


 Cite this: *RSC Adv.*, 2021, 11, 12442

Prominent roles of Ni(OH)₂ deposited on ZnIn₂S₄ microspheres in efficient charge separation and photocatalytic H₂ evolution†

 Zhuang Guo, Huixia Hou, Jingyi Zhang, Pinglong Cai and Jun Lin *

In this work, Ni(OH)₂-deposited ZnIn₂S₄ microspheres (Ni(OH)₂/ZnIn₂S₄) were fabricated using a hydrothermal process, followed by a facile *in situ* precipitation method. It was demonstrated that the deposition of Ni(OH)₂ on ZnIn₂S₄ effectively promotes the separation of charges photogenerated over ZnIn₂S₄, and significantly enhances photocatalytic H₂ evolution. The optimum rate of the photocatalytic H₂ evolution over the 6% Ni(OH)₂/ZnIn₂S₄ composite reaches 4.43 mmol g⁻¹ h⁻¹, which is 21.1 times higher than that of the pure ZnIn₂S₄. Based on various characterization results and Au photo-deposition on the composite, it was proposed that the capture of the photogenerated holes by the deposited Ni(OH)₂ would be responsible for the efficient charge separation, which allows more photogenerated electrons to be left on the ZnIn₂S₄ for the reduction of H⁺ to H₂ with a higher rate.

 Received 2nd March 2021
Accepted 23rd March 2021

DOI: 10.1039/d1ra01648b

rsc.li/rsc-advances

1. Introduction

Photocatalytic hydrogen production by water splitting has become one of the sustainable and environmentally friendly strategies for solving the consumption of fossil fuels and the resulting environmental pollution.^{1–3} For the full utilization of solar energy, a considerable number of narrow band gap semiconductors have been widely investigated as visible light photocatalysts for hydrogen production. Of these semiconductors, CdS, g-C₃N₄, and ZnIn₂S₄ have received intensive attention since their band gaps match well with the spectrum of sunlight, and their conduction band edges are more negative than the redox potential of H⁺/H₂.^{4–6} Unfortunately, the direct application of these semiconductors themselves for photocatalytic H₂ production is almost infeasible mainly due to their rapid charge recombination.^{7–9} For an efficient photocatalytic H₂ production reaction, it is indispensable to load a noble metal such as Pt, Pd, Ag, or Au as a cocatalyst on the host semiconductors.^{10–13} The noble metals as cocatalysts can not only facilitate the separation of electron–hole pairs over host semiconductor effectively, but also function as active sites for H₂ production. Nevertheless, the high cost and scarcity of these noble metals seriously hinder their practical application. Therefore, it is desirable to exploit noble metal-free, abundant, and durable cocatalysts for photocatalytic H₂ production.

Recently, numerous works reported that the modification of various narrow band gap semiconductors with molybdenum disulfide (MoS₂), an earth-abundant compound, significantly enhances photocatalytic H₂ production from water splitting and quantum efficiency.^{14–16} Both experimental and computational results also well revealed the photogenerated charge transfer, capture, and active sites for H₂ production in the systems with MoS₂ as a cocatalyst.^{17,18} Afterward, other transition metal (*e.g.* Ni, Co, Cu, Fe) disulfides and phosphides have been investigated and utilized as cocatalysts for assisting photocatalytic H₂ production.^{19–22} In addition, hydroxide can also act as a cocatalyst for photocatalytic H₂ production. In 2011, a typical pioneer work reported that Ni(OH)₂-decorated TiO₂ could give a H₂ evolution rate of 3056 μmol g⁻¹ h⁻¹ and a quantum efficiency of 12.4% under UV irradiation, which is 233 times than that of pure TiO₂.²³ Following this work, hydroxides such as Ni(OH)₂ and Co(OH)₂ have been widely applied as cocatalysts for photocatalytic H₂ production by coupling with proper narrow band gap semiconductors including CdS, g-C₃N₄, and ZnIn₂S₄.^{24–29} These works have well demonstrated that the hydroxides are capable of being alternatives for noble metal cocatalysts, and deserve more and further attention in photocatalytic H₂ production. Especially, the deepening of the knowledge of photogenerated charge transfer, capture, and active sites for H₂ production would be helpful for the design and optimization of hydroxide-modified photocatalysts. In the present work, we fabricated the Ni(OH)₂-deposited ZnIn₂S₄ composites by a facile *in situ* precipitation method. Upon visible light irradiation, the photocatalytic activity of ZnIn₂S₄ for H₂ evolution has been shown to be significantly enhanced after the deposition of Ni(OH)₂. Furthermore, the roles of the deposited Ni(OH)₂ in the enhanced photocatalytic H₂ evolution of the composite were

Department of Chemistry, Renmin University of China, Beijing 100872, People's Republic of China. E-mail: jlin@ruc.edu.cn; Fax: +8610-62516444; Tel: +8610-62514133

† Electronic supplementary information (ESI) available. See DOI: 10.1039/d1ra01648b



revealed according to various characterization results and photodeposition of Au nanoparticles on the composite. This work, we believe, offers a new insight into the photogenerated charge capture, separation, and active sites for H₂ evolution in the composite.

2. Experimental section

2.1. Sample preparation

ZnIn₂S₄ samples were synthesized by a literature method with a slight modification.³⁰ Briefly, 0.2862 g of ZnCl₂ and 1.2484 g of InCl₃·4H₂O were dissolved in 40 ml of distilled water under vigorous stirring, followed by the addition of polyethylene glycol (PEG-6000, 0.8836 g) and thioacetamide (TAA, 1.2096 g). The obtained mixture, a homogeneous solution, was transferred into a 100 ml Teflon-lined stainless steel autoclave and heated at 160 °C for 16 h in an oven. After cooled down to room temperature naturally, the yellow products ZnIn₂S₄ were collected by centrifugation and washed with water and ethanol for three times before dried at 60 °C in a vacuum oven for overnight.

The deposition of Ni(OH)₂ on the surface of ZnIn₂S₄ was conducted by a facile *in situ* precipitation method. In a typical procedure, 0.2 g of the as-prepared ZnIn₂S₄ was dispersed in 50 ml of NaOH aqueous solution (0.25 M). Under agitation, into the dispersion was the desired amount of Ni(NO₃)₂·6H₂O aqueous solution (0.05 M) added dropwise. The resulting mixture was stirred for 5 h at room temperature. Subsequently, the final product was collected by centrifugation, and thoroughly washed with deionized water, and finally dried in a vacuum oven at 60 °C for 12 h. According to the nominal molar ratios of Ni(NO₃)₂ to (Ni(NO₃)₂ + ZnIn₂S₄) in the above procedure, the obtained samples were denoted as 0%, 2%, 4%, 6%, and 8% Ni(OH)₂/ZnIn₂S₄, respectively.

2.2. Characterization

The polycrystalline X-ray diffraction (XRD) patterns of the prepared samples were collected on an X-ray diffractometer (Shimadzu, XRD-7000) with Cu K α radiation under 40 kV and 150 mA. The morphological and microstructural features of the samples were captured by using a field-emission scanning microscope (FESEM) (JEOL 6701F) and a high-resolution transmission electron microscope (HRTEM) (JEOL-2010), respectively. X-ray photoelectron spectroscopy (XPS) analysis was performed in a Thermo ESCALAB 250 electron spectrometer with a monochromatic Al K α source. All the binding energies were referenced to the C 1s peak of the surface adventitious carbon at 284.6 eV. The optical absorption properties of the samples were analyzed with UV-visible diffuse reflectance spectroscopy (Hitachi UH-4150) with BaSO₄ as a reflectance standard.

Transient photocurrent response and electrochemical impedance spectroscopy (EIS) measurements were carried out in a three-electrode system on an electrochemical work station (Chenhua, Shanghai). A Pt wire and a Ag/AgCl in a saturated KCl solution were employed as the counter electrode and the reference electrode, respectively. The working electrode was prepared

by coating sample slurry onto ITO glass substrate with a fixed area of 1 × 1 cm² followed by drying with an infrared lamp irradiation. A 1.0 M Na₂SO₄ aqueous solution was used as the electrolyte for both photocurrent response and electrochemical impedance spectroscopy (EIS) measurements. The visible light irradiation source is a 3 W monochromatic light (λ = 420 nm).

2.3. Photocatalytic experiments

The experiments of the photocatalytic H₂ production over these prepared samples irradiated by visible light were carried out in a gas-closed Pyrex flask at ambient temperature. Typically, 20 mg of the prepared sample powder was suspended in 100 ml of 10 vol% lactic acid aqueous solution under magnetic stirring. The suspension was thoroughly degassed with N₂ for 30 min before irradiated by a 300 W Xe arc lamp (LabSolar II, Perfect Light Co., Ltd) equipped with a cut-off filter (λ > 420 nm). The amount of hydrogen evolution during the reaction was periodically analyzed by a gas chromatography (GC-2014C, Shimadzu, Japan) with a TCD detector and a molecular sieve 5A column with N₂ as the carrier gas.

To study the reduction sites for H₂ evolution in the Ni(OH)₂/ZnIn₂S₄ composite, the photocatalytic deposition of Au on 6% Ni(OH)₂/ZnIn₂S₄ was performed at ambient temperature. Briefly, 50 mg of 6% Ni(OH)₂/ZnIn₂S₄ composite was dispersed in 50 ml of 10 vol% benzyl alcohol aqueous solution under stirring, followed by the addition of 52 μ l of HAuCl₄·4H₂O aqueous solution (1 g/50 ml). Prior to the irradiation by a 300 W Xe arc lamp (LabSolar II, Perfect Light Co., Ltd) equipped with a cut-off filter (λ > 420 nm), the dispersion was thoroughly degassed with N₂ for 30 min. After the irradiation for 2 h, the composite was collected by centrifugation, washed with ethanol and water several times, and finally dried at 60 °C in a vacuum oven overnight for further TEM observation.

3. Results and discussion

3.1. Phase structure and morphology

The polycrystalline X-ray diffraction patterns of the prepared pure ZnIn₂S₄ and Ni(OH)₂/ZnIn₂S₄ composites are shown in

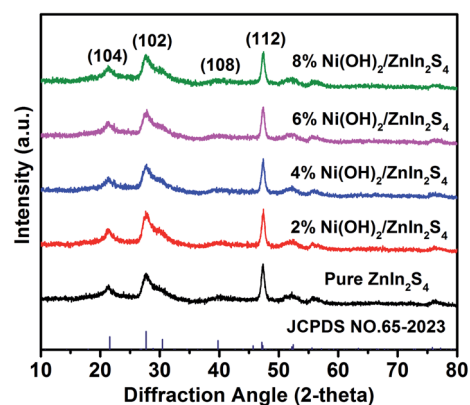


Fig. 1 Polycrystalline X-ray diffraction patterns of pure ZnIn₂S₄ and Ni(OH)₂/ZnIn₂S₄ composites.

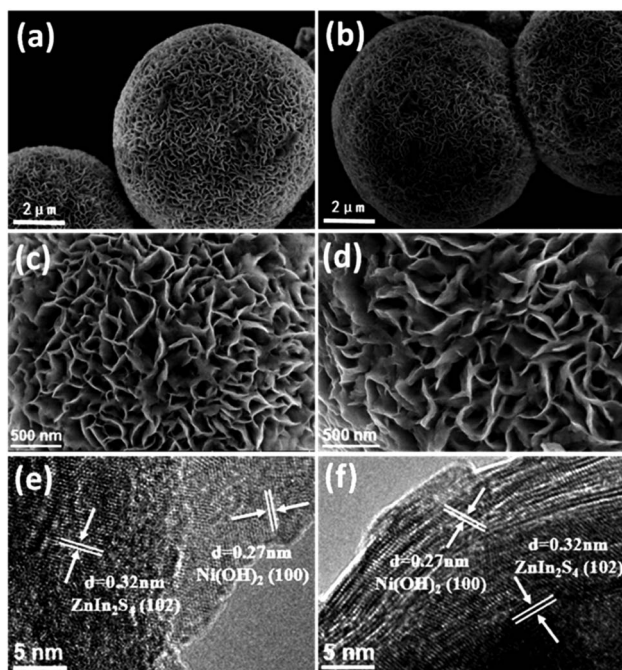


Fig. 2 FESEM images of (a and c) pure ZnIn_2S_4 and (b and d) 6% $\text{Ni}(\text{OH})_2/\text{ZnIn}_2\text{S}_4$ with different scales; (e and f) HRTEM images of 6% $\text{Ni}(\text{OH})_2/\text{ZnIn}_2\text{S}_4$.

Fig. 1. All samples exhibit a single characteristic hexagonal phase of ZnIn_2S_4 (JPCDS no. 65-2023), and no changes in the intensities and widths of the XDR peaks occur with the $\text{Ni}(\text{OH})_2$

loading. These indicate that the deposition of $\text{Ni}(\text{OH})_2$ on ZnIn_2S_4 doesn't alter the phase structure and crystallinity of ZnIn_2S_4 substrate. Notably, the relative intensity of (112) diffraction peak at approximately 47.5 degree for all samples is obviously enhanced as compared to the corresponding one of the reference (JPCDS no. 65-2023). This is perhaps due to the preferential orientation growth of the crystalline plane (112) in our synthesis process. Moreover, no characteristic XRD peaks associated with $\text{Ni}(\text{OH})_2$ are observed in all $\text{Ni}(\text{OH})_2/\text{ZnIn}_2\text{S}_4$ composites, which is probably due to the low content and high dispersion of $\text{Ni}(\text{OH})_2$ on ZnIn_2S_4 . The presence of $\text{Ni}(\text{OH})_2$ would be confirmed by the HRTEM observation and XPS analysis below.

Fig. 2a and b display the FESEM images of the pure ZnIn_2S_4 and 6% $\text{Ni}(\text{OH})_2/\text{ZnIn}_2\text{S}_4$ composite, respectively. As can be seen in Fig. 2a, the pure ZnIn_2S_4 shows uniform microspheres with an average diameter of ca. 6–8 μm . These microspheres (Fig. 2c) consist of a great number of curling nanosheets, which could be helpful for the deposition of $\text{Ni}(\text{OH})_2$ and photocatalytic H_2 evolution by offering a large surface area. A careful observation (Fig. 2b and d) indicates that the introduction of $\text{Ni}(\text{OH})_2$ doesn't alert the morphology and size of ZnIn_2S_4 microsphere, except that the curling nanosheets become a little rough. The HRTEM images (Fig. 2e and f) of 6% $\text{Ni}(\text{OH})_2/\text{ZnIn}_2\text{S}_4$ composite reveals that the crystalline $\text{Ni}(\text{OH})_2$ are well deposited onto the surface of well-crystalline ZnIn_2S_4 to form heterostructures with the intimate interfaces.^{7,8} The lattice fringes with the spacing of ca. 0.32 nm and 0.27 nm well correspond to the crystallographic plane (102) of hexagonal ZnIn_2S_4 and the crystallographic plane (100) of hexagonal $\text{Ni}(\text{OH})_2$,

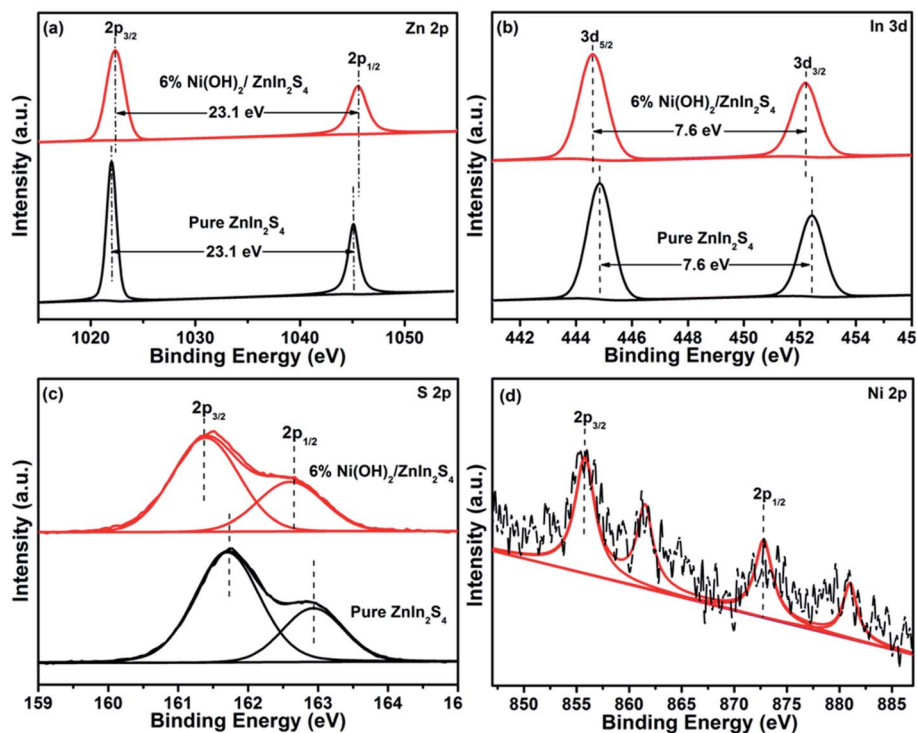


Fig. 3 High resolution XPS spectra of Zn 2p (a), In 3d (b), and S 2p (c) in pure ZnIn_2S_4 and 6% $\text{Ni}(\text{OH})_2/\text{ZnIn}_2\text{S}_4$, and Ni 2p (d) in 6% $\text{Ni}(\text{OH})_2/\text{ZnIn}_2\text{S}_4$.

respectively.^{25,31} The high-angle annular dark field-scanning transmission electron microscopy (HAADF-STEM) image (Fig. S1a†) and energy dispersive spectroscopy (EDS) elemental mapping (Fig. S1b–f†) analysis of 6% Ni(OH)₂/ZnIn₂S₄ composite was performed to characterize the elemental constitute and distribution. The elemental mapping confirms the uniform distribution of Zn, In, S, Ni, and O elements over the selected detection area of the composite. The weaker signals of Ni and O are well consistent with the lower molar percentage of Ni(OH)₂ in the composite.

3.2. XPS analysis and optical property

The compositions and chemical states of the elements in the pure ZnIn₂S₄ and 6% Ni(OH)₂/ZnIn₂S₄ were further analyzed by XPS. The XPS survey spectra, as displayed in Fig. S2,† clearly indicate the presence of Zn, In, S, O, and C in both samples, and Ni in 6% Ni(OH)₂/ZnIn₂S₄ only. Fig. 3a–c show the high resolution spectra of Zn 2p, In 3d, and S 2p regions of the pure ZnIn₂S₄ and 6% Ni(OH)₂/ZnIn₂S₄, respectively. In the Zn 2p core-level spectrum of pure ZnIn₂S₄ (Fig. 3a), two peaks at the binding energies of 1021.9 and 1045.0 eV, with a separation of 23.1 eV, are assigned to Zn 2p_{3/2} and Zn 2p_{1/2} of Zn²⁺, respectively.³² The two symmetric peaks of In 3d located at the binding energies of 444.8 and 452.4 eV in the In 3d core-level spectrum of pure ZnIn₂S₄ with a peak difference of 7.6 eV (Fig. 3b) are ascribed to In 3d_{5/2} and In 3d_{3/2} of In³⁺, respectively.^{33,34} The S 2p spectrum of pure ZnIn₂S₄ shown in Fig. 3c appears to be a broad peak, which can be deconvoluted two peaks with the binding energies of 161.7 and 162.9 eV, corresponding to S 2p_{3/2} and S 2p_{1/2}, respectively.^{31,35} Collectively, the binding energies of Zn, In, and S match well the feature of ZnIn₂S₄. The high resolution XPS spectrum of Ni 2p, as shown in Fig. 3d, clearly demonstrates two main peaks at 855.7 and 873.1 eV corresponding to typical Ni 2p_{3/2} and Ni 2p_{1/2}, respectively.²⁵ Two shake-up satellite peaks for Ni 2p_{3/2} and Ni 2p_{1/2} are observed at 861.5 and 880.8 eV. These binding energies of Ni 2p indicate the characteristic of Ni²⁺ in Ni(OH)₂ based on the literature reports.³⁶ It is worth noting that the deposition of Ni(OH)₂ on ZnIn₂S₄ cause a slight shift in the binding energies of Zn 2p, In 3d, and S 2p peaks. The observed shifts suggest a strong chemical bond between Ni(OH)₂ and ZnIn₂S₄, which would be favorable for the charge transfer between them. The XPS measurements evidence the formation of Ni(OH)₂-deposited ZnIn₂S₄ heterostructures with the well-contacted interfaces, further confirming the above HRTEM observation.

The optical absorption properties of the pure ZnIn₂S₄ and Ni(OH)₂/ZnIn₂S₄ composites with the different amount of deposited Ni(OH)₂ were investigated by UV-visible diffuse reflectance spectroscopy. As displayed in Fig. 4, the pure ZnIn₂S₄ exhibits an intense absorption with an edge at ca. 525 nm, which can be attributed to the intrinsic band gap absorption of hexagonal ZnIn₂S₄ (~2.36 eV). This coincides with the reported value of ZnIn₂S₄.³⁷ In contrast with the pure ZnIn₂S₄, the deposition of Ni(OH)₂ enhances the light absorption in the visible region. The absorption intensity of the composites in visible region gradually increases with the

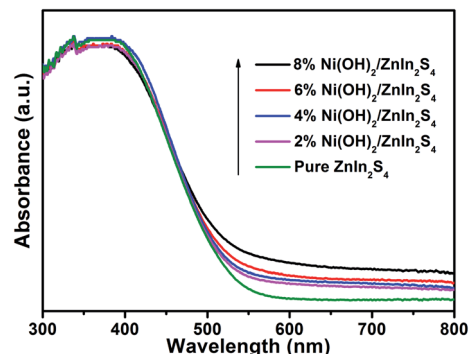


Fig. 4 UV-vis diffuse reflectance spectra of pure ZnIn₂S₄ and Ni(OH)₂/ZnIn₂S₄ composites.

increase of the molar ratio of Ni(OH)₂ in the composites. Furthermore, almost no obvious absorption edge differences among the absorption spectra of the pure ZnIn₂S₄ and Ni(OH)₂/ZnIn₂S₄ composites suggest the deposition of Ni(OH)₂ on the surface of ZnIn₂S₄.

3.3. Photocatalytic H₂ evolution

The photocatalytic H₂ evolution over the pure ZnIn₂S₄, Ni(OH)₂, and Ni(OH)₂/ZnIn₂S₄ composites was evaluated under visible light ($\lambda > 420$ nm) irradiation in the presence of lactic acid as a sacrificial reagent. Control experiments show that no appreciable H₂ evolution is detected in the absence of either visible light irradiation or catalyst. As depicted in Fig. 5a, H₂ evolution rate over the pure ZnIn₂S₄ is negligible due to the rapid recombination of electron–hole pairs over the irradiated pure ZnIn₂S₄, and also no appreciable H₂ activity is observed on pure Ni(OH)₂. However, a proper combination of both generates excellent photocatalytic H₂ evolution. As the deposition of 2% Ni(OH)₂ on ZnIn₂S₄, the rate of H₂ evolution is significantly enhanced to 2.20 mmol g⁻¹ h⁻¹. The rate of H₂ evolution further increases with the amount of deposited Ni(OH)₂, and reaches an optimum of 4.43 mmol g⁻¹ h⁻¹ over 6% Ni(OH)₂/ZnIn₂S₄, which is 21.2 times higher than that of pure ZnIn₂S₄. After the optimum, the reduction in H₂ evolution rate over 8% Ni(OH)₂/ZnIn₂S₄ would be attributed to the shielding effect of excessive Ni(OH)₂ which impedes the light absorption of the substrate ZnIn₂S₄. The above result well demonstrates the deposition of Ni(OH)₂ with an appropriate amount is an effective method for boosting the photocatalytic H₂ evolution over ZnIn₂S₄, which is consistent with the related literatures.²⁵

The stability of photocatalytic H₂ evolution over 6% Ni(OH)₂/ZnIn₂S₄ was examined by conducting the photocatalytic recycle experiments. As shown in Fig. 5b, after three recycle (12 h), no apparent decrease in H₂ evolution over the composite can be observed, indicating the good stability of the composite for photocatalytic H₂ evolution.

3.4. Mechanism of enhanced photocatalytic H₂ evolution over Ni(OH)₂/ZnIn₂S₄

To understand the mechanism of the enhanced photocatalytic H₂ evolution over Ni(OH)₂/ZnIn₂S₄, the role of the deposited

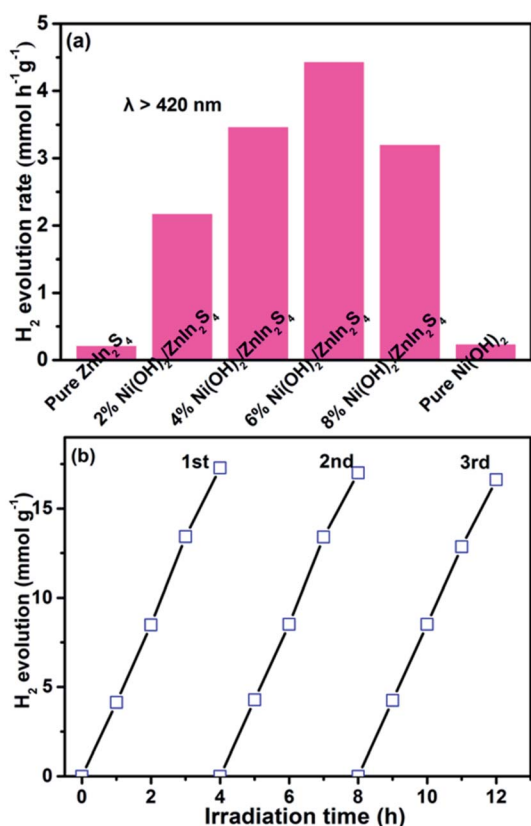


Fig. 5 (a) Photocatalytic H₂ evolution rates over pure ZnIn₂S₄, Ni(OH)₂, and Ni(OH)₂/ZnIn₂S₄ composites. (b) Cycling photocatalytic H₂ evolution over 6% Ni(OH)₂/ZnIn₂S₄.

Ni(OH)₂ on the surface of ZnIn₂S₄ in the transfer and separation of charges photogenerated over ZnIn₂S₄ was investigated by measuring the transient photocurrent response. Fig. 6a shows the transient photocurrent responses of the pure ZnIn₂S₄ and 6% Ni(OH)₂/ZnIn₂S₄ under visible light irradiation ($\lambda = 420$ nm) with 50 s light on/off cycles. It can be clearly observed that 6% Ni(OH)₂/ZnIn₂S₄ exhibits much higher photocurrent density than pure ZnIn₂S₄. As well known, the photocurrent density is directly proportional to the transfer and separation of photo-generated charge.^{38,39} The higher photocurrent density over 6% Ni(OH)₂/ZnIn₂S₄ composite than pure Ni(OH)₂ reveals that the deposition of Ni(OH)₂ on ZnIn₂S₄ benefits the charge transfer across the intimate interfaces between Ni(OH)₂ and ZnIn₂S₄, and achieves the efficient separation of charges photogenerated over ZnIn₂S₄. Moreover, the interfacial charge transfer and separation of two samples was also characterized by electrochemical impedance spectroscopy (EIS) measurements, as shown in Fig. 6b. Generally, the small curvature radius of the Nyquist curves represents a low charge transfer resistance, suggesting the efficient separation and transfer of photo-generated charges. The smaller curvature radius of the EIS plot of 6% Ni(OH)₂/ZnIn₂S₄ compared to that of pure ZnIn₂S₄ further confirms that the efficient separation and transfer of photo-generated charges are realized after the introduction of Ni(OH)₂.⁴⁰ The transient photocurrent response and

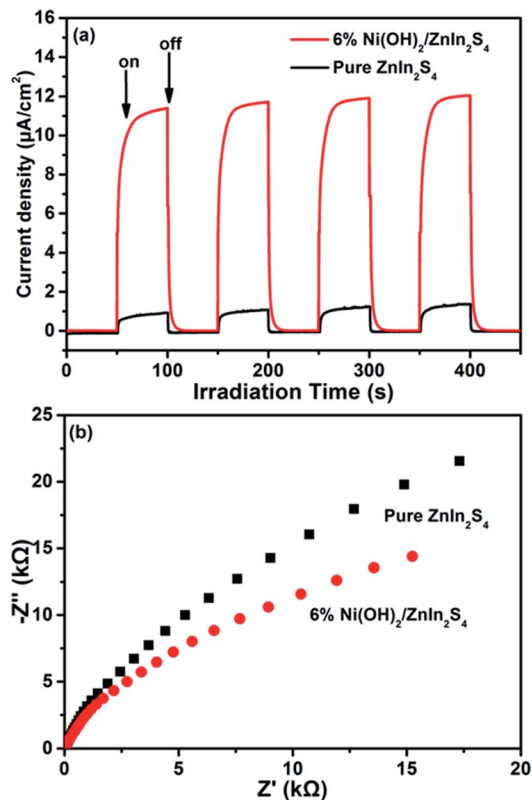


Fig. 6 Transient photocurrent responses (a) and electrochemical impedance spectroscopy Nyquist plots (b) of pure ZnIn₂S₄ and 6% Ni(OH)₂/ZnIn₂S₄.

electrochemical impedance spectroscopy (EIS) results of two samples parallel their performances (Fig. 5a) for photocatalytic H₂ evolution.

Based on the above results of the transient photocurrent response and electrochemical impedance spectroscopy measurements, without a doubt, it is the deposition of Ni(OH)₂ on the surface of ZnIn₂S₄ that the efficient separation of electron-hole pairs photogenerated over ZnIn₂S₄ has been achieved through the charge transfer across the intimate interfaces between Ni(OH)₂ and ZnIn₂S₄. Subsequently, we need to elucidate how the deposited Ni(OH)₂ effectively promotes the charge transfer to realize the separation of electron-hole pairs. According to the literature reports, the conduction band (CB) and valence band (VB) edges of ZnIn₂S₄ are -1.35 V and $+1.4$ V vs. NHE, respectively,³¹ while the redox potentials of Ni(OH)₂/Ni and Ni(OH)₃/Ni(OH)₂ are -0.72 V and $+0.48$ vs. NHE, respectively.⁴¹ From the view of thermodynamics, thus, there are two possible paths that the deposited Ni(OH)₂ promotes the separation of electron-hole pairs photogenerated over ZnIn₂S₄ composite. In path I, the photo-induced electrons on CB of ZnIn₂S₄ transfer to the deposited Ni(OH)₂ and reduce partial Ni²⁺ to form Ni⁰, where the bound proton H⁺ accepts the electrons from Ni⁰ to be reduced to H₂. In path II, the photo-induced holes on VB of ZnIn₂S₄ are scavenged by the deposited Ni(OH)₂ to form Ni(OH)₃, allowing the electrons left on CB of ZnIn₂S₄ to reduce H⁺ to H₂. Obviously, the reduction sites of

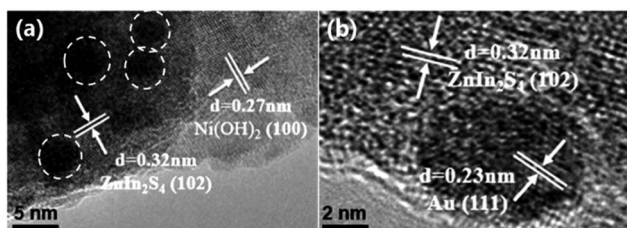
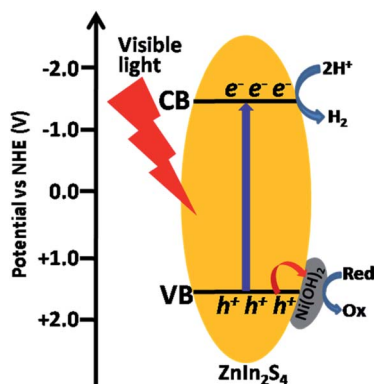


Fig. 7 TEM (a) and HRTEM (b) images of Au-photodeposited 6% Ni(OH)₂/ZnIn₂S₄.

H⁺ to H₂ in two paths are on the deposited Ni(OH)₂ and ZnIn₂S₄, respectively. Either path I or path II is an actual running one. This problem, we believe, can be clarified by the identification of the reduction sites in Ni(OH)₂/ZnIn₂S₄ composite. To this end, the photocatalytic deposition of Au on 6% Ni(OH)₂/ZnIn₂S₄ composite was conducted in the presence of HAuCl₄·4H₂O as Au precursor. As shown in Fig. 7a, after the photo-deposition of Au on the composite, several dark gray nanoparticles clearly appear on the surface of the crystalline ZnIn₂S₄ only.^{7,8} A HRTEM (Fig. 7b) analysis further indicates that the lattice fringe of 0.23 nm in a dark gray nanoparticle matches the crystallographic plane (111) of metallic cubic-phase Au.⁴² The results well demonstrate that the reduction of AuCl₄⁻ to Au⁰ by the photogenerated electrons in the composite occurs on the surface of ZnIn₂S₄ rather than Ni(OH)₂, suggesting that the photogenerated electrons are left on the ZnIn₂S₄, not transferred to the Ni(OH)₂. In the same way, the sites for the reduction of H⁺ to H₂ in Ni(OH)₂/ZnIn₂S₄ composite should be also on the surface of ZnIn₂S₄, which excludes the possibility of path I.

According to the above discussion and various experiments, therefore, a understanding of the enhanced photocatalytic H₂ evolution over Ni(OH)₂/ZnIn₂S₄ composite can be schematically illustrated in Scheme 1. The H₂ evolution rate is very low over the pure ZnIn₂S₄ due to the rapid recombination of CB electrons and VB holes. After the deposition of Ni(OH)₂ on ZnIn₂S₄, the VB holes can be scavenged by deposited Ni(OH)₂ to form Ni(OH)₃ across the intimate interfaces between ZnIn₂S₄ and Ni(OH)₂ since the valence band edge of ZnIn₂S₄ (+1.4 V vs. NHE) is more positive than the redox potential of Ni(OH)₃/Ni(OH)₂



Scheme 1 Schematic illustration of photocatalytic H₂ evolution over Ni(OH)₂/ZnIn₂S₄ composite.

(+0.48 vs. NHE).⁴¹ This leads to an efficient separation of charges photogenerated over ZnIn₂S₄ and allows more photogenerated electrons left on the surface of ZnIn₂S₄ to reduce the bound protons H⁺ to H₂, enhancing photocatalytic activity. Meanwhile, the formed Ni(OH)₃ can easily become back to Ni(OH)₂ through the oxidation of the added lactic acid as a sacrificial reagent, continuously driving the charge separation.

4. Conclusion

In summary, the crystalline Ni(OH)₂ have been successfully deposited on the surface of ZnIn₂S₄ through a facile *in situ* precipitation method. The deposition of Ni(OH)₂ on ZnIn₂S₄ was demonstrated to significantly enhance the photocatalytic H₂ evolution over ZnIn₂S₄. Various characterization results indicate that the deposition of Ni(OH)₂ on ZnIn₂S₄ effectively promotes the separation of charges photogenerated over ZnIn₂S₄. Furthermore, the experiment of the photodeposition of Au nanoparticles reveals that the scavenging of the photogenerated holes by the deposited Ni(OH)₂ effectively inhibits the recombination rate of the electron-hole pairs, boosting a high photocatalytic H₂ evolution rate over ZnIn₂S₄.

Author contributions

Zhuang Guo synthesized samples, conducted various characterizations, and drafted the paper. Huixia Hou, Jingyi Zhang and Pinglong Cai performed the electrochemical measurements and participated in the photocatalytic experiments. Jun Lin conceived the idea, revised the paper, and approved the final version.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (Grant No. 21673287).

Notes and references

- 1 A. Kudo and Y. Miseki, *Chem. Soc. Rev.*, 2009, **38**, 253–278.
- 2 U. Maitra, U. Gupta, M. De, R. Datta, A. Govindaraj and C. Rao, *Angew. Chem., Int. Ed.*, 2013, **52**, 13057–13061.
- 3 Y. X. Fang, X. C. Li and X. C. Wang, *ACS Catal.*, 2018, **8**, 8774–8780.
- 4 X. Yan, Z. L. Jin, Y. P. Zhang, H. Liu and X. L. Ma, *Phys. Chem. Chem. Phys.*, 2019, **21**, 4501–4512.
- 5 H. Wei, W. A. McMaster, J. Z. Y. Tan, L. Cao, D. Chen and R. A. Caruso, *J. Phys. Chem. C*, 2017, **121**, 22114–22122.
- 6 Z. Guan, Z. Xu, Q. Li, P. Wang, G. Li and J. Yang, *Appl. Catal., B*, 2018, **227**, 512–518.
- 7 A. Luna-Flores, M. A. Morales, R. Agustín-Serrano, R. Portillo, J. A. Luna-López, G. F. Pérez-Sánchez, A. D. Hernández-de la Luz and N. Tepale, *Catalysts*, 2019, **9**, 817.

- 8 M. A. Morales, I. Fernández-Cervantes, R. Agustín-Serrano, S. Ruíz-Salgado, M. P. Sampedro, J. L. Varela-Caselle, R. Portillo and E. Rubio, *Results Phys.*, 2019, **12**, 1344–1356.
- 9 S. Kim, Y. Wang, M. S. Zhu, M. Fujitsuka and T. Majima, *Chem.–Eur. J.*, 2018, **24**, 14928–14932.
- 10 S. Z. Liu, Z. Guo, X. H. Qian, J. Y. Zhang, J. X. Liu and J. Lin, *Sustainable Energy Fuels*, 2019, **3**, 1048–1054.
- 11 F. N. Sayed, O. D. Jayakumar, R. Sasikala, R. M. Kadam, S. R. Bharadwaj, L. Kienle, U. Schürmann, S. Kaps, R. Adelung, J. P. Mittal and A. K. Tyagi, *J. Phys. Chem. C*, 2012, **116**, 12462–12467.
- 12 S. Onsuratoom, T. Puangpetch and S. Chavadej, *Chem. Eng. J.*, 2011, **173**, 667–675.
- 13 M. Murdoch, G. I. N. Waterhouse, M. A. Nadeem, J. B. Metson, M. A. Keane, R. F. Howe, J. Llorca and H. Idriss, *Nat. Chem.*, 2011, **3**, 489–492.
- 14 S. Hong, D. P. Kumar, E. H. Kim, H. Park, M. Gopannagari, D. A. Reddy and T. K. Kim, *J. Mater. Chem. A*, 2017, **5**, 20851–20859.
- 15 S. Zhang, X. Liu, C. Liu, S. Luo, L. Wang, T. Cai, Y. Zeng, J. Yuan, W. Dong, Y. Pei and Y. Liu, *ACS Nano*, 2018, **12**, 751–758.
- 16 H. Han, K. M. Kim, C. W. Lee, C. S. Lee, R. C. Pawar, J. L. Jones, Y. R. Hong, J. H. Ryu, T. Song, S. H. Kang, H. Choi and S. Mhin, *Phys. Chem. Chem. Phys.*, 2017, **19**, 28207–28215.
- 17 X. H. Qian, J. Y. Zhang, Z. Guo, S. Z. Liu, J. X. Liu and J. Lin, *Appl. Surf. Sci.*, 2019, **481**, 795–801.
- 18 D. A. Reddy, H. Park, S. Hong, D. P. Kumar and T. K. Kim, *J. Mater. Chem. A*, 2017, **5**, 6981–6991.
- 19 Y. Lu, D. Chu, M. Zhu, Y. Du and P. Yang, *Phys. Chem. Chem. Phys.*, 2015, **17**, 17355–17361.
- 20 J. Y. Zhao, X. M. Yan, N. Zhao, X. Li, B. Lu, X. H. Zhang and H. T. Yu, *RSC Adv.*, 2020, **10**, 32652–32661.
- 21 Z. Sun, Q. Yue, J. Li, J. Xu, H. Zheng and P. Du, *J. Mater. Chem. A*, 2015, **3**, 10243–10247.
- 22 K. H. Sun, J. Shen, Y. T. Yang, H. Tang and C. S. Lei, *Appl. Surf. Sci.*, 2020, **505**, 144042.
- 23 J. G. Yu, Y. Hai and B. Cheng, *J. Phys. Chem. C*, 2011, **115**, 4953–4958.
- 24 J. R. Ran, J. G. Yu and M. Jaroniec, *Green Chem.*, 2011, **13**, 2708–2713.
- 25 S. S. Li, D. S. Dai, L. Ge, Y. Q. Gao, C. C. Han and N. Xiao, *Dalton Trans.*, 2017, **46**, 10620–10629.
- 26 R. Y. Cao, H. C. Yang, S. W. Zhang and X. J. Xu, *Appl. Catal., B*, 2019, **258**, 117997.
- 27 X. A. Zhou, J. Jin, X. J. Zhu, J. Huang, J. G. Yu, W. Y. Wong and W. K. Wong, *J. Mater. Chem. A*, 2016, **4**, 5282–5287.
- 28 J. G. Yu, S. H. Wang, B. Cheng, Z. Lin and F. Huang, *Catal. Sci. Technol.*, 2013, **3**, 1782–1789.
- 29 L. R. Nagappagari, S. Samanta, N. Sharma, V. R. Battula and K. Kailasam, *Sustainable Energy Fuels*, 2020, **4**, 750–759.
- 30 X. Gou, F. Cheng, Y. Shi, L. Zhang and P. Shen, *J. Am. Chem. Soc.*, 2006, **128**, 7222–7229.
- 31 Z. Z. Zhang, L. Huang, J. J. Zhang, F. J. Wang, Y. Y. Xie, X. T. Shang, Y. Y. Gu, H. B. Zhao and X. X. Wang, *Appl. Catal., B*, 2018, **233**, 112–119.
- 32 M. H. Xiong, B. Chai, J. T. Yan, G. Z. Fan and G. S. Song, *Appl. Surf. Sci.*, 2020, **514**, 145965.
- 33 J. G. Hou, C. Yang, H. J. Cheng, Z. Wang, S. Q. Jiao and H. M. Zhu, *Phys. Chem. Chem. Phys.*, 2013, **15**, 15660–15668.
- 34 C. Liu, B. Chai, C. L. Wang, J. T. Yan and Z. D. Ren, *Int. J. Hydrogen Energy*, 2018, **43**, 6977–6986.
- 35 J. Y. Liu, W. J. Fang, Z. D. Wei and Z. Qin, *Catal. Sci. Technol.*, 2018, **8**, 1375–1382.
- 36 Z. P. Yan, X. X. Yu, A. Han, P. Xu and P. W. Du, *J. Phys. Chem. C*, 2014, **118**, 22896–22903.
- 37 Q. W. Liu, M. D. Wang, Y. S. He, X. X. Wang and W. Y. Su, *Nanoscale*, 2018, **10**, 19100–19106.
- 38 S. Wang, B. Y. Guan, Y. Lu and X. W. Lou, *J. Am. Chem. Soc.*, 2017, **139**, 17305–17308.
- 39 B. Qiu, Q. Zhu, M. Du, L. Fan, M. Xing and J. Zhang, *Angew. Chem., Int. Ed.*, 2017, **56**, 2684–2688.
- 40 L. L. Bi, D. D. Meng, Q. J. Bu, Y. H. Lin, D. J. Wang and T. F. Xie, *Phys. Chem. Chem. Phys.*, 2016, **18**, 31534–31541.
- 41 A. J. Bard, R. Parsons and J. Jordan, *Standard Potentials in Aqueous Solution*, Routledge, New York, 1985.
- 42 M. S. Nasir, G. R. Yang, L. Ayub, S. L. Wang and W. Yan, *Appl. Surf. Sci.*, 2020, **519**, 146208.