ZnO/Ag/Ag₂WO₄ photo-electrodes with plasmonic behavior for enhanced photoelectrochemical water oxidation

Rania E. Adam, Mahsa Pirhashemi, Sami Elhag, Xianjie Liu, Aziz Habibi-Yangjee, Magnus Willander and Omer Nur

Ag-based compounds are excellent co-catalyst that can enhance harvesting visible light and increase photo-generated charge carrier separation owing to its surface plasmon resonance (SPR) effect in photoelectrochemical (PEC) applications. However, the PEC performance of a ZnO/Ag/Ag₂WO₄ heterostructure with SPR behavior has not been fully studied so far. Here we report the preparation of a ZnO/Ag/Ag₂WO₄ photo-electrode with SPR behavior by a low temperature hydrothermal chemical growth method followed by a successive ionic layer adsorption and reaction (SILAR) method. The properties of the prepared samples were investigated by different characterization techniques, which confirm that Ag/Ag₂WO₄ was deposited on the ZnO NRs. The Ag₂WO₄/Ag/ZnO photo-electrode showed an enhancement in PEC performance compared to bare ZnO NRs. The observed enhancement is attributed to the red shift of the optical absorption spectrum of the Ag₂WO₄/Ag/ZnO to the visible region (>400 nm) and to the SPR effect of surface metallic silver (Ag⁰) particles from the Ag/Ag₂WO₄ that could generate electron–hole pairs under illumination of low energy visible sun light. Finally, we proposed the PEC mechanism of the Ag₂WO₄/Ag/ZnO photo-electrode with an energy band structure and possible electron–hole separation and transportation in the ZnO/Ag/Ag₂WO₄ heterostructure with SPR effect for water oxidation.

1 Introduction

Solar driven photocatalysis activities of semiconductors (i.e. dye photodegradation, hydrogen production, and CO₂ reduction, etc.) have recently gained great interest because they are related to the utilization of a sustainable energy source and hence are of positive impact to the environment and energy availability issues.¹–⁴ Photoelectrochemical (PEC) applications are promising for water splitting to produce hydrogen and oxygen via the conversion of solar energy to chemical energy.³ Various nanostructured metal oxides have been investigated for PEC applications such as WO₃, TiO₂, Fe₂O₃, BiVO₄, and ZnO.⁵–¹⁸ From above mentioned semiconductors, ZnO is the most favorable due to its wide band gap (Eg ~ 3.3 eV), and relatively high carriers mobility.¹⁹–¹⁴ ZnO possesses many point defects that form many shallow and deep levels within the bandgap resulting in deep level emission (DLE). These point defects are introduced into the crystal lattice of the ZnO nanostructures during the growth and will increase the materials photocatalytic activities within the visible light spectrum and can shift the absorption towards the visible light band from 400 nm and up to 700 nm by creating intermediates states preventing electron–hole pair recombination and enhance photocatalytic activities.¹⁶ These defects explain all of the visible colors of luminescence observed from different ZnO samples.²²,²³ However the high recombination rate of photo-generated charge carriers are the most influential factor that limits the efficiency of the photocatalytic processes of the ZnO.¹²,¹³,¹⁸,¹⁹ To tackle these obstacle, and to increase the photocatalytic activities of the ZnO under visible solar light, variety of studies are conducted to increase the photocatalytic response of the ZnO through coupling with other semiconductors or photosensitizer to form an efficient heterostructure material.¹²,²⁰,²¹ Currently, Ag-based compounds are regarded as an excellent candidate as a co-catalyst that can largely enhance solar energy conversion efficiency and charge separation, which lead to further boost the PEC performance. Recent studies have proven that the deposition of Ag-containing species on the surface of composites, can lead to effectively improve harvesting visible light and increase the photo-generated charge carriers separation owing to the surface plasmon resonance (SPR) effect.¹²,¹³,¹⁹,²¹ The net result will be an enhanced PEC activity of the Ag containing composites. In this regard, silver tungsten (Ag₂WO₄) with a band gap between 2.9–3.1 eV, have been used for preparation of different outstanding plasmonic photo-catalysts. For example, Vignesh et al.²² studied the photocatalytic activity of Ag₂WO₄/g-C₃N₄ nanocomposite for
degradation of methylene blue (MB) under solar light radiation. Their result showed an enhancement on the degradation efficiency of MB. Also, Jingjing Li investigated the formation of Ag₂WO₄/AgX (X = Cl, Br, I) hybrid nanorods to enhance visible light driven PEC properties. Recently, Pirhashemi et al. reported a highly enhanced photodegradation of organic pollutants with a plasmonic ZnO/Ag₂WO₄ heterostructures. Very recently, an effective PEC performance is achieved through Ag₂WO₄/AgX (X = Cl, Br, I) sensitized TiO₂ nanotube array, and the deposition of the Ag₂WO₄ was carried out by the successive ionic layer adsorption and reaction (SILAR) method. According to the literature review, Ag/Ag₂WO₄ is a promising candidate to be used to develop a plasmonic sensitizer for ZnO nanostructures for optimum utilization of the solar power and accelerating charge transfer, leading to greatly enhance the PEC activities. Considering the above review, we report in this work the synthesis, characterization, and PEC activities of Ag/Ag₂WO₄ grown on top of ZnO nanorods (NRs). Firstly, ZnO NRs is synthesized using the hydrothermal low temperature chemical method. This was followed by the Ag/Ag₂WO₄ deposition on top of the ZnO NRs using the SILAR method. To the best of our knowledge there are no reports about the preparation and study of a plasmonic ZnO/Ag/Ag₂WO₄ photo-electrode for PEC activities. Our results showed an enhancement on the photocurrent and the current–voltage measurements. These observations are promising results for water splitting applications.

2 Experimental part

2.1 Photoelectrode preparation

The photoelectrode prepared in three steps: substrate preparation, growth of ZnO NRs, and deposition of Ag/Ag₂WO₄ as shown in the schematic diagram in Fig. 1 which explained in the following section.

2.1.1 Substrate preparation

2.1.1.1 Au coated glass preparation. In our work we have been using Au coated glass substrate that is prepared as described below, because Au coated glass has been used by many researchers as efficient electrode after deposition of ZnO based nanostructures materials, and with SPR effect. Also, it is found that the stability of electrodes can be improved by deposition of thin layer of gold. Therefore, Au coated glass was used as substrate to grow ZnO NRs and ZnO/Ag/Ag₂WO₄ heterostructure for PEC performance. For Au coated glass preparation, glass substrates were cleaned with acetone, isopropanol, and deionized water, respectively under ultrasonic bath for about 15 min. Then, the substrates were fixed into a vacuum chamber of an evaporator instrument. After that, an adhesive layer of 20 nm of titanium was evaporated followed by a 100 nm thickness layer of gold.

2.1.1.2 Deposition of seed layer. Then a seed solution contains ZnO nanoparticles (NPs) deposited on to the substrate via spin coating at 3000 rpm for 25 s. The spin coating was repeated three times to have full and uniform coverage of the ZnO NPs onto the substrate. After that, the substrates were dried into an air oven at 120 °C for 10 min. The ZnO seed precursor was prepared by adding potassium hydroxide (KOH) solution (0.03 M in methanol) drop wise into zinc acetate dehydrate solution (0.01 M in methanol) under magnetic stirring (750 rpm) at 60 °C for 2 h.

2.1.2 Growth of ZnO NRs. The ZnO NRs were grown on the above prepared substrates containing the seed layer of ZnO NPs by low temperature aqueous chemical growth. The precursor solution was prepared by dissolving equal molecular (0.05 M) of zinc nitrate hexahydrate [Zn(NO₃)₂·6H₂O] and hexamethylenetetramine (HMT) in deionized (DI) water. The substrates that contain seed layer were immersed horizontally after they were fixed in Teflon sample holder into the precursor solution and loaded into a preheated oven at 90 °C for 5 hours. After the samples were cooled down to the room temperature, they were rinsed with DI water to remove any undesired particles, then dried with blowing nitrogen for few seconds and kept for further process.

2.1.3 Deposition of Ag/Ag₂WO₄ on ZnO NRs. Ag₂WO₄ was deposit on the prepared ZnO NRs using SILAR method. An
anionic and cationic aqueous precursor solutions was prepared separately using 0.05 M of silver nitrate (Ag(NO₃) and 0.05 M of sodium tungstate (Na₂WO₄·2H₂O), respectively. The deposition take place by immersion of the prepared ZnO NRs sample into Ag(NO₃) solution for 2 minutes to absorb the silver ions (Ag⁺) and then they were washed with DI water to remove excess ions or any other particles. Then the sample immersed into the Na₂WO₄·2H₂O solution for 2 minutes and again washed with DI water. This cycle was repeated for 10 times to obtain enough Ag/Ag₂WO₄ particles on the ZnO NRs. Also, Ag/Ag₂WO₄ was deposited on ZnO NRs that grown on a pure glass substrate for some optical characterization.

2.2 Characterization

Powder X-ray diffraction (XRD) was used to study the structural properties of the prepared samples using Philips powder diffractometer (1729 PW) equipped with (Cu Kα) radiation with generator running at voltage of 40 kV and current of 40 mA. Field emission scanning electron microscope (FE-SEM) using a LEO 1550 Gemini field emission gun at 15 kV was used to investigate the morphology of the prepared samples. The corresponding energy depressive X-ray (EDX) with EDX mapping was investigated to identify the elemental and chemical properties of the prepared samples. The absorption spectra of the prepared samples were characterized by Perkin Elmer Lambda 900 UV-visible spectrophotometer. The chemical composition of the samples was investigated using X-ray photoelectron spectroscopy (XPS) which recorded by Scienta ESCA-200 spectrometer using monochromatic Al Kα X-ray source with a power of (1486.6 eV).

The photoelectrochemical activities were studied by using three electrode photoelectrochemical measurements using SPE-200 potentiostat (Bio-Logic, Claiix, France). A platinum (Pt) sheet was used as the counter electrode and a standard Ag/AgCl in 3 M KCl (as a reference electrode) was used with (0.1 M) of sodium sulfate (Na₂SO₄) electrolyte. The total area of the electrode that immersed in the electrolyte was 1 cm². The sun light was obtained by a solar simulator that uses a 100 W ozone free xenon lamp with an output power of 1 sun (AM 1.5).

3 Result and discussion

3.1 Characterization analysis

Fig. 2 shows the structural investigation by XRD for ZnO and ZnO/Ag/Ag₂WO₄ samples. It could be observed that all the obtained XRD diffraction peaks in Fig. 2(a) are belonging to the hexagonal wurtzite pure phase of ZnO (JCPDS no. 36-1451) which suggest that there are no other phases of ZnO or impurities have been observed. In the XRD pattern of ZnO/Ag/Ag₂WO₄ heterostructure (Fig. 2(b)), more peaks were identified, which were assigned to the planes (042), (025), and (135) for Ag₂WO₄ (JCPDS no. 33-1195). The peak at 78° is assigned to the reflections of cubic Ag (JCPDS no. 65-2871).²⁸

Fig. 3(a) and (b), shows the morphology of ZnO NRs and ZnO/Ag/Ag₂WO₄ heterostructure that was measured by the FE-SEM imaging. Fig. 3(a) shows the SEM image of the ZnO NRs, which reveal that the ZnO NRs were vertically aligned and are having hexagonal shape as expected. The diameter size of the ZnO NRs found to be ~100 nm. After deposition of the Ag/Ag₂WO₄ on the ZnO NRs, a heterostructure was formed and Ag/Ag₂WO₄ particles were distributed on the surface of the ZnO NRs as it can be seen in Fig. 3(b). Ag/Ag₂WO₄ nanoparticles size were estimated from SEM imaging to vary between ~30 to ~150 nm, the bigger size of the nanoparticles might be due to the agglomeration of smaller nanoparticles. It is worth to note that the SPR effect depends on the size and the shape of the nanostructure, and it is quite unique in the nanostructures size from 10 to 100 s of nanometers.²⁸ Therefore, the size of the prepared ZnO/Ag/Ag₂WO₄ heterostructure are favorable for SPR effect. The corresponding EDX spectrum of the ZnO/Ag/Ag₂WO₄ heterostructure were examined to show the composition of elements in the sample which consists of Zn, O, Ag, and W without any other elements detected (see Fig. 3(c)).

The EDX result is in good agreement with the XRD result. To further understand the distribution of the elements, the ZnO/Ag/Ag₂WO₄ photo-electrode was further studied by elemental mapping analysis, as shown in Fig. 3(d). From the present elementals map with particular colors for each element, it is clear that the Zn, O, Ag and W components are uniformly distributed on the sample. It is worth noting that better distribution provides strong physical coupling between counterparts. Hence, it is beneficial to efficient generation and separation of charge carriers which leads to superior PEC performance of the nanocomposite. Moreover, the EDX mapping of the ZnO NRs after it was immersed into the Ag (NO₃) solution and before the synthesis of the Ag₂WO₄ was examined for the confirmation of the Ag nanoparticles existence into the heterostructure. As it can be seen in Fig. 4, Ag was detected.

Furthermore, the chemical state of the elements in ZnO/Ag/Ag₂WO₄ heterostructure were examined by XPS measurements. The XPS peaks of the all elements in the ZnO/Ag/Ag₂WO₄ are observed in Fig. 5. The observed XPS spectrum shown in Fig. 5 is in agreement with the EDX result that was presented in Fig. 3.
The XPS peak of C 1s at 284.6 eV is related to carbon from the XPS instrument. Fig. 6(a) shows the XPS core level spectra of Zn 2p of ZnO/Ag/Ag2WO4 heterostructure which is composed of two peaks centered at 1022.43 and 1045.25 eV, which are attributed to the binding energy lines of Zn 2p3/2 and Zn 2p1/2, respectively and they represented the formation of Zn–O bonds within the ZnO crystal lattice. Fig. 6(b) shows the O1s core level XPS spectra of ZnO/Ag/Ag2WO4 heterostructure which is divided into two peaks. The peak at low binding energy centered at 531.15 eV, is related to oxygen deficient region, whereas, the peak at higher binding energy centered at 532.58 eV can be ascribed to the oxygen on the ZnO surface and water molecules H2O. The XPS spectrum of Ag 3d is shown in Fig. 6(c). The peaks at 368.21 and 374.23 eV are assigned to Ag 3d5/2 and Ag 3d3/2, respectively. The Ag 3d5/2 is further divided into two different peaks at 367.87 and 368.47 eV and the Ag 3d3/2 peak is also divided into two different peaks at 373.89 and 374.40 eV. The peaks at low energies 367.87 and 373.89 eV are accounted for the Ag+ in Ag2WO4, whereas, the peaks at higher energies 368.47 and 374.40 is related to metallic Ag0. The UV-vis absorption spectra of the ZnO and ZnO/Ag/Ag2WO4 heterostructure show similar absorption trends (see Fig. 7). Compared to pristine ZnO NRs, ZnO/Ag/Ag2WO4 heterostructure exhibits an obvious red shift of the optical absorption in the visible region (>400 nm). The optical band gaps were found to be 3.2 and 3.1 eV for ZnO and ZnO/Ag/Ag2WO4, respectively. This result could be explained due to formation of Ag2WO4 on the top of the ZnO NRs forming the heterostructure (i.e. bandgap engineering). Also, note that metallic silver could be produced during the sample preparation and can trigger surface plasmonic effect.

3.2 Photoelectrochemical and water oxidation analysis

The charge carrier characteristics at the semiconductor/electrolyte interface for pristine ZnO NRs and ZnO/Ag/Ag2WO4 heterostructure were examined via linear sweep voltammetry measurements as shown in Fig. 8. From Fig. 8 both pristine ZnO NRs and ZnO/Ag/Ag2WO4 heterostructure showed a reasonable response upon illumination by solar light, whereas the response at dark is relatively shows very low and flat curves were observed. However, the I–V curve of the ZnO/Ag/Ag2WO4 photo-electrode under simulated sun light confirms a higher photoelectric conversion than that of the ZnO NRs photo-electrode. The observed photocurrent density at the potential of 1.23 V
(vs. Ag/AgCl) is 0.9 mA cm\(^{-2}\) for ZnO NRs and increased by a factor of three to 3 mA cm\(^{-2}\) for the ZnO/Ag/Ag\(_2\)WO\(_4\) photo-electrode. This result might be attributed to the higher separation and transportation of photo-induced charge carriers\(^25\) due to the presence of the Ag/Ag\(_2\)WO\(_4\) particles that affected the band gap of the heterostructure. In addition to that, the presence of metallic Ag\(_0\) particles (as discussed above in the XPS analysis) would enhance the absorption of visible light and then improve the separation rate of the photo-generated electrons–holes pairs because of the SPR effect which can locally amplify the incident electromagnetic field at the metal surface by several orders of magnitude.\(^{12,29}\)

The photo response over time of the samples were investigated through the chronoamperometry measurements which record the photocurrent density versus time in dark (light off) and under illumination (light on) with an applied potential of 0.5 V as shown in Fig. 9. From Fig. 8 we could see the result with different amount of Ag/Ag\(_2\)WO\(_4\) that was prepared by different SILAR cycles. It is clear that the photo response increases with increasing the number of SILAR cycles. However, the photocurrent is decreased when the deposition cycle increased up to 15 times. The possible reason for that is the effect of additional deposition cycles lead to the formation of larger aggregates around the ZnO NRs. In turn, this might cause a destruction of the junctions and the result of that is that the separation of the charge carriers at the interfaces of the heterojunction will be reduced. The photocurrent density of the ZnO was found to be 0.6 mA cm\(^{-2}\), and it is increased to 1.6 mA cm\(^{-2}\) after deposition of Ag/Ag\(_2\)WO\(_4\) 10 times on the ZnO NRs.

To understand the electronic properties of the ZnO/Ag/Ag\(_2\)WO\(_4\) in contact with the electrolyte solution, we performed electrochemical impedance measurement in dark and Mott–Schottky (M–S) plot (1/C\(^2\) versus potential) was analyzed. One can extrapolate the position of the flat band potential \(V_{FB}\) (versus Ag/AgCl) from the x-axis intercept at selected frequency (3 kHz), which was found to be +0.60 and +0.4 V for ZnO and ZnO/Ag/Ag\(_2\)WO\(_4\) photo-electrodes, respectively (see Fig. 10). The shift in \(V_{FB}\) is suggesting the presence of more surface states which

---

**Fig. 4** EDX mapping show the elements distribution for the ZnO NRs after immersion on the AgNO\(_3\) solution and before the synthesis of the Ag\(_2\)WO\(_4\) for Ag nanoparticles detection confirmation. The red dots represent Ag that appears very clearly to exist on top of the ZnO NRs.

**Fig. 5** XPS spectrum survey scan of the ZnO/Ag/Ag\(_2\)WO\(_4\) heterostructure.
could lead to considerable change in the band position. The positive slopes were determined from M–S plot indicated the n-type nature of the samples. From the dielectric constant of ZnO ($\varepsilon = 10$) and the permittivity of vacuum ($\varepsilon_0 = 8.85 \times 10^{-14}$ F cm$^{-1}$) the charge carrier density can be calculated from eqn (1):

$$N_d = \frac{2}{\varepsilon_0 \varepsilon_0 [d(1/C^2)dV]}$$  \hspace{1cm} (1)

The charge carrier densities were found to be $\sim 2.8 \times 10^{19}$ and $\sim 2.5 \times 10^{19}$ cm$^{-3}$ for ZnO NRs and ZnO/Ag/Ag$_2$WO$_4$ photo-electrodes, respectively which are of the same order. The estimated values of flat band potential and charge carrier densities are in the agreement with those reported previously in the literature.

The incident photon to current conversion efficiency (IPCE) is used in PEC to measure the efficiency of converting an individual photon to an extractable electron. Which performed with a monochromator light source to have a spectral distribution that is selective by wavelength in the range (300–700 nm), and at the same time the current density generated at each wavelength were measured. Then IPCE is calculated from eqn (2):

$$\text{IPCE\%} = \frac{1240 \times I_{ph}}{\lambda \times J_{light}} \times 100$$  \hspace{1cm} (2)

where $I_{ph}$ is the photocurrent density, $\lambda$ is the incident wavelength and $J_{light}$ is the incident irradiation.
Fig. 11 compares the IPCE curves for ZnO NRs, and the ZnO/Ag/Ag₂WO₄ photo-electrodes. In general, the IPCE curves of the pristine ZnO NRs and the ZnO/Ag/Ag₂WO₄ photo-electrodes are consistent with the optical absorption spectra of the pristine ZnO NRs, and ZnO/Ag/Ag₂WO₄ photo-electrodes. The ZnO photo-electrode exhibits PEC activity on the UV region and exhibits some activities in the visible region but it is relatively weaker than that for the UV region. For the ZnO/Ag/Ag₂WO₄ photo-electrode, the photo response range of IPCE is slightly extended in the UV and visible light region in addition to the increase in IPCE, in accordance with the improved optical absorption including increased absorption and extended absorption region of the ZnO/Ag/Ag₂WO₄. The extension of the IPCE in the visible region between 400 to 450 is suggested to be due to the effect of SPR. The enhancement in the IPCE is more remarkable than the increase in optical absorption of the ZnO/Ag/Ag₂WO₄ as compared to that of the ZnO NRs, which is increased by factor of 1.5. At the wavelength 400 nm the IPCE value is 30% for ZnO/Ag/Ag₂WO₄ and 20% for ZnO NRs. This can be attributed to the role of Ag⁰ that is embedded during the sample preparation. The Ag⁰ is expected to facilitate the transfer of electrons generated in ZnO and Ag₂WO₄ under solar illumination in the PEC process.

3.3 Proposed photoelectrochemical mechanism for water oxidation

It is known to all that the enhancement of PEC activity of semiconductor-based photo-electrodes was mainly attributed to electrons and holes transfer at the interfaces of the photo-electrodes. It is clear that the band edge potential values of the ZnO and the Ag/Ag₂WO₄ materials played an important role in the efficiency of generation and separation process of the electrons and holes pairs. The conduction band (CB) and valence band (VB) edge potential of a semiconductor at the point of zero charge can be estimated by the Mulliken electronegativity theory:

\[ E_{VB} = X - E^e + 0.5E_g \]  \hspace{1cm} (3)

where \( E^e \) is the energy of free electrons on the hydrogen scale (about 4.5 eV) and \( E_{VB} \) is the VB edge potential. \( X \) is the absolute electronegativity of the semiconductor, and \( E_g \) is the band gap energy of the semiconductor. Meanwhile, the CB edge potential \( (E_{CB}) \) can be calculated by the equation:

\[ E_{CB} = E_{VB} - E_g \]  \hspace{1cm} (4)

Here, the \( X \) values for ZnO and Ag₂WO₄ are about 5.76 and 5.98 eV, and the \( E_{VB} \) of ZnO and Ag₂WO₄ are calculated to be +2.86 and +3.03 eV, respectively. Moreover, \( E_{CB} \) of ZnO and Ag₂WO₄ are estimated to be −0.34 and −0.07 eV, respectively. Depending on the above results, a probable mechanism of the PEC activity can be described as illustrated in Fig. 12. In the presence of solar light, both the semiconductors absorb light and the electrons in the VB get excited up to a higher potential of −0.07 eV for the Ag₂WO₄ and −0.34 eV for the ZnO. Therefore, the effective charge transfer process proceeds within the...
Due to the SPR effect, Ag nanoparticles cause effective separation of electron/hole pairs upon absorption of visible light. Electrons from the Ag nanoparticles are transferred to the CB of the ZnO and the Ag2WO4, while holes remain in the Ag nanoparticles. Meanwhile, the photogenerated electrons in the CB of C will be transferred to the Ag nanoparticles to occupy the vacant holes generated by the plasmonic absorption. With this mechanism, the photo-generated charge carriers can be efficiently separated, resulting in an enhanced PEC performance. Furthermore, the photo-generated electrons will ultimately arrive at the Pt counter electrode and contribute to H2 production. Also, the photo-generated holes in the valence band of ZnO NRs and Ag2WO4 will contribute on O2 generation through water oxidation. Therefore, these results confirm that the Ag/Ag2WO4 modification is an effective way to obtain a high PEC activity using ZnO NRs arrays.

4 Conclusion

In summary, we report a preparation of ZnO/Ag/Ag2WO4 photo-electrode for PEC water oxidation with surface plasmonic resonance behavior via low temperature hydrothermal chemical growth followed by SILAR method. The structural and morphology characterization studies revealed that ZnO/Ag/Ag2WO4 heterostructure was prepared successfully. Whereas the EDX and XPS characterization confirms the elemental composition of ZnO/Ag/Ag2WO4 which consist of Zn, O, Ag, and W without any other elements detected, and the energy state of the elements on ZnO/Ag/Ag2WO4 heterostructure. ZnO/Ag2WO4 heterostructure shows an obvious red shift of the optical absorption in the visible region than that of pristine ZnO NRs with calculated optical band gaps of 3.2, and 3.1 eV for ZnO NRs and ZnO/Ag/Ag2WO4, respectively. Compared with ZnO NRs, the ZnO/Ag/Ag2WO4 exhibits a higher PEC performance. By the deposition of the Ag/Ag2WO4 on the ZnO NRs, a new heterostructure was obtained via SILAR method, leading to higher photocurrent of 3 mA cm\(^{-2}\) measured at 1.23 V (vs. Ag/AgCl) for ZnO/Ag/Ag2WO4, which is 3 times the photocurrent achieved by ZnO NRs photo-electrode. Also, the photo response over time shows a higher photocurrent for the ZnO/Ag/Ag2WO4 photo-electrode (1.6 mA cm\(^{-2}\)) compared to that of the ZnO NRs photo-electrode (0.6 mA cm\(^{-2}\)). In addition to that, the overall IPCE of the ZnO/Ag/Ag2WO4 photo-electrode was observed to increase by a factor of 1.5 compared to the ZnO NRs photo-electrode with extension of the IPCE curve in the visible light region due to the SPR effect. The high PEC performance of our samples could be attributed to the higher separation and transportation of photo-induced charge carriers. This is due to the enhancement in the absorption of visible light which improves the separation rate of the photo-generated electron–hole pairs because of the band gap engineering and to the SPR effect of the metallic silver that was introduced during the sample preparation. Our study exposes the potential of ZnO/Ag/Ag2WO4 photo-electrode for high performance in PEC water splitting.

Conflicts of interest

There are no conflicts of interest to declare.
Acknowledgements

The authors acknowledge the department of Science and Technology (ITN), at Campus Norrköping, Linköping University, Sweden for partial financial support. Sami Elhag acknowledges the partial financial support from the Aedges through the project no 17-457.

References