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Three-dimensional MoS₂/reduced graphene oxide aerogel as a macroscopic visible-light photocatalyst

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ABSTRACT

Photocatalysis is regarded as an ideal technology for solving the urgent environmental and energy issues that we face today. Among the reported photocatalysts, molybdenum disulfide (MoS₂) is very promising for applications in hydrogen production and pollutant photodegradation. However, its lack of active sites and the difficulty of recovering catalysts in powder form have hindered its wide application. Here, we report the successful preparation of a macroscopic visible-light responsive MoS₂/reduced graphene oxide (MoS₂/RGO) aerogel. The obtained MoS₂/RGO aerogel exhibits enhanced photocatalytic activity towards hydrogen production and photoreduction of Cr(VI) in comparison with the MoS₂ powder. In addition, the low density (56.1 mg/cm³) of the MoS₂/RGO aerogel enables it to be used as an efficient adsorption material for organic pollutants. Our results demonstrate that this very promising multifunctional aerogel has potential applications in environmental remediation and clean energy production.

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1. Introduction

Serious environmental pollution and the depletion of energy resources are two of the most urgent issues that we face today. Recently, two-dimensional layered materials have attracted worldwide attention in the environmental and energy fields owing to their unique properties and numerous potential applications [1]. Among them, MoS₂ is a semiconductor with a tunable bandgap that depends on the number of MoS₂ layers. Theoretically, the bandgap of bulk MoS₂ is 1.2 eV, whereas that of monolayer MoS₂ is 1.9 eV [2]. MoS₂ can be used in a very wide range of applications, such as solid lubricants [3], electrocatalysts for hydrogen evolution [4], and energy storage for

batteries and supercapacitors [5]. Each layer of MoS₂ has a sandwich structure with strong covalent bonding between the Mo and S atoms. However, the weak inter-layer binding allows other molecules to insert between the MoS₂ layers, resulting in materials with fascinating properties [6]. MoS₂ has also been considered as an alternative co-catalyst to the noble metal platinum because of its low cost and conduction band (CB) edge potential (−0.1 eV) that allows electrons from another semiconductor to be transferred to MoS₂ and enhance electrical transport [7]. Nevertheless, both theory and experiment have demonstrated that only the edge sites of MoS₂ are catalytically active. In addition, the fast recombination of the photo-generated charge carriers in MoS₂ further limits its application as a

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photocatalyst [8]. Many studies have been conducted to overcome these bottlenecks, for example through the fabrication of defect-rich MoS₂ ultrathin nanosheets [9] and hybrids of MoS₂ with platinum [10], graphene [11], polyaniline (PANI) [12], or other highly conductive materials. Gao et al. [12] developed PANI-modified three-dimensional (3D) flower-like MoS₂, which exhibited enhanced adsorption and photoreduction of Cr(VI). Chang et al. [13] demonstrated that the S atoms on the exposed edge sites played an important role in the adsorption of H⁺, and allowed the reduction from H⁺ to H₂. However, these improvements are primarily applied to MoS₂ in powder form, which is not only difficult to recover, but also has a strong tendency to agglomerate [14]. Hence, the fabrication of a macroscopic MoS₂ photocatalyst remains a great challenge.

Graphene aerogel (GA), which has a low density, large surface area, and high porosity, has received enormous attention as a supercapacitor, catalyst support, and adsorbent material [15,16]. Importantly, GA could act as an ideal scaffold for catalysts owing to its porous 3D network structure and multi-dimensional electron transport pathways [8]. Considerably enhanced photocatalytic activity has been observed after coupling photocatalysts with GA or its derivatives, reduced graphene oxide (RGO) and graphene oxide (GO) aerogels. Liu et al. [17] reported a facile hydrothermal method for the preparation of TiO₂/GA, which can photocatalytically degrade various pollutants. Fan and co-workers [18] demonstrated that AgBr and AgCl showed an enhanced photocatalytic performance when grown on the surface of GA. In our previous work, we revealed that macroscopic C₃N₄/GO aerogel photocatalysts with various sizes and shapes could be fabricated through a cost-effective freeze-casting process [19]. Nevertheless, to the best of our knowledge, there is no research reporting photocatalytic H₂ production and photoreduction of Cr(VI) using a macroscopic MoS₂ aerogel photocatalyst.

In the present work, we report a facile method for the fabrication of a macroscopic MoS₂/RGO aerogel photocatalyst using a hydrothermal method followed by freeze-drying. The obtained MoS₂/RGO aerogel exhibited considerably enhanced photocatalytic activity towards both photocatalytic H₂ production and photoreduction of Cr(VI) compared with the MoS₂ powder. In addition, owing to the low density (56.1 mg/cm³) of the MoS₂/RGO aerogel, adsorption capacities of 10–20 times the weight of the aerogel sample could be achieved, depending on the density of the adsorbed organics.

2. Experimental

2.1. Materials

Natural graphite flakes (32 mesh) were purchased from Qingdao Jin Ri Lai Graphite Co., Ltd. Other reagents were purchased from Chengdu Kelong Chemical Co., Ltd. All reagents were of analytical grade and used without further purification.

2.2. Preparation

MoS₂ powder was prepared via a hydrothermal method. In a

typical synthesis, 106 mg ammonium molybdate ((NH₄)₆Mo₇O₂₄·4H₂O) and 1 g thiourea (CS(NH₂)₂) were placed in a 25 mL Teflon-lined stainless steel autoclave containing 15 mL deionized water. After stirring for 30 min, the autoclave was heated at 180 °C for 24 h and then cooled naturally to room temperature. The final black powder was washed several times with deionized water and ethanol and dried at 60 °C. GO was prepared using a modified Hummers method as described in our previous work [15,16]. The final concentration of the GO solution was 3 mg/mL.

For the preparation of the MoS₂/RGO aerogel, 106 mg ammonium molybdate and 1 g thiourea were dispersed in 5 mL deionized water in a 25 mL Teflon-lined stainless steel autoclave under stirring. Then, 10 mL GO solution (3 mg/mL) and 40 μL ammonia were added. After stirring for 1 h, the autoclave was heated at 180 °C for 24 h and cooled naturally to room temperature. The obtained hydrogels were washed with deionized water and then frozen at –80 °C for 2 h. The MoS₂/RGO aerogel was produced after freeze-drying for 48 h. The weight ratio of MoS₂ to RGO was 7:3.

2.3. Characterization

Powder X-ray diffraction (XRD) was performed on a PANalytical X'pert diffractometer operated at 40 kV and 40 mA with Cu K_α radiation. The morphology and microstructure of the prepared samples were investigated by scanning electron microscopy (SEM) using a ZEISS EVO MA15 microscope and transmission electron microscopy (TEM) was performed on a FEI tecnai G2 F30 microscope. UV-vis-near infrared (NIR) spectroscopy was performed on a Shimadzu UV-2600 spectrophotometer. Fourier transform infrared spectra (FTIR) were recorded on a Thermo Nicolet 6700 spectrometer. X-ray photoelectron spectroscopy (XPS) was carried out using a Thermo Scientific Escalab 250Xi spectrometer and the binding energy shifts were corrected using the C 1s signal at 284.6 eV. The specific surface area (SSA) was measured in suspension using UV-vis spectroscopy (UV-5100, Anhui Wanyi) with the methylene blue (MB) staining method [20] and calculated using the following equation:

$$SSA = N_A A_{MB} (C_0 - C_e) V / (M_{MB} m_s) \quad (1)$$

where N_A is Avogadro's number ($6.02 \times 10^{23} \text{ mol}^{-1}$), A_{MB} is the surface coverage per molecule of MB (typically 1.35 nm²), C_0 and C_e are the initial and equilibrium concentrations of MB, respectively, V is the volume of the MB solution, M_{MB} is the molecular mass of MB, and m_s is the mass of the sample.

2.4. Photocatalytic activity and adsorption capacity measurements

Photocatalytic hydrogen evolution was determined using a 500 W high pressure Hg lamp (15.7 mW/cm²) as the light source with a visible light filter (> 420 nm). The samples (5 mg) were dispersed in 10 mL of a mixed solution of sodium sulfide (0.1 mol/L) and sodium sulfite (0.6 mol/L) as a sacrificial agent system in a Pyrex tube. Ar was bubbled for 30 min to remove O₂ and 1 mL CH₄ gas was injected as an internal standard, and

then the tube was sealed with a rubber septum and placed on a stirrer under illumination. The amount of generated hydrogen was analyzed with a Shimadzu GC-2010Plus gas chromatograph. For the Cr(VI) photoreduction experiments, 100 mg samples were placed in a glass reactor with 150 mL potassium dichromate solution (100 mg/L). The reactor was placed on a stirrer and irradiated with a 300W Xe lamp (545 mW/cm²). The concentration of Cr(VI) was measured using a UV-vis spectrophotometer (UV-5100, Anhui Wanyi).

To test the adsorption performance of the prepared aerogel, 20 mg samples were immersed into various organic solvents (carbon tetrachloride, *n*-hexane, pyridine, and dimethylformamide (DMF)). After reaching the adsorption-desorption equilibrium, the adsorbents were weighed again. The adsorption capacity (Q_{wt}) was calculated as follows:

$$Q_{wt} = (m - m_0) / m_0 \quad (2)$$

where m_0 and m are the weights of the aerogel before and after adsorption, respectively.

3. Results and discussion

3.1. Preparation of the macroscopic MoS₂/RGO photocatalyst

The synthetic route to the MoS₂/RGO aerogel is briefly illustrated in Scheme 1. The MoS₂/RGO hydrogel was obtained from an aqueous solution containing MoS₂ precursors (ammonium molybdate and thiourea) and GO using a hydrothermal method. In this process, the precursor molecules were uniformly attached onto the surface of the graphene sheets and formed MoS₂. At the same time, the graphene sheets were connected through chemical self-assembly with ammonia as the reducing agent to give a 3D network [16]. In the final step, the MoS₂/RGO aerogel was obtained from the MoS₂/RGO hydrogel by freeze-drying.

3.2. Structure, morphology, and optical properties

Fig. 1 shows the XRD patterns of MoS₂ powder, the MoS₂/RGO aerogel and commercial MoS₂ as a reference. It is worth noting that the excess ammonium ions obtained from the hydrolysis of the ammonium molybdate and thiourea precursors can easily insert into the spaces between the MoS₂ layers. This is a result of the weak van der Waals interaction between the MoS₂ layers, and ultimately results in the shift of the (002) and (004) peaks to 9.65° and 18.89°, respectively [6]. The

Fig. 1. XRD patterns of MoS₂ powder, the MoS₂/RGO aerogel, and commercial MoS₂.

difference in the (002) interplanar spacing between commercial MoS₂ and the MoS₂/RGO aerogel is 0.33 nm. This agrees well with the hydrogen-bonding diameter (about 0.35 nm) of ammonium ions in metal disulfides [21], and indicates the presence of ammonium ions in the MoS₂ structure. In addition, an additional diffraction peak at 25.16° was observed for the MoS₂/RGO aerogel; this peak corresponds to the characteristic (001) plane of graphene sheets [15].

The morphologies and microstructures of MoS₂ powder and the MoS₂/RGO aerogel were studied by SEM and TEM (Fig. 2). The SEM image (Fig. 2(a)) of the MoS₂ powder reveals its nanosheet morphology. The addition of GO to the reaction system not only supported the formation of the hydrogel but also changed the morphology of the MoS₂. The MoS₂/RGO aerogel displayed a hierarchical morphology constructed from nanosheet building blocks (Fig. 2(b)). In general, GO contains many functional groups, such as OH, COOH, and epoxy groups, on its basal planes and edges. These groups could act as nucleation centers and thus considerably affect the hydrothermal growth process of MoS₂ [22]. The TEM image (Fig. 2(c)) of the MoS₂/RGO aerogel further confirms the flower-like hierarchical MoS₂ layer assembled on the RGO. The observed lattice fringes with an interlayer distance of 0.68 nm in the HRTEM image (Fig. 2(d)) indicate the instability of the intercalated ammonium ions [6]. Moreover, various dislocations and distortions of the MoS₂ crystals can be observed in the HRTEM image (Fig.

Scheme 1. Schematic illustration of the fabrication process of MoS₂/RGO aerogel.

Fig. 2. SEM images of MoS₂ powder (a) and the MoS₂/RGO aerogel (b); TEM (c) and HRTEM (d) images of the MoS₂/RGO aerogel.

2(d)); these could lead to the formation of additional exposed edge sites [9].

XPS studies were performed to verify the surface chemical composition and chemical states of the prepared MoS₂/RGO aerogel. After calibrating the binding energy of the C 1s peak at

284.6 eV, the peaks at 229.0 and 232.2 eV, corresponding to Mo 3d_{5/2} and Mo 3d_{3/2}, respectively, were assigned to Mo(IV) in MoS₂. The peaks at 229.7 and 233.1 eV revealed the existence of MoO₃ because the electronegativity of O (3.44) is higher than that of S (2.58) [Fig. 3(a)] [23–25]. Fig. 3(b) shows the S 2p XPS

Fig. 3. High-resolution XPS spectra of the MoS₂/RGO aerogel. (a) Mo 3d; (b) S 2p; (c) N 1s; (d) C 1s.

signal of the MoS₂/RGO aerogel. The low energy component of each peak at 161.8 and 163.1 eV was ascribed to S²⁻ in MoS₂, whereas the high energy component at 162.1 and 164.2 eV indicated unsaturated S atoms on the edge sites of MoS₂ [26,27]. The N 1s peak at 401.7 eV (Fig. 3(c)) was assigned to the N atom of NH₄⁺ [6], and confirmed the presence of intercalated NH₄⁺ ions in the MoS₂ structure, in line with the XRD results (Fig. 1). The peak at 398.4 eV was assigned to pyridinic N [28] and the peak at 395.1 eV to Mo 3p_{3/2} [29]. The C 1s peak at 284.6 eV was attributed to the graphene carbon (sp² C) whereas the peak at 286.3 eV was associated with the oxygen groups (C–O) on the surface of the graphene (Fig. 3(d)). The low intensity of this oxygen signal suggests that most of the oxygen groups of the GO precursor were removed through the reduction of ammonia, which in turn suggests the formation of RGO. Fig. 4(a) shows the FTIR spectra of MoS₂ powder and the MoS₂/RGO aerogel. The peak at 3428 cm⁻¹ corresponds to the –OH bond of water, and these at 1625 and 1401 cm⁻¹ can be assigned to C=C and –CH₃ bonds, respectively. Notably and in accordance with the XPS analysis, the peak at 3116 cm⁻¹ in MoS₂ powder (–OH bond of COOH) became much weaker after the formation of the aerogel owing to the reduction of ammonia [28]. Importantly, after combination with RGO, the three sharp peaks at 1195, 1106, and 1037 cm⁻¹ corresponding to the C–O bond were shifted to 1128, 1056, and 999 cm⁻¹ and indicate the interaction between MoS₂ and RGO through the formation of hydrogen bonds.

To be effective as a photocatalyst, the catalyst should be responsive to visible light because UV irradiation represents only

4% of the energy of the sunlight arriving on the earth's surface [30,31]. Fig. 4(b) shows the UV-vis-NIR absorption spectra of MoS₂ powder and the MoS₂/RGO aerogel. The prepared MoS₂ powder exhibits a weak absorption at 1377 nm, whereas the MoS₂/RGO aerogel shows a strong absorption at 576 nm. The higher absorption intensity of the MoS₂/RGO aerogel in the visible light region may be attributed to the black-body properties of RGO [32] and the surface sensitization of the carbonaceous species [33]. In addition, the 3D hierarchical morphology of the MoS₂/RGO aerogel (Fig. 2(b) and (c)) could also promote the response to visible light because the light can reflect repeatedly in the flower-like structure [34]. An additional peak at 221 nm was observed for MoS₂ powder. This peak can be attributed to the –NH₂ excitonic state, and further confirms the presence of NH₄⁺ ions in the MoS₂ structure.

3.3. Photocatalytic performance and adsorption capacity

To explore the photocatalytic application of the MoS₂/RGO aerogel, we carried out experiments to measure both photocatalytic H₂ production and photoreduction of Cr(VI). As shown in Fig. 5(a), after 8 h visible light irradiation, the amount of hydrogen evolved over the MoS₂/RGO aerogel was 38.9 μmol/g, which is considerably higher than that observed for the MoS₂ powder (23.1 μmol/g). Similar results were observed for the photoreduction of Cr(VI) (Fig. 5(b)). Cr(VI) was chosen to evaluate the photoreduction performance because it is a common industrial pollutant and has high carcinogenic and mutagenic effects. Approximately 92% of the Cr(VI) was reduced to harmless Cr(III) by the MoS₂/RGO aerogel after irradiation for 2 h, whereas the MoS₂ powder showed almost no activity in the photoreduction of Cr(VI). These results demonstrate that the MoS₂/RGO aerogel prepared in this study can be used not only for clean energy production but also for environmental remediation. It is worth noting that the commercial MoS₂ shows no photocatalytic activity towards hydrogen evolution (Fig. 5(a)). The photocatalytic performance of the obtained MoS₂ powder may originate from the defect-rich structure as shown in the HRTEM image (Fig. 2(d)), which leads to a greater number of exposed active edge sites [9]. Repeated photocatalytic hydrogen evolution experiments were performed to investigate the stability of the MoS₂/RGO aerogel photocatalyst. As shown in Fig. 5(c), the photocatalytic hydrogen evolution of the MoS₂/RGO aerogel decreased considerably after the first run, and further decreased in the third run. This unstable photocatalysis may be due to the instability of the ammonium ions between the MoS₂ layers as well as photoinduced corrosion on the edge and defect sites of MoS₂ [6,35].

The MoS₂/RGO aerogel also shows good adsorption capacity for various organic solvents, which are important sources of water pollution [36]. Fig. 5(d) illustrates adsorption capacities of 10–20 times the weight of the MoS₂/RGO aerogel towards different organic solvents. Moreover, the MoS₂/RGO aerogel has a low density (56.1 mg/cm³), equal to just 1.1% of the density of bulk MoS₂ (5.06 g/cm³) [37]. This low density allows the MoS₂/RGO aerogel to float on water and be easily recycled. These multifunctional properties suggest that the MoS₂/RGO

Fig. 4. FTIR (a) and UV-vis-NIR (b) spectra of MoS₂ powder and the MoS₂/RGO aerogel.

Fig. 5. (a) Visible light photocatalytic activity for hydrogen evolution; (b) Photoreduction of Cr(VI) over MoS₂ powder and the MoS₂/RGO aerogel; (c) Repeated tests of photocatalytic hydrogen evolution of the MoS₂/RGO aerogel; (d) Adsorption capacity of the MoS₂/RGO aerogel.

aerogel holds great promise for water pollution remediation.

Based on the above results and analysis, a possible mechanism for photocatalysis with the MoS₂/RGO aerogel is illustrated in Fig. 6. Typically, the photocatalysis process involves three steps [38,39]. First, the H⁺ or Cr(VI) ions in the water are adsorbed onto the surface of the photocatalyst. The MoS₂/RGO aerogel has a larger surface area (599.7 m²/g) than the MoS₂ powder (128.4 m²/g), which suggests that it has a higher adsorption capacity for H⁺ and Cr(VI) ions. Indeed, the MoS₂/RGO aerogel shows better adsorption for Cr(VI) (110.1 mg/g) than

Fig. 6. Schematic illustration of the photocatalytic process in the MoS₂/RGO aerogel.

the MoS₂ powder (62.4 mg/g) (Fig. 5(b)). Next, under visible light irradiation, the catalyst absorbs photons and excites electrons and holes simultaneously. Finally, photo-generated electrons are transferred to the surface of the catalyst and reduce H⁺ or Cr(VI) to H₂ or Cr(III), while the holes are consumed by the hydroxyl and carboxylic groups of the RGO [33,40,41]. Without the introduction of RGO, the MoS₂ cannot efficiently absorb visible light, and the photo-generated electron-hole pairs are more likely to recombine, which ultimately results in a low photocatalytic activity. When MoS₂ is combined with RGO, a greater number of electrons are excited by the strong adsorption of visible light, and they then react with the adsorbed H⁺ and Cr(VI) at the active edges of the MoS₂. Furthermore, the high conductivity of RGO may promote the electron transfer [42]. In summary, the large surface area, strong visible light absorption and fast electrical transport work together to enhance the photocatalytic performance.

4. Conclusions

A macroscopic MoS₂/RGO aerogel with an efficient visible light response has been successfully prepared by a hydrothermal method followed by freeze-drying. The addition of GO to the hydrothermal reaction system not only supported the formation of the hydrogel but also promoted the growth of the 3D

hierarchical MoS₂ structure. The excess thiourea precursor resulted in the intercalated ammonium ions between the MoS₂ layers and the additional exposed active edge sites. Importantly, the hydrogen evolution (38.9 $\mu\text{mol/g}$) and photoreduction ratio of Cr(VI) (92%) over the MoS₂/RGO aerogel were considerably higher than those observed for the MoS₂ powder. In addition, the as-prepared MoS₂/RGO aerogel had a low density (56.1 mg/cm³) and showed good adsorption capacity towards various organic solvents. The excellent photocatalytic performance and adsorption capacity of the MoS₂/RGO aerogel make it a promising candidate for clean energy production and environmental remediation.

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Graphical Abstract

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Three-dimensional MoS₂/reduced graphene oxide aerogel as a macroscopic visible-light photocatalyst

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A macroscopic MoS₂/RGO aerogel with enhanced visible-light photocatalytic performance was successfully prepared and can be used for photocatalytic hydrogen evolution, photoreduction of Cr(VI) and adsorption of organic pollutants.

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三维二硫化钼/还原氧化石墨烯气凝胶用作宏观可见光催化剂

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摘要: 近年来, 光催化技术在解决环境污染和能源短缺方面展现出巨大潜力. 二硫化钼(MoS₂)作为一种二维层状光催化材料受到广泛关注. MoS₂具有可调的带隙(1.2–1.9 eV)、低的成本和高的存储量, 是一种可替代铂的理想助催化剂. 然而, MoS₂本身光催化活性较低. 理论和实验已经证明, MoS₂只有暴露的边缘具有催化活性, 并且MoS₂的光生电子-空穴对容易复合, 导致其光催化效率低. 增加暴露的活性边缘以及有效分离电子-空穴对是提高MoS₂光催化活性的关键. 而石墨烯气凝胶是一种理想的催化剂载体, 其高比表面积和高孔隙率可以有效提高催化剂利用率. 同时, 其高导电性可以促进光生电子-空穴对分离. 因此, 将MoS₂负载到石墨烯气凝胶上制备宏观可回收光催化材料具有广阔的应用前景. 然而, 目前尚未见到有关MoS₂/石墨烯气凝胶光催化产氢以及还原Cr(VI)的报道.

本文以钼酸铵为钼源, 硫脲为硫源和还原剂, 同时加入氧化石墨烯及其还原剂氨水, 通过一步水热法制备出二硫化钼/还原氧化石墨烯(MoS₂/RGO)水凝胶. 最后通过冷冻干燥得到MoS₂/RGO气凝胶. 经光催化测试发现其产氢达到38.9 μmol/g, 光还原Cr(VI)达到92%, 明显高于MoS₂粉体. 采用X射线衍射(XRD)、扫描电镜(SEM)、透射电镜(TEM)、X射线光电子能谱(XPS)、紫外-可见-近红外吸收光谱(UV-Vis-NIR)及红外光谱(FTIR)等手段研究了其光催化性能提高的原因.

XRD测试显示, 过量的NH₄⁺离子插入到MoS₂层与层之间增加了(002)面的晶面间距; SEM观察到在形成气凝胶后, MoS₂从粉末的片状转变成花状, 这是因为氧化石墨烯上的含氧官能团促进MoS₂成核同时限制其生长导致的; TEM观察到MoS₂上存在大量的脱节和扭曲, 这是由于过量硫脲阻碍了MoS₂晶体的取向生长而产生缺陷; XPS发现, 除了形成MoS₂之外, 还形成了MoO₃, 同时大量的暴露边缘导致不饱和硫产生; FTIR表明MoS₂与RGO之间通过氢键链接在一起; UV-Vis-NIR吸收光谱显示, MoS₂/RGO气凝胶在可见光区具有很强的吸收, 这是黑色的RGO以及光在花状结构的不断反射共同作用导致的.

综合以上结果, 我们提出了MoS₂/RGO光催化性能增强的机理. 首先, 三维的气凝胶网状结构以及花状结构的MoS₂所带来的高比表面积(599.7 m²/g)使得材料对H⁺和Cr(VI)吸附量增加; 其次, 黑色的RGO以及入射光在花状结构层片间的不断反射增加了MoS₂/RGO气凝胶对可见光的吸收; 最后, RGO本身的高导电性促进了光生电子-空穴有效分离, 电子通过RGO快速转移到材料表面参与光催化反应. 因此, 将MoS₂负载在RGO上可提高光催化效率. 另外, 低密度的MoS₂/RGO气凝胶(56.1 mg/cm³)可以有效吸附有机溶剂且容易回收. 综上所述, 本文制备的MoS₂/RGO气凝胶光催化材料在环境与能源方面表现出潜在的应用前景.

关键词: 二硫化钼/石墨烯气凝胶; 复合材料; 光催化; 可见光; 吸附

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