Enhanced hydrogen evolution via interlaced Ni$_3$S$_2$/MoS$_2$ heterojunction photocatalysts with efficient interfacial contact and broadband absorption

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**Abstract**

The development of transition-metal sulfides, such as nickel sulfides (e.g., Ni$_3$S$_2$), as catalysts for the hydrogen evolution reaction is one potential solution to environmental pollution and energy crisis. However, its limited utilization of visible light and high recombination ratio of photoinduced electron–hole pairs suppress its photocatalytic activity. The key issue in improving photocatalytic efficiency lies in fabricating a p–n heterojunction with efficient interfacial contact and broadband absorption. Here, we developed a method for fabricating an interlaced Ni$_3$S$_2$/MoS$_2$ heterostructure with close interfacial contact. In our fabrication approach, a porous Ni$_3$S$_2$ scaffold is prepared by chemical vapor deposition and a hydrothermal method is used to prepare a Ni$_3$S$_2$/MoS$_2$ photocatalyst with close interfacial contact. The numerous interfaces of the interlaced Ni$_3$S$_2$/MoS$_2$ heterostructures promote effective electron–hole pair separation and facilitate electron transfer. Meanwhile, the hybrid Ni$_3$S$_2$/MoS$_2$ nanostructures favor broadband absorption extending from 300 to 800 nm. As a result, the hybrid Ni$_3$S$_2$/MoS$_2$ exhibits a remarkable rate of hydrogen evolution (540.75 μmol g$^{-1}$ h$^{-1}$), which is 5.71 and 3.89 times greater than those of pure Ni$_3$S$_2$ and MoS$_2$, respectively, under otherwise identical conditions. The results of this work are significant for developing promising transition-metal sulfide heterostructures in the field of hydrogen evolution by photocatalytic water splitting.

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1. Introduction

Solar energy and hydrogen are clean and renewable energy resources that may be viable alternatives for alleviating the environmental problems and energy crisis associated with fossil fuels. Photocatalytic water splitting provides a promising and effective path for producing hydrogen using solar energy [1–3]. Consequently, the development of semiconductor photocatalysts has become an active research topic [4,5]. However, the design and construction of new semiconductor nanostructures are capable of broadband light harvesting and effective electron–hole pair separation as well as outstanding electron transfer remains a formidable challenge [6,7]. The synthesis of efficient and low-cost photocatalysts will promote their practical application.

Numerous reports have indicated that transition-metal sulfide semiconductor materials are good photocatalyst candidates [8,9]. Among the transition-metal sulfides, nickel sulfides include numerous species that can catalyze the hydrogen evolution reaction, such as, NiS, NiS$_2$, Ni$_3$S$_2$, and Ni$_3$S$_4$ [10–15]. Nickel subsulfide (Ni$_3$S$_2$), a metallic sulfide semiconductor [16], exhibits good optical and electrical properties in addition to certain limited photocatalytic properties. However, its limited utilization of visible light and its high recombination ratio of photoinduced electron–hole pairs suppress its photocatalytic activity. The unsatisfactory photocatalytic performance of simple Ni$_3$S$_2$ has led to the development of several strategies for increasing its photocatalytic efficiency [17,18]. For example,
Lin et al. combined Erythrosin Yellow (Ery) as a sensitizer, carbon nanotubes, and Au nanoparticles with NiS2 to improve its photocatalytic activity [19]. However, the introduction of Au nanoparticles increases the cost, and Ery is an environmental pollutant.

An alternative approach to improve the photocatalytic performance of photocatalysts is to form a semiconductor heterojunction [20–23]. Heterostructured photocatalysts broaden the scope of light harvesting. Furthermore, band alignment between the two semiconducting materials of a heterojunction results in a built-in field at the interface of the junction for the spatial separation of photoinduced electron–hole pairs and the transport of electrons and holes. However, the architectural design of heterostructures should be improved. The issue of fabricating a heterojunction with efficient interfacial contact is a key obstacle to improve photocatalytic efficiency. MoS2, a low-cost few-layered molybdenum disulfide, has attracted extensive attention as a hydrogen evolution reaction catalyst. Combining MoS2 as a catalyst with traditional photocatalysts can result in enhanced solar energy absorption in the visible region. Furthermore, if the band states of the photocatalysts and MoS2 match each other, the heterostructure assists in electron transport and in retarding charge recombination. Since of its advantageous optical and electronic properties, MoS2 can ultimately be used to improve photocatalytic activity.

In this work, a facile method is developed for fabricating an interlaced Ni3S2/MoS2 heterostructure with intimate interfacial contact. In this approach, Ni foam is sulfured in a chemical vapor deposition (CVD) system and forms a porous Ni3S2 scaffold. A molybdenum and sulfur precursor solution then comes into contact with the scaffold sufficiently to enable MoS2 growth via a hydrothermal reaction. The optical absorption region of the Ni3S2/MoS2 heterostructures ranges from 300 to 800 nm. The numerous interfaces of the interlaced Ni3S2/MoS2 heterostructures promote effective electron–hole pair separation and facilitate electron transfer. As a result, the photocatalytic hydrogen evolution rate of the Ni3S2/MoS2 photocatalyst is 5.71 (3.89) times higher than that of pure Ni3S2 (MoS2) under the same test conditions. We also obtained a series of measurements to elucidate the mechanism of photocatalysis.

2. Experimental section

2.1. Synthesis of the Ni3S2, MoS2, and Ni3S2/MoS2 heterostructure

The Ni3S2 was synthesized through a CVD method. Ni foam (2 × 2 cm2) was vulcanized by sulfur powder in a 100 sccm argon atmosphere tube furnace at 700 °C and 250 Pa for 10 min. The Ni3S2/MoS2 heterostructure was obtained via a hydrothermal reaction. As-synthesized Ni3S2 was added to a 50 mL Teflon-lined stainless steel autoclave to which Na2MoO4 (3.0 mmol) and L-cysteine solution (6.0 mmol) were added; the Ni3S2/MoS2 heterostructure was subsequently obtained after the autoclave was heated at 200 °C for 16 h and allowed to cool to room temperature naturally. The product was precipitated by centrifugation at 6000 rpm for 10 min. Single MoS2 was prepared though hydrothermal method, which is consistent with the preparation condition of MoS2 in heterojunction. We added the Na2MoO4 (3.0 mmol) and L-cysteine solution (6.0 mmol) into a 50 mL Teflon-lined stainless steel autoclave. Subsequently, the autoclave was heated at 200 °C for 16 h and allowed to cool to room temperature naturally. The product was precipitated by centrifugation at 6000 rpm for 10 min. Finally, the three products were separately dispersed in distilled water by ultrasonication for 30 min.

2.2. Morphology and structural characterization

The morphologic micrographs of the Ni3S2/MoS2 heterostructure were obtained using a scanning electron microscope (FEI Tecnai F30G2). An X-ray diffractometer (PANalytical B.V., Cu-Kα radiation, λ = 1.54178 Å) was used for phase analysis. XPS (Escalab 250Xi) was performed to identify the elements present at the surface and their oxidation states. The optical properties of the samples were characterized by UV–vis spectrophotometry (PerkinElmer Lambda 35 UV-Vis) and Raman spectrometry (Renishaw inVia) with a 532 nm excitation laser with a spot diameter of 1 μm. The photoluminescence emission spectra at room temperature were acquired using a fluorescence spectrometer (FLS 980) with a 325 nm Xe arc lamp and a 5 nm slit width.

2.3. Photocatalytic activity

H2 evolution reactions were carried out in a 40 mL gas-tight glass system under vacuum. A 150 W Xe arc lamp served as the light source and was placed 10 cm from the reactor, which was mounted with a fan for dissipating excessive heat. During the photocatalytic reaction with 0.1 mol L−1 Na2S·9H2O and 0.1 mol L−1 Na2SO3 as hole sacrificial reagents, 0.05 g of photocatalyst was dispersed in distilled water (40 mL) and kept in an ultrasonic device for 30 min. Then, in order to compare the photocatalytic ability of Ni3S2/MoS2 heterojunction with single Ni3S2 and MoS2, we added the same mass (0.05 g) of three kinds of photocatalyst to conduct the hydrogen evolution reaction. After every 20 min cycle under light irradiation, the gas was transferred into a sample loop via a peristaltic pump and subsequently analyzed by gas chromatography on a gas chromatograph (Shimadzu GC-2014c) equipped with a thermal conductivity detector [24,25].

2.4. Photoelectrochemical measurements

Photoelectrochemical experiments were conducted on a Chenhua 760 electrochemical workstation using a three-electrode reactor with Na2SO4 solution (0.5 mol L−1) as the electrolyte. Pt foil served as the counter electrode and an Ag/AgCl electrode served as the reference electrode. A 100 μL sample solution was coated onto the surface of a 1 cm2 fluorine doped tin oxide (FTO) substrate and heated at 50 °C for 10 min; this electrode was subsequently used as the working electrode. In the photoelectrochemical experiments, a 150 W Xe lamp irradiated the working electrode. The electrochemical impedance spectroscopy (EIS) and Mott–Schottky measurements were conducted in light at a frequency of 10,000 Hz. The photocurrent was measured by chronoamperometry.

3. Results and discussion

The Ni3S2/MoS2 heterostructures were fabricated via the following method. As shown in Scheme 1, the Ni3S2 nanostructure was generated on a Ni foam through sulfuration procedure by the CVD method; MoS2 was then grown along the Ni3S2 nanostructure, resulting in the formation of the Ni3S2/MoS2 heterostructure through a hydrothermal procedure, in which L-cysteine and Na2MoO4 were used as sulfur and molybdenum precursors, respectively. Since the Ni3S2 nanostructure was fabricated on Ni foam, it could be used as a scaffold. The subsequent decorated MoS2 achieved intimate contact with the Ni3S2 scaffold, resulting in efficient interfacial contact.

X-ray diffraction (XRD) was used to characterize the crystal structure of the Ni3S2 and the Ni3S2/MoS2 heterostructure. XRD patterns for the Ni3S2 and Ni3S2/MoS2 samples are shown in Fig. 1(a). These data match those in PDF card 44-1418 (Ni3S2) and PDF card 01-075-1539 (MoS2). The XRD pattern of the Ni foam after CVD vulcanization shows peaks at 2θ = 21.61° and 30.92°, which
Scheme 1. The fabrication process of interlaced Ni$_3$S$_2$/MoS$_2$ heterostructures.

Fig. 1. (a) XRD patterns for the Ni$_3$S$_2$ and Ni$_3$S$_2$/MoS$_2$ samples; (b) Scheme of the contact type of the interlaced Ni$_3$S$_2$/MoS$_2$ heterostructure; (c, d) SEM images of the Ni$_3$S$_2$; (e) EDXA of the Ni$_3$S$_2$; (f, g) SEM images of the Ni$_3$S$_2$/MoS$_2$ heterostructures; (h) EDXA of the Ni$_3$S$_2$/MoS$_2$ heterostructures; (i, j) TEM images of the Ni$_3$S$_2$/MoS$_2$ heterostructure; (k, l) TEM images at the interface of the Ni$_3$S$_2$/MoS$_2$ heterostructure.
originates from the (101) and (110) planes of Ni$_3$S$_2$, respectively. In
the XRD pattern of the hybrid structure, apart from the peaks
assigned to Ni$_3$S$_2$, the peaks at 2$\theta = 14.13^\circ$ and 39.51$^\circ$ are assigned
to the (002) and (103) planes of MoS$_2$ (2H-MoS$_2$). Thus, the Ni$_3$S$_2$/
MoS$_2$ heterostructures comprise Ni$_3$S$_2$ and MoS$_2$. The morphology
of the samples was characterized by scanning electron microscopy
(SEM) and transmission electron microscopy (TEM). As shown in
Fig. 1(c) and (d), the morphology of the Ni$_3$S$_2$ obtained by sulfurization
of Ni foam comprises many thin nanosheets, which tend to
grow on the Ni foam at a certain oblique angle and are inter-
connected. Energy-dispersive X-ray analysis (EDXA) confirms that
only Ni and S are present in the nanostructures (Fig. 1(e)). SEM
images of the Ni$_3$S$_2$/MoS$_2$ heterostructures after the introduction of
MoS$_2$ are shown in Fig. 1(f) and (g). The Ni$_3$S$_2$ is covered with MoS$_2$
nanosheets that grow densely on the surface of the Ni$_3$S$_2$. Mean-
while, EDXA also confirms that Ni, Mo, and S are present in the
Ni$_3$S$_2$/MoS$_2$ heterostructure (Fig. 1(h)). To further explore the
detailed characteristics of the heterostructures, we used TEM to
characterize the samples. Fig. 1(i) and (j) show some hybrid
spherical particles with a diameter of approximately 200 nm. The
two materials are interwoven with each other and form interlaced
Ni$_3$S$_2$/MoS$_2$ heterostructures with intimate interfacial contact.
Furthermore, TEM images of the interfaces are shown in Fig. 1(k)
and (l). Two distinct lattice fringes belonging to MoS$_2$ and Ni$_3$S$_2$,
respectively, are revealed. An interlayer spacing of 0.61 nm is
observed, which is assigned to the lattice spacing of the (002) plane
of MoS$_2$ [26,27], whereas the observed lattice spacing of 0.20 nm
corresponds to the (202) facet of Ni$_3$S$_2$ [28]. The MoS$_2$/Ni$_3$S$_2$ het-
terostructures are constituted by numerous interfaces that consist of
comprise the (002) facet of MoS$_2$ and the neighboring (202) facet of
Ni$_3$S$_2$. As shown in Fig. 1(b), the MoS$_2$ and Ni$_3$S$_2$ nanosheets align in
a specific direction and contact with each other, resulting in the
observed interlaced structure.

To further characterize the Ni$_3$S$_2$/MoS$_2$ heterostructure, X-ray
photoelectron spectroscopy (XPS) was performed to identify the
elemental compositions and the oxidation states of the elements at
the surface of the heterostructure. In Fig. 2(a), the XPS survey
spectrum show the Ni 2p, Mo 3d, and S 2p signals of the Ni$_3$S$_2$/MoS$_2$
sample. As shown in Fig. 2(b), the Ni 2p XPS spectrum contains two
main peaks at 855.9 and 873.6 eV, which are attributed to Ni 2p$_{3/2}$
and Ni 2p$_{1/2}$, respectively. The other two peaks correspond to the
satellite peaks of Ni 2p$_{3/2}$ and Ni 2p$_{1/2}$, respectively. The other two peaks correspond to the
satellite peaks of Ni 2p$_{3/2}$ and Ni 2p$_{1/2}$, respectively. In the Mo 3d region
Fig. 2(c)), the peaks at 228.7 and 232.2 eV are ascribed to Mo 3d$_{5/2}$
and Mo 3d$_{3/2}$, respectively. This spectrum indicates a $+$4 oxidation
state of Mo and confirms the formation of MoS$_2$ [26]. Nearby S 2s
peaks were fitted at 226.1 and 227.2 eV, corresponding to the two
chemical states of S species bonding with Mo and Ni ions. The S 2p
spectrum was deconvoluted into four peaks. In Fig. 2(d), the peaks
at 162.91 and 163.94 eV are assigned to the S 2p$_{3/2}$ and S 2p$_{1/2}$ or-
bital of divalent sulfide ions (S$^{2-}$) in MoS$_2$, and the peaks at 161.81
and 163.81 eV correspond to the S 2p$_{3/2}$ and S 2p$_{1/2}$ orbitals associ-
ated with Ni–S bonding [29].

The amount of visible-light-driven photocatalytic hydrogen gas
production of the MoS$_3$, Ni$_3$S$_2$, and the MoS$_2$/Ni$_3$S$_2$ heterostructure

![Fig. 2. (a) XPS survey spectrum of the Ni$_3$S$_2$/MoS$_2$ sample; (b) XPS spectrum of Ni 2p; (c) XPS spectrum of Mo 3d; (d) XPS spectrum of S 2p.](image-url)
was tested using Na₂S–Na₂SO₃ as the sacrificial agent. As shown in Fig. 3(a), the amount of hydrogen gas produced when the Ni₃S₂ structure was tested for 100 min in the first cycle was 157.79 μmol g⁻¹, and the amount of hydrogen gas produced when the MoS₂ structure was tested for 100 min in the first cycle was 231.47 μmol g⁻¹. In the case of the hybrid Ni₃S₂/MoS₂ heterostructure, an obvious improvement was observed in the quantity of hydrogen gas production. Specifically, the amount of hydrogen gas production with the Ni₃S₂/MoS₂ heterostructure increased to 901.25 μmol g⁻¹. In addition, after three continuous cycles, the hybrid Ni₃S₂/MoS₂ heterostructure maintained comparable photocatalytic activity. The calculated rates of hydrogen gas production indicate that the interlaced Ni₃S₂/MoS₂ heterostructure (540.75 μmol g⁻¹ h⁻¹) manifests a 5.71- and 3.89-fold enhancement in the hydrogen production rate compared with the production rates of the Ni₃S₂ (94.67 μmol g⁻¹ h⁻¹) and MoS₂ (138.88 μmol g⁻¹ h⁻¹) nanomaterials, respectively (Fig. 3(b)).

To elucidate the mechanism of photocatalysis, we conducted two-part tests involving optical and electrical properties. In terms of the optical process, a photocatalyst should ideally exhibit strong light-harvesting ability to produce a large number of excitons. Fig. 4(a) shows a comparison of the UV–vis absorption spectra of Ni₃S₂, MoS₂, and the Ni₃S₂/MoS₂ heterostructures. In the case of the simple Ni₃S₂ nanosheets, substantial absorption occurs at approximately 430 nm. The UV–vis absorption spectrum of the MoS₂ nanosheets shows two characteristic absorption peaks at 607 and 670 nm [30]. The Ni₃S₂/MoS₂ heterostructure achieves a broad and strong absorption band covering the whole visible spectrum from 300 to 800 nm, which is beneficial for the utilization of solar energy for photocatalysis [31]. The Raman spectra of Ni₃S₂, MoS₂, and the MoS₂/Ni₃S₂ heterostructure further clarify the optical properties of the MoS₂/Ni₃S₂ heterostructure (Fig. 4(b)). The MoS₂ spectrum shows two obvious peaks at 377 and 403 cm⁻¹, which correspond to the E₁²g and A₁g Raman modes of MoS₂, respectively. Generally, the in-plane E₁²g mode is attributed to an opposite vibration of the Mo atom with respect to two S atoms, and the A₁g mode is related to the out-of-plane vibration of only S atoms along opposite directions. The Raman peaks at 188 cm⁻¹, 202 cm⁻¹, 224 cm⁻¹, 304 cm⁻¹, 325 cm⁻¹, and 350 cm⁻¹ are assigned to the vibration modes of Ni₃S₂ [32]. After the formation of Ni₃S₂/MoS₂ heterojunction, Ni₃S₂ nanostructures attach to MoS₂ nanosheets, changing the vibration mode (E₁²g and A₁g) of MoS₂ because of interfacial stress between Ni₃S₂ and MoS₂. Thus, the formation of Ni₃S₂/MoS₂ heterojunction leads to the Raman shift of MoS₂ [33].

The excitons' dissociation, transport, and recombination during the electrical transport process were studied. Photoluminescence
(PL) emission spectra can illustrate the excitons’ separation and the electron–hole pair recombination. Fig. 5(a) shows the PL emission spectra of the samples excited by a 325 nm Xe arc lamp. The characteristic peak at 682 nm is attributed to the bandgap exciton transition for 2H-MoS2 [34]. The characteristic peaks in the Ni3S2 emission spectrum appear at 667, 720, and 741 nm. Remarkably, the overall intensity of the PL emission spectra decreases in the case of the Ni3S2/MoS2 heterostructure, which indicates an improvement in the separation efficiency of electron–hole pairs [35–38]. Researcher has shown that exciton binding energy is approximately equal to the difference between electronic gap and optical gap [39–41]. The exciton binding energies of electron-hole pairs of

![Graphs showing PL emission spectra, Mott–Schottky plot, impedance data, and chronoamperometry measurement.](image)

Fig. 5. (a) Photoluminescence emission spectra of the Ni3S2, MoS2, and the interlaced Ni3S2/MoS2 heterostructure; (b) Mott–Schottky plot, (c) the electrochemical impedance data, and (d) chronoamperometry measurement of pure Ni3S2 and MoS2 and the interlaced Ni3S2/MoS2 heterostructure; (e) Scheme of the bandgap alignment between Ni3S2 and MoS2 and the transfer of photo-excited electrons and holes.
Ni$_3$S$_2$ and MoS$_2$ are approximately 0.32 eV and 0.01 eV, respectively. The Mott–Schottky plots of the Ni$_3$S$_2$, MoS$_2$, and the Ni$_3$S$_2$/MoS$_2$ heterostructure are displayed in Fig. 5(b); the curved slope reflects the semiconductor type and the charge carrier density ($N_q$). The Ni$_3$S$_2$, MoS$_2$, and Ni$_3$S$_2$/MoS$_2$ are n-type semiconductors, and the Ni$_3$S$_2$/MoS$_2$ heterostructure possesses a higher concentration of photoexcited carriers than the individual Ni$_3$S$_2$ and MoS$_2$ materials. Consequently, the higher $N_q$ values of the Ni$_3$S$_2$/MoS$_2$ heterostructure indicate a faster carrier transfer than in the individual Ni$_3$S$_2$ and MoS$_2$, resulting in enhanced water-splitting performance [31]. The electrochemical impedance spectra of the three samples are compared in Fig. 5(c). The arc radius in the Nyquist plots decreases in the order of Ni$_3$S$_2$ > MoS$_2$ > Ni$_3$S$_2$/MoS$_2$. A smaller arc radius indicates lower electrical impedance [42,43], which suggests more effective carrier transport. The heterostructure indeed exhibits improved transport of photogenerated charge carriers because the Nyquist plot of the Ni$_3$S$_2$/MoS$_2$ photocatalyst exhibits the smallest arc radius. Fig. 5(d) shows the photocurrent–time curves under dark and visible-light conditions in an on-and-off cycle mode. All of the samples quickly exhibited a photocurrent response as they are irradiated with light. Within the first few seconds of illumination, a slight photocurrent decay for each simple material appears in the diagram. This is caused though the concentration gradient exists at the interface of the semiconductors (Ni$_3$S$_2$/MoS$_2$, MoS$_2$, Ni$_3$S$_2$/MoS$_2$) and electrolyte (0.5 mol L$^{-1}$ Na$_2$SO$_4$ solution), while the system is not stirring [44]. Overall, the samples, including Ni$_3$S$_2$/MoS$_2$ heterostructure, single MoS$_2$ and Ni$_3$S$_2$, exhibit stable photocurrent response finally during the photoelectrochemical test process. Besides, the heterostructure shows higher photocurrent response intensity than that of single MoS$_2$ and Ni$_3$S$_2$, which is consistent with that the Ni$_3$S$_2$/MoS$_2$ heterostructure exhibits the best photocatalytic hydrogen evolution performance. Thus, the separation efficiency of electron–hole pairs is distinctly enhanced by the abundant interfaces of the Ni$_3$S$_2$/MoS$_2$ heterostructure. This phenomenon can be explained by the energy-level alignment of the semiconductor band states. The staggered gap [45] of Ni$_3$S$_2$ and MoS$_2$ leads to a built-in field at the junction interface, driving the photoexcited electron–hole pairs to separate and transport to the respective sides of the heterojunction [46]. The electrons preferentially transfer from the conduction band of Ni$_3$S$_2$ to the conduction band of MoS$_2$, accelerating the separation of photoexcited electron–hole pairs and facilitating the transport of electrons to the active sites of MoS$_2$ for photocatalytic hydrogen evolution (Fig. 5(e)). In general, the interlaced hybrid structure with a high carrier concentration reduces carrier recombination and promotes the migration of electrons, resulting in spatial separation of electron–hole pairs.

4. Conclusion

In summary, an interlaced Ni$_3$S$_2$/MoS$_2$ heterostructure with abundant intimate interfacial contacts was synthesized via a hydrothermal method. Ni foam was sulfurized in a CVD system, leading to a porous Ni$_3$S$_2$ scaffold; Ni$_3$S$_2$ nanosheets grew at certain oblique angle and were interconnected. Then, MoS$_2$ grew via a hydrothermal method and contacted with the Ni$_3$S$_2$ intimately. The Ni$_3$S$_2$/MoS$_2$ heterostructure exhibited an extended optical absorption region from 300 to 800 nm. PL spectra and photoelectrochemical measurements revealed that the interlaced Ni$_3$S$_2$/MoS$_2$ structure indeed reduced carrier recombination, accelerated the separation of photoexcited electron–hole pairs in the semiconductors, and facilitated the transport of carriers. Consequently, the Ni$_3$S$_2$/MoS$_2$ heterostructure showed a larger rate of hydrogen evolution (540.75 μmol g$^{-1}$ h$^{-1}$) than the pure Ni$_3$S$_2$ (94.67 μmol g$^{-1}$ h$^{-1}$) and MoS$_2$ (138.88 μmol g$^{-1}$ h$^{-1}$). Moreover, the interlaced Ni$_3$S$_2$/MoS$_2$ heterostructure itself is a promising photocatalyst because of its high natural abundance and low cost. Our research provides a useful approach to improving photocatalytic performance.

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