available at www.sciencedirect.com

journal homepage: www.elsevier.com/locate/chnjc

Article

Dependence of photocatalytic activity of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ quantum dot composition

Alice Hospodková^a, Ladislav Svoboda^{b,c}, Petr Praus^{b,c,*}^a Institute of Physics of the Academy of Sciences of the Czech Republic, v. v. i., CZ-16200 Prague 6, Czech Republic^b Department of Chemistry, VŠB-Technical University of Ostrava, 17. listopadu 15, 708 33 Ostrava-Poruba, Czech Republic^c Institute of Environmental Technology, VŠB-Technical University of Ostrava, 17. listopadu 15/2172, Ostrava 708 33, Czech Republic

ARTICLE INFO

Article history:

Received 3 October 2014

Accepted 26 November 2014

Published 20 March 2015

Keywords:

Quantum dot

 $\text{Zn}_x\text{Cd}_{1-x}\text{S}$

Photocatalysis

Quantum level

ABSTRACT

Aqueous colloidal dispersions containing $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ quantum dots (QDs) of different x compositions were prepared by precipitating zinc and cadmium acetates with sodium sulphide, in the presence of a cetyltrimethylammonium bromide stabilizer. Ultraviolet-visible absorption spectroscopy was used to determine the transition energies of the QDs, which in turn were used to calculate their sizes, which depended on their composition. The QD size decreased with increasing Zn content. The photocatalytic activity of the $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs was studied by the decomposition of methylene blue under ultraviolet irradiation, at a maximum intensity at 365 nm (3.4 eV). Three different photocatalytic activity regions were observed, which depended on the Zn content. The quantum levels of the QDs could be excited by incident irradiation, and influenced the resulting photocatalytic activity. Maximum photocatalytic activity was achieved at $x = 0.6$, where the QD transition energy was equal to the irradiation photon energy. The photocatalytic efficiency of the QDs depended on their surface area and arrangement of quantum levels, because of the quantum size effect.

© 2015, Dalian Institute of Chemical Physics, Chinese Academy of Sciences.

Published by Elsevier B.V. All rights reserved.

1. Introduction

The photocatalytic activity of semiconductor nanoparticles such as quantum dots (QDs) has been intensively studied over the past decade. The main advantage of QDs is their large surface area, which increases their photocatalytic efficiency. However, the quantum size effect of QDs smaller than the Bohr exciton radius also significantly influences their photocatalytic activity. Photocatalytic reactions on semiconductor QDs involve excitation of electrons from the valence to conduction band, by absorbing photons with energy equal to or higher than the transition energy between the corresponding electron and hole states. Generated electrons and holes at corresponding quan-

tum levels can recombine, or partake in oxidation and reduction reactions of photocatalytic processes on the QDs surface.

$\text{Zn}_x\text{Cd}_{1-x}\text{S}$ is a direct band gap semiconductor with a gap energy between 2.4 (CdS) and 3.7 (ZnS) eV at 300 K [1–3]. Similarly to ZnS and CdS, $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ exhibits photocatalytic properties (see below). The advantage of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ photocatalysts is its larger excitation radius of between 2.5 nm (ZnS) and 3 nm (CdS), compared with photocatalysts such as TiO_2 or ZnO with exciton Bohr radii nearer 2 nm. This allows quantum size effects to be exploited for QDs smaller than 3 nm, so that their electron or hole energies can be adjusted for photocatalytic reactions. Another advantage is the decreased probability of radiative recombination of carriers in QDs smaller than 3 nm

* Corresponding author. Tel: +420-59-7321527; E-mail: petr.praus@vsb.cz

This work was supported by the Czech Science Foundation (P107/11/1918), by the Ministry of Education, Youth and Sports of the Czech Republic in the "National Feasibility Program I", project LO1208 "TEWEP" and by VŠB-Technical University of Ostrava (SP 2014/55).

DOI: 10.1016/S1872-2067(14)60269-2 | http://www.sciencedirect.com/science/journal/18722067 | Chin. J. Catal., Vol. 36, No. 3, March 2015

and compositions close to CdS [4], which can increase their photocatalytic efficiency.

Syntheses and applications of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ nanostructures have been thoroughly described [5–10]. $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ nanoparticles show promise in the visible light photocatalytic production of hydrogen [11,12]. The syntheses and applications of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ nanoparticles were comprehensively reviewed by Fang et al. [13]. We previously investigated the potential of ZnS and CdS QDs in the photocatalytic reduction of CO_2 [14,15]. A ZnS nanocomposite containing the clay mineral montmorillonite (MMT) was also tested for the photodecomposition of phenol [16]. Combinations of ZnS and CdS in core/shell CdS/ZnS nanostructures were studied for the photocatalytic decomposition of methylene blue [17].

The current study investigates how the photocatalytic activity of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs depends on their composition x . MB is used for this purpose, and can be decomposed by hydroxyl radicals formed by the reaction of electrons and holes, according to the scheme published in Ref. [18]. The photocatalytic activity of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs depends on their composition. The experimental results are explained by calculating the QD sizes, and thus the energy levels of electrons and holes involved. To the best of our knowledge, this approach combining reaction kinetics results and quantum calculations has not previously been used to study ternary semiconductor QDs.

2. Experimental

2.1. Materials and chemicals

All solvents and chemicals were of analytical reagent grade. Zinc acetate, cadmium acetate, and sodium sulphide were from Lachema, Czech Republic, and cetyltrimethylammonium bromide (CTBA) was from Sigma-Aldrich, USA. All water used to prepare solutions was deionized by reverse osmosis (Aqua Osmotic, Czech Republic). MMT was purchased from the Source Clays Repository of the Clay Mineral Society (West Lafayette, USA).

2.2. Preparation of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs

$\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs were prepared by precipitating aqueous solutions of zinc and cadmium acetates with sodium sulfide, in the presence of CTAB. We previously found that CTAB created positively charged bilayers around the QDs, thus stabilizing the resulting colloid dispersions [19]. The CTAB concentration was held at ~ 4 mmol/L, to ensure the formation of micelles. The $\text{Zn}(\text{Cd})\text{:S:CTAB}$ molar ratio was 1:1.5:2 [15].

The QDs were deposited on MMT (QDs/MMT) prior to characterization. Depositions of ZnS, CdS, and ZnS/CdS (core/shell) QDs covered by positively charged CTAB layers were attracted to the negatively charged MMT surface, as described previously [14–17,19]. The resulting QDs/MMT solid samples were easily handled, stored and analysed by powder X-ray diffraction (XRD) and transmission and scanning electron microscopies (TEM and SEM).

2.3. Characterization

Ultraviolet-visible (UV-Vis) absorption spectra of ZnS, CdS, and $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ dispersions were measured in 1-cm-pathlength quartz cuvettes using a UV-VIS spectrometer Lambda 25 (Perkin Elmer, USA), at 200–800 nm. Photoluminescence spectra of CdS and $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ nanoparticles were measured by a spectrometer FLS920 (Edinburgh Instrument Ltd., UK) equipped with a 450-W Xenon lamp (Xe900). The excitation wavelength was 365 nm, and the excitation and emission slit widths were 3 nm. A 395-nm absorption filter was used.

Powder XRD patterns were recorded using $\text{Co } K_\alpha$ radiation ($\lambda = 0.1789$ nm) with a Bruker D8 Advance diffractometer (Bruker AXS), equipped with a fast position sensitive detector VÅNTEC 1. Measurements were carried out in reflection mode, on powder samples pressed in a rotational holder. Phase compositions were evaluated using the database PDF 2 Release 2004 (International Centre for Diffraction Data).

High resolution TEM images of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs as QDs/MMT samples were collected on a JEM 220FS microscope (Jeol, Japan), operated at 200 kV. QDs/MMT particles were dispersed in ethanol, and droplets of the resulting dispersion deposited on a TEM grid with a carbon holey support film, using an ultrasonic sprayer.

SEM was performed with a XL 30 Philips SEM microscope (the Netherlands) equipped with a Robinson backscattered electron detector, to examine the $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ morphologies and Zn and S compositions. Powder samples were first coated with gold and palladium in an ionization chamber. Elemental analysis was performed using energy dispersive X-ray spectroscopy (EDX).

2.4. Photocatalytic decomposition of methylene blue (MB)

The photocatalytic activity of colloidal dispersions of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs was evaluated by their degradation of MB under UV irradiation, with a maximum emission wavelength at 365 nm (Hg lamp HSC-1L Pen-Ray, UVP, Germany). Experiments were performed in a stirred batch reactor open to the air. In a typical experiment, a colloidal dispersion of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs was added to an aqueous solution of MB, to give a total volume of 100 mL. The initial concentrations of MB and $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ were 8×10^{-3} and 2 mmol/L, respectively. Before photocatalysis, the MB solution in contact with the QDs was stirred for 10 min in the dark, to reach adsorption equilibrium and homogenize the dispersion [17]. The UV lamp was then switched on. The reactor temperature was kept at 18 °C.

3. Theoretical calculations

QD energy levels were calculated based on the spherical effective mass approximation. In the case of infinite potential barriers, the energy of a particle on the n -th quantum level can be expressed as:

$$E_n = \frac{h^2 \pi^2 n^2}{2mR^2} \quad (1)$$

Table 1Measured and calculated parameters of the $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs.

$\text{Zn}_x\text{Cd}_{1-x}\text{S}$ composition x	Transition energy (eV)	E_g (bulk) (eV)	QD radius infinite barrier (nm)	QD radius finite barrier (nm)	Kinetic constant (s^{-1})
0	2.583	2.4	2.62	2.71	0.00843
0.1	2.707	2.53	2.50	2.52	0.00590
0.2	2.818	2.66	2.46	2.46	0.00216
0.3	2.945	2.79	2.36	2.29	0.00268
0.4	3.155	2.92	1.99	1.76	0.01260
0.5	3.238	3.05	2.06	1.84	0.01248
0.6	3.435	3.18	1.82	1.53	0.02066
0.7	3.594	3.31	1.71	1.29	0.00843
0.8	3.735	3.44	1.65	1.30	0.00495
0.9	3.792	3.57	1.77	1.40	0.00317
1	3.924	3.7	1.74	1.34	0.00124

sorption spectra.

The photoluminescence spectra in Fig. 3 show that increasing the Zn content increased the emission intensity. Small peaks at ~ 418 nm were likely caused by Raman scattering of water molecules. The high intensity emission at ~ 580 nm was probably caused by surface defects and traps, with slow radiative recombination. The decay time of these wide maxima was typically several μs . Under low excitation intensity, slow transitions dominated the spectra, and band edge luminescence was negligible. Under high excitation intensity (laser source), these

Fig. 2. UV-Vis absorption spectra of ZnS, CdS, and $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ colloidal dispersions. **Fig. 3.** Photoluminescence of ZnS, CdS, and $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs in colloid dispersion.

energy levels were saturated, and much faster excitonic transitions become dominant. This phenomenon has been observed in other materials with deep defect luminescence [24]. Similar spectra under low intensity excitation from a Xe lamp, and a comparison of different decay times for different excitation intensities, have been reported previously [25].

Complexes with deep acceptor surface states were probably responsible for the broad luminescence maxima. The position and intensity of the broad maximum slightly differed between samples, because the concentration and energy of deep defects depended on the QD composition and specific surface. The lowest intensity broad peak was observed for the CdS QDs, probably because of their lowest surface area. Different kinds of deep defects were responsible for the photoluminescence of the ZnS QDs. Only electrons contributed to the photocatalytic decomposition of MB, so deep acceptor levels could increase the photocatalytic activity of the QDs, by decreasing the radiative recombination rate.

4.2. XRD results

The QDs were unable to be deposited on non-diffractive silicon or glass. Thus, $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs were deposited on MMT and studied by XRD (Fig. 4). The intensities of diffraction peaks characteristic of the QDs were low, and were largely obscured by the stronger diffraction peaks of MMT and quartz [26]. No

Fig. 4. XRD patterns of $\text{Zn}_{0.1}\text{Cd}_{0.9}\text{S}$ (1), $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{S}$ (2), $\text{Zn}_{0.4}\text{Cd}_{0.6}\text{S}$ (3), $\text{Zn}_{0.7}\text{Cd}_{0.3}\text{S}$ (4) QDs deposited on MMT. The (101) peak is the most intense XRD peak of cadmium zinc sulphide.

ZnS and CdS diffractions were observed, indicating that there was no phase separation of ZnS and CdS within $\text{Zn}_x\text{Cd}_{1-x}\text{S}$. The XRD patterns showed that the QDs were of hexagonal phase, with the strongest (101) peak for zinc cadmium sulphide observed at $2\theta = 34.3^\circ$ (PDF 00-04901302).

4.3. SEM results

The SEM image (Fig. 5(a)) shows $\text{Zn}_{0.4}\text{Cd}_{0.6}\text{S}$ QDs deposited on MMT. The EDX spectrum (Fig. 5(b)) indicated the presence of Zn, Cd, and S in the $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs. The C and Br peaks were due to the presence of the CTAB stabilizer. Other elements were components of montmorillonite. EDX indicated that the true composition of $\text{Zn}_{0.2}\text{Cd}_{0.8}\text{S}$ was $\text{Zn}_{0.21}\text{Cd}_{0.79}\text{S}$, and that of $\text{Zn}_{0.4}\text{Cd}_{0.6}\text{S}$ was $\text{Zn}_{0.38}\text{Cd}_{0.62}\text{S}$.

4.4. TEM results

The QDs/MMT samples were examined by TEM. Fig. 6 shows a TEM image of the $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{S}$ QDs, and their corresponding size distribution. The average sizes of the $\text{Zn}_{0.1}\text{Cd}_{0.9}\text{S}$, $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{S}$, $\text{Zn}_{0.4}\text{Cd}_{0.6}\text{S}$, and $\text{Zn}_{0.7}\text{Cd}_{0.3}\text{S}$ particles estimated from the TEM images were 5.0, 5.4, 5.2, and 4.2 nm, respectively. The corresponding radii were approximately 2.1–2.5 nm, which were consistent with the calculated radii shown in Table 1. QDs sizes estimated from the TEM images may have been influenced by the thickness of the adsorbed CTAB layer [19].

4.5. Photocatalytic decomposition of MB

The photocatalytic efficiencies of the CdS, ZnS, and $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs were investigated by their photocatalytic decomposition of

Fig. 5. SEM image (a) and EDX spectrum (b) of $\text{Zn}_{0.4}\text{Cd}_{0.6}\text{S}$ QDs deposited on MMT.

Fig. 6. TEM image of $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{S}$ QDs with a size distribution histogram (inset).

MB. The rate of this heterogeneous reaction ($\langle r \rangle$) can be described by the Langmuir-Hinshelwood equation [27–29]:

$$\langle r \rangle = k_{\text{obs}} c_{\text{MB}} \quad (8)$$

where k_{obs} is the observed kinetic rate constant, and c_{MB} is the MB concentration. k_{obs} was calculated by fitting the measured data, using the integrated rate equation based on first order kinetics ($\ln c_0/c = k_{\text{obs}} t$, where c_0 and c are the concentrations of MB at time $t = t$ and $t = 0$, respectively). The same photocatalytic experiments were performed using the CdS and ZnS QDs for comparison, and also in the absence of QDs to observe any MB photocatalysis, which was found to be negligible.

Aqueous dispersions of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs were prepared with x ranging from 0 (CdS) to 1 (ZnS) in 0.1 increments. The kinetic rate constants for the decomposition of MB are shown in Fig. 7. Increasing Zn content in $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs was expected to increase the photocatalytic activity, owing to the higher electron energy, as discussed below. However, three distinct regions were observed, each with different dependence of photocatalytic activity on QD composition.

In region A ($x \leq 0.3$), the photocatalytic efficiency decreased with increasing Zn content. The expected increase in photo-

Fig. 7. Kinetic rate constants for the photocatalytic decomposition of MB in aqueous dispersions of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs. Three regions exhibited differing dependence of photocatalytic activity on $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ composition.

catalytic efficiency was observed in region B, and efficiency reached a maximum at $x = 0.6$. Efficiency then decreased continually with increasing Zn content in region C.

The QD sizes were necessary to explain this result. QD radii were derived from the measured transition energies determined using Eq. (5), and are summarized in Table 1 and Fig. 8. This energy was equal to the transition energy between the ground (1st) electron and hole levels (E_{t1}) (Fig. 1). QD radii were calculated using Eqs. (3) and (4), and also by approximation with infinite energy barriers using Eq. (6). The radii calculated using these two methods are compared in Fig. 8. Values were similar for larger QDs, but deviated for smaller QDs. The penetration of electrons into the energy barriers (water) was more significant for smaller QDs. Approximation with a finite barrier and penetration of carriers into the energy barrier region was considered to yield more precise QD radii values, so were used as input parameters for further calculations. The calculated $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QD radii decreased with increasing Zn content.

We calculated the transition energies between the electron and hole energy levels for the first three corresponding electron and hole quantum states, for the series of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs. These results are shown in Fig. 9. When the quantum levels were close to the barrier energy, they were much less influenced by the QD composition. Larger QDs possessed quantum levels located deeper within the potential well. Thus, their transition energies were more influenced by the gap energy, which corresponded to the $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ composition. The composition of smaller QDs ($R = 1.3\text{--}2.7\text{ nm}$) only slightly influenced their properties.

We now consider the dependence of photocatalytic activity on $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QD composition in the different regions in Fig. 7. The excitation energy was compared with the transition energies between electron and hole quantum levels in the QDs, as shown in Fig. 9. The three sets of curves show the calculated transition energies of the 1st, 2nd, and 3rd quantum states for $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs with $x = 0, 0.2, 0.5$, and 1. Squares represent experimental data for the lowest energy transition between the first electron and hole levels. These transition energies (E_{t1})

Fig. 8. Measured transition energies for QDs with different composition, and radii calculated using the infinite barrier energy and finite barrier energy approaches.

Fig. 9. Dependence of transition energies on $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QD radius. Squares: ground state transitions; circles: transition between the second electron and hole quantum levels. The excitation energy is marked for comparison.

were derived from the UV-Vis absorption spectra. Circles represent the calculated excited states transition (E_{t2}) (between the 2nd electron quantum state and 2nd hole quantum state). Black lines connecting these points show approximate transition energies of the QDs, which could theoretically be prepared using the current method. These black curves show that the QD size decreased with increasing x (crossovers of straight and structured lines of calculated transition energies).

The transition energies of the QDs were compared with the excitation energy, to explain the photocatalytic efficiencies of the QDs. Two crossovers of black lines with excitation energy defined the three regions with different numbers of quantum states, which could be excited. For QD radii $> 2.5\text{ nm}$ in region I, photons with excitation energy of 3.4 eV were sufficient to generate electron-hole pairs in two quantum states. In region II, QDs had radii of $1.7\text{--}2.5\text{ nm}$. These QDs could absorb the photon energy, but it was only sufficient for generating electron-hole pairs in the ground quantum states. For QDs with smaller radii in region III, the photon energy was insufficient to generate electron-holes pair in any quantum state. These three regions are closely related to regions A–C exhibiting different photocatalytic behaviour in Fig. 7.

Comparing regions in Figs. 7 and 9 must be done while considering that the QD size distribution was not sharp, and the QD radius calculated from E_{t1} reflected the maximum of the QD size distribution (Fig. 6). In region A of Fig. 7, the QD Zn content was < 0.3 , and the QD radius was $> 2.5\text{ nm}$. Thus, the electron-hole pairs could be generated in two quantum states, corresponding to region I in Fig. 9. With increasing Zn content, the QD radius decreased to the QD size limit, where only one quantum dot level could be activated by the excitation. In this region, the number of QDs where two quantum levels could be excited decreased with increasing Zn content. The second quantum level contained three times more electron states than the first. The number of excited electrons decreased steeply, and could

not be compensated by the increased QD density and increased surface area, as a result of the decreasing QD size. The fewer available electrons excited by the incident irradiation also suppressed the photocatalytic activity. This was consistent with the dependence of photocatalytic activity on QD composition in region A of Fig. 7.

When almost all QDs crossed this limit, only the ground quantum level in the QDs could be excited (region B in Fig. 7, and region II in Fig. 9). In region B, further increasing the Zn content increased the photocatalytic efficiency, mainly due to the increased QD surface area. This was inversely proportional to the decreasing QD radius and increased QD density in the dispersion. The increased penetration of electrons into aqueous solution, and the increased probability of QD excitation with increased E_{t1} , also contributed.

The maximum photocatalytic activity was achieved for the QDs with $x = 0.6$. Here, E_{t1} for the 1st quantum level was equal to with excitation energy, which increased the excitation probability of this quantum state. The number of QDs able to be excited sharply decreased at higher Zn content. No electron-hole pairs were generated in the majority of these QDs, and their photocatalytic activity under the current excitation decreased (region C in Fig. 7, corresponding to region III in Fig. 8).

5. Conclusions

Aqueous dispersions of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs ($x = 0-1$) were prepared by precipitating zinc and cadmium acetate with sodium sulphide in the presence of CTAB. The transition energies between the first electron and hole quantum levels indicated that the QD size was influenced by the $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ composition. QD size decreased with increasing Zn content. The photocatalytic activity of the $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs did not simply increase with increasing Zn content. The maximal photocatalytic decomposi-

tion of MB was observed for $x = 0.6$, when the QD transition energy was equal to photon energy (3.4 eV). Three different $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ composition regions exhibited different dependences of photocatalytic activity on Zn content. The number of quantum levels which could be excited influenced the photocatalytic activity of the $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ QDs. Engineering QDs with suitable composition and size is important for maximizing their photocatalytic activity. These findings aid our understanding of processes involved in photocatalysis. They provide a way to optimize QD properties, and achieve high photocatalytic activity with respect to the incident irradiation.

Acknowledgments

The authors thank Dr. K. Mamulová Kutlárková and Mrs. M. Heliová (both from Nanotechnology Centre, VŠB-Technical University of Ostrava) for measuring the XRD patterns and the SEM analysis, respectively.

References

- [1] Hirai T, Sato H, Komasaawa I. *Ind Eng Chem Res*, 1994, 33: 3362
- [2] Schmid G. *Nanoparticles: From Theory to Applications*. Weinheim: Wiley-VCH, 2010
- [3] Dutta K, Manna S, De S K. *Synth Metals*, 2009, 159: 315
- [4] Dib M, Chamarro M, Voliotis V, Fave J L, Guenand C, Roussignol P, Gacoin T, Boilot J P, Delerue C, Allan G, Lanoo M. *Phys Stat Sol (b)*, 1999, 212: 293
- [5] Li Q, Meng H, Yu J G, Xiao W, Zheng Y Q, Wang J. *Chem Eur J*, 2014, 20: 1176
- [6] Xu X, Lu R J, Zhao X F, Xu S, Lei X D, Zhang F Z, Evans D G. *Appl Catal B*, 2011, 102: 147
- [7] Xu X, Lu R J, Zhao X F, Zhu Z, Xu S, Zhang F Z. *Appl Catal B*, 2012, 125: 11
- [8] Li Y C, Ye M F, Yang C H, Li X H, Li Y F. *Adv Func Mater*, 2005, 15: 433

Graphical Abstract

Chin. J. Catal., 2015, 36: 328–335 doi: 10.1016/S1872-2067(14)60269-2

Dependence of photocatalytic activity of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ quantum dot composition

Alice Hospodková, Ladislav Svoboda, Petr Praus*

Institute of Physics of the Academy of Sciences of the Czech Republic, Czech Republic; VŠB-Technical University of Ostrava, Czech Republic

The size of $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ quantum dots decreased with increasing Zn content. Their photocatalytic activity depended on the number of quantum states which could be excited by the incident irradiation.

- [9] Liu Y K, Zapien J A, Shan Y Y, Gen C Y, Lee C S, Lee S T. *Adv Matter*, 2005, 17: 1372
- [10] Zhong X H, Liu S H, Zhang Z H, Li L, Wei Z, Knoll W. *J Mater Chem*, 2004, 14: 2790
- [11] Li Q, Meng H, Zhou P, Zheng Y, Wang J, Yu J G, Gong J R. *ACS Catal*, 2013, 3: 882
- [12] Yu J G, Zhang J, Jaroniec M. *Green Chem*, 2010, 9: 1611
- [13] Fang X S, Zhai T Y, Gautam U K, Li L, Wu L M, Bando Y, Golberg D. *Prog Mater Sci*, 2011, 56: 175
- [14] Kočí K, Reli M, Kozák O, Lacný Z, Plachá D, Praus P, Obalová L. *Catal Today*, 2011, 176: 212
- [15] Praus P, Kozák O, Kočí K, Panáček A, Dvorský R. *J Colloid Interf Sci*, 2011, 360: 574
- [16] Praus P, Matys J, Kozák O. *J Braz Chem Soc*, 2012, 23: 1900
- [17] Praus P, Svoboda L, Tokarský J, Hospodková A, Klem V. *Appl Surf Sci*, 2014, 292: 813
- [18] Chiou C H, Wu C Y, Juang R S. *Sep Purif Technol*, 2008, 62: 559
- [19] Praus P, Dvorský R, Horínková P, Pospíšil M, Kovář P. *J Colloid Interf Sci*, 2012, 377: 58
- [20] Schooss D, Mews A, Eychmüller A, Weller H. *Phys Rev B*, 1994, 49: 17072
- [21] Zgaren I, Balti J, Jaziri S. *Solid State Commun*, 2011, 151: 1743
- [22] Brus L E. *J Chem Phys*, 1984, 80: 4403
- [23] Tauc J, Grigorovici R, Vancu A. *Phys Stat Sol (b)*, 1966, 15: 627
- [24] Hospodková A, Nikl M, Pacharová O, Oswald J, Brůža P, Pánek D, Foltynski B, Hulicius E, Beitlerová A, Heuken M. *Nanotechnology*, 2014, 25: 455501
- [25] Kulkarni S K, Winkler U, Deshmukh N, Borse P H, Fink R, Umbach E. *Appl Surf Sci*, 2001, 169-170: 438
- [26] Tokarský J, Matějka V, Neuwirthová L, Vontorová J, Mamulová Kutláková K, Kukutschová J, Čapková P. *Chem Eng J*, 2013, 222: 488
- [27] Roberts G W, Satterfield C N. *Ind Eng Chem Fund*, 1965, 4: 288
- [28] Kumar K V, Porkodi K, Rocha F. *Catal Commun*, 2008, 9: 82
- [29] Brosillon S, Lhomme L, Vallet C, Bouzaza A, Wolbert D. *Appl Catal B*, 2008, 18: 232