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Article

Selective synthesis of Sb_2S_3 nanostructures with different morphologies for high performance in dye-sensitized solar cells

Xue Chen ^a, Xuemin Li ^a, Pengkun Wei ^a, Xiaoyong Ma ^{c,*}, Qinlin Yu ^{b,#}, Lu Liu ^{a,\$}^a Tianjin Key Laboratory of Environmental Remediation and Pollution Control, College of Environmental Science and Engineering, Nankai University, Tianjin 300350, China^b Key Laboratory of Molecular Microbiology and Technology, College of Life Science, Nankai University, Tianjin 300350, China^c Shanxi Provincial Research Academy of Environmental Sciences, Taiyuan 030027, Shanxi

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ABSTRACT

In this work, we initially synthesized Sb_2S_3 with uniform flower-like structures via a facile hydrothermal method through the modification of the Sb source and pH value. Afterward, Sb_2S_3 with a nanosheet structure was successfully synthesized on reduced graphene oxide ($\text{Sb}_2\text{S}_3/\text{RGO}$). The flower-like Sb_2S_3 and the $\text{Sb}_2\text{S}_3/\text{RGO}$ nanosheets were tested as the counter electrode (CE) of dye-sensitized solar cells, and the latter exhibited a higher electrocatalytic property than the former owing to the introduction of graphene. The results from electrochemical tests indicated that the as-prepared $\text{Sb}_2\text{S}_3/\text{RGO}$ nanosheets possess higher catalytic activity, charge-transfer ability, and electrochemical stability than Sb_2S_3 , RGO, and Pt CEs. More notably, the power conversion efficiency of $\text{Sb}_2\text{S}_3/\text{RGO}$ reached 8.17%, which was higher than that of the standard Pt CE (7.75%).

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1. Introduction

In recent decades, global warming and energy crises have become critical, and the need for inexhaustible clean energy technologies has become urgent [1,2]. In 1991, Grätzel [3] firstly reported dye-sensitized solar cells (DSSCs). DSSCs have aroused interest from researchers owing to their low price, excellent theoretical power conversion efficiency (PCE), environmental friendliness, and multi-color transparency [4,5]. In general, DSSCs consist mainly of a dye-sensitized photoanode, a counter electrode (CE), an electrolyte-based on iodine, and an external circuit [6]. The CE, a critical component of DSSCs, affects the catalytic reduction of redox couples and plays an im-

portant role in the photovoltaic conversion efficiency. A superior electrocatalytic activity for the regeneration of redox couples, excellent electrical conductivity, and good mechanical stability are characteristics of a promising CE in the electrolytic cell system [7,8]. Usually, Pt is utilized as a standard CE in DSSCs on the basis of its outstanding electrocatalytic activity and ability [4,9]. However, due to the expensive and rare properties of Pt, large-scale commercialization is unrealistic. Therefore, it is important to exploit low-cost, efficient, large-scale commercial, and stable alternative Pt-free CE materials.

In the past years, researchers have made great efforts to find alternatives to Pt, such as alloys, metal oxides, and sulfur compounds, and to achieve excellent catalytic activity and

* Corresponding author. E-mail: hkyshtygs@sohu.com

Corresponding author. E-mail: yuqilin@mail.nankai.edu.cn

\$ Corresponding author. E-mail: liul@nankai.edu.cn

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conductivity of DSSCs via modulating their crystal structures, morphologies, or chemical compositions [10–13]. Metallic sulfur compounds with ultrathin nanostructures have received considerable attention due to their short transport paths and high surface area in chemical/physical processes [14]. In recent years, antimony sulfide (Sb_2S_3) has been applied in DSSCs due to its excellent light absorption coefficient (up to 10^5 cm^{-1}) [15]. For example, Yong et al. [16] reported that Sb_2S_3 -based solar cells constructed on the sensitized device structure achieved a high PCE of 7.5%. Sun and co-workers [17] synthesized a hybrid catalyst composed of mesoporous carbon nanoparticle films and Sb_2S_3 , and its PCE reached 6.69%. Sb_2S_3 is considered one of the most promising CE materials due to its 1.5–2.2 eV gap width, which covers a large proportion of the visible spectrum [18,19]. Besides, Sb_2S_3 is the main component of nontoxic antimony minerals, which are abundant in the earth [20]; they are also applied in other fields as solar energy conversion materials [21], catalysts [22], and photoconductive detectors [23]. Generally, graphene possesses a large specific surface area, remarkable carrier mobility, and excellent thermal/chemical stability, which makes it a suitable candidate for improving the electron transfer efficiency and electrocatalytic activity [24–28]. In addition, the introduction of graphene into the CEs of DSSCs effectively raises the electron transfer of the TiO_2 conductive band to the external circuit, decreases the charge recombination, and enhances the conversion efficiency [29,30]. Based on the aforementioned characteristics, graphene is considered a perfect backing material for growing the nano-materials applied in the CEs of DSSCs [31].

In this study, we fabricated uniform flower-like Sb_2S_3 via an uncomplicated procedure after adjusting the experimental conditions (Sb source and pH value). Afterward, with the addition of graphene in the synthesis, the morphology of the products changed from a flower-like structure to nanosheets, and the Sb_2S_3 nanosheets on the reduced graphene oxide ($\text{Sb}_2\text{S}_3/\text{RGO}$) were synthesized. We assessed the photovoltaic property and electrocatalytic activity of the as-synthesized samples used as CEs of DSSCs. It was confirmed experimentally that $\text{Sb}_2\text{S}_3/\text{RGO}$ exhibited an excellent PCE of 8.17%, which was better than those of the flower-like Sb_2S_3 (7.38%), RGO (2.66%), and standard Pt CEs (7.75%). We provide a convenient approach to synthesizing an alternative material for Pt in the field of DSSCs. To the best of our knowledge, this is the first time that Sb_2S_3 nanosheets on RGO have been applied as a CE in DSSCs.

2. Experimental

2.1. Synthesis of graphite oxide (GO) nanosheets

GO nanosheets were prepared according to the modified Hummers method [32]. Briefly, 2 g of graphite powder was added to 100 mL of concentrated H_2SO_4 at 0 °C. Gradually, 6 g of KMnO_4 was added to the above mixture. Subsequently, the obtained suspension was continuously stirred for 15 h at 35 °C. Thereafter, 200 mL of distilled water was gradually added, and the temperature was maintained at 98 °C for 2 h. When the

temperature dropped to 60 °C, 10 mL of H_2O_2 (30%) was added into the suspension in a dropwise manner to thoroughly eliminate the additional KMnO_4 . After the above process, a bright yellow mixture was obtained, which was centrifuged and washed with conductivity water until the supernatant was neutral. The final precipitate was GO. The GO powder was obtained by ultrasonication of the GO precipitates dispersed in water, followed by drying for 10 h at 50 °C.

2.2. Synthesis of $\text{Sb}_2\text{S}_3/\text{RGO}$ nanosheets

The GO powder obtained above was uniformly dispersed in ethylene glycol under ultrasound, and the final concentration was 0.1 mg/mL; thereafter, 0.228 g of antimony trichloride (SbCl_3) was added to 20 mL of ethylene glycol under stirring to form a clear solution. Afterward, 0.485 g of L-cysteine and 20 mL of ethylene glycol containing graphene were successively added into the solution. After 10 min of stirring, 0.4 g of SDS (sodium dodecyl sulfate) was added as the template. The pH of the reaction system was adjusted to 10 with a 10 mol/L NaOH aqueous solution. Subsequently, the well-mixed liquid was transferred into a Teflon-lined autoclave and kept at 150 °C for 24 h. When the temperature of the autoclave was lowered to room temperature, the precipitate obtained by centrifugation was washed several times with deionized water and ethanol. The obtained samples were desiccated under vacuum at 60 °C all-night and then calcined at 200 °C for 2 h under argon protection.

2.3. Characterization

The crystalline structures of the obtained samples were analyzed by X-ray diffraction (XRD, Rigaku D/max2500) with $\text{Cu K}\alpha$ radiation ($\lambda = 1.54056 \text{ \AA}$). Scanning electron microscopy (SEM, Nanosem 430, FEI) was utilized to measure the morphology of the samples, and transmission electron microscopy (TEM, Tecnai G2 F20, operating voltage of 200 kV, FEI) and energy-dispersion spectroscopy (EDS) were utilized to characterize the detailed microstructure information and element composition of the samples. The Brunauer-Emmett-Teller (BET) specific surface areas of the samples were studied by the BET equation in a Tristar 3000 nitrogen adsorption apparatus.

2.4. Preparation of CEs and DSSCs

The mixture composed of 0.1 g of the sample and 0.025 g of PEG20000 (polyethylene glycol 20,000) was continuously ground in ethanol to obtain a smooth mud. The obtained mud was coated on a clean fluorine-doped tin oxide (FTO) glass substrate with a doctor blade to form a film. The film was stabilized by drying at room temperature for one day in a vacuum oven. Subsequently, $\text{Sb}_2\text{S}_3/\text{RGO}$ CEs were obtained from the conductive glass covered with film heated under argon protection at 400 °C for 2 h. For comparison, $\text{Sb}_2\text{S}_3/\text{RGO}$ CE and RGO CE were prepared by the same process as above.

The TiO_2 film was fabricated with a commercial TiO_2 sol by the same procedure. The dye-sensitized TiO_2 electrodes were

obtained by soaking the FTO glass plates with TiO_2 films in a solution of N719 dye (di-tetrabutylammonium cis-bis (isothiocyanato), bis(2, 2'-bipyridyl-4,4'-dicarboxylato) ruthenium (II)), and ethanol in the dark for one day. DSSCs were assembled in a cell composed of a TiO_2 photoanode, CE, and liquid electrolyte. Surlyn 1702 (a thermoplastic frame) was used as the interval between the two electrodes. To avert leakage of the electrolyte solution, paraffin wax acted as a sealant to clamp the two electrodes together. Other DSSCs were prepared with Sb_2S_3 or RGO, or Pt while other processes remained unchanged.

2.5. Electrochemical measurements

The Zahner IM6 electrochemical workstation was applied to measure all the electrochemical performance. The photocurrent–voltage curves were obtained with a Keithley digital source meter (Keithley 2410, USA). Cyclic voltammetry (CV) curves were recorded using a three-electrode system on the electrochemical station, in the range of -0.4 – 1.2 V, at a scan rate of 25 mVs^{-1} .

Electrochemical impedance spectroscopy (EIS) testing was performed under the following conditions: zero bias potential, a frequency range of 0.1 Hz – 1 MHz , and a 5 mV sinusoidal AC voltage signal. The obtained impedance spectra were analyzed with the A-view 2.0 software. The Tafel-polarization curves were measured in a symmetric virtual cell employed for the EIS experiments, using the same electrolyte as in the DSSCs. The voltage range was -1.0 – 1.0 V, and the scan rate was 20 mVs^{-1} .

3. Results and discussion

3.1. Investigation of synthesis conditions and characterization of samples

The morphology of the Sb_2S_3 sample changes with the pH value in the experimental process when the Sb source is invariable. In Fig. S1, antimony triacetate is employed as the Sb source. Fig. S1(a) shows that the Sb_2S_3 morphology is identical to an integrated nanorod structure ($\text{pH} = 3$). When the pH is 6, the morphology of the sample is an irregular sphere (Fig. S1b). Nanosheet structure begins to appear when the pH is 8 (Fig. S1(c)), although there is no uniform structure with nanosheets in Fig. S1(d) ($\text{pH} = 10$). According to the XRD analysis (Fig. S1(e)), the diffraction peaks of the sample are consistent with that of the standard card (JCPDS card No.42–1393) only when the pH is 3. Antimony chloride is used as the Sb source in Fig. S2. Similarly, the morphology of the sample changed from the

irregular rod-like shape ($\text{pH} = 3$, Fig. S2(a)) to nanospheres ($\text{pH} = 6$, Fig. S2(b)), followed by nanosheets structure ($\text{pH} = 8$, Fig. S2(c)). Differently, the nanosheets form uniform flower-like structures when the pH is 10 (Fig. S2d). The results of XRD analysis show that the diffraction peaks of samples match the values well in the standard card (JCPDS card No. 42–1393), except for the sample obtained at a pH of 3 (Fig. S2(e)). The seriousness of the results indicates that the Sb source and alkaline environmental conditions of the synthesis are indispensable in forming Sb_2S_3 with a uniform flower-like structure composed of nanosheets.

Subsequently, graphene was introduced in the synthesis, and $\text{Sb}_2\text{S}_3/\text{RGO}$ composites with a nanosheet structure (Fig. 1(a)) were successfully synthesized using antimony chloride as the source of Sb at a pH of 10; other conditions remain unchanged. Fig. 1(b) shows that the graphene nanosheet is considerably visible in the $\text{Sb}_2\text{S}_3/\text{RGO}$ composites. In the inset of Fig. 1(b), the lattice spacing of 0.358 nm is consistent with the d -spacing between the adjacent (130) crystallographic planes of the $\text{Sb}_2\text{S}_3/\text{RGO}$ composite. The elemental mapping (EM) of the sample was used to examine the compositional uniformity of $\text{Sb}_2\text{S}_3/\text{RGO}$. Fig. 1(c) demonstrates that the C, S, and Sb elements of the $\text{Sb}_2\text{S}_3/\text{RGO}$ composites were uniformly distributed. The diffraction peaks of $\text{Sb}_2\text{S}_3/\text{RGO}$ are noticeable, clear, and in agreement with the values from the standard card (JCPDS card No. 42–1393) (Fig. 2(a)), and there are no characteristic peaks of other impurities. The elemental composition of the as-fabricated $\text{Sb}_2\text{S}_3/\text{RGO}$ composite is further analyzed by EDS. Fig. 2(b) shows that there are C, S, and Sb elements in the $\text{Sb}_2\text{S}_3/\text{RGO}$ composite, and C originates from graphene.

Figs. 3(a) and 3(b), respectively, display the aperture structure and pore diameter distribution of Sb_2S_3 nanospheres and $\text{Sb}_2\text{S}_3/\text{RGO}$ nanosheets, analyzed by the nitrogen sorption method. The two isotherms have similar hysteresis loops and both belong to the type IV sorption isotherm. Using BET calculation, the specific surface of Sb_2S_3 is $\sim 41.72 \text{ m}^2\text{g}^{-1}$, while that of the $\text{Sb}_2\text{S}_3/\text{RGO}$ composites is $\sim 44.53 \text{ m}^2\text{g}^{-1}$. The above results can be ascribed to the addition of RGO, which provided more active surface sites and increased the adsorption of the reactants owing to its large surface area [33]. According to the results from the Barrett-Joyner-Halenda (BJH) pore-size distribution test, the average pore diameters of both samples are 31.08 and 22.65 nm , respectively. The results indicate that both Sb_2S_3 and the $\text{Sb}_2\text{S}_3/\text{RGO}$ composites possess a mesoporous structure, which provides vast access to the internal electrocatalyst, thereby improving the catalytic capacity of CE and promoting the electrochemical reaction [34].

Fig. 1. SEM (a) TEM (b) images, and elemental mappings (c) of the $\text{Sb}_2\text{S}_3/\text{RGO}$ composite samples.

Fig. 2. (a) XRD patterns of RGO and the Sb₂S₃@RGO composites; (b) EDS analysis of the Sb₂S₃@RGO composites.

Fig. 3. N₂ adsorption-desorption isotherms and the corresponding pore size distribution plot (inset) of the Sb₂S₃ (a) and Sb₂S₃@RGO (b) samples.

3.2. Electrocatalytic performances of the DSSC devices based on Sb₂S₃@RGO nanosheets

EIS is utilized to assess the electrochemical properties of the electrode material, which can reflect information about the impedance from the chemical reaction kinetics between the electrode interface and the electrolyte [35]. The EIS curves of various CEs are displayed in Fig. 4, and the matching data cal-

culated from the results are shown in Table 1. The ohmic series resistance (R_s) is directly connected with the electrolyte property and CE sheet resistance, acquired from the X-intercept in the high-frequency region of EIS. The R_s values of the Sb₂S₃@RGO composites, Sb₂S₃, RGO, and Pt are 10.75, 11.12, 12.28, and 11.5 Ω , respectively. The R_s of the Sb₂S₃@RGO composites is lower than that of Pt, suggesting the relatively high conductivity of the composites. The charge transfer resistance (R_{ct}) is crucial to the electron exchange between the CE and the electrolytes [36]. The lesser R_{ct} value of the Sb₂S₃@RGO composites (1.099 Ω) compared to those of Sb₂S₃ (1.40 Ω), RGO (7.88 Ω), and Pt (1.28 Ω) indicates the better catalytic activity of the CEs and a high PCE of the DSSCs combined with these CEs [37]. The above results indicate that the Sb₂S₃@RGO composites possess an outstanding electrocatalytic ability in the reaction of I₃⁻ to I⁻.

Fig. 4. Nyquist plots for the four as-prepared electrodes.

Table 1
Corresponding parameters of different CEs.

CEs	R_s (Ω)	R_{ct} (Ω)	E_{pp} (mV)	J_{ox-1} (mA cm ⁻²)	$\log J_{lim}$ (mA cm ⁻²)	$\log J_0$ (mA cm ⁻²)
Sb ₂ S ₃ @RGO	10.75	1.009	0.303	2.39	2.12	1.16
Sb ₂ S ₃	11.12	1.40	0.463	2.05	1.88	0.97
RGO	12.28	7.88	0.580	1.50	1.40	0.48
Pt	11.5	1.28	0.399	2.29	1.95	1.03

Fig. 5. Cyclic voltammograms of four CE tested at a scan rate of 25 mVs⁻¹.

CV was carried out with a three-electrode system to evaluate the electrocatalytic performance of Sb₂S₃@RGO. In addition, the electrocatalytic properties of Sb₂S₃, RGO electrode, and Pt electrode were detected under the same test conditions. All the CV curves (-0.3–1.65 V) have two pairs of redox peaks; the left pair (Ox₁/Red₁) is attributed to the reaction of I₃⁻/I⁻, and the right one (Ox₂/Red₂) belongs to the reaction of I₂/I₃⁻ (Fig. 5). The peak-to-peak separation (E_{pp}) and peak current density (J_A) are two vital data for assessing the electrochemical property of the catalytic electrodes [38]. From Table 1, the relatively high J_A and low E_{pp} values belong to the Sb₂S₃@RGO CE, indicating the higher electrocatalytic activity than that of the standard Pt CE [39]. In addition, the results show that the Sb₂S₃@RGO CE presents a higher electrocatalytic performance than that of the pure Sb₂S₃ CE, which suggests that adding RGO into the Sb₂S₃ sample improved the electrocatalytic activity. To investigate the electrochemical invertibility and stability of the Sb₂S₃@RGO CE, successive CV experiments were carried out at a scan rate of 25 mVs⁻¹. There is a negligible change in E_{pp} and J_A , illustrating that the Sb₂S₃@RGO CE possesses excellent cyclic reversibility and stability (Fig. 6).

Tafel polarization testing was carried out to further analyze the electrocatalytic properties of the samples. Fig. 7 displays four Tafel curves of the cells based on Sb₂S₃@RGO, Sb₂S₃, RGO,

Fig. 6. 20-cycle CVs of the Sb₂S₃@RGO CE at a scan rate of 25 mVs⁻¹.

Fig. 7. Tafel polarization curves of different CEs.

and Pt. The limiting diffusion current density (J_{lim}) refers to the junction of the Y-axis with the cathodic branch, which is closely related to the diffusion rate of the I₃⁻/I⁻ redox couples [40]. The exchange current density (J_0) is acquired from the slope of the anodic or cathodic branches by linear extrapolation [41]. The value of J_0 is positively correlated with the catalytic activity of the cathode for I₃⁻ [42]. As shown in Table 1, the largest values of both log J_{lim} (2.12 mAcm⁻²) and log J_0 (1.16 mAcm⁻²) are generated from the Sb₂S₃@RGO composite CEs, which indicates that the Sb₂S₃@RGO nanosheets possess a superior electrocatalytic property to that of the Pt CEs. Additionally, the results of the Tafel polarization testing are in line with the outcome of the CV.

The photocurrent density-voltage (J - V) curves of the DSSCs based on the Sb₂S₃@RGO composites, Sb₂S₃, RGO, and Pt are displayed in Fig. 8, and the related test parameters are summarized in Table 2. From Fig. 8, we can see that the DSSCs assembled with the Sb₂S₃@RGO composites possess a PCE of 8.17%, which is higher than those of the DSSC models with Pt CEs (7.75%), RGO CEs (2.66%), and Sb₂S₃ CEs (7.38%). The detailed corresponding test data in Table 2 shows that the Sb₂S₃@RGO CE exhibited a higher fill factor (FF = 0.68) and short-circuit current (J_{sc} = 16.23 mAcm⁻²) than those of the Pt CE (FF = 0.66, J_{sc} = 15.87 mAcm⁻²). The high catalytic activity for I₃⁻ reduction

Fig. 8. Photocurrent density-voltage characteristics of the DSSCs based on four CEs.

Table 2

Corresponding parameters of the DSSCs.

CEs	V_{oc} (V)	J_{sc} (mA cm ⁻²)	FF	PCE (%)
Sb ₂ S ₃ @RGO	0.74	16.23	0.68	8.17
Sb ₂ S ₃	0.74	15.34	0.65	7.38
RGO	0.71	6.83	0.55	2.66
Pt	0.74	15.87	0.66	7.75

led to the enhanced J_{sc} value [35] and the higher FF value benefited from the relatively small series resistance (R_s) in the EIS experiment [31], which eventually led to the superior PCE value of the DSSC based on Sb₂S₃@RGO. The result of the Sb₂S₃@RGO CE from photoelectric conversion efficiency testing matches the results of CV, polarization, and EIS. All the above results have verified its high-efficiency electrocatalytic performance.

4. Conclusions

In summary, by changing the Sb source and pH value as well as introducing graphene, we successfully synthesized Sb₂S₃@RGO composites with a nanosheet structure by a facile and economical hydrothermal method. Based on the electrochemical experimental results, we summarize that the composites, as CE materials, displayed excellent electrochemical and photovoltaic properties applied in DSSCs. Notably, a higher PCE (8.17%) of the Sb₂S₃@RGO composites was achieved, compared with that of the standard Pt (7.75%). The obtained results also indicated that the addition of RGO not only changed the morphology but also improved the electrocatalytic performance of the Sb₂S₃@RGO composites when compared with that of the rare Sb₂S₃. We believe the current work could serve as a reference and provide guidance for designing high-performance DSSCs.

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Graphical Abstract

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Selective synthesis of Sb₂S₃ nanostructures with different morphologies for high performance in dye-sensitized solar cells

Xue Chen, Xuemin Li, Pengkun Wei, Xiaoyong Ma*, Qinlin Yu*,
Lu Liu*
Nankai University; Shanxi Provincial Research Academy of
Environmental Sciences

Sb₂S₃ nanosheets grown on reduced graphene oxide (Sb₂S₃@RGO) were successfully synthesized, and the power conversion efficiency (PCE) of the DSSCs based on Sb₂S₃@RGO CEs reached 8.17%, which is higher than that of the standard Pt CE (7.75%).

a

b

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选择性合成不同形貌的Sb₂S₃纳米结构应用于高性能的染料敏化太阳能电池

陈 学^a, 李雪敏^a, 卫朋坤^a, 马小勇^{c,*}, 喻其林^{b,#}, 刘 璐^{a,s}

^a南开大学环境科学与工程学院环境修复与污染控制天津重点实验室, 天津300350

^b南开大学生命科学学院分子微生物与技术重点实验室, 天津300350

^c山西省环境科学研究院, 山西太原030027

摘要: 近几十年来, 随着全球变暖和能源危机的日益严重, 对取之不尽、用之不竭的清洁能源技术的需求越来越迫切。1991年Gratzel首次报道了染料敏化太阳能电池(DSSCs), 它以低廉的价格、优异的理论功率转换效率(PCE)、环保、多色透明等优点而引起了研究者的关注。Sb₂S₃因其1.5–2.2 eV的间隙宽度被认为是最有前途的对电极材料之一。此外, Sb₂S₃是地球中含量丰富的无毒锑矿物的主要成分, 还被广泛应用于太阳能转换材料、催化剂、光导探测器等领域。众所周知, 石墨烯具有巨大的比表面积、显著的载流子迁移率和优异的热/化学稳定性, 这使得提高电子转移效率和电催化活性成为可能。

首先, 采用改进的Hummers方法制备了氧化石墨烯纳米片; 然后采用水热法通过改变Sb源以及实验pH值, 合成了Sb₂S₃和Sb₂S₃@RGO样品。对样品进行X射线粉末衍射(XRD)、扫描电子显微镜(SEM)、投射电子显微镜(TEM)以及比表面积表征。结果表明, 在Sb源不变的情况下, Sb₂S₃样品的形貌随pH值的变化而变化。以三乙酸锑为Sb源, 在pH=3时, Sb₂S₃的形貌类似于一个完整的纳米棒结构; 在pH值为6时, 样品为不规则球体; 当pH值为8时, 纳米片结构开始出现; 但当pH=10时, 纳米片结构并不均匀。根据XRD分析, 只有当pH值为3时, 样品的衍射峰才与标准卡(JCPDS 42-1393)的衍射峰一致。当以氯化锑作为锑源, 样品的形貌由不规则的杆状(pH=3)转变为纳米球(pH=6), 然后出现纳米片结构(pH=8)。不同的是, 当pH值为10时, 纳米薄片形成均一的花状结构。XRD结果表明, 除pH值为3外, 样品的衍射峰与标准卡(JCPDS 42-1393)的值吻合较好。结果表明, 合成条件所需的Sb源和碱性环境是合成具有均匀花状结构的纳米片状Sb₂S₃所必不可少的。测得Sb₂S₃的比表面积约为41.72 m²g⁻¹, 平均孔径为31.08 nm, Sb₂S₃@RGO的分别为44.53 m²g⁻¹和22.65 nm。Sb₂S₃和Sb₂S₃@RGO复合材料均具有介孔结构, 为内部电催化剂提供了广阔的通道, 从而提高了对电极的催化能力, 促进了电化学反应。

将Sb₂S₃纳米花球和Sb₂S₃@RGO纳米薄片作为染料敏化太阳能电池的对电极进行了测试, 由于石墨烯的引入, 后者比前者具有更好的电催化性能。电化学实验结果表明, 与Sb₂S₃, RGO, Pt作为对电极相比, 制备的Sb₂S₃@RGO纳米薄片具有更好的催化活性、电荷转移能力和电化学稳定性, Sb₂S₃@RGO的功率转换效率达到8.17%, 优于标准Pt对电极(7.75%)。

关键词: Sb₂S₃; 还原性石墨烯; 对电极; 染料敏化电池; 功率转换效率

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*通讯联系人. 电子信箱: hkyshyts@sohu.com

#通讯联系人. 电子信箱: yuqilin@mail.nankai.edu.cn

s通讯联系人. 电子信箱: liul@nankai.edu.cn

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