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Red Phosphor/g-C₃N₄ Heterojunction with Enhanced Photocatalytic Activities for Solar Fuels Production

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Abstract:

We report a composite photocatalyst by coupling red phosphor (r-P) and graphitic carbon nitride (g-C₃N₄). The introduction of g-C₃N₄ onto r-P surface led to considerable improvement on the photocatalytic activity for H₂ production and CO₂ conversion into valuable hydrocarbon fuel (CH₄) in the presence of water vapor. The enhancement could be attributed to the effective separation of photogenerated electrons and holes across the r-P/g-C₃N₄ heterojunction. Owing to the advantages of non-toxicity, low cost and abundance in nature, this active heterostructural r-P/g-C₃N₄ photocatalyst would have great potential for efficient solar fuels production.

Keywords: photocatalysis, H₂ production, CO₂ conversion, heterostructure, carbon nitride
1. Introduction

Solar fuels have been considered as one of the most important renewable clean energy resources in the future. In the past decade, it has attracted tremendous efforts on developing various photocatalysts to generate chemical fuels through solar water splitting or CO$_2$ reduction [1-5]. Researchers have recognized that a single-component semiconductor photocatalyst is hardly competent for efficient solar fuels generation due to the problems of limited visible-light harvesting, rapid charge recombination, and poor stabilities [1-3]. Therefore, recently more and more attentions have focused on multi-component photocatalysts consisting of different semiconductor nanostructures, such as CdS/TiO$_2$ and p-CaFe$_2$O$_4$/n-PbBi$_2$Nb$_{0.9}$W$_{0.1}$O$_{9}$ photocatalytic nanodiode [6-8], in which the created heterojunctions can significantly improve the photogenerated charge separation and thereby promote the photocatalytic efficiency. Nevertheless, these hybrid photocatalysts involve at least one metal-containing semiconductor as a major component that would raise economic cost concern in terms of large-scale production.

Herein, we report a new hybrid photocatalyst made by coupling red phosphor (r-P) with graphitic carbon nitride (g-C$_3$N$_4$), referred as PCN-x (x is the mass percentage of g-C$_3$N$_4$ in the hybrid). Both components in this hybrid photocatalyst are composed by inexpensive earth-abundant elements, and exhibit wide absorption range in the visible light [9-13]. Although their conduction band edges are capable of reducing water for H$_2$ evolution according to literatures, the individual use of either material showed limited photocatalytic efficiency because of the high recombination rate of photogenerated electrons and holes [11-17]. Significantly, we found that the prepared PCN-x hybrids exhibit remarkably enhanced H$_2$ evolution yield in visible-light-driven water reduction. Even more, such a combination leads to a surprising enhancement on the
CH$_4$ production yield in photocatalytic CO$_2$ conversion. This discovery demonstrates the potential of using economic materials for efficient solar fuels production.

2. EXPERIMENTS

2.1. Preparation of PCN-x hybrids

All of the reagents were used without further treatment. The g-C$_3$N$_4$ used in this study was prepared by heating urea (≥97.0%, Sigma-Aldrich) to 550 °C for 4 h in Ar atmosphere. Red phosphor/g-C$_3$N$_4$ hybrids (PCN-x) were prepared by annealing the mixture of red phosphor and g-C$_3$N$_4$ in inert atmosphere. In a typical process, an appropriate amount of g-C$_3$N$_4$ was mixed with r-P (≥97.0%, Sigma-Aldrich). The mixture was ground for 30 min in a mortar and transferred into an alumina crucible that was sealed with aluminium silicate. The crucible was calcined at 380 °C for 2 h in Ar atmosphere, and then cooled down to room temperature in Ar atmosphere. Pure red phosphor sample without mixing g-C$_3$N$_4$ was also treated under the identical condition for comparison purpose.

2.2. Characterizations

X-ray powder diffraction (XRD) data were collected on a Shimadzu XRD-6000 X-ray diffractometer using Cu Kα1 radiation at a scan rate of 1°/min. The acceleration voltage and the applied current were 40 kV and 40 mA, respectively. Morphologies and structure of PCN-x hybrids were observed by field emission scanning electron microscopy (SEM: JEOL JSM-7600F) and transmission electron microscopy (TEM: JEOL JEM-2100F). TEM was operated at an accelerating voltage of 200 kV. UV–vis diffuse reflectance spectra (DRS) were recorded over the spectral range 320-800 nm on a Lambda 750 UV/Vis/NIR spectrophotometer (Perkin Elmer, USA). BaSO$_4$ was used as a reflectance standard. The photoluminescence (PL) spectra were obtained on a Shimazu RF-5310PC fluorometer at an excitation wavelength of 350 nm. X-ray
photoelectron spectra (XPS) of the as-prepared photocatalysts were recorded on a Thermo Scientific Theta Probe XPS using Al Kα radiation (1486.6 eV) and the binding energy values were calibrated with respect to C (1s) peak (284.6 eV). Fourier transform infrared spectra (FTIR) of the samples were recorded between 400 and 4000 cm⁻¹ on an IRAffinity-1 FTIR spectrometer.

2.3. Photocatalytic hydrogen evolution

Photocatalytic H₂ production reactions were carried out in a 50-mL closed quartz flask reactor, which was sealed with Suba Seal rubber septa (Sigma-Aldrich). Typically, 10 mg of the prepared PCN-x hybrids were suspended in 10 mL aqueous solution of L-ascorbic acid (0.1 M, pH=4.0). A small amount of H₂PtCl₆ solution (61 uL, 0.08 wt%) was injected into the reactor to load 0.5 wt % Pt as co-catalyst on PCN-x surfaces through photodeposition. The reactor was purged with argon to drive away the residual air. The photocatalytic hydrogen evolution was initiated by irradiating the suspension with a 300-W xenon lamp (MAX-302, Asahi Spectra, USA) coupled with a UV cut-off filter (λ > 420 nm). The gas product were analyzed periodically through a gas chromatograph (GC-7890A, Agilent) with a TCD detector.

2.4. Photocatalytic conversion of CO₂ into CH₄

The photocatalytic CO₂ reduction was performed in a 100 mL gastight reactor with a quartz window and two side-sampling ports. In a typical process, 0.5 wt% Pt loaded PCN-x hybrids (20 mg) were dispersed on a 4-cm² glass substrate. The glass with powder photocatalysts was then put into the reactor. Prior to the irradiation, the reaction system was purged with high purity CO₂ for 30 min to remove the residual air and 0.2 ml ultrapure water was injected into the reaction system. A 500-W xenon arc lamp was used as the light source for the photocatalytic reaction. During the reaction, the gas product was analyzed periodically through a gas chromatograph (GC-7890A, Agilent) with a TCD detector.
3. RESULTS AND DISCUSSION

3.1. Sample characterizations

The PCN-x photocatalysts were prepared by annealing the mixture of red phosphor and g-C$_3$N$_4$ with different mass ratio in Ar atmosphere, as illustrated in Fig. 1A. PCN-5 and PCN-30 were used as representative samples for the studies. X-ray diffraction (XRD) patterns (Fig. 2) show no phase changes of both r-P and g-C$_3$N$_4$, and no sign of new product formation during the annealing process. The characteristic peak at 27.4° as the signature of interlayer aromatic packing indicates that the crystal structure of C$_3$N$_4$ was retained after the thermal treatment [11]. The FT-IR analyses (Fig. S1) further confirm that the original graphitic C-N backbones keep unchanged after hybridization with r-P, and show no vibrational peak of P-related groups in the PCN-x hybrids, indicating that the annealing process unlikely initiates new chemical bonding between r-P and g-C$_3$N$_4$. The UV-vis spectra (Fig. 3) of the PCN-x hybrids exhibit mixed absorption features of r-P and g-C$_3$N$_4$ [9, 11]. As expected, r-P and g-C$_3$N$_4$ show their fundamental absorption edge at 700 nm and 460 nm, respectively. The absorption edge of g-C$_3$N$_4$ becomes more evident with the increase of g-C$_3$N$_4$ content in PCN-x hybrids.

Scanning electron microscopy (SEM) analyses (Fig. 1) reveal that in the PCN-5 hybrid, large g-C$_3$N$_4$ nanosheets with thickness of several tens nanometers are coating on the surface of r-P particles, while pure r-P particles show quite smooth and clean surfaces. The g-C$_3$N$_4$ layer was confirmed by energy-dispersive X-ray spectroscopy (EDS) as shown in Fig. S2. Increasing the g-C$_3$N$_4$ ratio leads to heavier g-C$_3$N$_4$ coverage over the r-P surfaces (Fig. 1D). Notably, g-C$_3$N$_4$ preferably coats on the uneven r-P surface area as evidenced by the less g-C$_3$N$_4$ coating on the very smooth area of r-P surfaces (Fig. S3, indicated by arrow 1) with some free g-C$_3$N$_4$ particles inevitably existing (Fig. S3, indicated by arrow 2).
This heavy g-C$_3$N$_4$ coating was hardly visualized in transmission electron microscopy (TEM), nevertheless, we still can observe g-C$_3$N$_4$ nanosheets adhering on the r-P edges as shown in Fig. 4. However, high-resolution TEM images of the samples are not attainable because these g-C$_3$N$_4$ nanosheet structures seem too thin and tend to transform into spherical structures under high energy focusing electron beam (Fig. S4). Note that upon thermal treatment (380 °C for 2 h), the pure g-C$_3$N$_4$ appears as velvet-like sheets with rolling edges (Fig. S5). Such flexible structures allow g-C$_3$N$_4$ anchoring on the r-P surfaces and in particular wrapping on the r-P edges, which creates heterojunctions between r-P and g-C$_3$N$_4$ for charge transfer [18].

3.2. Photocatalytic H$_2$ evolution

In order to identify the contribution of these heterojunctions, we have compared these samples for visible-light-driven (λ > 420 nm) photocatalytic H$_2$ generation from water reduction. Ascorbic acid (0.1 M) was used as sacrificial reagent, and Pt (0.5 wt%) were loaded as co-catalyst on the samples via in-situ photodeposition [19]. Control experiments confirm no H$_2$ evolution without photocatalysts or light illumination. As illustrated in Fig. 5A, the pure r-P sample showed very weak activity for H$_2$ production (22 μmol·h$^{-1}$·g$^{-1}$). However, upon loading of 5 wt% g-C$_3$N$_4$ (as PCN-5) onto r-P surfaces, the H$_2$ evolution rate (310 μmol·h$^{-1}$·g$^{-1}$) was enhanced more than ten times and even comparable to that of pure g-C$_3$N$_4$ (340 μmol·h$^{-1}$·g$^{-1}$). In comparison, a simple mixture of r-P with 5 wt% g-C$_3$N$_4$ only showed a H$_2$ evolution rate of 70 μmol·h$^{-1}$·g$^{-1}$. These results demonstrate that thermal annealing facilitates the formation of r-P/g-C$_3$N$_4$ heterojunctions for effective charge separation in PCN-5, thereby leading to this enhanced H$_2$ evolution rate (more than 4 times enhancement by annealing). The photocatalytic activity can be further enhanced (up to 1000 μmol·h$^{-1}$·g$^{-1}$ for H$_2$ evolution) by increasing g-C$_3$N$_4$ content to 30 wt% (PCN-30). The above results clearly demonstrate that the r-P/g-C$_3$N$_4$ interface plays an essential
role on enhancing photocatalytic H₂ evolution. Higher g-C₃N₄ loading on r-P leads to larger interfaces and thereby effective separation of photogenerated electrons and holes towards enhanced photocatalytic activities [20-22].

3.3. Photocatalytic CO₂ conversion

Furthermore, since the reduction potential from CO₂ to CH₄ (CO₂ + 8H⁺ + 8e⁻ → CH₄ + 2H₂O) is around -0.24 V, the high conduction band (CB) edge of r-P (-0.25 V vs. NHE) and g-C₃N₄ (-1.2 V vs. NHE) allows us to use the PCN hybrids for photocatalytic conversion of CO₂ into hydrocarbon fuels [9, 11, 23-25]. As shown in Fig. 5B, the PCN-30 exhibited a CH₄ production yield of 295 μmol·h⁻¹·g⁻¹, which is twice higher than pure r-P (145 μmol·h⁻¹·g⁻¹) and nearly three times higher than pure g-C₃N₄ (107 μmol·h⁻¹·g⁻¹). This comparison results further demonstrate that the coupling between r-P and g-C₃N₄ effectively promote the overall photocatalytic activity for CO₂ reduction.

3.4. Mechanism of enhanced photocatalytic activity

The enhanced photocatalytic activity could be attributed to the effective interfacial charge transfer between r-P and g-C₃N₄ across the heterojunction as illustrated in Fig. 6. Since the CB edge of g-C₃N₄ (-1.2 V vs. NHE) is more negative than that of r-P (-0.25 V vs. NHE), the photoexcited electrons on g-C₃N₄ surface could transfer to r-P through the interfaces created by annealing. Similarly, the photoinduced holes on the r-P surface move towards g-C₃N₄ due to the difference in valence band (VB) edge potentials. The accumulated electrons on r-P surfaces reduce the H⁺ or CO₂ into valuable fuels, while the holes on g-C₃N₄ surfaces oxidize the electron donor (ascorbic acid for H₂ production and OH⁻ for CO₂ reduction, respectively). The effective separation of photogenerated electrons and holes thus enhances the photocatalytic activities [21,
In addition, the network structure of g-C_3N_4 can acts as an excellent electron transport platform to facilitate the charge transfer process [17, 18].

The interfacial charge transfer could be also evidenced by the decreased photoluminescence (PL) intensity in the PCN-5 hybrid (Fig. 7) as compared to pure g-C_3N_4. This result further confirms photoinduced electron flowing direction from g-C_3N_4 to r-P, causing PL quenching of g-C_3N_4 in PCN-5. Meanwhile, the interfacial charge transfer could be further supported by the enhanced TAOH fluorescence intensity on PCN-5 as compared to that on pure g-C_3N_4 (Fig. S6, see supporting information for details). This observation also indicated that the r-P/g-C_3N_4 heterojunctions allow the photocatalyst to supply more photogenerated holes to generate more ·OH radicals and thus higher TAOH concentration with stronger fluorescence signal.

In addition, X-ray photoelectron spectroscopy (XPS) analyses reveal that the annealing process neither creates new species such as P_3N_5 nor leads to P-doping into the g-C_3N_4 lattice (P_3N_5 is a very stable species) [26]. As shown in Fig. S7, the P 2p signal can be deconvoluted into ~129.3 eV and ~130.1 eV for P 2p_3/2 and P 2p_1/2, respectively, which are the typical signatures for 2p binding energy of red phosphor. No binding energy shift is observed for PCN-30 as compared to pure r-P, indicating no P-N bonding formation.

4. Conclusions

In summary, hybrid structures of r-P and g-C_3N_4 are prepared through solid state annealing method. We found that small amount introduction of g-C_3N_4 onto r-P surface led to considerable improvement on the photocatalytic activity for H_2 production and CO_2 conversion into CH_4. The enhancement could be attributed to the effective separation of photogenerated electrons and holes across the r-P/g-C_3N_4 heterojunction. This work provides a new insight on developing
active metal-free heterostructural photocatalysts and demonstrates the great potential of using economic materials for efficient solar fuels production.

Acknowledgements

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Electronic Supplementary Information

Supplementary data associated with this article can be found, in the online version, at doi:XXXX

References


Figure Captions

Fig. 1. (A) schematic illustration of hybridizing g-C$_3$N$_4$ on r-P surfaces via annealing. Increasing the g-C$_3$N$_4$ mass ratio leads to higher surface coverage of g-C$_3$N$_4$ on r-P surfaces. (B)-(D) SEM images of r-P, PCN-5, and PCN-30. The right column shows the magnified images of r-P, PCN-5, and PCN-30, respectively. Scale bar: 10 μm.

Fig. 2. XRD patterns of PCN-x hybrids. The XRD patterns of pure g-C$_3$N$_4$ and r-P that were treated at 380 °C for 2 h were also provided for comparison.

Fig. 3. UV-vis absorption spectra of PCN-5, PCN-30, g-C$_3$N$_4$ and r-P sample.

Fig. 4. TEM image of PCN-30. The covered g-C$_3$N$_4$ layer on r-P surfaces, and linked g-C$_3$N$_4$ particle were labeled.

Fig. 5. Photocatalytic (A) H$_2$ and (B) CH$_4$ production rate of r-P, PCN-5, PCN-30, and g-C$_3$N$_4$ photocatalysts.

Fig. 6. Energy band diagram of p-n junction for PCN-x under zero bias and schematic illustration of electron-hole separation process after excitation.

Fig. 7. Photoluminescence spectra of r-P, PCN-5 and g-C$_3$N$_4$ at an excitation wavelength of 350 nm.