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Preparation and visible light catalytic activity of three-dimensional ordered macroporous CdS/TiO₂ films

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ABSTRACT

A three-dimensional ordered macroporous CdS/TiO₂ film was prepared by the sol-gel method with a colloidal crystal template and S²⁻ ion exchange, and it exhibited high visible light photocatalytic activity for the aqueous degradation of rhodamine B and 4-chlorophenol. The modification with CdS gave visible light absorption by photosensitization and better separation of photo-induced electrons and holes. The ordered macroporous structure gave higher light utilization and faster reactant transport.

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1. Introduction

Organic pollutants are the main source of global pollution, especially water pollution [1,2]. The removal of organic pollutants by photocatalytic degradation technology has the advantages of environmental friendliness, mild reaction conditions, low energy consumption, and low cost [3,4]. Although the commonly used TiO₂ photocatalyst is stable, non-toxic, and cheap, it can be only excited by UV light and has low utilization of solar light because of the large band gap. At the same time, its quantum efficiency is very low [5,6]. TiO₂ can be modified to give a photocatalytic reaction under visible light irradiation [7]. The CdS/TiO₂ visible light photocatalyst has attracted much attention because the photosensitization by CdS gives a narrow band gap (2.4 eV) [8]. Previous research has mainly focused on the CdS/TiO₂ powder [9,10], but this is difficult to separate from the reaction in the aqueous solution.

A photocatalytic film reactor can allow the continuous treatment of aqueous organic pollutants because there is no need for catalyst separation. At present, it is still very difficult to prepare a CdS/TiO₂ film with a good distribution of CdS and strong bonding of CdS to TiO₂. Furthermore, the light utilization of most photocatalytic films is low, and mass transfer limitation is severe. A three-dimensional ordered and macroporous structure has been confirmed as effective for increasing the surface area, enhancement of reactant transfer, and increased light absorbance, and it has received much attention for applications in pollutant control and solar energy utilization [11,12]. Here, a three-dimensional ordered macroporous CdS/TiO₂ film was prepared by the sol gel method with a colloidal crystal template and S²⁻ ion exchange. The CdS/TiO₂ film exhibited improved light harvesting and visible light photocatalytic activity.

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2. Experimental

2.1. Preparation of the CdS/TiO₂ membrane

2.1.1. Fabrication of the colloidal crystal template

The mono-dispersed polystyrene microspheres used as the colloidal crystal template were prepared by emulsifier-free batch emulsion polymerization [13]. Styrene (21 ml), acroleic acid (0.95 ml), and methyl methacrylate (1.1 ml) were dissolved in 6.3 mmol ammonium bicarbonate buffer solution (0.50 g ammonium bicarbonate added in 100 ml distilled water) and kept at 70 °C for 0.5 h. Then, 2.3 mmol ammonium persulfate was added and the solution was heated to 80 °C with stirring for 10 h to get a suspension of mono-dispersed polystyrene microspheres of poly[styrene-methyl methacrylate-acroleic acid] (denoted P(ST-MMA-AA).

2.1.2. Fabrication of the colloidal crystal film

The glass substrate with the size 2.5 cm × 2.0 cm was first treated with 1.0 mol/L NaOH solution for 2 h, ultrasonically cleaned with acetone, ethanol, and water three times, respectively, and then dried in air. The glass substrate was immersed vertically in the aqueous suspension of PS colloidal crystal of 0.25 wt % and kept at 60 °C for 24 h to get the colloidal crystal film on the substrate by the evaporation effect.

2.1.3. Fabrication of the 3D OM CdS/TiO₂ film

TiCl₄ (1.0 ml) was added dropwise into 20 ml ethanol solution with stirring for 5 min. The desired amount of Cd(NO₃)₂ was added with stirring and completely dissolved, and 3.0 ml tetrabutyl titanate was then added, followed by stirring for 2 h to get the CdS/TiO₂ precursor. Then, 0.10 ml precursor was dropped into the voids of the PS colloidal crystal template at a 15° inclination angle of glass substrate and dried at ambient temperature. The sample was calcined at 400 °C for 6 h by heating at 2 °C/min. After it was cooled, the sample was immersed into 0.20 mol/L Na₂S solution for 12 h for the ion exchange, followed by washing in deionized water and drying. The sample obtained was denoted xCdS/TiO₂, in which x was the Cd/Ti molar ratio, with values of 0.00%, 0.25%, 0.50%, 0.75%, and 1.0%, respectively. The macroporous structure was not obtained with higher Cd/Ti molar ratios.

For comparison, two film samples, TiO₂(C) and 1.0%CdS/TiO₂(C), were prepared by the dip-coating process with the same sol gel precursor in the absence of the PS colloidal crystal template. The 1.0%CdO/TiO₂ film was synthesized without the Na₂S ion exchange.

2.2. Characterization

The photocatalyst structure was determined from X-ray diffraction (XRD) patterns recorded on a Rigaku Dmax-3C apparatus with Cu K_α radiation (λ = 0.154 nm, 4°/min). Surface morphologies were observed by field emission scanning elec-

tron microscopy (FESEM, HITACHI S-4800) and high resolution transmission electronic microscopy (HRTEM, JEM-2010). N₂ adsorption-desorption isotherms were measured on a Quantachrome NOVA 4000e at -196 °C. The Brunauer-Emmett-Teller (BET) method was used to calculate the specific surface area (*A*_{BET}), and the pore distribution was obtained from the adsorption branch. The transmittance spectra were obtained on a Shimadzu UV-2450 UV-Vis spectrophotometer in the range of 200 to 800 nm using BaSO₄ as the reflectance standard. X-ray photoelectron spectroscopy (XPS, Versa Probe PHI 5000) was employed to determine surface electronic states (Al K_α radiation, 1486.6 eV). The shift of the binding energy due to surface charging was corrected using the C 1s level at 284.8 eV as an internal standard. Photoluminescence spectra (PLS) were collected on a Varian Cary-Eclipse 500 (65 W Xe lamp, 600 nm/min).

2.3. Photocatalytic test

A glass sheet (2.5 cm × 2.5 cm) coated with the CdS/TiO₂ catalyst was placed in 5.0 ml 10 mg/L rhodamine B (RhB) solution or 5.0 ml 15 mg/L 4-chlorophenol (4-CP) solution for the evaluation of photocatalytic activity. The photocatalytic film was illuminated by a 500 W Xe lamp. UV light with wavelengths less than 420 nm were removed by a glass filter. The reaction temperature was 30 °C. Adsorption-desorption equilibrium was achieved by adsorption for 30 min in the dark before the photocatalytic reaction. After irradiation for 100 min, the concentration of RhB or 4-CP was determined by measuring the light absorbance using the UV-Vis spectrophotometer using the characteristic peak of RhB (554 nm) or 4-CP (224 nm), and the degradation rate was calculated.

3. Results and discussion

3.1. Characterization results

FESEM images (Fig. 1) of the 1.0%CdO/TiO₂ and 1.0%CdS/TiO₂ films reveal that an ordered macroporous structure was present on a large scale in the 1.0%CdO/TiO₂

Fig. 1. FESEM images of different films. (a) 1.0%CdO/TiO₂; (b) Enlarged view of (a); (c) 1.0%CdS/TiO₂; (d) Enlarged view of (c).

Fig. 2. XRD patterns of TiO_2 and the 1% CdS/TiO_2 film.

sample and that this was maintained well in the 1.0% CdS/TiO_2 film after the ion exchange. The pore diameter was 300 nm and the thickness of the pore wall was 40 nm. This indicates that an ordered macroporous CdS/TiO_2 film can be successfully prepared by the sol gel method with a colloidal crystal template and S^{2-} ion exchange. From the XRD patterns in Fig. 2, the 1.0% CdS/TiO_2 film has the same diffraction peaks as the TiO_2 film composed of anatase TiO_2 (JCPDS 21-1272). No obvious peak for CdS was observed due to the high dispersion and low concentration of CdS.

In the HRTEM image of the 1.0% CdS/TiO_2 film in Fig. 3, two crystal lattice fringes with the inter-planar spaces for the $\text{TiO}_2(101)$ plane (0.35 nm) and $\text{CdS}(002)$ plane (0.34 nm), re-

Fig. 3. HRTEM and inset TEM images of the 1.0% CdS/TiO_2 film.

spectively, were observed, which was in accordance with a previous report [14]. It was further confirmed that CdS was uniformly distributed in the TiO_2 ordered macroporous structure with high crystallization. The inset TEM image also shows the structure of ordered macropores, corroborating the above results.

Figure 4 shows the XPS spectra of the 1.0% CdS/TiO_2 film, which showed that the peak positions of Ti 2p, O 1s, and Cd 3d were the same as those of pure TiO_2 and CdS [15,16]. It was demonstrated that the CdS was present in combination with TiO_2 in a composite because the radius of Cd^{2+} (97 pm) was larger than that of Ti^{4+} (61 pm), which makes it difficult to enter the crystal lattice of TiO_2 to give ion doping.

The N_2 adsorption-desorption isotherm and pore size distribution of the 1.0% CdS/TiO_2 sample are presented in Fig. 5.

Fig. 4. XPS spectra of the 1.0% CdS/TiO_2 film.

Fig. 5. N_2 adsorption-desorption isotherm (a) and pore size distribution (b) of 1.0% CdS/TiO_2 .

Fig. 6. UV-Vis DRS spectra of 1.0%CdS/TiO₂, TiO₂, and TiO₂(C) film.

The pore sizes were in the range of 2.0–3.8 nm, implying the existence of a mesoporous structure in the macroporous wall, which would be beneficial for the adsorption of reactants. The A_{BET} was 43 m²/g, as calculated by the BET method.

Figure 6 shows the UV-Vis diffuse reflectance (DRS) spectra of the various samples, which revealed that the macroporous structure in the TiO₂ film was favorable for light absorption and it gave a higher light harvest than the TiO₂(C) film. This can be attributed to light multiple reflection in the macroporous structure. In addition, the modification with CdS by ion exchange further enhanced the absorption of visible light. The 1.0%CdS/TiO₂ film showed a lower PL peak intensity than the TiO₂ film (see Fig. 7), which indicated a lower recombination probability of the photo-induced charges due to the formation of the CdS-TiO₂ heterojunction. This would benefit the quantum efficiency of the photocatalytic reaction. This can be ascribed to that the photo-generated electrons were transferred from CdS to the TiO₂ conduction band under light irradiation so that the electron density in the TiO₂ conduction band was increased and this efficiently inhibited the recombination of photo-induced holes and electrons, as shown in Fig. 8.

3.2. Photocatalyst activity

The photo-degradation of RhB under visible light irradiation

Fig. 7. PL spectra of 1.0%CdS/TiO₂ and TiO₂ films. The excitation wavelength is 280 nm.

Fig. 8. Illustration of electron transfer between CdS and TiO₂ in the CdS/TiO₂ film.

with the various samples and without a catalyst are presented in Fig. 9. The degradation rate of RhB without a catalyst was less than 2% and it can be neglected. Macroporous TiO₂ and the 1.0%CdS/TiO₂ film exhibited obviously increased activity over the TiO₂(C) and 1.0%CdS/TiO₂(C) films without template, which was ascribed to the enhancement of light harvest and faster reactant transport in the macropores. Furthermore, the sensitization effect of CdS promoted visible light photoactivity. In comparison to the pure TiO₂ film, the CdS/TiO₂ films with different CdS contents showed higher activities. The highest activity was with the 1.0% CdS molar ratio with a degradation rate of > 50% in 100 min. This resulted from improved visible light utilization and lower recombination due to CdS modification, leading to a higher quantum efficiency and photocatalytic activity [17]. In order to avoid the sensitization effect of RhB, the photo-degradation of 4-CP by the different CdS/TiO₂ films was also investigated under visible light irradiation (Fig. 10). The pure TiO₂ film did not degrade 4-CP under visible light. The degradation rates of the CdS-modified samples increased with increasing CdS concentration and reached the highest rate at the 1.0% CdS molar ratio, in agreement with the degradation of RhB. This further confirmed that the improved effect was due to CdS-sensitization of the photocatalyst.

Fig. 9. Photocatalytic activity of different catalyst films for RhB degradation. Reaction conditions: surface area of film = 18.75 cm², 5 ml RhB solution (10 mg/L), one 500 W Xe lamp, $\lambda \geq 420$ nm, 30 °C.

Graphical Abstract

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Preparation and visible light catalytic activity of three-dimensional ordered macroporous CdS/TiO₂ filmsCHEN Xiaofang, ZHANG Jia, HUO Yuning*, LI Hexing*
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Three-dimensional ordered macroporous CdS/TiO₂ films prepared by the sol-gel method with a colloidal crystal template and S²⁻ ion exchange exhibited improved visible light photocatalytic activity due to improved light utilization and CdS photosensitization.

Fig. 10. Photocatalytic activity of different catalyst films for 4-CP degradation. Reaction conditions: surface area of film = 18.75 cm², 5 ml 4-CP solution (15 mg/L), one 500 W Xe lamp, $\lambda \geq 420$ nm, 30 °C.

4. Conclusions

Three-dimensional ordered macroporous CdS/TiO₂ films were synthesized using the sol gel method with a colloidal crystal template and S²⁻ ion exchange. CdS was uniformly distributed in the anatase TiO₂ macroporous structure. The light utilization was enhanced by light multiple reflection in the ordered macroporous structure. The modification with CdS enabled visible light harvest and improved the separation of photo-induced electrons and holes. The CdS/TiO₂ film with the 1% CdS molar ratio showed the highest visible light photocatalytic

activity in the aqueous degradation of RhB and 4-CP.

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三维有序大孔CdS/TiO₂薄膜的制备及其可见光催化性能陈晓芳, 张 佳, 霍宇凝*, 李和兴[#]

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摘要: 采用胶体晶体模板辅助溶胶-凝胶法以及S²⁻离子交换法合成了三维有序大孔CdS/TiO₂膜。结果表明, 该薄膜材料在可见光催化降解污染水中罗丹明B和对氯苯酚的反应中表现出高活性。这可归因于修饰剂CdS的光敏化作用实现可见光催化, CdS-TiO₂之间形成了异质结, 促进了电子和空穴的分离; 另一方面, 有序大孔结构有利于光的利用以及反应物的扩散和吸附。

关键词: 硫化镉/二氧化钛薄膜; 三维有序大孔结构; 可见光; 光催化

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1. 前言

有机污染物是造成全球性污染, 尤其是水污染的主要因素^[1,2]. 利用光催化技术降解有机污染物具有环境友好、反应条件温和、节能和成本低等优点^[3,4]. 虽然目前常用的TiO₂光催化剂表现出性能稳定、无毒、无二次污染、价格低廉等特点, 但由于其禁带宽度较大, 只能被紫外光激发, 因而不能有效利用太阳光, 同时量子效率低^[5,6]. 采用不同方法对TiO₂进行修饰可有效实现在可见光下进行光催化反应^[7]. 其中, 基于CdS的敏化作用(禁带宽度为2.4 eV)而使CdS/TiO₂成为广受关注的可见光催化剂^[8]. 目前, 研究较多的是粉末状CdS/TiO₂^[9,10], 但在液相反应中, 光催化剂粉体与反应体系分离困难.

光催化膜反应器由于无需进行催化剂的分离, 因此可实现水中有机污染物的连续治理. 但是, 目前仍难以制备CdS分布均匀且CdS-TiO₂结合力强的CdS/TiO₂膜; 同时, 大多数膜光催化剂对光的利用率不高, 且存在较大的传质限制. 研究表明, 三维有序大孔结构有利于提高材料的比表面积, 促进反应物的传输以及对光的吸收利用, 因而在环境污染物控制以及太阳能利用等领域备受关注^[11,12]. 本文采用胶体晶体模板辅助溶胶-凝胶法以及离子交换法制备了三维有序大孔CdS/TiO₂薄膜材料, 以提高薄膜材料的可见光吸收性能和光催化活性.

2. 实验部分

2.1. CdS/TiO₂膜的制备

2.1.1. 胶粒晶体模板的制备

采用无乳化剂的乳化聚合法制备胶粒晶体^[13]. 取21 ml苯乙烯、0.95 ml丙烯酸及1.1 ml甲基丙烯酸甲酯分散于6.3 mmol重碳酸铵缓冲溶液(0.50 g碳酸氢铵溶于100 ml蒸馏水)中, 在70 °C反应0.5 h, 然后加入2.3 mmol过硫酸铵水溶液, 升温至80 °C, 持续搅拌10 h, 即获得单分散的核壳乳胶粒晶体悬浮液, 即聚(苯乙烯-甲基丙烯酸甲酯-丙烯酸), 简称为P(ST-MMA-AA).

2.1.2. 胶体晶体薄膜的制备

使用1.00 mol/L的NaOH溶液浸泡载玻片2 h, 之后分别使用丙酮、乙醇和去离子水超声清洗后烘干备用.

配制0.250%核壳乳胶粒悬浮液于50 ml烧杯中, 超声使得溶液分散均匀, 沿烧杯壁垂直置入处理好的玻片, 在60 °C烘箱中放置24 h后取出. 由于蒸发作用, 核壳乳胶粒粒子会向载玻片表面迁移, 最终在表面形成薄膜.

2.1.3. 有序大孔CdS/TiO₂薄膜的制备

采用胶体晶体模板辅助溶胶-凝胶法制备有序大孔CdS/TiO₂薄膜. 于20 ml乙醇中逐滴加入1.0 ml四氯化钛, 搅拌5 min后加入不同摩尔浓度的硝酸镉, 搅拌至溶解, 之后加入3.0 ml钛酸四丁酯, 搅拌2 h后即得到硝酸镉含量不同的TiO₂前驱体溶胶. 将带有胶体晶体模板薄膜的载玻片倾斜15°放置, 取0.10 ml溶胶滴加在载玻片表面, 前驱体溶胶通过毛细作用渗透到模板空隙内后, 置于室温中晾干, 并于400 °C焙烧6 h(升温速率2 °C/min). 冷却后将载玻片置于Na₂S溶液(0.20 mol/L)中, 浸渍12 h以进行离子交换, 使用去离子水冲洗干净, 烘干后即可得到样品, 记为xCdS/TiO₂, 其中x为Cd/Ti摩尔比, 分别为0.00%, 0.25%, 0.50%, 0.75%和1.0%. 继续增加Cd/Ti摩尔比则无法得到大孔结构.

作为对比, 在无模板的条件下, 采用以上溶剂凝胶过程制备得到的薄膜材料分别记为TiO₂(C)和1.0%CdS/TiO₂(C). 未采用Na₂S进行离子交换的样品记为1.0%CdO/TiO₂.

2.2. 催化剂的表征

采用Rigaku公司Dmax-3C型X射线衍射(XRD)仪进行薄膜的物相分析, Cu辐射源(0.154 nm), 扫描速率4°/min. 采用日立公司S-4800型扫描电子显微镜(SEM)以及JEOL TEM 2011型高分辨透射电子显微镜(TEM)测试样品的形貌. 采用Quantachrome公司NOVA 4000e型自动物理吸附仪测定样品的N₂吸附-脱附曲线, 用BET方程计算催化剂的比表面积(A_{BET}), 由脱附曲线得到孔径分布. 在岛津UV-2450型分光光度计上进行紫外-可见漫反射光谱(UV-Vis DRS)测试, 测试范围200~800 nm, 以高纯BaSO₄为标准试剂. 采用Versa Probe PHI 5000型X射线光电子能谱(XPS)仪对催化剂样品进行测试. 以Al (1486.6 eV)为发射源, 以污染碳的结合能(C 1s = 284.8 eV)为基准进行结合能校正. 采用Varian Cary-Eclipse 500型荧光(PL)光谱仪测试样品的荧光光

谱, 65 W 氙灯作为激发光源, 扫描速率600 nm/min.

2.3. 催化剂的评价

将3片镀有CdS/TiO₂光催化薄膜的载玻片(2.5 cm × 2.5 cm)置于聚四氟乙烯反应器中, 取5.0 ml 罗丹明B (RhB)溶液(初始浓度10 mg/L)或5.0 ml 对氯苯酚(4-CP)溶液(初始浓度15 mg/L)为目标降解物进行光催化反应. 以一只500W 氙灯为光源, 使用滤波片去除 $\lambda < 420$ nm的光, 反应温度为30 °C. 光催化活性测试前, 吸附0.5 h 以达到吸附平衡. 开灯反应100 min后, 取出反应溶液, 使用UV-Vis 分光光度计分别在 $\lambda = 554$ 和224 nm处测定RhB和4-CP溶液浓度, 并计算各自的降解率.

3. 结果与讨论

3.1. 催化剂的结构

图1为有序大孔1.0% CdO/TiO₂及1.0% CdS/TiO₂薄膜材料的FESEM照片. 可以看出, 1.0% CdO/TiO₂薄膜为大面积的有序大孔结构, 离子交换处理后得到的1.0% CdS/TiO₂薄膜仍很好地保持了三维有序大孔结构, 孔径约为300 nm, 孔壁厚度约为40 nm, 说明胶体晶体模板辅助溶胶-凝胶法结合离子交换法可成功制得有序大孔CdS/TiO₂薄膜材料. 图2为它们的XRD谱. 由图可见, 1.0% CdS/TiO₂大孔薄膜与TiO₂大孔薄膜的衍射峰位置一致, 可归属为锐钛矿相TiO₂(JCPDS 21-1272). 由于CdS的分散度高、含量低, 故无明显的CdS衍射峰.

图3为1.0% CdS/TiO₂薄膜样品的HRTEM照片. 可以观察到两种不同的晶面间距, 即TiO₂(101)面(0.35 nm)和CdS(002)面(0.34 nm), 与文献^[14]一致, 进一步证实CdS均匀分布于TiO₂有序大孔结构中且结晶度较高. 从插图中的TEM照片亦可明显看出规整排布的大孔结构, 与之前的结果一致.

图4为1.0% CdS/TiO₂薄膜样品的XPS谱. 可以看出, Ti 2p, O 1s 和 Cd 3d 谱峰位置与纯相TiO₂及CdS的一致^[15,16], 进一步证明该复合材料是以CdS复合TiO₂的形式存在. 这是由于CdS中Cd²⁺半径(97 pm)远大于Ti⁴⁺ (61 pm), 因而CdS无法进入TiO₂的晶格形成离子掺杂.

图5为1.0% CdS/TiO₂薄膜的N₂吸附-脱附等温线及孔径分布图. 由图可见, 样品的孔径主要集中在2.0~3.8 nm, 说明薄膜材料的大孔孔壁中含有介孔, 因而有利于反应物的吸附; 测得其比表面积为43 m²/g.

图6为不同薄膜材料的UV-Vis DRS谱. 由图可知, TiO₂薄膜的大孔结构有助于提高催化剂对光的吸收, 因

而较TiO₂(C)薄膜表现出更高的光吸收强度. 这主要是由于规整的大孔结构可产生光在其中的多次反射效应所致. 同时, 对TiO₂薄膜通过离子交换处理进行CdS修饰后可有效增强薄膜的可见光吸收. 图7为1.0% CdS/TiO₂与TiO₂薄膜样品的PL谱. 由图可见, 1.0% CdS/TiO₂薄膜的发射峰强度低于TiO₂薄膜, 表明1.0% CdS/TiO₂薄膜由于形成了CdS-TiO₂异质结, 复合材料中光生载流子的复合效率更低, 因而有利于提高光催化过程的量子效率. 这可归因于受光激发后光生电子由CdS传输至TiO₂导带, 增加了TiO₂导带上的电子密度, 因而有效抑制了光生空穴和电子的复合, 如图8所示.

3.2. 催化剂的光催化活性

图9为不同薄膜样品及无催化剂时在可见光下降解RhB的性能. 由图可见, 无催化剂作用时, RhB的光降解率低于2%, 可以忽略不计; 而大孔结构的TiO₂薄膜及1.0% CdS/TiO₂薄膜的光催化活性明显高于无模板制备的TiO₂(C)薄膜及1.0% CdS/TiO₂(C)薄膜. 这可归因于规整的大孔结构增强了光吸收并有利于反应物的传输. 同时, CdS的修饰进一步增强了可见光活性, 与纯TiO₂薄膜相比, 不同CdS含量的CdS/TiO₂薄膜样品的光催化活性均有提高, 其中1.0% CdS/TiO₂薄膜的活性最佳, 在100 min内RhB降解率达到50%以上. 这是由于CdS修饰后有效增加了TiO₂催化剂对可见光的吸收, 同时降低了光生空穴与电子的复合效率, 因而有利于提高光催化过程的量子效率并提高光催化活性^[17].

为了消除RhB的敏化作用, 本文还考察了不同CdS/TiO₂薄膜样品在可见光下光催化降解4-CP的性能, 结果示于图10. 可以看出, 可见光下TiO₂薄膜样品无明显活性, 经CdS修饰的样品上4-CP降解速率随着CdS含量的增加而增加, 至1.0%时活性最佳, 与样品光催化降解RhB的规律一致. 这再次证明了CdS修饰对光催化活性的促进作用.

4. 结论

采用胶体晶体模板辅助溶胶-凝胶法以及离子交换法合成的三维有序大孔CdS/TiO₂薄膜中, CdS均匀分布于锐钛矿相TiO₂的有序大孔结构中. 由于光在有序大孔中的多次反射效应, 增强了光吸收. CdS的修饰实现了TiO₂薄膜对可见光的利用并促进了电子和空穴的分离. 在可见光催化降解水中模拟污染物RhB及4-CP的反应中, CdS含量为1%的CdS/TiO₂薄膜的光催化活性最佳.