave, sealed and heated at 180 °C for 12 hours. The product was collected by centrifugation and dried at 80 °C overnight. Finally, the product was calcination at 550 °C for 3 hours to improve its crystallinity.

**Deposition of \( \text{Cr}_2\text{O}_3 \) nanocrystals on \( \text{WO}_3 \) electrode.** The \( \text{Cr}_2\text{O}_3 \) nanocrystals were deposited onto the \( \text{WO}_3 \) electrode by electrophoretic method. 5 mg of the \( \text{Cr}_2\text{O}_3 \) nanocrystals was dispersed in 25 mL of acetone solution of iodine (5 mg, making the particles positive charged). A \( \text{WO}_3 \) electrode and an auxiliary FTO glass were fixed in parallel with a distance of 1 cm. The bottom parts of the FTO glasses (1.5×1.5 cm²) were immersed into the suspension. Then 20 V of dc voltage was applied between the two electrodes for 10, 25 and 85 seconds. The yellow \( \text{WO}_3 \)-FTO electrode became light green after the deposition.

**Materials Characterization.** Scanning electron microscopy (SEM) observations were carried out using the Hitachi Model S-4800, FEI Quanta 400 and (JEOL) JSM–7500F microscopes. The (JEOL) JSM–7500F microscope is coupled with an energy dispersive X-ray (EDX) spectrometer (Oxford Instrument). Transmission electron microscopy (TEM) was conducted with a CM-120 microscope (Philips, 120 kV) coupled with an energy-dispersive X-ray (EDS) spectrometer (Oxford Instrument). X-ray diffraction (XRD) patterns were collected on a Rigaku SmartLab X-ray diffractometer using a Cu Kα source irradiation (\( \lambda=1.5406 \) Å). X-Ray photoelectron spectroscopy (XPS) analysis was performed using a Sengyang SKL-12 spectrometer equipped with a VG CLAM 4 MCD electron energy analyzer and twin anode Mg Kα radiation (1253.6 eV) or Al Kα radiation (1496.3 eV) X-ray sources.

**Photoelectrochemical measurements.** \( \text{WO}_3 \) and \( \text{Cr}_2\text{O}_3/\text{WO}_3 \) electrodes were fixed into the photoanodes by securing a copper wire onto a bare portion of the substrates via silver paste. All the photoelectrochemical measurements were performed in a three-electrode cell with a saturated-potassium-chloride silver chloride electrode (Ag/AgCl) as a reference electrode, a platinum foil (1.0×1.0 cm²) as a counter electrode, and the \( \text{WO}_3 \) and \( \text{Cr}_2\text{O}_3/\text{WO}_3 \) photoanodes as the working electrodes. The electrolyte was 0.1M Na₂SO₄. Linear sweeps and transient photocurrent were measured by a CHI 660D electrochemical workstation. The lifetime of electron was measured by plotting the Bode phase at open-circuit voltage. A 300 W Xenon arc lamp coupled with an Air Mass (AM) 1.5 global filter (100 mW cm⁻²) were used as the light source. The AM 1.5 global filter corrects the output of a Xenon lamp to better match the solar spectrum with a 37 degree tilt angle. A series of band-pass light filters were also equipped onto the Xenon arc lamp for IPCE measurements.

**Gases evolution measurements.** The gases (oxygen/hydrogen) evolution by photoelectrochemical water splitting was conducted in the airtight H-type reactor connected to a closed gas circulation system. The experiment was carried out at 1.0 V vs. RHE in 0.1 M Na₂SO₄ electrolyte under the illumination of a 300 W Xenon arc lamp. The yield of oxygen and hydrogen was measured by a gas chromatography equipped with a TCD detector.

**Results and Discussion**

In a typical synthesis, the \( \text{WO}_3 \) nanosheets were prepared on a FTO conducting glass. Fig. 1a shows that the size of \( \text{WO}_3 \) nanosheets is c.a. 1 μm, and the thickness is c.a. 200 nm. Its XRD pattern (Fig. 2) is well indexed with the standard card of monoclinic \( \text{WO}_3 \) (JCPDS No. 43-1035). The \( \text{Cr}_2\text{O}_3 \) nanocrystals have a uniform size of c.a. 20–40 nm with a rhombohedral crystalline phase (ESI, Fig. S1, XRD see Fig. 2, JCPDS No. 38-1479). Then, the \( \text{Cr}_2\text{O}_3 \) nanocrystals were deposited on the surface of \( \text{WO}_3 \) nanosheets by an electrophoresis method. After 10 s of deposition, the \( \text{WO}_3 \) nanosheets were homogeneously covered by \( \text{Cr}_2\text{O}_3 \) nanocrystals (Fig. 1b, c). The HRSEM images show that the \( \text{Cr}_2\text{O}_3 \) nanocrystals can locate at the top/lateral faces of \( \text{WO}_3 \) nanosheets, and they contact well with each other (Fig. 1c, d). The XRD pattern of \( \text{Cr}_2\text{O}_3/\text{WO}_3 \) displays the peaks of both monoclinic \( \text{WO}_3 \) and rhombohedral \( \text{Cr}_2\text{O}_3 \), which further confirms the formation of their heterostructure (Fig. 2). The EDX (SEM) results show that the molar ratio of Cr: W is approx. 0.70 after 10 s of deposition (average value from 5 sites, Table S1). TEM analysis is then performed here to further study its microstructure (Fig. 1e, f; the low resolution image and EDX see ESI, Fig. S2). As shown in Fig. 1e, a \( \text{Cr}_2\text{O}_3 \),
nanocrystal contacts intimately with a WO$_3$ nanosheet. From its enlarged image, the clear lattice fringes with $d$-spacing of 0.36 nm and 0.26 nm can be ascribed to the (012) facets of Cr$_2$O$_3$ and (202) facets of WO$_3$, respectively (Fig. 1f). This result directly evidences their close interface contact, which will promote the charge separation in the PECs.

To further study the chemical nature of Cr$_2$O$_3$/WO$_3$ heterostructure, its XPS spectra were recorded (ESI, Fig. S3). The W 4f spectrum of Cr$_2$O$_3$/WO$_3$ shows two peaks at 35.2 eV and 37.4 eV, indicating the presence of W$^{6+}$ (ESI, Fig. S3a). This is consistent with that of WO$_3$ nanosheets, which suggests that the WO$_3$ kept stable during the electrophoresis process (ESI, Fig. S3b). Its O 1s spectrum can be deconvoluted into two main components after Gaussian fitting. One is 530.3 eV (O$_2$), corresponding to the O$^{2-}$ ions in the WO$_3$ and Cr$_2$O$_3$ lattices. The other is 531.8 eV (O$_3$), indexing to the O$^{2-}$ ions in the oxygen-deficient regions (ESI, Fig. S3c). Compared with the O 1s spectrum of WO$_3$ nanosheets, the relative quantity of O$_3$ peak in Cr$_2$O$_3$/WO$_3$ is larger, which can be ascribed to more defect regions in Cr$_2$O$_3$ nanocrystals.

The ass-prepared WO$_3$ nanosheets on FTO exhibit a light yellow color (Fig. 3a). This is consistent with its UV-vis diffuse reflectance spectrum with an absorption edge at c.a. 460 nm (Fig. 3b). The band gap of WO$_3$ nanosheets is estimated to be c.a. 2.7 eV from the linear approximation in the Kubelka–Munk plot (ESI, Fig. S3). Its absorption edge is at c.a. 430 nm, corresponding to a band gap of 2.9 eV (Fig. 3b, d). This value is smaller than that of its bulk counterpart (3.5 eV), which can be ascribed to the quantum confinement effect. The Cr$_2$O$_3$/WO$_3$ on FTO also displays a pale green color due to the coating of Cr$_2$O$_3$ nanocrystals (Fig. 3a). Its UV-vis diffuse reflectance spectrum exhibits the characteristic of both Cr$_2$O$_3$ and WO$_3$.

PEC measurements were conducted in a three-electrode electrochemical cell in 0.1 M Na$_2$SO$_4$ solution (pH: c.a. 7.0). The Linear sweep voltammograms were recorded under the irradiation of a 100 mW cm$^{-2}$ simulated sunlight in the potential range of 0.8 to 2.2 V vs. RHE, as shown in Fig. 4a (their dark currents see ESI, Fig. S4). The photocurrent density ($J$) of WO$_3$ begins to rise at 1.0 V vs.
RHE and reaches about 0.7 mA cm⁻² at 1.8 V vs. RHE. The onset potential is 0.45 V positive than its flat band potential (Fig. 4a) due to poor charge transfer at the interface induced by slow water oxidation kinetic.⁴⁰, ⁴⁷, ⁴⁸ After 10 s electrophoresis deposition of Cr₂O₃ nanocrystals, the saturated photocurrent increases from 0.7 to 1.8 mA cm⁻² (Fig. 4a). This suggests the charge separation in the photoanode is greatly enhanced. However, with longer electrophoresis duration, excessive amounts of Cr₂O₃ nanocrystals will be deposited (ESI, Fig. S5, Fig. S6), and they will block light and decrease the photocurrent density (Fig. 4a, ESI, Fig. S5). Different from the saturated photocurrent density, the onset potentials are stable at 0.9 V vs. RHE for all the Cr₂O₃/WO₃ photoanodes (Fig. 4a). This is 0.1 V lower than that of bare WO₃ photoanode. In addition, we also conducted the calcination of photoanodes (Fig. 4a). This is 0.1 V lower than that of bare WO₃ photoanode. In addition, we also conducted the calcination of Cr₂O₃/WO₃ at 550 °C and test its photocurrent density. However, the photocurrent density decreased slightly after heating, which was possible due to particles agglomeration (ESI, Fig. S7).

This suggests the enhancement is mainly due to faster charge separation rather than wider light absorption, which is consistent with the UV-Vis spectra of Cr₂O₃/WO₃ (Fig. 3b). Moreover, the IPCE is measured at different pH in 0.5M H₂SO₄, 0.1M Na₂SO₄ and 1M NaOH (ESI, Fig. S9). Results show that the IPCE values increase with decreasing pH for both WO₃ and Cr₂O₃/WO₃.

The incident photon-to-current efficiency (IPCE) measurements were carried out according to the following equation:⁴⁹⁻⁵²

\[
\text{IPCE} = \frac{(1240 \times I_s)}{(\lambda \times J_{\text{light}})} \times 100
\]

where \(I_s\) is the photocurrent density (mA cm⁻²), \(\lambda\) the incident light wavelength (nm), and \(J_{\text{light}}\) the power density of monochromatic light at a specific wavelength (mW cm⁻²). Compared with pure WO₃, the Cr₂O₃/WO₃ photoanode exhibits a one-fold enhancement in IPCE between 360-430 nm (Fig. 5b, ESI, Fig. S8 enlarges the part from 430 nm to 480 nm). After 430 nm, little enhancement is observed.
ESI, Fig. S10). The Mott-Schottky plots of WO₃, Cr₂O₃ and Cr₂O₃/WO₃ are plotted according to the following equation,\(^{53,55}\)

\[
\frac{1}{C^2} = \frac{2 \varepsilon \varepsilon_0 \varepsilon_0 N_D}{e^2}(E - E_{FB} - kT)
\]

(2)

where \(C\) is the space charge capacitance, \(\varepsilon\) and \(\varepsilon_0\) the permittivity of the electrode and free space, \(e_0\) the elementary charge, \(E\) the applied potential, \(E_{FB}\) the flat band potential, \(k\) the Boltzmann’s Constant, and \(T\) the temperature. Table 1. The time constants \(\tau_1\) (fast) and \(\tau_2\) (slow) for WO₃ and Cr₂O₃/WO₃ calculated from the decay profile of photocurrent, bias: 1.0 V and 1.23 V vs. RHE. In the Mott-Schottky plot, a positive slope often reflects the n-type nature of the semiconductor, while a negative slope reflects the p-type semiconductor.\(^{53,56,57}\) As shown in Fig. 5a, the WO₃, a well-known n-type semiconductor, exhibits a positive slope. While the p-type Cr₂O₃ shows a negative slope (Fig. 5b). The p-type nature of the Cr₂O₃ can also be confirmed by its cathodic photocurrent in CV and transient photocurrent measurement (ESI, Fig. S10). This suggests that a p-n junction is established between Cr₂O₃ and WO₃.

With the formation of p-n junction, the carrier density on the Cr₂O₃/WO₃ photoanode also increases remarkably. As shown in Fig. 5a, the drop of slope in the Mott-Schottky plot indicates the increase of charge carrier. The carrier density of WO₃ is calculated to be 1.31 \(\times 10^{20}\) cm\(^{-3}\), while that of Cr₂O₃/WO₃ is 5.87 \(\times 10^{20}\) cm\(^{-3}\) according to the following equation: \(^{53,56,57}\)

\[
N_D = \frac{2}{\varepsilon \varepsilon_0 e_0} \frac{dE}{dC^2} = \frac{2}{\varepsilon \varepsilon_0 e_0} \frac{1}{\text{slope}}
\]

(3)

The valence band position of Cr₂O₃ and WO₃ is measured by the edge of maximum energy in valence XPS spectrum (Fig. 5c).\(^{58,59}\) The value of WO₃ indicates that its valence band is 2.0 V below the Fermi level, which is consistent with previous report.\(^{59}\) In the spectrum of Cr₂O₃/WO₃, an additional shoulder with the edge of maximum energy of 0.2 eV appears. It should originate from the Cr₂O₃. The small value of 0.2 eV is consistent with the p-type nature of Cr₂O₃, in which the valence band is very close to the Fermi level. Thus the band structure of Cr₂O₃/WO₃ can be established (Fig. 5d).

An explanation for the enhanced photocurrent density and earlier onset potential of Cr₂O₃/WO₃ photoanode is the suppressed charge recombination inside the p-n junction. To prove this, transient photocurrent measurement is performed to measure the bulk recombination rate of electron/hole pairs.\(^{50}\) As shown in Fig. 7a, when light is turned on, a relative large transient photocurrent spike is observed, indicating the separation of photoexcited electron/hole pairs.\(^{61}\) The spike then decays due to the recombination of charge carriers during their migration (holes to the electrolyte and electrons to the external circuit). Finally, a steady-state photocurrent is achieved when charge separation and recombination reach equilibrium. The decay kinetic follows a two order logarithmic equation with two time constants \(\tau_1\) (fast) and \(\tau_2\) (slow):\(^{52}\)

\[
y = y_0 + Ae^{-x/\tau_1} + Be^{-x/\tau_2}
\]

(4)

Fig. 6b displays the photocurrent transient profile of WO₃ and Cr₂O₃/WO₃ at 1.0 and 1.23 V vs. RHE (original curves see ESI, Fig. S11). The simulated results are shown in Table 1. After formation of p-n junction, the \(\tau_1\) and \(\tau_2\) increase at both 1.0 and 1.23 V vs. RHE, suggesting a lower recombination rate in the p-n junction. This result is further supported by longer life time of electrons. It is reported that the lifetime of electrons can be evaluated by the maximum frequency peaks \(f_{\text{max}}\) in the Bode phase plots according to \(\tau_2 = 1/(2\pi f_{\text{max}})\) (Fig. 6c, d, original Nyquist plots see ESI, Fig. S12).\(^{60,63-65}\) As shown in Fig. 6d, the \(f_{\text{max}}\) of WO₃ decreases from 1.00 to 0.58 Hz after the deposition of Cr₂O₃, indicating that the lifetime of electrons increases from 159 to 275 ms. Therefore, the formation of p-n junction can effectively reduce the charge recombination in the photoanode. As a result, more electrons could reach the external circuit. This is probably the main reason for the enhancement of photocurrent density and onset potential.

In addition, it is possible that the Cr₂O₃ could also produce photoexcited charge carriers and improve the photocurrent and onset potential. As shown in ESI, Fig. S13 (its IPCE curve), the Cr₂O₃ can generate photoexcited charge carriers before 440 nm, which is consistent with its UV-Vis spectrum. This suggests that the photoexcitation of Cr₂O₃ can also contribute to the efficiency of Cr₂O₃/WO₃ photoanode. But its photocurrent density (about 2 uA cm\(^{-2}\)) and IPCE value (<0.5 %) are much smaller than those of WO₃ or Cr₂O₃/WO₃, suggesting the contribution from the excitation of Cr₂O₃ is small. Besides, the photovoltage of the p-n junction is also slight larger than that of pure WO₃ photoanode (ESI, Fig. S14). This should be another reason for the negative shift of onset potential.

Another key parameter to evaluate a WO₃ photoanode is the charge-to-chemical faradaic efficiency.\(^{10,14-22}\) Faradaic efficiency is defined as the ratio between the charge consumed in the O₂ evolution reaction and the total charge measured during the photocurrent measurement.\(^{1}\) It displays the utilization efficiency of charges for an electrochemical reaction.

The faradaic efficiency can be evaluated by monitoring the yield of oxygen at 1.0 V vs. RHE (Fig. 4c, V vs. RHE (volt) = V vs. Ag/AgCl (volt)+[0.059(volt)×pH]+0.236 (volt)). Since this potential is lower than the theoretical threshold of electrolysis water oxidation, the water oxidation is due to photocatalysis. The yield of oxygen from WO₃ is 0.034 mL per hour.

The faradaic efficiency is calculated according to the following equation:\(^{58,66,67}\)
Therefore, faradaic efficiency for WO₃ is found to be 73.9%. With Cr₂O₃ decorated, the WO₃ photoanode exhibits higher photocurrent and faster oxygen evolution rate (Fig. 4c). The photocurrent of Cr₂O₃/WO₃ is 1.33 times as high as that of WO₃. Its yield of oxygen increases to 0.058 mL. This is 1.70 times as high as that of WO₃. Accordingly, the faradaic efficiency for oxygen evolution rises to 92.0%. In addition, the hydrogen evolution on the Pt counter electrode is also recorded (ESI, Fig. S15, Fig. S16).

The enhanced faradaic efficiency of Cr₂O₃/WO₃ can be ascribed to the suppression of side reactions induced by the photoexcited electrons (Fig. 7b). In a PEC, the generated oxygen will firstly dissolve in the electrolyte, and then diffuse to the atmosphere for detection. It is reported that the dissolved oxygen is easy to be reduced into hydrogen peroxide by the photoexcited electrons on the surface of photoanodes. Besides, the hydroxyl intermediates formed during water oxidation will also be reduced by the photoexcited electrons, which will decrease the yield of oxygen. Therefore, the amount of detected oxygen will decrease and lead to a drop in the faradaic efficiency. This phenomenon is more pronounced for n-type WO₃ with electrons as major carrier. However, Cr₂O₃/WO₃ p-n junction can effectively suppress these side reactions induced by photoexcited electrons. As shown in Fig. 7b, the Cr₂O₃ will block the migration of photoexcited electrons from WO₃ to the photoanode/electrolyte interface. This is because the conduction band of Cr₂O₃ is higher than that of WO₃, which is evidenced by XPS valence band (Fig. 5d). Additionally, as the minor carrier, the electron density of the p-type Cr₂O₃ is much lower than that of WO₃. Thus, compared with bare WO₃ photoanode, the total density of photoexcited electrons is lower on the surface of the p-n junction covered with Cr₂O₃ nanocrystals (Fig. 1c, d). This difference will bring a decreased possibility of oxygen and hydroxyl intermediates reduction. As a result, the faradaic efficiency can be enhanced.

Conclusions

In summary, a nanostructured Cr₂O₃/WO₃ p-n junction photoanode is constructed for photoelectrochemical water oxidation. Its band alignment and special morphology result in a low recombination rate and the suppression of side reactions. Therefore, the Cr₂O₃/WO₃ p-n junction photoanode exhibits enhanced PEC activity and a high faradaic efficiency. This work is useful for further understanding the role of p-n junction in photoelectrochemical reaction. Moreover, it will also bring inspiration for fabricating other p-n junction photoanodes with better PEC performance.

Acknowledgements

This work was partially supported by the Shenzhen Basic Research Scheme (JCYJ20120619151417947) and a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China, under Theme-based Research Scheme through Project No. T23-407/13-N. This work was also supported by the National Natural Science Foundation of China (Grant no. 21303118).

Notes and references

A nanostructured Cr$_2$O$_3$/WO$_3$ p-n junction photoanode has been prepared, which is toward high faradaic efficiency in water oxidation.